Future Water Cherenkov Detectors Experiments

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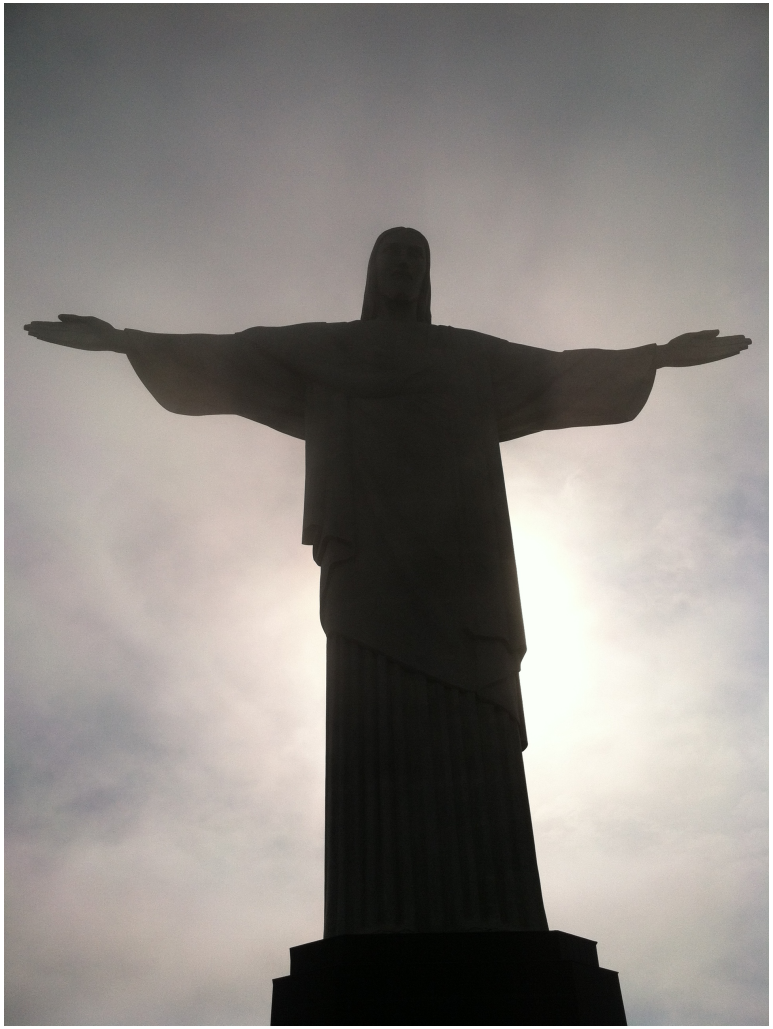


In this talk

- Brief overview of proposed water Cherenkov experiments
  - HYPER-K
  - MEMPHYS
  - LBNE Water option (RIP); other USA efforts: ANNIE and WATCHMAN

- Some of the other science goals
  - Beam/atmospheric neutrino characterization via neutron tagging
  - Super-nova
  - Reactor anti-neutrino measurements

- Improvements for Water Cherenkov Detectors
  - Improvement in current PMT technology
  - Improvement in light collection devices (LBNE WCD R&D perspective)
  - Water-based liquid scintillation

Why water?

- Many of the unresolved physics (δ_{cp}, mass hierarchy, proton decay) require larger scale detectors, megaton scale would be ideal

- There are challenges in going megaton scale
  - Cost
  - Light attenuation concerns
    - Liquid Scintillator ~20 m
    - CH_2 ~ 25-40 m
    - H_2O ~ 100 m
  - Pressure concerns (prevent Super-K tube implosion risk)

Liquid Scintillation (versus Water Cherenkov)

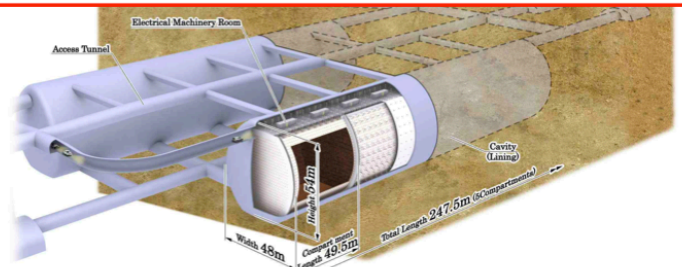
Cons	Pros
Safety: Chemical hazard, Fire hazard, and Reactivity	orders of magnitudes light output: smaller detector or less photo-sensors
Cost: $2k/ton or $100M for 50 KT	Physics of charged particles below Cherenkov threshold
Handling & ES&H	Excellent PSD to suppress background events
event reconstruction and PID	Sub-MeV (geo-, solar- and reactor) neutrinos

Minfang Yeh, ANT 2010

HYPER-K

Hyper-K overview

Total vol.	0.99 Mton
Fiducial vol.	0.56 Mton (0.056 Mton x 10 compartments)
Photo-sensors	99,000 of 20-inch PMTs for Inner Detector (20% photo-coverage) 25,000 of 8-inch PMTs for Outer Detector



x 25 of Super-K

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Nakaya, NNN2012

Sensitivity to Science Goals

Physics Target	Sensitivity	Conditions
Neutrino study w/ J-PARC ν		1.66 MW $\times$ 5 years (1 year $\equiv 10^7$ sec)
– CP phase precision	$< 18^\circ$	@ $s^2 2\theta_{13} (\equiv \sin^2 2\theta_{13}) > 0.03$ and mass hierarchy (MH) is known
– CPV 3σ discovery coverage	74% (55%)	@ $s^2 2\theta_{13} = 0.1$, MH known(unknown)
	74% (63%)	@ $s^2 2\theta_{13} = 0.03$, MH known(unknown)
	66% (59%)	@ $s^2 2\theta_{13} = 0.01$, MH known(unknown)
Atmospheric neutrino study		10 years observation
– MH determination	$> 3\sigma$ CL	@ $0.4 < s^2\theta_{23}$ and $0.04 < s^2 2\theta_{13}$
– θ_{23} octant determination	$> 90\%$ CL	@ $s^2 2\theta_{23} < 0.99$ and $0.04 < s^2 2\theta_{13}$
Nucleon Decay Searches		10 years data
– $p \to e^+ + \pi^0$	1.3×10^{35} yrs (90% CL)	
	5.7×10^{34} yrs (3σ CL)	
– $p \to \bar{\nu} + K^+$	2.5×10^{34} yrs (90% CL)	
	1.0×10^{34} yrs (3σ CL)	
Solar neutrinos		
– ^{8}B ν from Sun	200 ν's / day	7.0 MeV threshold (total energy) w/ osc.
– ^{8}B ν day/night accuracy	$< 1\%$	5 years, only stat. w/ SK-I BG $\times 20$
Astrophysical objects		
– Supernova burst ν	170,000~260,000 ν's	@ Galactic center (10 kpc)
	30~50 ν's	@ M31 (Andromeda galaxy)
– Supernova relic ν	830 ν's / 10 years	
– WIMP annihilation at Sun		5 years observation
	$\sigma_{SD} = 10^{-39}\text{cm}^2$	@ $M_{\text{WIMP}} = 10$ GeV, $\chi\chi \to b\bar{b}$ dominant
	$\sigma_{SD} = 10^{-40}\text{cm}^2$	@ $M_{\text{WIMP}} = 100$ GeV, $\chi\chi \to W^+W^-$ dominant

Letter of Intent:

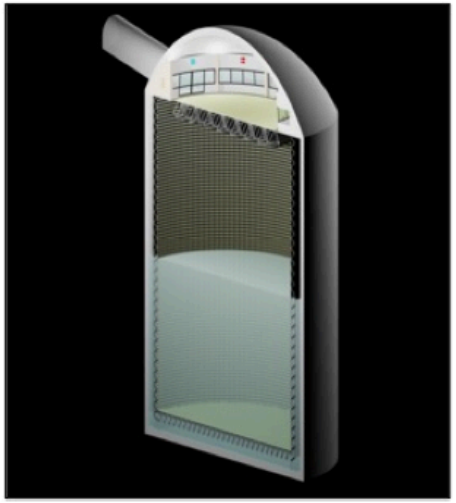
The Hyper-Kamiokande Experiment — Detector Design and Physics Potential — arxiv.1109.3262v1

