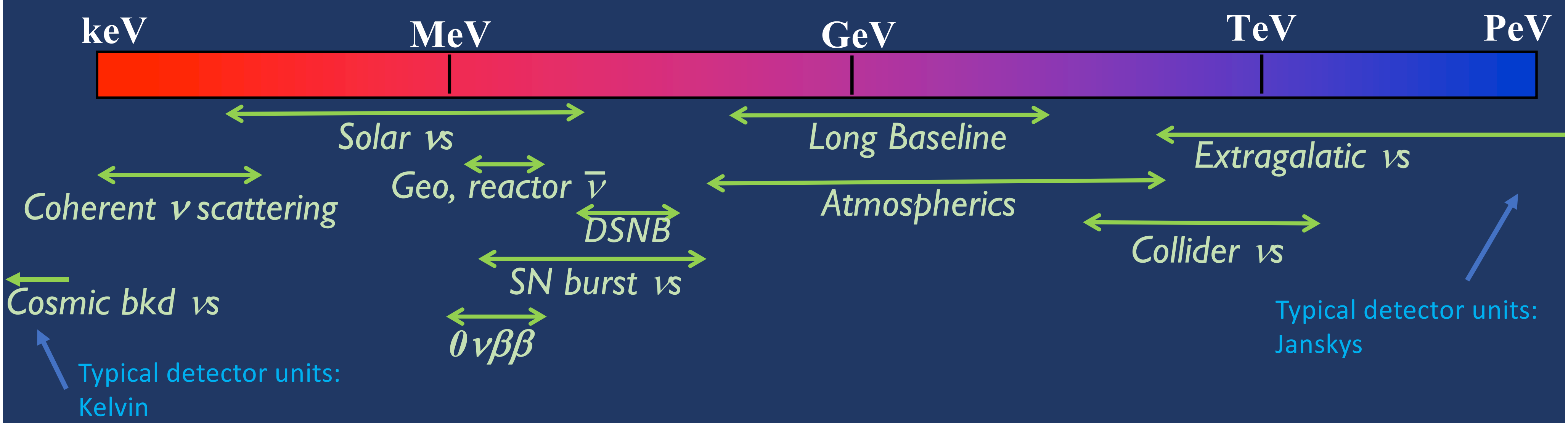
Water Cherenkov [and Hybrid] Detectors for Neutrino Physics

- Water Cherenkov Detector Overview
- Techniques and Instrumentation Responsible for Success
- Technical and Instrumentation Challenges and Development Work

Penn
University of Pennsylvania

Josh Klein
8 September
TIPP 2023
Cape Town

Breadth of Neutrino Physics



Could build a different detector type with a different technology for every physics topic…

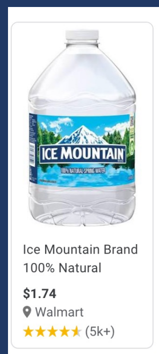
HOWEVER…

“Neutrinos don’t really *do* anything…"

- Detectors need to be big
  - To get enough ν interactions
  - And to contain produced muons
- Need to be affordable
- Sensitive to a broad range of energies
  - Because neutrino physics…

Water Cherenkov Detectors

Water is cheap!

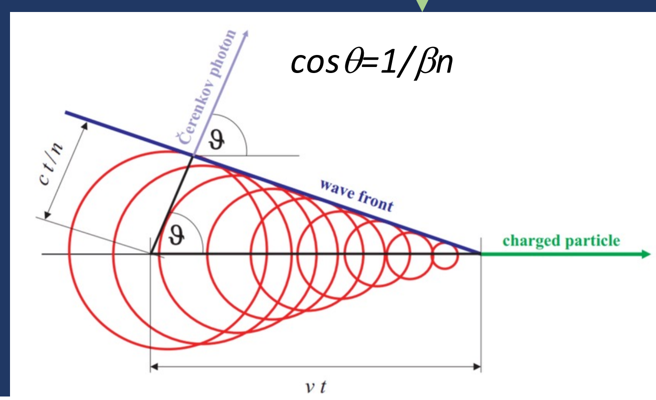


Ice is even cheaper…
Sea water is "even more" cheaper…
(Heavy water is expensive but SNO got it for free)

And has pretty high index of refraction:

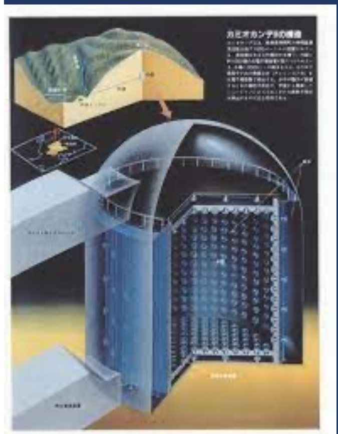
Cherenkov threshold: $\beta = 1/n = 1/1.33 = 0.75$ in water

And water is transparent to $1/\lambda^2$ Cherenkov spectrum in visible window



Particle	Kinetic energy threshold in MeV
electron	0.26
muon	54
pion	72
proton	480
tau	920
alpha	1929

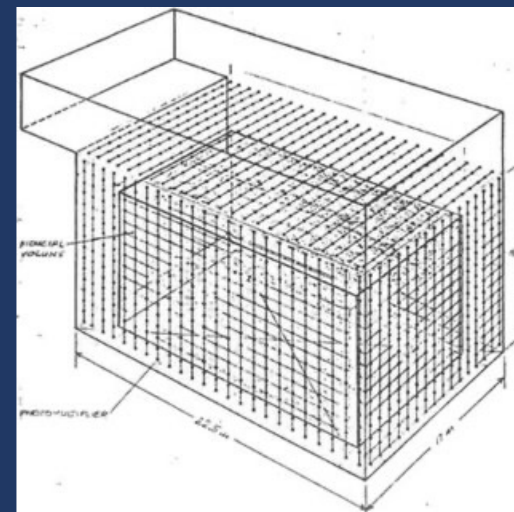
Kamiokande

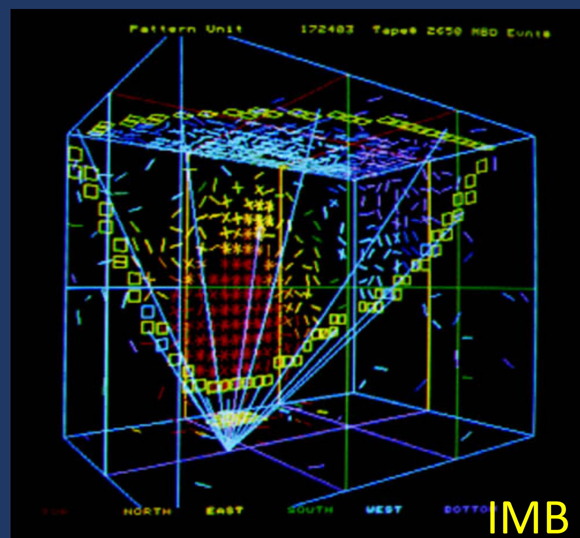


Water Cherenkov Detectors

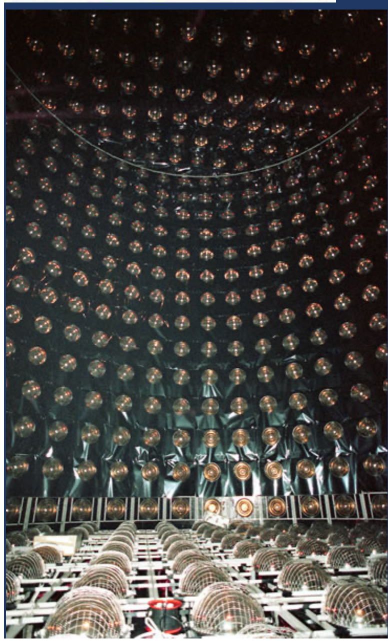
First Large Scale Detectors

IMB





IMB

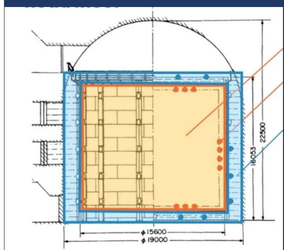


About 40 years ago…

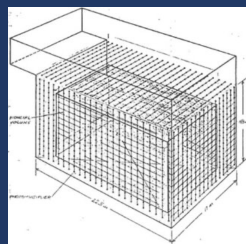
Water Cherenkov Detectors

"Monolithic" (MeV-TeV)