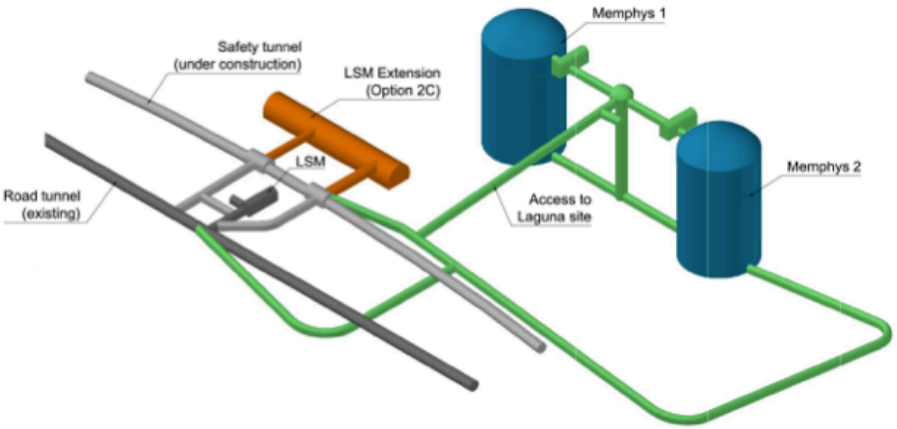
MEgaton Mass PHYSics

MEMPHYS

- Part of the Laguna Design Study, as a second option
- Rock overburden of 4800 m.w.e. at Frejus
- 2 modules of 103m height and 65m diameter
- 500 kton of fiducial volume
- 81 000 12” PMTs to reach 30% coverage

  or
- 40% coverage with 20” PMTs



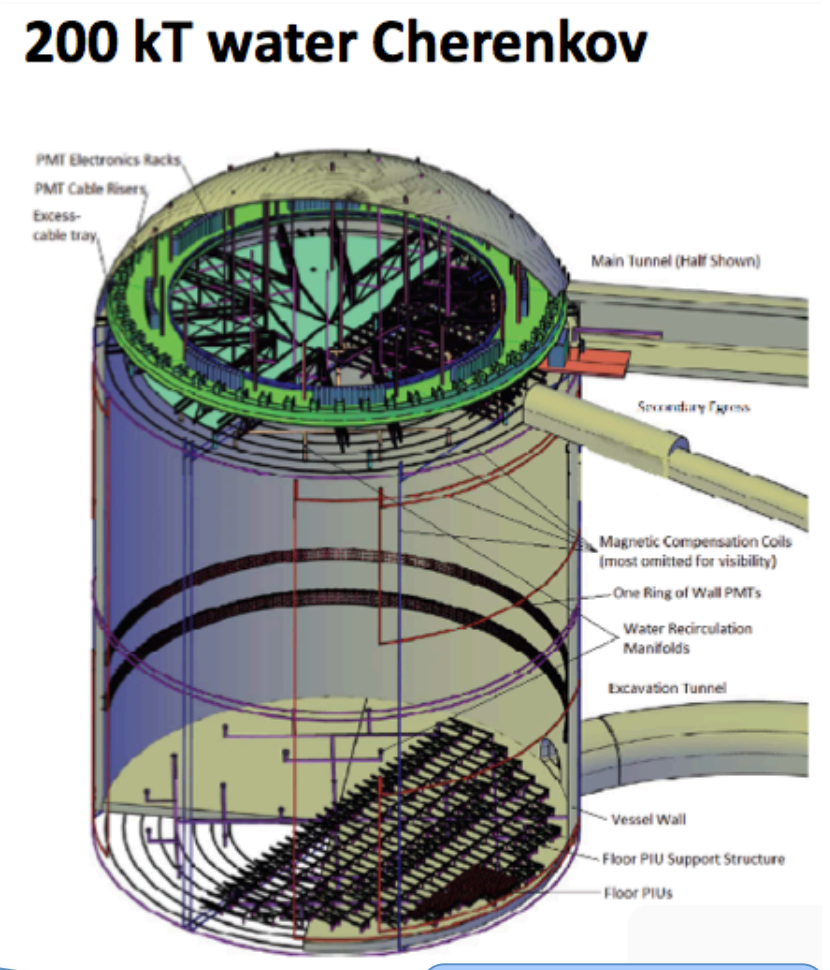


arXiv:1206.6665v2

LBNE Water Cherenkov Detector (RIP)

What was proposed

- 200 kton FV
- Homestake 4850 ft level
- Total 29,000 PMTs, in order to reduce total cost:
  - Total PMT area of 9.8%
  - With HQE PMT increase to 15%
  - Light collectors (assumed to increase the light collection by 40%) will extend the coverage to 20%.
  - Smaller PMT size relative to SK-II would have resulted in a 30% finer granularity.
- The LAr option was chosen (has should not be news to anyone)



More on this later

Long-Baseline Neutrino Experiment (LBNE) Conceptual Design Report - The LBNE Water Cherenkov Detector
April 12, 2012 arXiv:1204.2295v1

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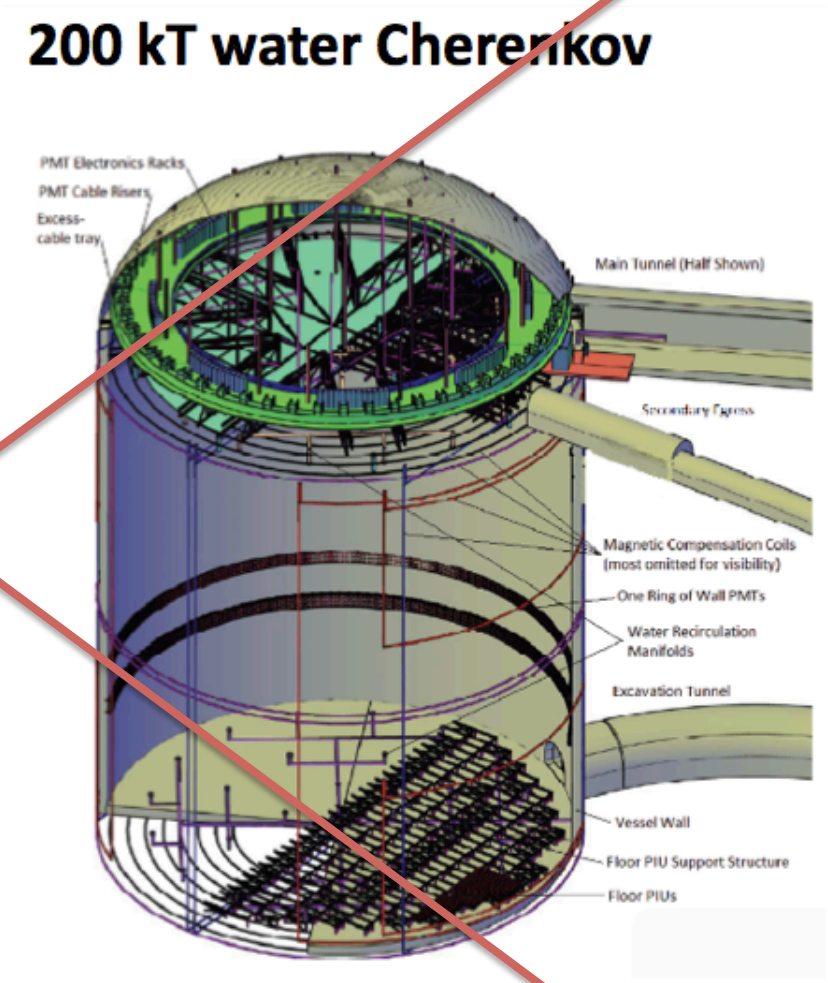

Long-Baseline Neutrino Experiment (LBNE) Conceptual Design Report - The LBNE Water Cherenkov Detector
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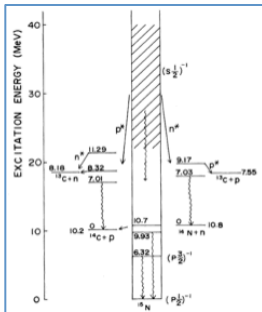
Some physic topics and new proposed experiments

Isolating *p* decay via neutron tagging



Nuclear Physics of Proton Decay in ^{16}O

Spectroscopic factors measured in $^{16}O(e,ep)^{15}N$ experiment

Gamma-ray emission measured in $^{16}O(p,2p)^{15}N$ experiment

Hole	Residual	States	(k)	E_γ	E_p	E_n	$B(k)$
$(p_{1/2})_p^{-1}$	g.s.	$\frac{1}{2}^-$	^{15}N	0	0	0	0.25
$(p_{3/2})_p^{-1}$	6.32	$\frac{3}{2}^-$	^{15}N	6.32	0	0	0.41
	9.93	$\frac{3}{2}^-$	^{15}N	9.93	0	0	0.03
	10.70	$\frac{3}{2}^-$	^{15}N	0	0.5	0	0.03
$(s_{1/2})_p^{-1}$	g.s.	1^+	^{14}N	0	0	~ 20	0.02
	7.03	2^+	^{14}N	7.03	0	~ 13	0.02
	g.s.	$\frac{1}{2}^-$	^{13}C	0	1.6	~ 11	0.01
	g.s.	0^+	^{14}C	0	~ 21	0	0.02
	7.01	2^+	^{14}C	7.01	~ 14	0	0.02
	g.s.	$\frac{1}{2}^-$	^{13}C	0	~ 11	~ 2	0.03
$(j)_p^{-1}$	others		many states	$\leq 3-4$			0.16

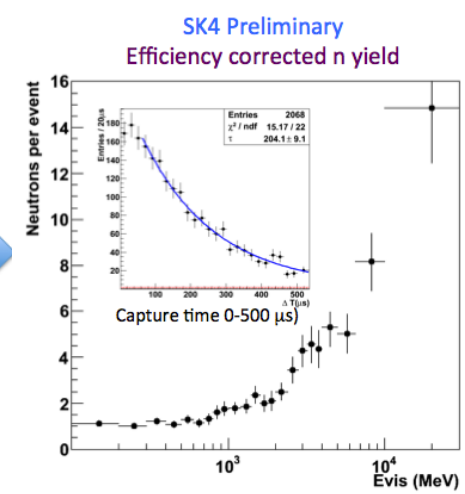
Motivation: Proton decay have a low chance of producing FSI neutron

gamma modes that can help tag proton decay candidate

Super-K have started studying neutron production from atmospheric neutrinos

They are seeing an average of 2 neutrons per neutrino at the proton decay energy

- New SK electronics (SK4 only) allows search for neutron associated with atmospheric neutrinos (capture on free proton, 2.2 MeV γ).
- Other current, near future, and recent past experiments can also search. T2K, SciBooNE e.g.

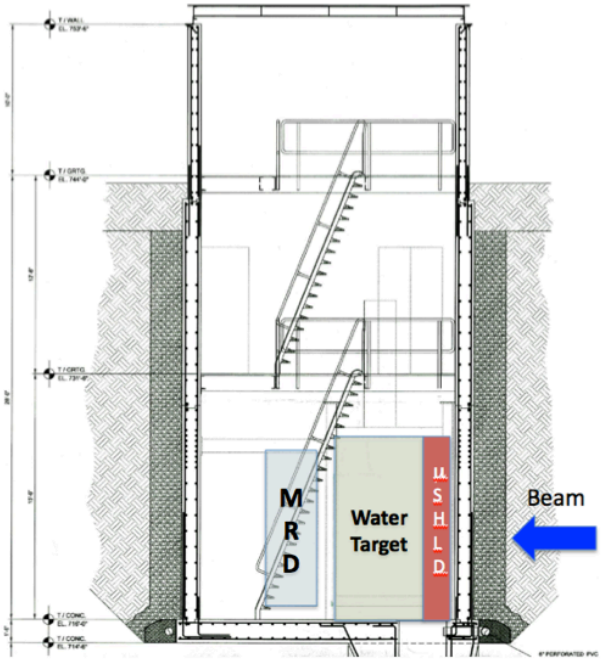


Ed Kearns, NNN2012

Atmospheric Neutrino Neutron Interaction Exploration

ANNIE

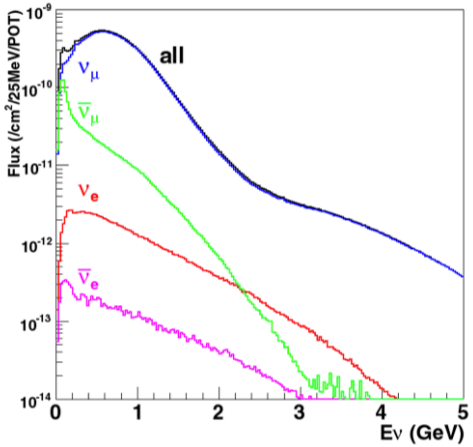
- Dedicated experiment to measure neutron yield from MeV to GeV scale neutrinos
- Would use existing SciBooNE hall in the FNAL booster beam
- Gd-doped Water Target possibly upgraded to CH_2 : 3 m x 3 m and 2 m thick Muon Range Detector (MRD) :
  - 12 2-inch-thick iron plates between 13 scintillation panels
  - 362 two-inch PMTs.
- LOI to be submitted to FNAL PAC before the end of the year, interested collaborators are welcomed



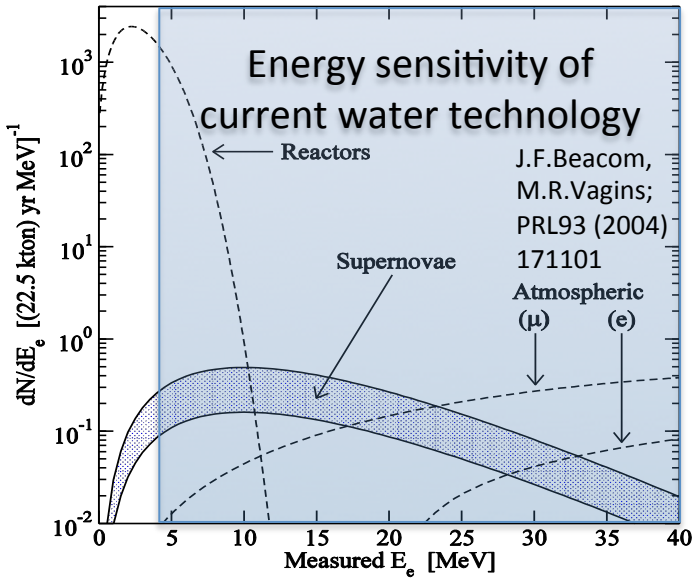
Rates Expected with 1×10^{20} POT exposure at SciBooNE pit