Kamiokande I & II
3000 tons H_2O



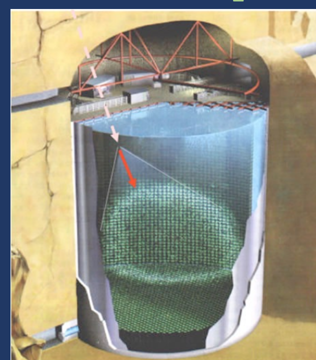
IMB
8000 tons H_2O



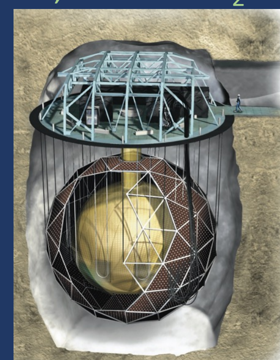
Pioneering
(~ 1000 PMTs)

Current/Recent (~10,000 PMTs)

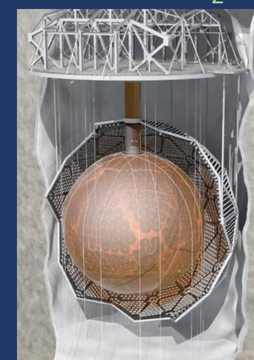
Super-Kamiokande
40,000 tons H_2O



SNO
1,000 tons D_2O

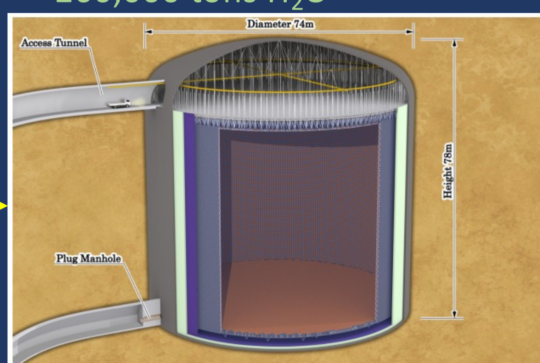


SNO+ Phase I
900 tons H_2O

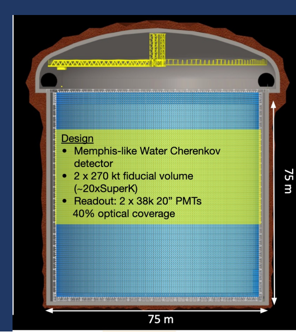


Hyper-Kamiokande
260,000 tons H_2O

Coming soon
(~50,000 PMTs)

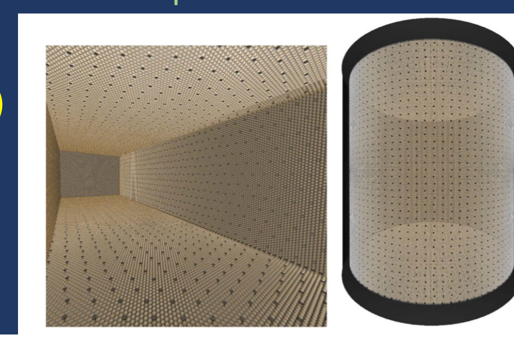


ESSνSB Far Detector
2x270,000 tons H_2O



Future
(~50,000 PMTs)

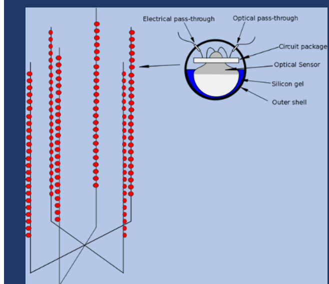
Theia
25,000/100,000 tons water-based liquid scintillator



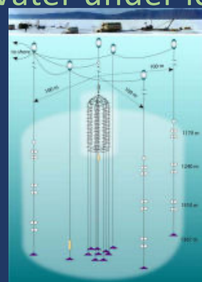
Water Cherenkov Detectors

"Embedded" (TeV-PeV)

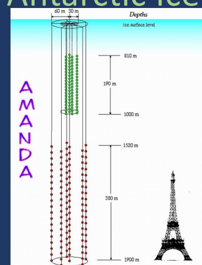
DUMAND
Sea Water (Hawaii)



Lake Baikal
Water under ice



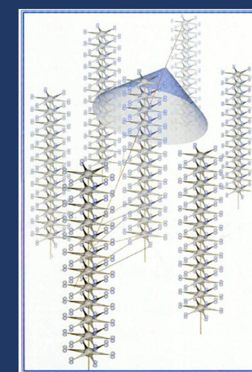
AMANDA
Antarctic Ice



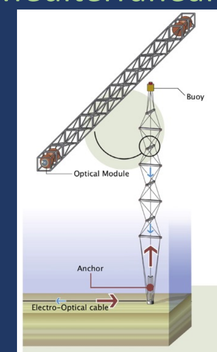
← Pioneering

Current/Recent

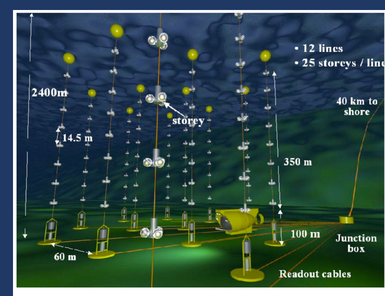
Nestor
Mediterranean



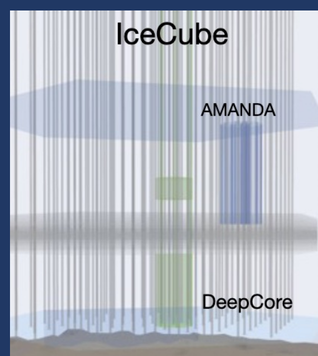
NEMO
Mediterranean



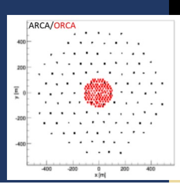
Antares
Mediterranean

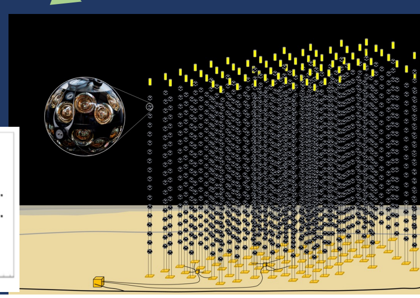


ICECUBE/Deep Core
Antarctic Ice



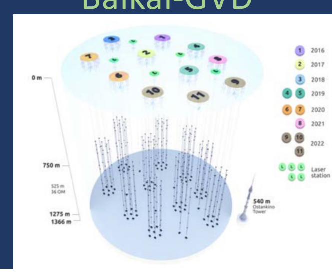
KM3NET:ARCA/ORCA
Mediterranean



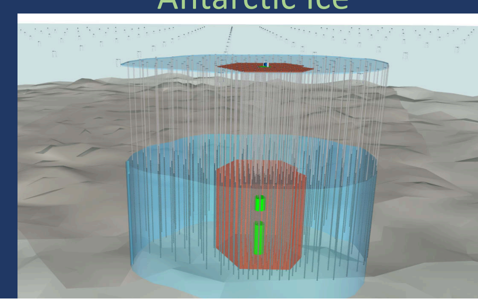


Operating/Expanding

Baikal-GVD



ICECUBE-GEN2
Antarctic Ice

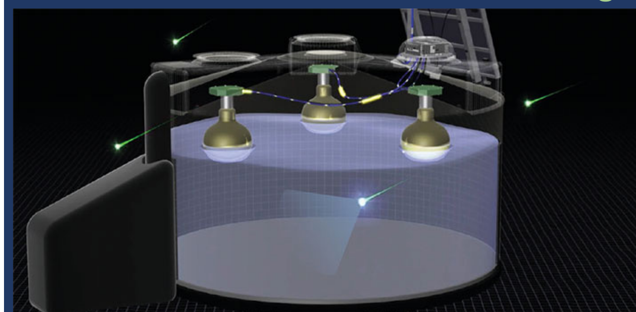


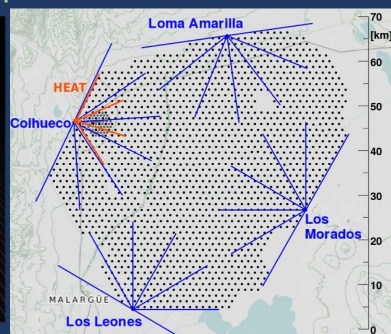
Water Cherenkov Detectors

(Not "direct" ν experiments, but can have relevant technical developments)