Djurcic

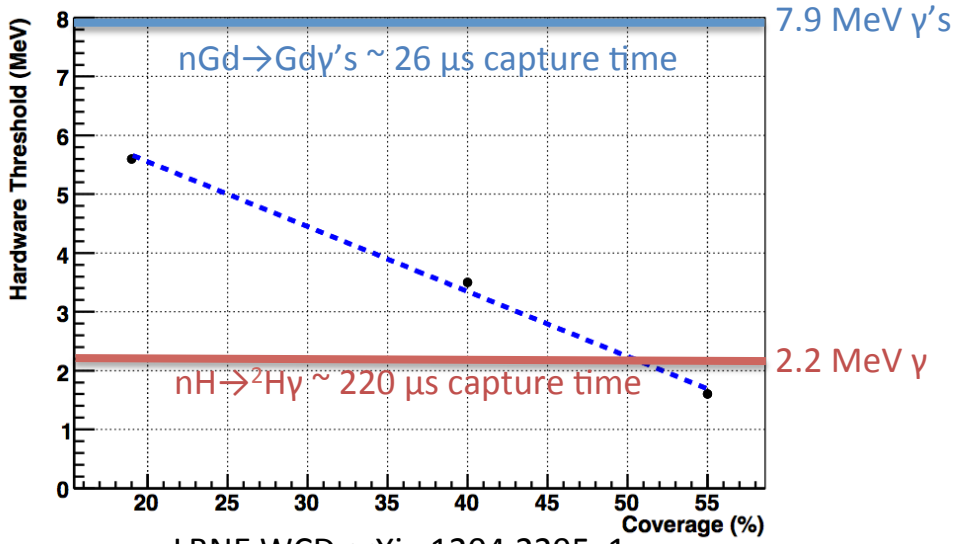
	Total Events [1/1ton/10^{20}POT]	ν-type	Total (per ν-type)	Charged Current	Neutral Current
Booster Beam (ν-mode, Target = CH_2)	10419	ν_μ	10210	7265	2945
		anti-ν_μ	133	88	45
		ν_e	72	52	20
		anti-ν_e	4.4	3	1.4
Booster Beam (ν-mode, Target = H_2O)	10612	ν_μ	10405	7443	2962
		anti-ν_μ	129	85	44
		ν_e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



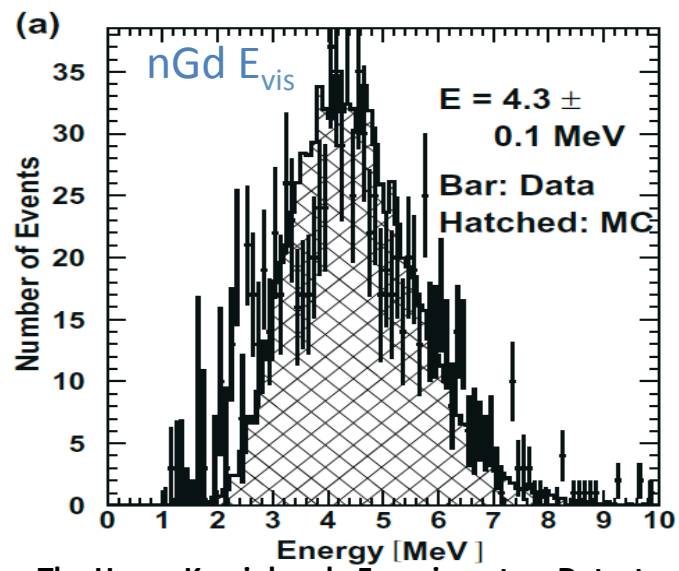
Capturing the neutron: Challenges of energy sensitivity of Cherenkov detector



- Coverage important on energy threshold
- LBNE R&D allow improvement on the energy sensitivity
- EGADS is paving the way for water-soluble Gd-loading for neutron detection



LBNE WCD arXiv:1204.2295v1

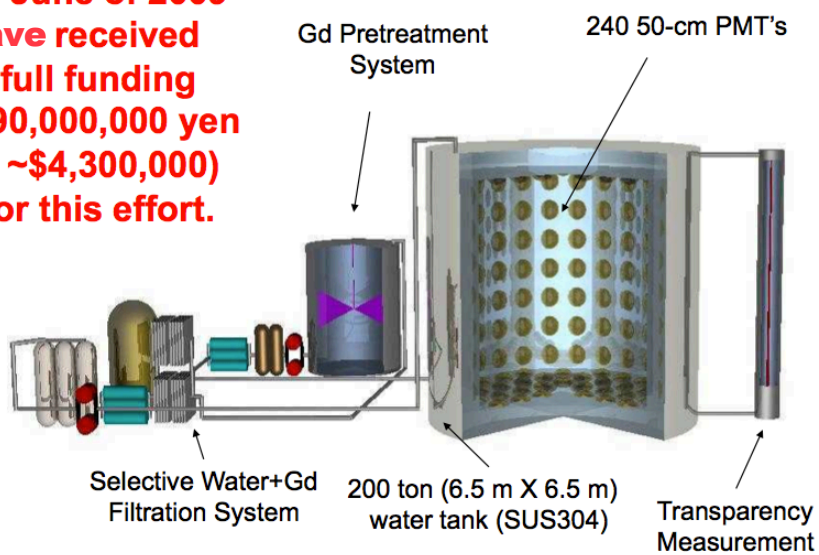


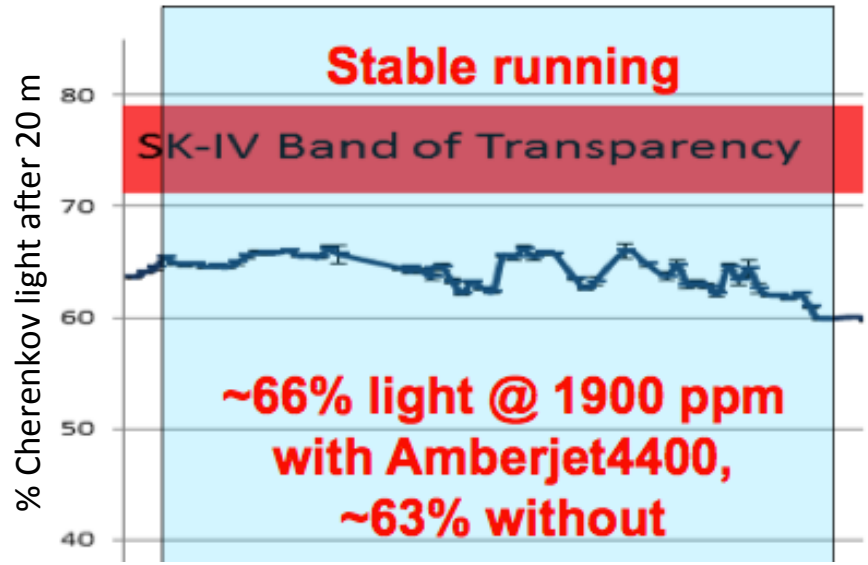
The Hyper-Kamiokande Experiment — Detector Design and Physics Potential — arxiv.1109.3262v1

Gd-doped water development at EGADS

EGADS Facility

In June of 2009 have received full funding (390,000,000 yen = ~$4,300,000) for this effort.





Studies continue, but have already achieved stable light levels of 66% at 20 meters with fully Gd-loaded water.

This should be compared to a range of 71%→79% for "perfect" pure water in SK-IV.

→ *No detected Gd loss after >100 complete turnovers.*←

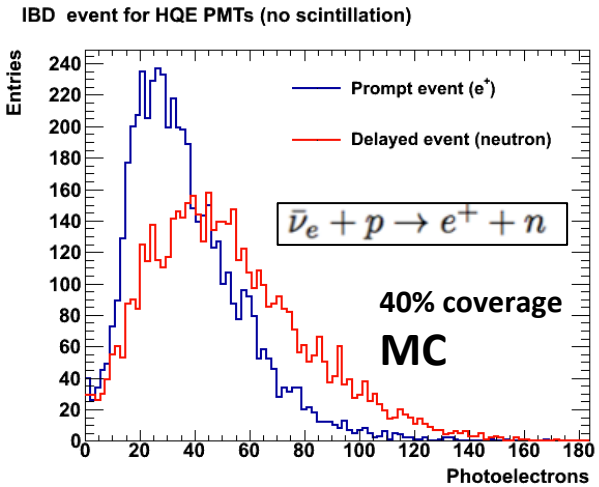
Mark Vagins, Kavli IPMU, UTokyo/UC Irvine (PACIFIC 2012)

WATer **CH**erenkov **M**onitoring of **A**nti-**N**eutrinos

WATCHMAN

Drafting proposal to National Nuclear Security Agency (DOE):

- 1 kiloton water-based Cherenkov detector
- 1 to 10 km standoff at 0.1 to 10 GWt reactor
- Background measurement (fast neutron/radio-nuclide) underway at KURF which will affect technology and site selection decision
- Light collection choice and detector improvement under review
- Science review this Fall, collaborator welcomed
- Decision late 2014 to early 2015
- Ocean deployment is also considered



Lawrence Livermore National Laboratory

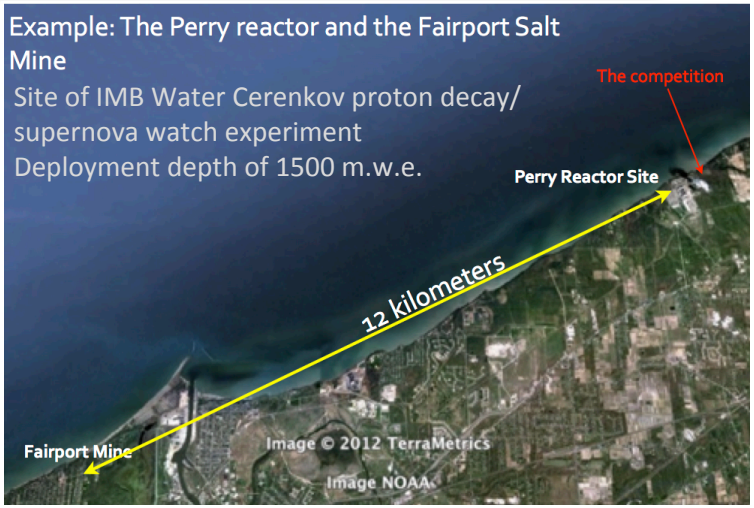
Sandia National Laboratories

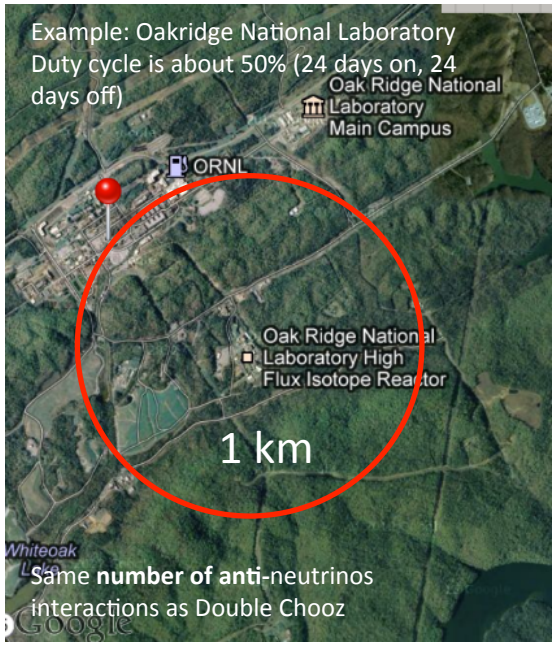
UC Berkeley

UC Davis

University of Hawaii

UC Irvine





Bergevin, NNN2012

Supernova rule of thumbs

HYPER-K 1 Megaton detector:

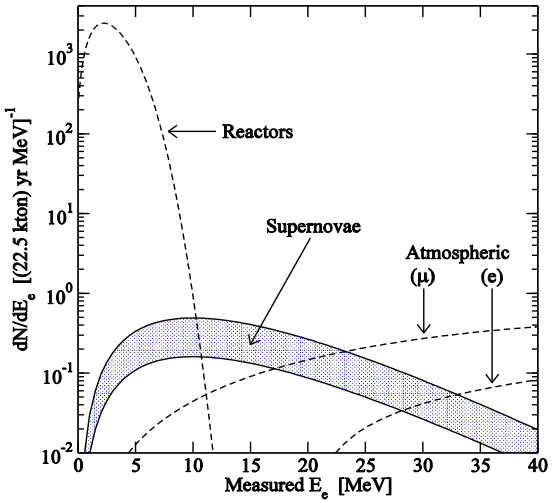
Astrophysical objects		
– Supernova burst ν	170,000~260,000 ν's	@ Galactic center (10 kpc)
	30~50 ν's	@ M31 (Andromeda galaxy)
– Supernova relic ν	830 ν's / 10 years	

- Expect 300 to 470 neutrinos per kiloton from burst
- Anti-neutrino reaction dominate

100 kton of water, for the 30% PMT coverage detector configuration

Channel	Events, "Livermore" model	Events, "GKVM" model
$\bar{\nu}_e + p \rightarrow e^+ + n$	27116	16211
$\nu_x + e^- \rightarrow \nu_x + e^-$	868	534
$\nu_e +^{16}\mathrm{O} \rightarrow e^- +^{16}\mathrm{F}$	88	379
$\bar{\nu}_e +^{16}\mathrm{O} \rightarrow e^+ +^{16}\mathrm{N}$	700	490
$\nu_x +^{16}\mathrm{O} \rightarrow \nu_x +^{16}\mathrm{O}^*$	513	124
Total	29285	17738

Kate Scholberg, Journal of Physics: Conference Series **309** (2011) 012028



Letter of Intent:

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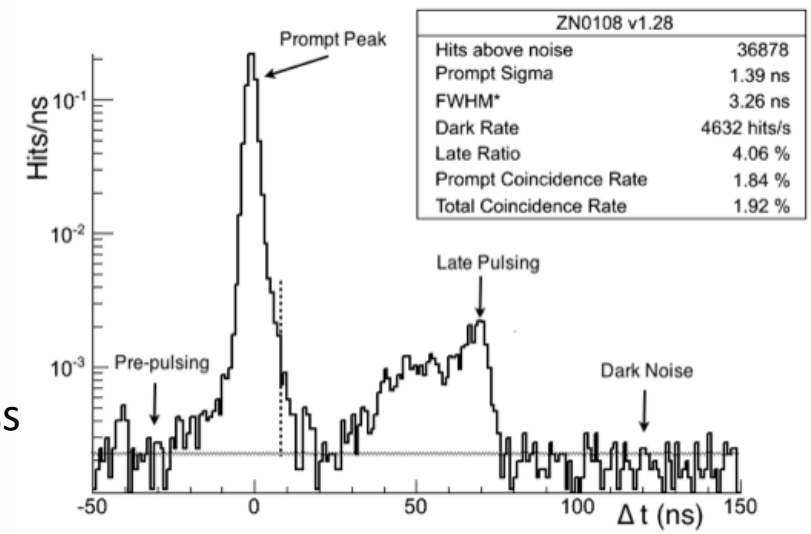
How to improve water-based detectors

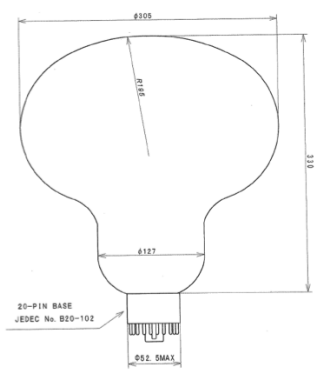
- Option I : Light collection improvements and what can be learned from a water R&D perspective (which is wrapping up):
  - High quantum efficiency PMTs
  - Winston cones
  - wavelength shifter plates
  - wavelength shifter films
  - Large Area Picosecond Photo-Detectors
- Option II : Light output improvements
  - Gd water loading R&D
  - Water-based scintillator