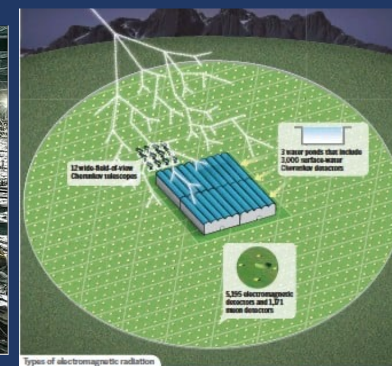
"Segmented"

Pierre Auger

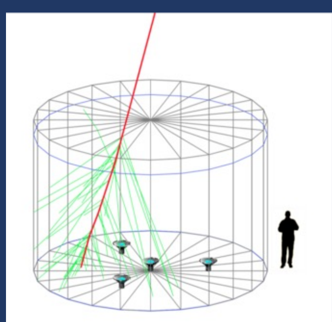




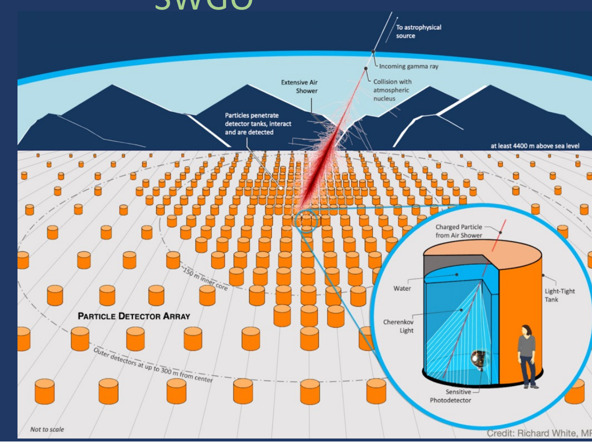
LHAASO



HAWC



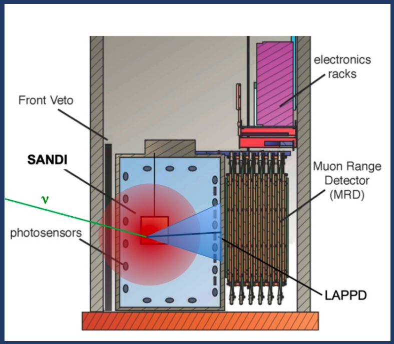
SWGO



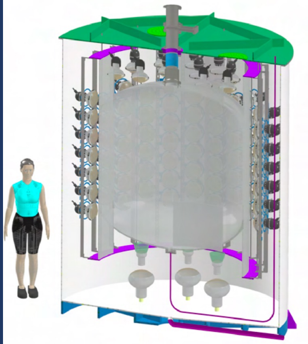
Water Cherenkov Detectors
Small Scale/Demonstrators

ANNIE (FNAL)
Water/Water-based LS

Operating

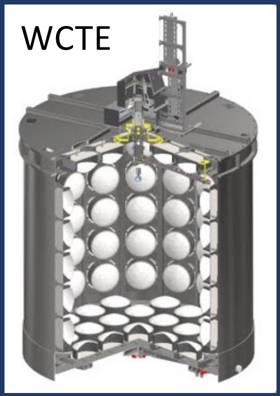


Eos (LBNL)
Water/Water-based LS



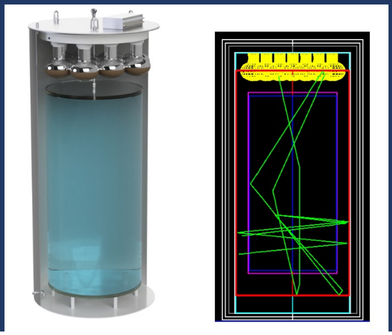
WCTE (CERN)
Water

Construction



COHERENT HWD (SNS)
D_2O

Planning



"30 ton" WbLS
demonstrator
(BNL)

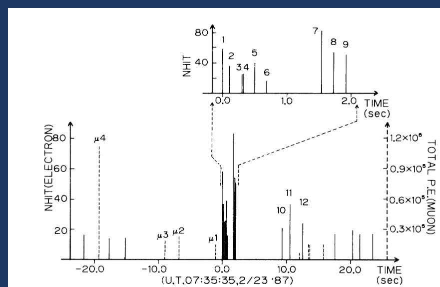
Construction

Water Cherenkov Detectors

Arguably the most successful single technology in neutrino physics

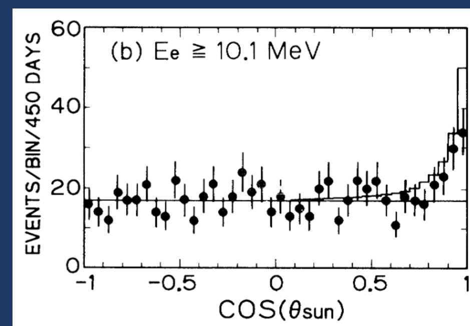
Observation of neutrinos from SN1987A

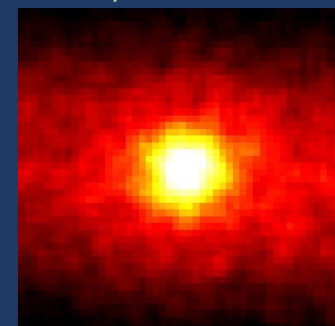
(Kamiokande II, IMB)



First directional observation of solar νs

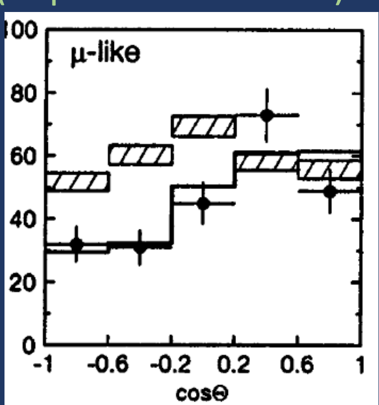
(Kamiokande II, Super-Kamiokande)

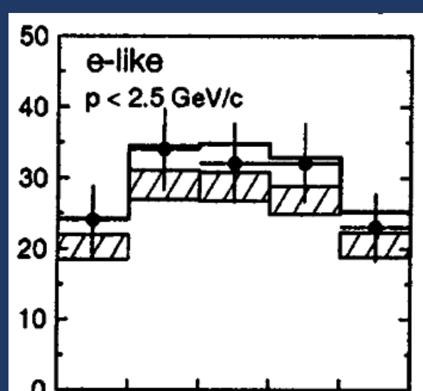




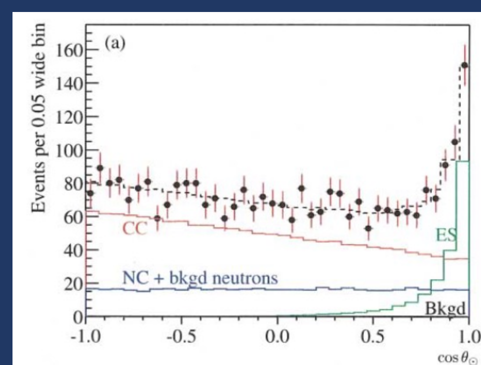
Discovery of atmospheric ν oscillations

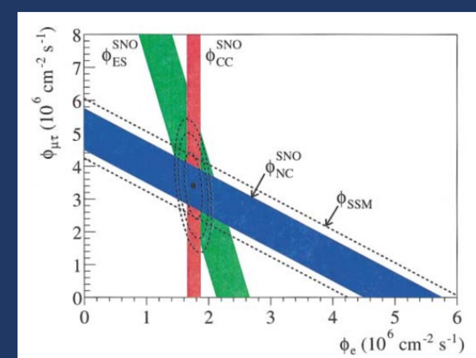
(Super-Kamiokande)





Resolution of Solar ν Problem (SNO)



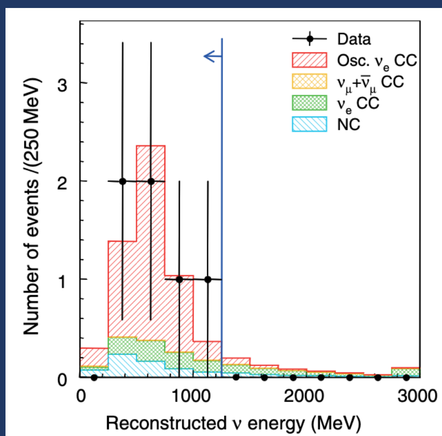


Water Cherenkov Detectors

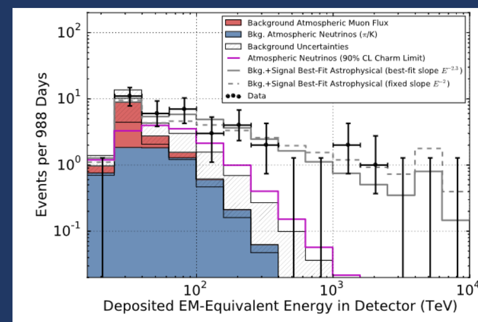
Arguably the most successful single technology in neutrino physics

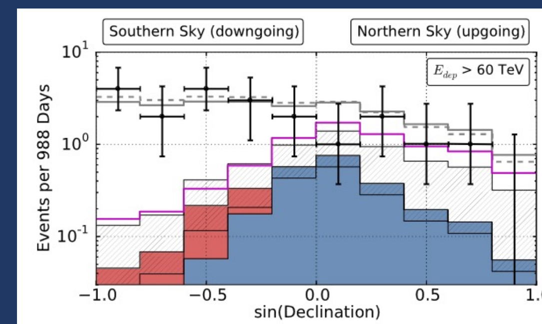
Observation of ν_e appearance via 3-flavor mixing

(T2K)



First detection of ultra-high energy extra-terrestrial νs (ICECUBE)





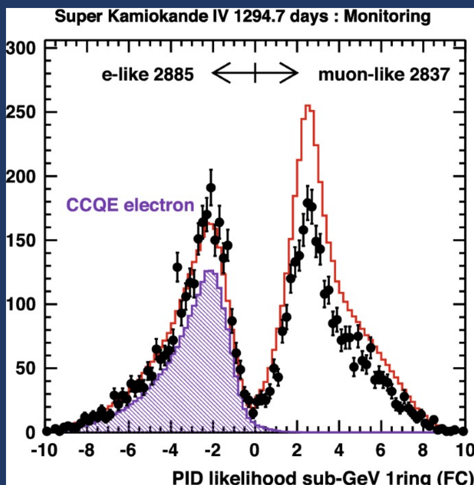
Milky Way map in neutrinos

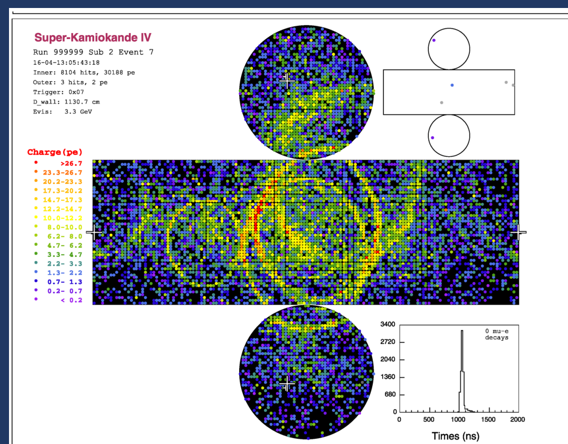
(ICECUBE)

Water Cherenkov Detectors

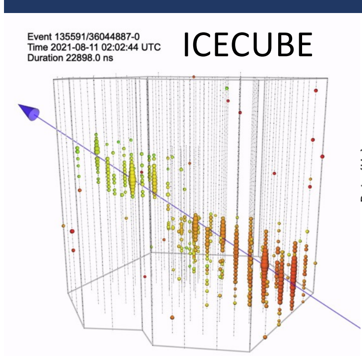
Why so successful?

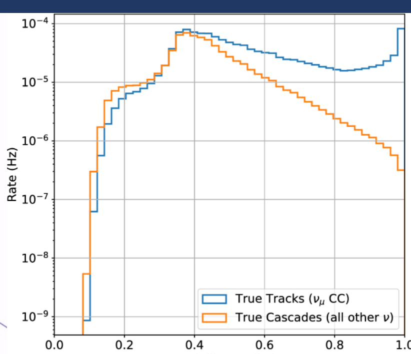
- Cherenkov ring imaging is simple but rich

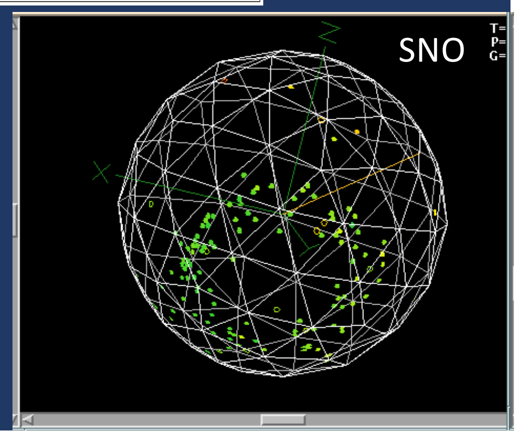


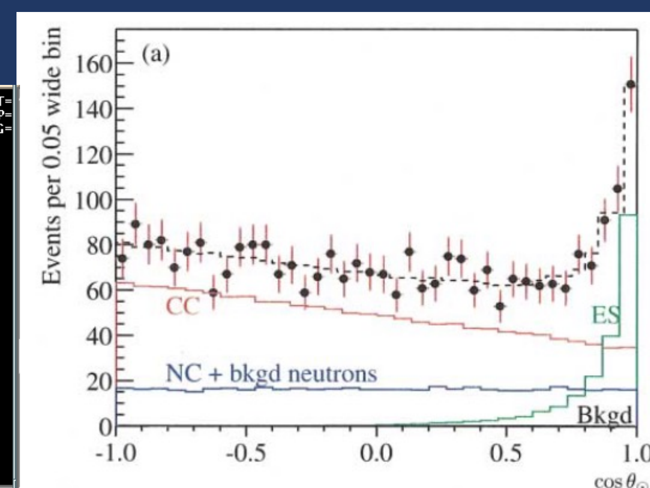


- Cherenkov angle provides particle β
- Ring "thickness" proportional to track length
- N_{photon} proportional to energy
- Multiple rings provide interaction multiplicity
- Showers are more diffuse
- Directionality sensitive to astrophysics
- Directionality separates event types







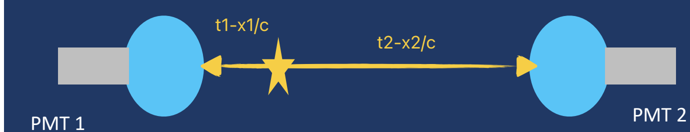


Water Cherenkov Detectors

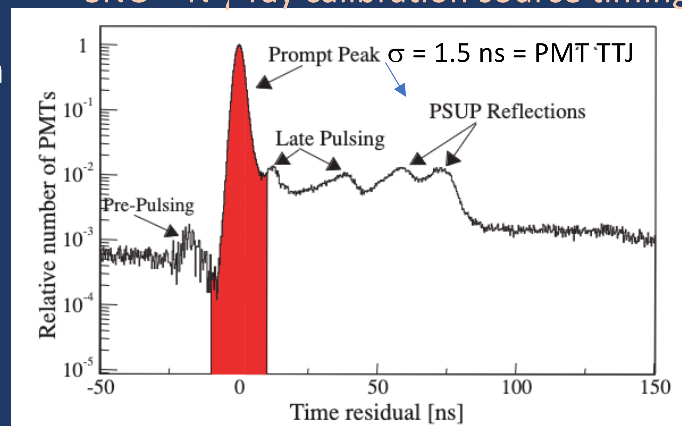
Why so successful?