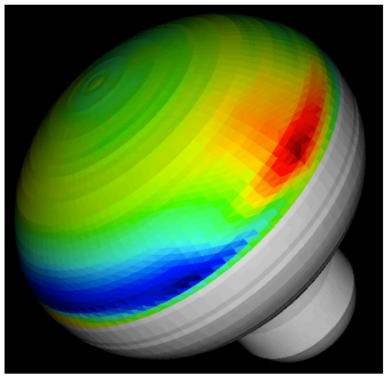
Light collection improvements

R&D High Quantum Efficiency Tubes

- Publication has recently been posted arXiv: 1210.2765v1
- Hamamatsu 12-inch R11780 PMT
- 52.4% increase in light collection at 400 nm
- Excellent candidate PMT for very large-scale water Cherenkov or scintillator detectors
- Charge and timing response is uniform across most of the photocathode surface
- Noticeable timing shifts near the edge of the PMT(mitigated by Hamamatsu new design)







timing shifts

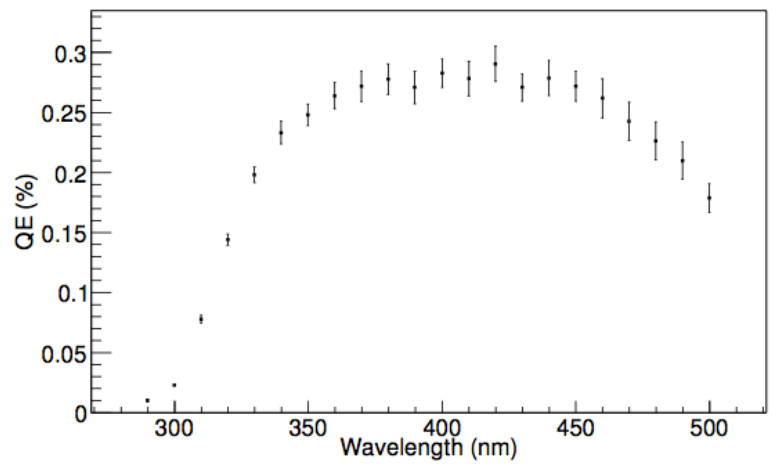


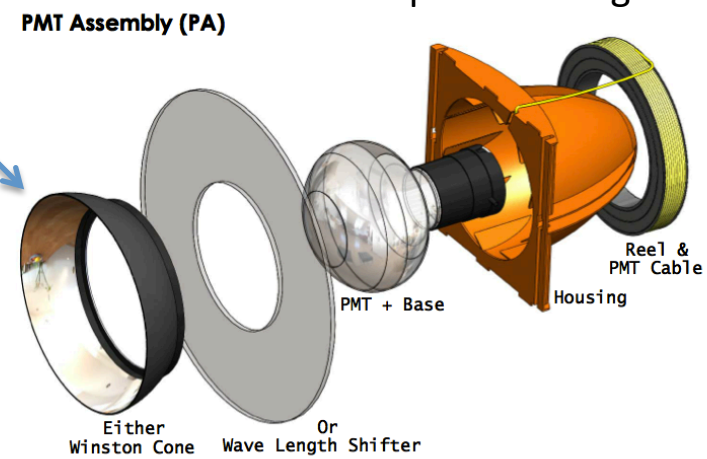
Figure 8: The measured absolute quantum efficiency of the 12" R11780 PMT

R&D Winston Cones

Advantages

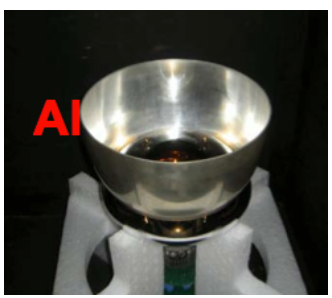
- ***Reduce # PMTs (costs) without reducing the amount of collected light***
- Winston Cone ~50$ PMT ~3000$
- Already successfully used in other experiments (SNO, Borexino-CTF), also being considered for LENA

40% improvement goal

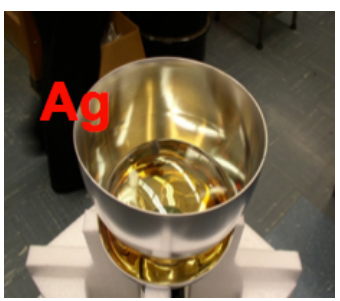


Concerns

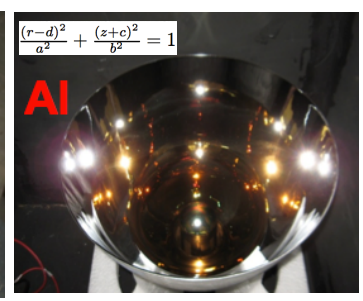
- Risk of Degradation in water volume
- Light Cones limit the PMT field of view
- Light Collection position dependent, may affect the FV definition and event reconstruction



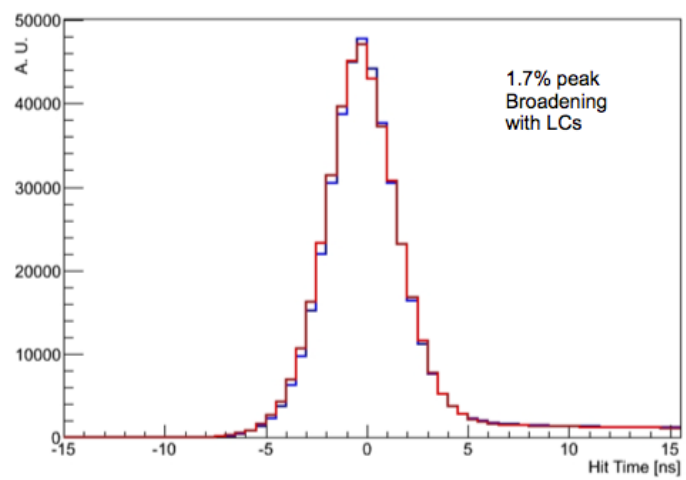
Winston



Winston



Ellipsoidal

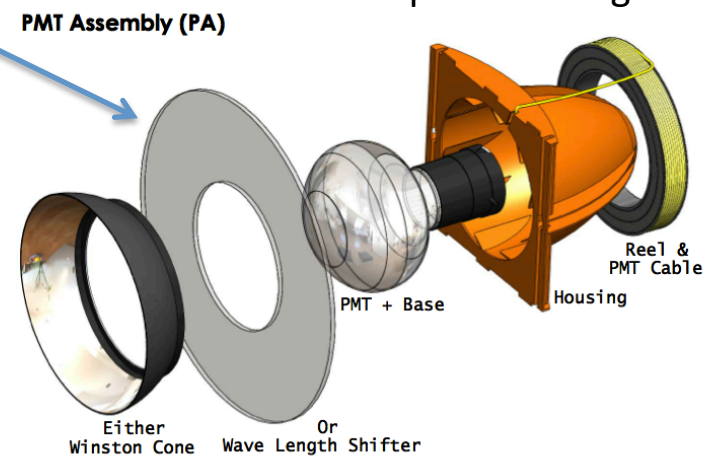


S. Perasso, J. Maricic, C. Lane
Drexel University, University of Hawaii

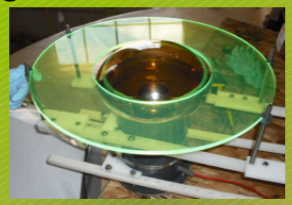
R&D wavelength shifter Plates

- Square plates have been used in IMB and in the outer-veto of Super-K
- R&D at Colorado State University with the goal of reaching an increase of 40% in light collection
- Thesis and publication are upcoming

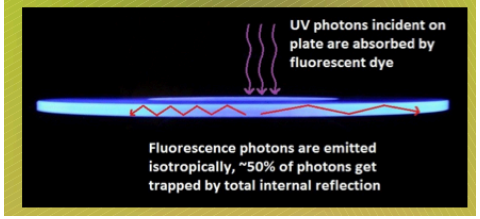
40% improvement goal



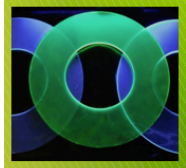
Flat plate guides light to PMT through total internal reflection



Square acrylic plates have been used in IMB and Super-Kamiokande outer detector



Wavelength-shifting plastics tested



- Bicron BC482a
- Decay time 7ns measured in lab
- Absorbs 370-470nm

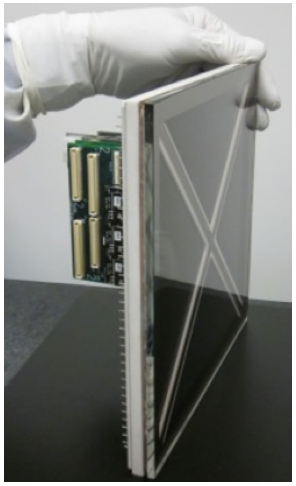
- Bicron BC499, Bicron BC499 (15 times higher dye concentration), Eljen EJ299
- Decay time 2 – 2.5ns measured in lab
- Absorbs 280 – 400nm
- Emits 420nm