- Fast timing allows precision reconstruction and background rejection
  - Cherenkov time scale << 1 ns
  - Totally dominated by photosensor timing, scattering, and photon dispersion

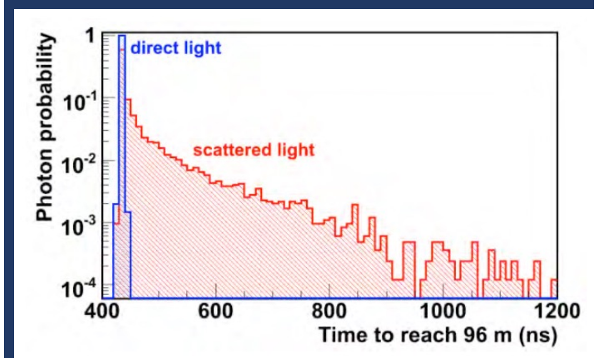
Position reconstruction done by time-of-flight residuals



SNO ^{16}N γ-ray calibration source timing



KM3NET direct vs. scattered



KM3NET TDR

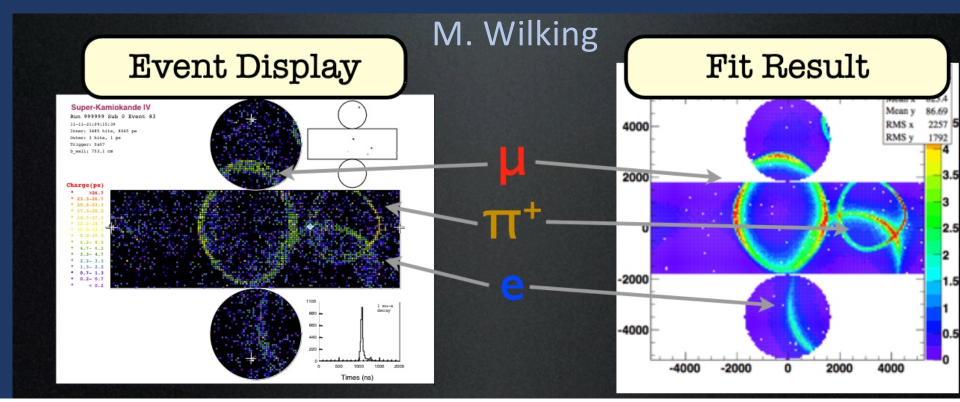
Typically done through a likelihood:

Super-K/T2K fitQUN likelihood

Time PDF

$$L(\boldsymbol{x}) = \prod_j^{unhit} P_j(unhit|\boldsymbol{x}) \prod_i^{hit} \{P_i(hit|\boldsymbol{x})\} f_q(q_i|\boldsymbol{x}) f_t(t_i|\boldsymbol{x})$$

But AI/ML techniques becoming more common

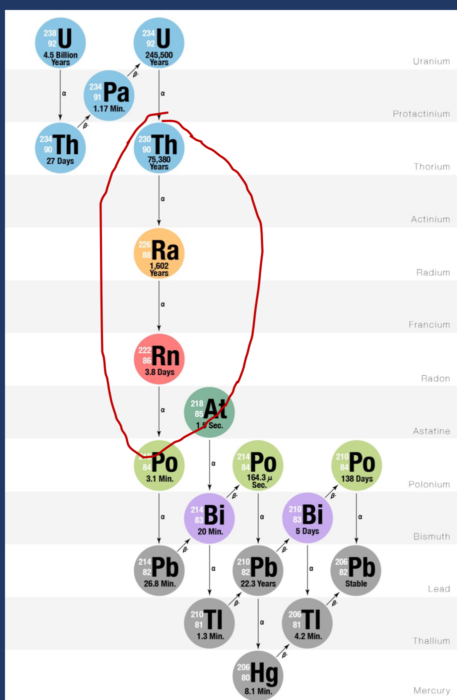


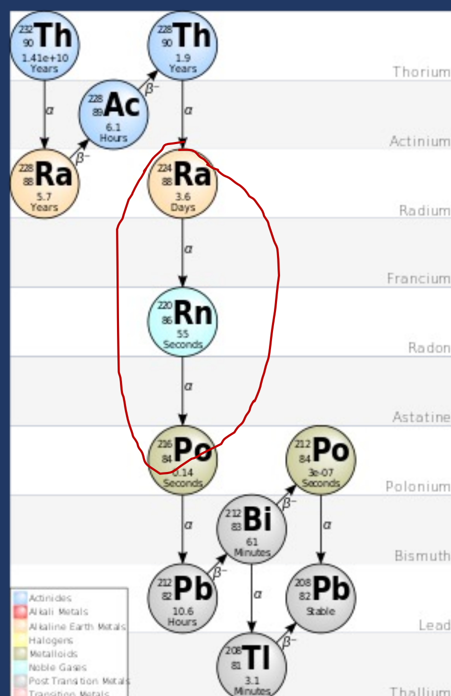
M. Wilking

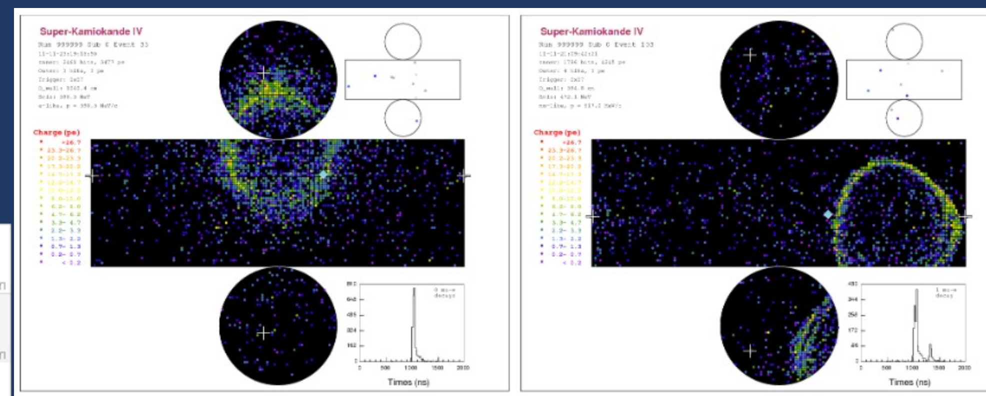
Water Cherenkov Detectors

Why so successful?

- Threshold
  - "Cleans up" Cherenkov rings using physics
  - Cherenkov threshold makes low energy backgrounds invisible (e.g. αs, low E γs)







Water Cherenkov Detectors

Why so successful?

- Detectors are simple, linear, with wide dynamic range
- **Detector response** =

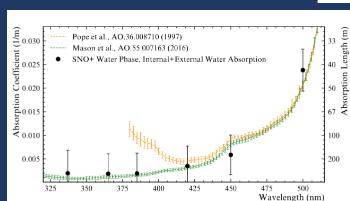
cross sections x particle propagation

x Cherenkov production

$$\frac{d^2N}{dx d\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)$$

Well-understood physics

x optics

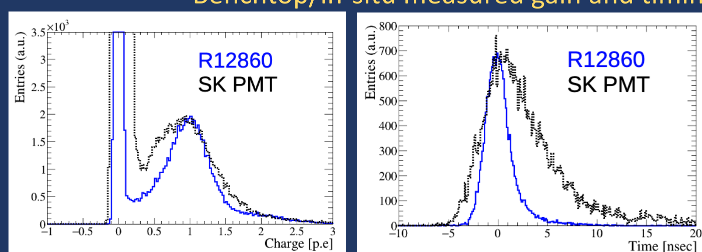


SNO+

In-situ measured *bulk physical* parameters

x sensor response

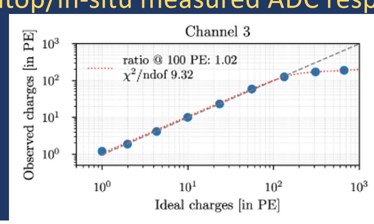
Benchtop/in-situ measured gain and timing



C. Bronner, Hyper-K

x DAQ response

Benchtop/in-situ measured ADC response, pedestals



ICECUBE-GEN2

All measurable and testable with optical or low-energy radioactive calibration sources and do not depend on particle species or energy.

Very few phenomenological parameters

Channel dynamic ranges are at most 1-1000 pe and rarely above 100 pe

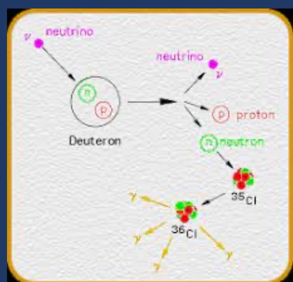
Channel-level observables are only $N_{photons}$ and t_i

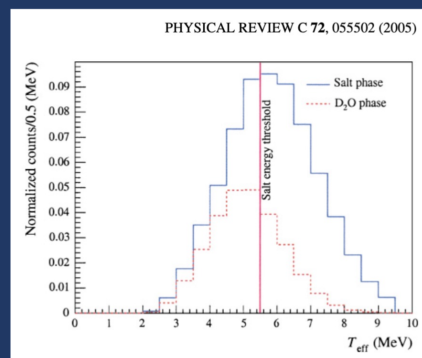
Energy scale uncertainties < 1%

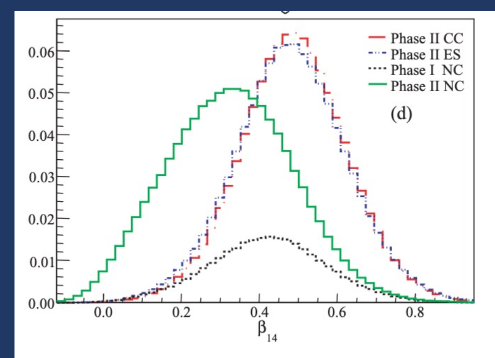
Water Cherenkov Detectors

Why so successful?

- Water can be "loaded" with isotopes easily for broader physics program
  - SNO Cl



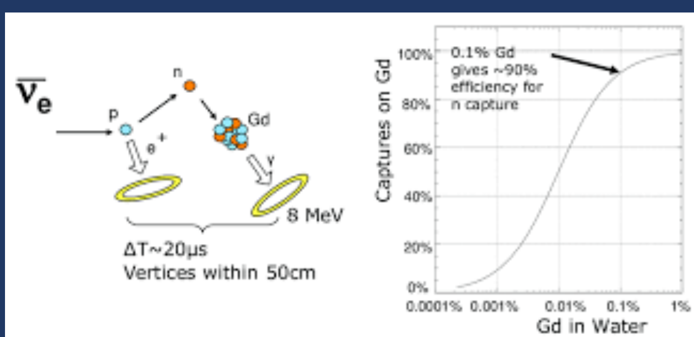


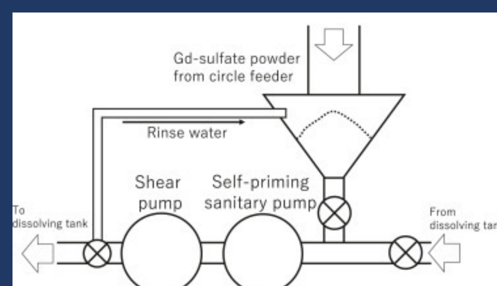


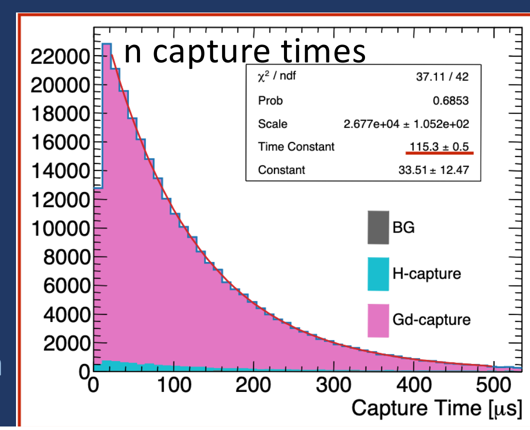
SNO: Increased precision on NC distintegration of deuterons

  - Super-K Gd

Super-K: Allows detection of antineutrinos, particularly from Diffuse Supernova ν Bkd





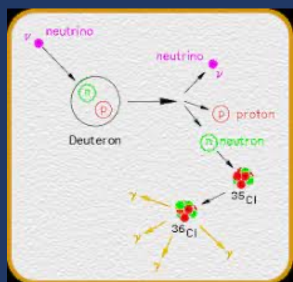


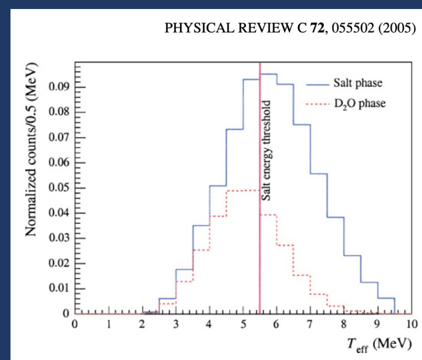
Masayuki Harada
TAUP 2023

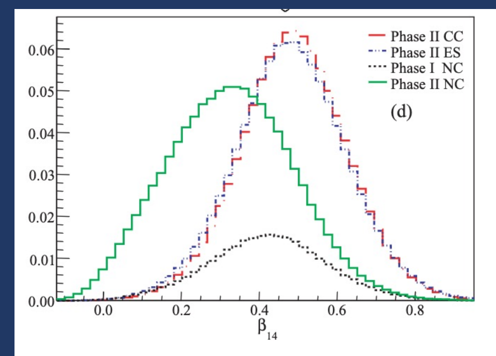
Water Cherenkov Detectors

Why so successful?

- Water can be “loaded” with isotopes easily for broader physics program
  - SNO Cl







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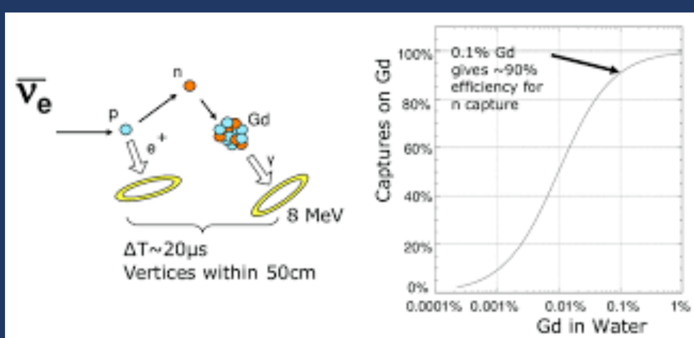
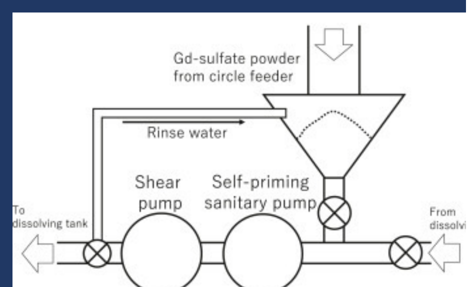
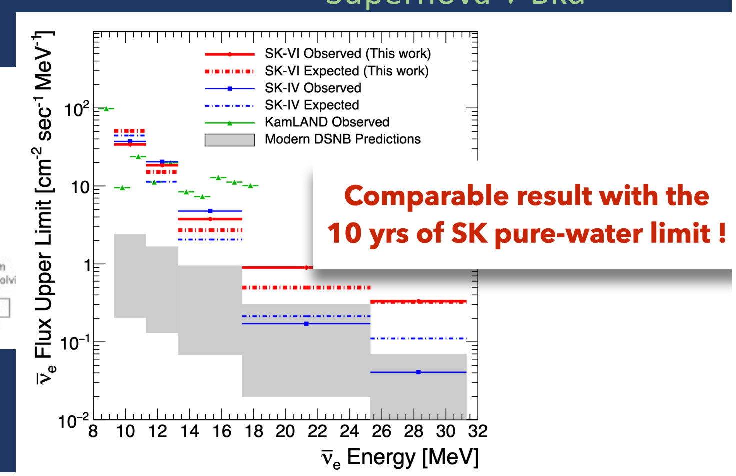