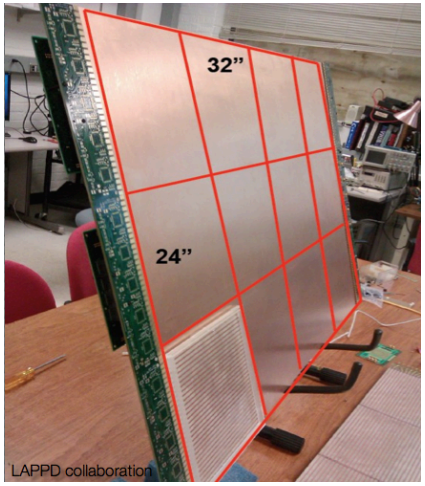
Blue → Green plate sharpens Cerenkov rings due to its lower sensitivity to Rayleigh scattered photons

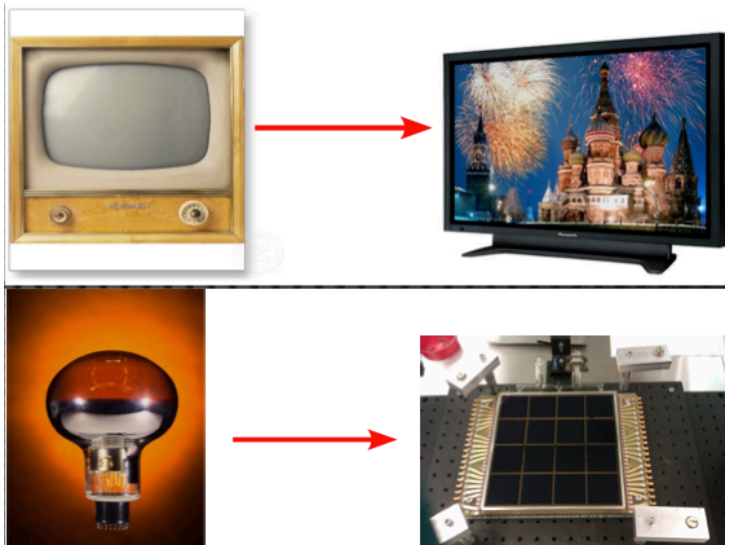
William Johnston and Norm Buchanan
Colorado State University

Large-Area Picosecond Photo-Detectors On wish-list

- Fast timing (in the range of **30–100 ps** rather than the **2 ns** typical for large PMTs).
- High spatial resolution (< 5 mm versus 25–50 cm typical of standard PMTs).
- Imaging detector rather than single pixel (PMT)
- Smaller magnetic field effects. No magnetic compensation system necessary.
- Possibility of π^0's background suppression for GeV scale interactions by gamma separation in both space and time
- Commercialization efforts are ongoing





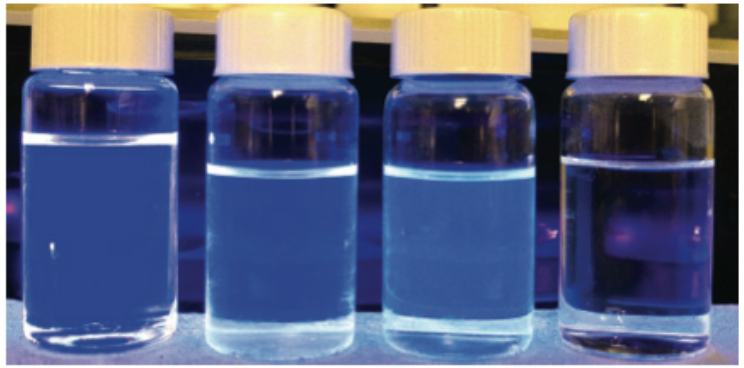


M. Wetstein (UChicago/ANL)
http://psec.uchicago.edu/

Light output improvements

Investigating water-based liquid scintillation wbLS

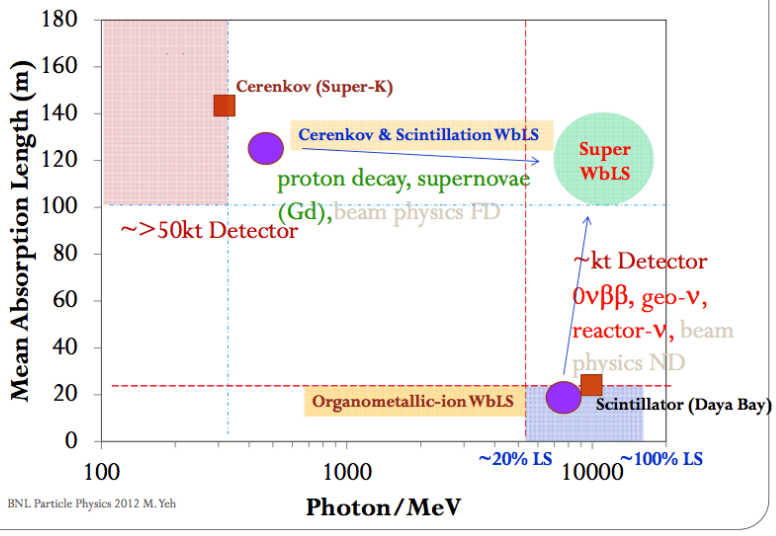
- Ongoing research in mixing oil and water. Surfactant is necessary to emulsify (or aggregate) organic liquid scintillator into the water solvent.
- Surfactant: Linear Alkylbenzene Sulfonic acid (LAS) used
- A stable, first-generation, WbLS with sufficient scintillation light has been developed at BNL



LS WbLS(1) WbLS(2) Water
with UV illumination

- Goals/challenges :
  - measure below Cherenkov threshold
  - keep track information
  - Improve energy resolution

Two WbLS-formulas for proton-decay and for DBD expts.



Benefits of and progress towards massive water-based liquid scintillator detectors,
David E. Jaffe, HYPER-K, 22-23 August 2012

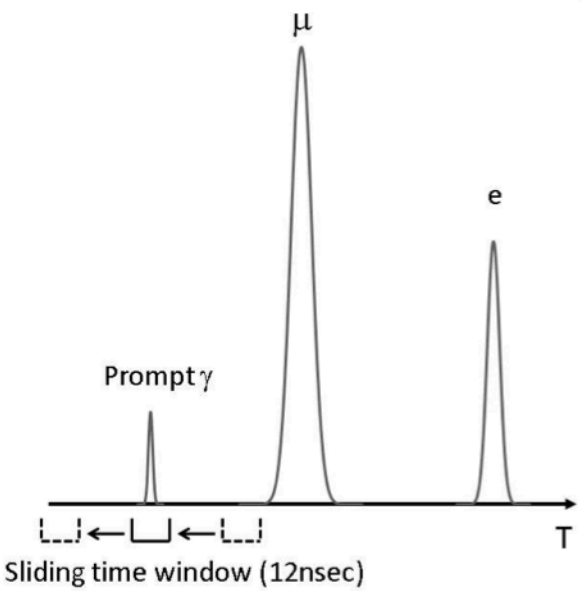
What wbLS can do for proton decay

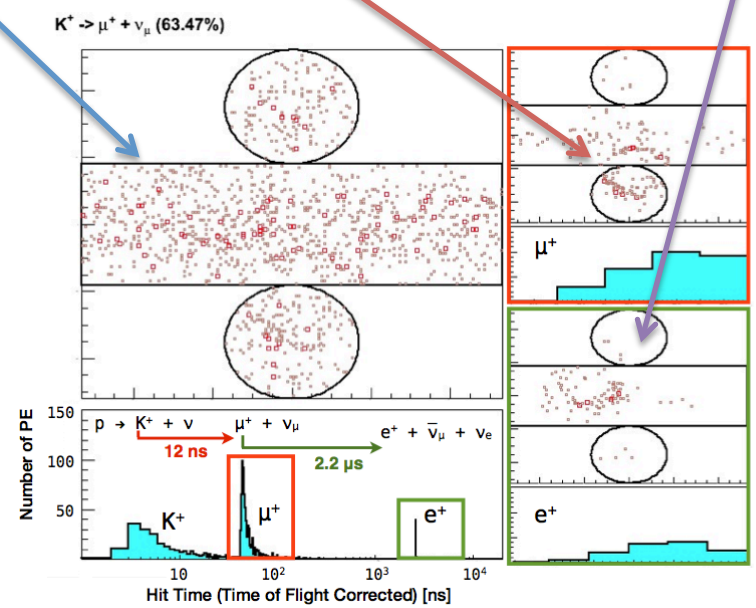
proton decay K mode tagging

no Cherenkov ring

μ ring

e ring



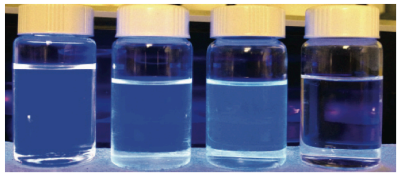


Simulation of SK-like geometry with 40% PMT coverage (WCsim).