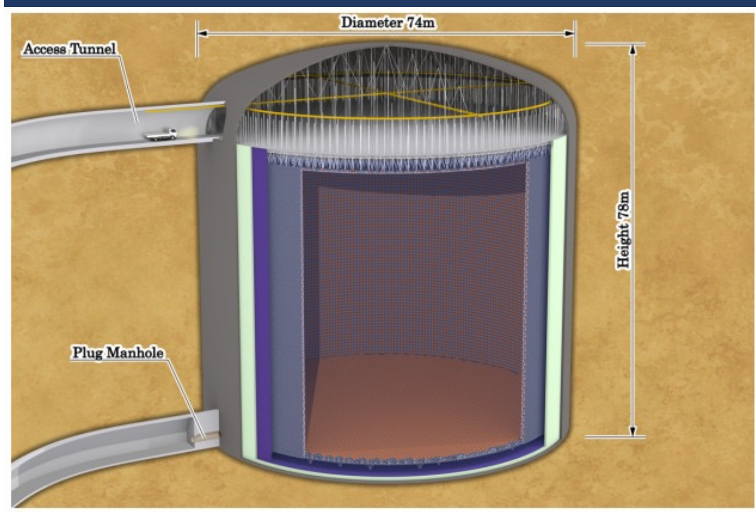


Masayuki Harada
TAUP 2023

Water Cherenkov Detectors

Upcoming Physics Program

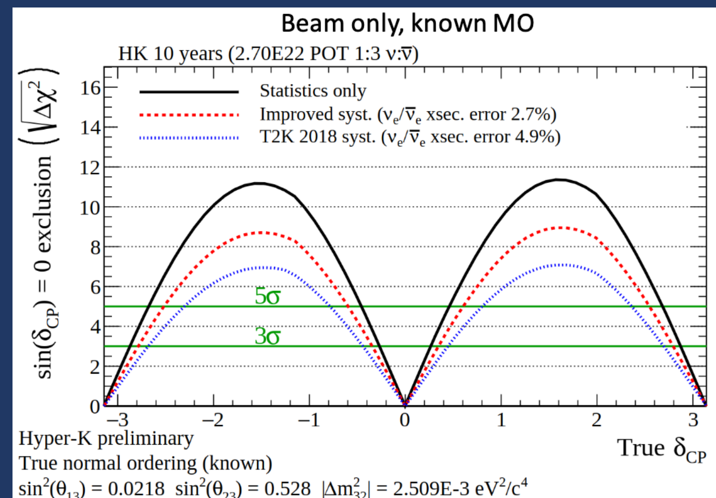
Hyper-Kamiokande



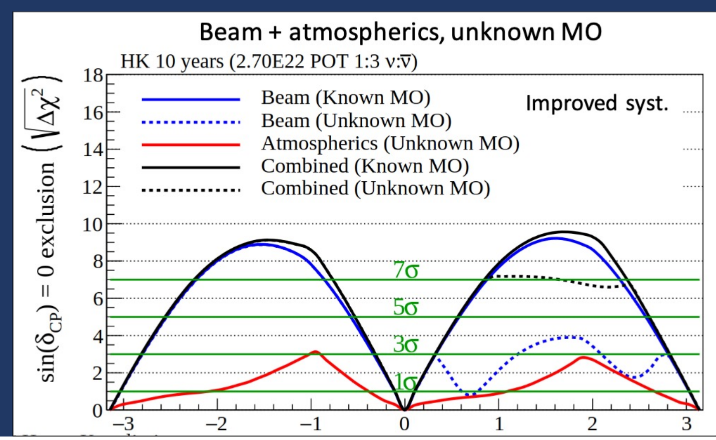
Expected to start in 2027

Also:

- Best limits on p decay to $e^+\pi^0$
- ^8B solar and Day/Night
- Diffuse Supernova ν background



By 2037

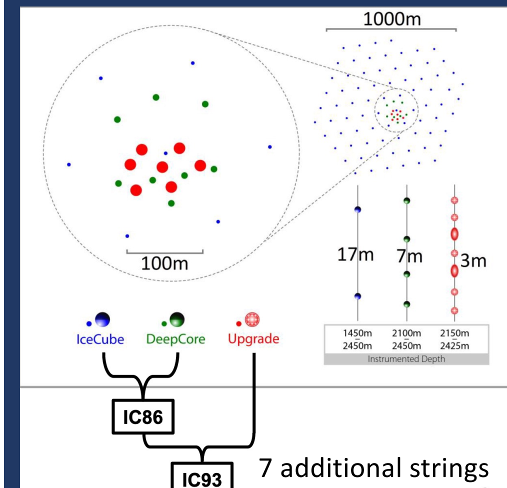


C. Naseby - Nufact 2023

Water Cherenkov Detectors

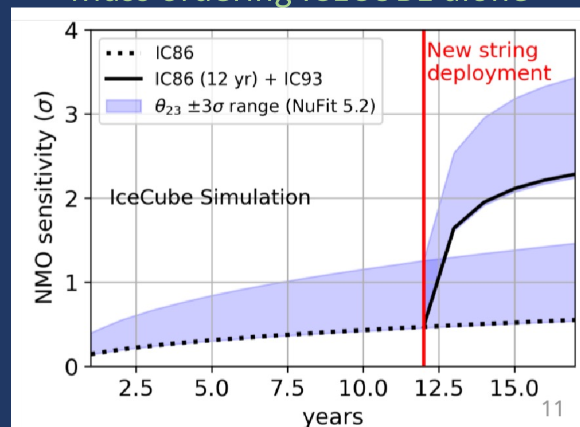
Upcoming Physics Program

ICECUBE Upgrade

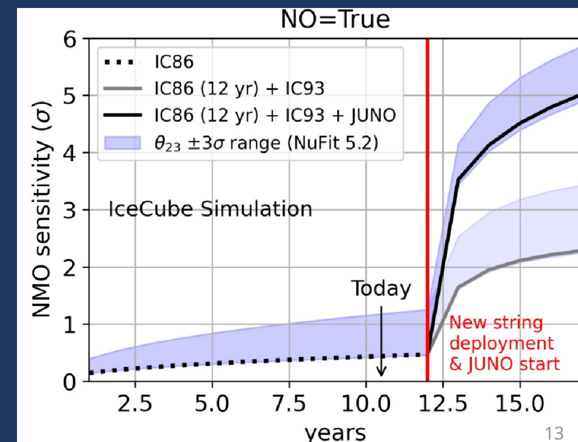


Jan Welder, TAUP 2023

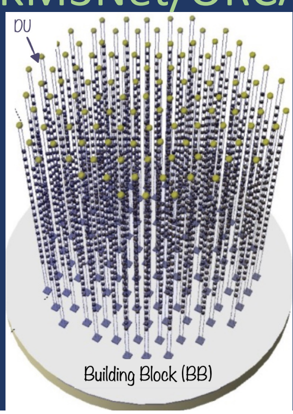
Mass ordering ICECUBE alone

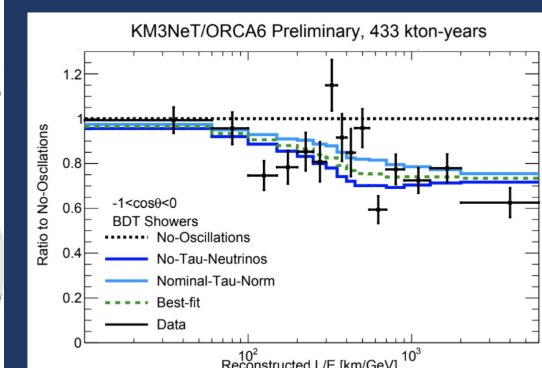


Mass ordering ICECUBE+JUNO



KM3Net/ORCA





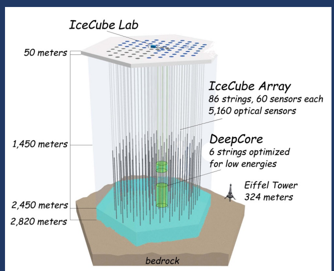
ν_τ appearance normalization test (~2.2 s exclusion of no ν_τ appearance)

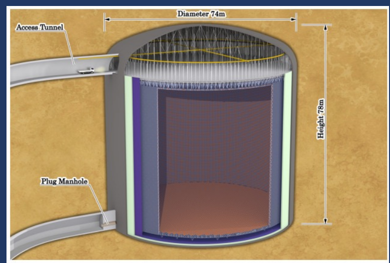
C. Lastoria TAUP 2023

Technical and Instrumentation* Challenges

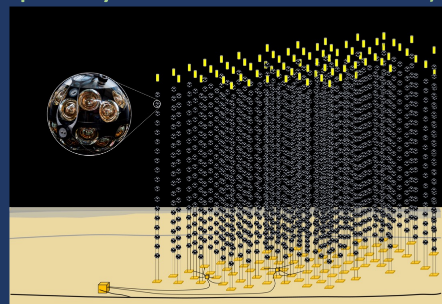
For Future Path Forward

1. Mass: ν physics and astrophysics, nucleon decay all depend on $N_{targets}$
   - Water is cheap, digging holes is not!