Scintillation yield: **90 optical photons/MeV**

Triple-coincidence:

	E(MeV)	τ	ring?
K^+	105	12ns	no
μ^+	152	2.2μs	yes
e^+	< 50	—	yes

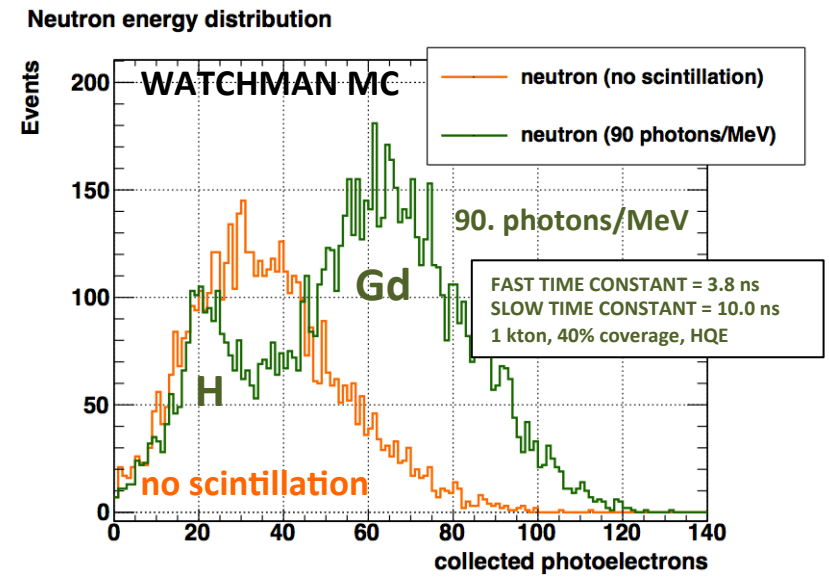


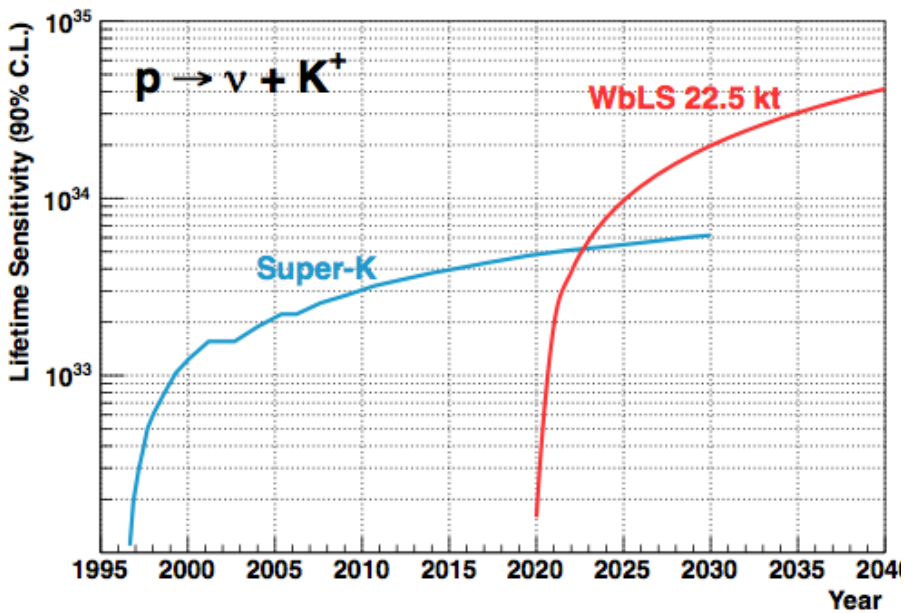
LS WbLS(1) WbLS(2) Water
with UV illumination

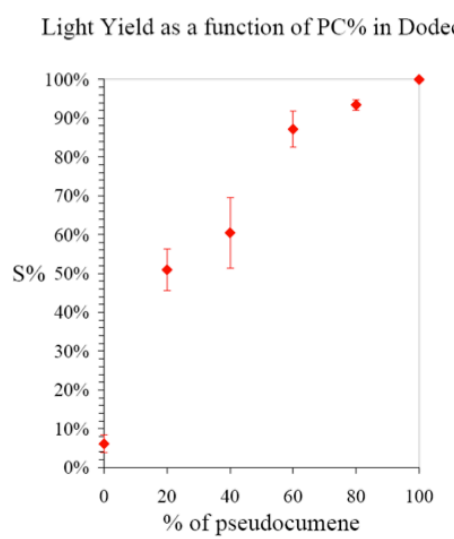
Benefits of and progress towards massive water-based liquid scintillator detectors, David E. Jaffe, HYPER-K, 22-23 August 2012

Turning on the Water LS

- Impact on proton decay sensitivity
- Impact on neutron detection efficiency







- *Adjustable light yield.* Non-linear dependence of light yield and LS concentration (left figure)
- Stability (First gen. WbLS stable for 2+ years)

Benefits of and progress towards massive water-based liquid scintillator detectors, David E. Jaffe, HYPER-K, 22-23 August 2012

Conclusion and Final thoughts

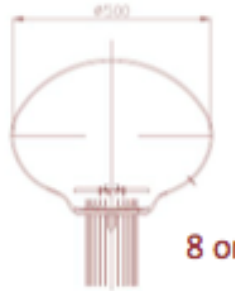
- Light attenuation studies and material testing are needed for both Gd or water-base liquid scintillator, but offer promising initial results
- When/if megaton detectors are built, there a many possible improvements that should be considered to increase light collection and lower overall cost
- Original water detector were created to measure proton decay, they have instead had incalculable impacts on neutrino oscillations:
  - The future ``interesting'' physic topics can change, neutron detection is key in increasing discovery potential

BACKUP | Hybrid PMT for Hyper-K

Candidate photodetectors

Hybrid-PhotoDetector (HPD)

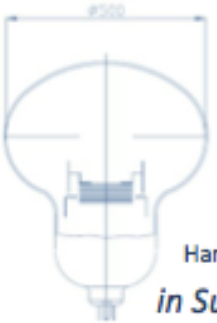
Avalanche diode



8 or 13 inch HPD is under testing

PMT

Dynode : Venetian-blind type



R3600
Hamamatsu
in Super-K

Another PMT with a different type of dynode is also a possible candidate that has a faster response time.

Selected by

- Better performance
- Reliability
- Low cost

20-inch HPD will be developed within a few years.

Fewer photodetectors, smaller size and photon-collecting reflectors may be considered to reduce cost.

The number of photodetectors

	Hyper-K	Super-K
Inner detector (for ν detection)	99,000 (20-inch)	11,129 (20-inch)
Outer detector (for cosmic-ray veto)	25,000 (8-inch)	1,885 (8-inch)
Photo-coverage	20%	40%†
QE (quantum efficiency)	**~30%**	22%

†) Except SK III period

Yasuhiro Nishimura, PhotoDet 2012