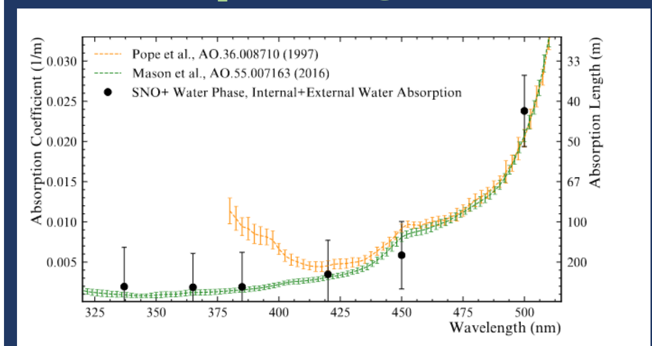


(OK: No holes in sea but plenty of cables to shore…)

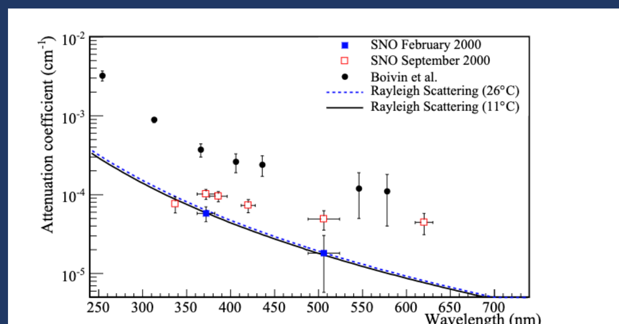


   - Size also limited by water/ice optics

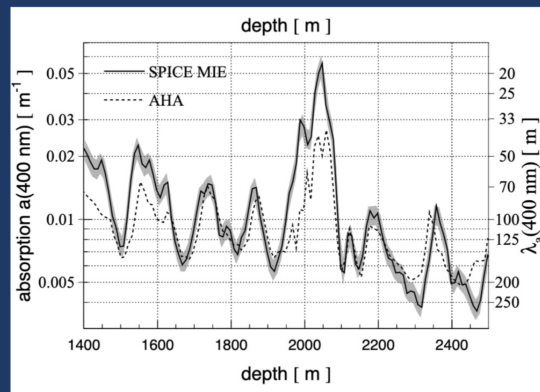
SNO+ H_2O –250 m @ 400 nm



SNO D_2O --100 m @ 400 nm



Antarctic Ice 30m—250 m (depth-dependent)



*Biggest challenge at high energies is physics: interaction cross sections and beam

Technical and Instrumentation Challenges

For Future Path Forward

2. Light Collection, Pixelization, and Timing

Physics depends on number of photons and ***information content*** of each

- Calorimetry depends on $N_{photons}$; at low energies detectors are "photon starved"
- Position and direction reconstruction also depends on timing and sensor location (pixels)
  - Information content/photon ~ $1/\sigma_{ttj}$ and ~$1/\sigma_{xyz}$ for position and direction
  - (Minus noise hit probability…)
- Particle ID dependent on timing and pixels

Photomultiplier tubes are nearly 100 years old!

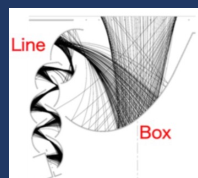
- Still the best game in town for most detectors
- But quantum efficiency (QE) historically only 20-25%
- Timing historically at > 5 ns FWHM level
- And still not cheap!…

Technical and Instrumentation Challenges

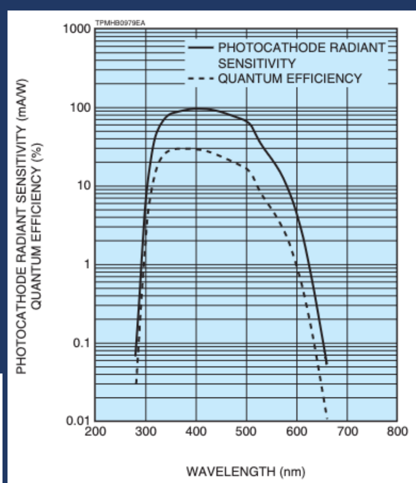
For Future Path Forward

2. Light Collection, Pixelization, and Timing

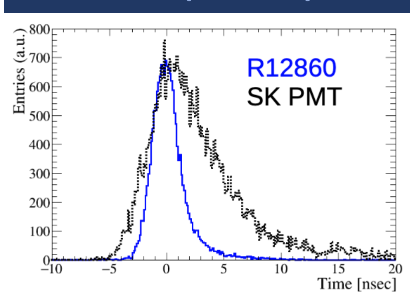
Hyper-K 50 cm PMT (R12860)
Box-and-line dynode



Peak QE = 30%



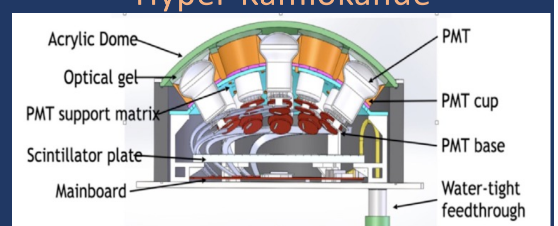
2.6 ns TTS (FWHM)



"multi-PMTs" provide better timing and pixelization, "quasi"-direction

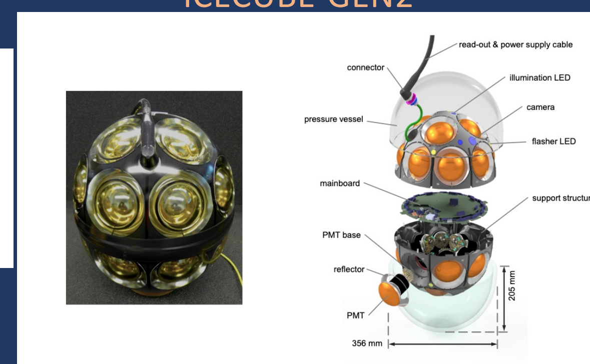
KM3NET

Hyper-Kamiokande



3" PMTs

ICECUBE-GEN2



igure 1: mDOM overview: *Left*: mDOM constructed for the Design Verification Test (DVT) campaign *ight*: Exploded view featuring main components.

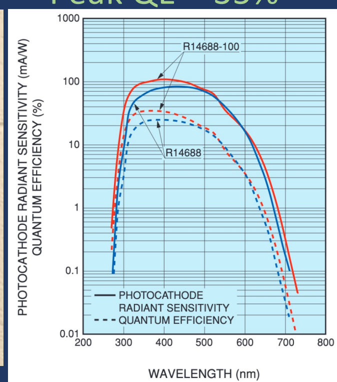
Technical and Instrumentation Challenges

For Future Path Forward

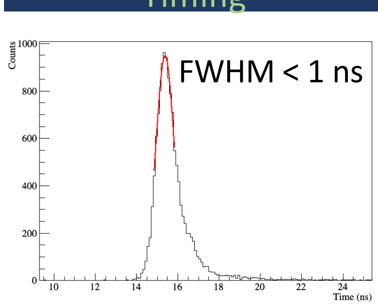
2. Light Collection, Pixelization, and Timing

Eos demonstrator:
R14668-100: **8"** PMT

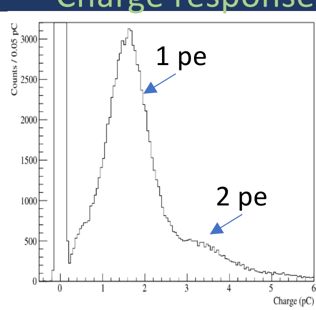
Peak QE ~ 35%



Timing



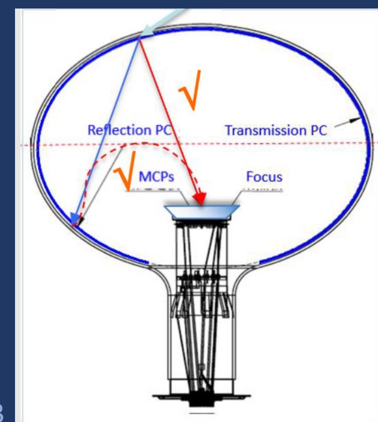
Charge response

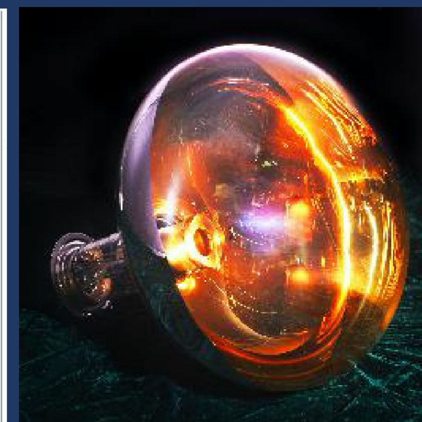


T. Kaptanoglu

T. Kaptanoglu

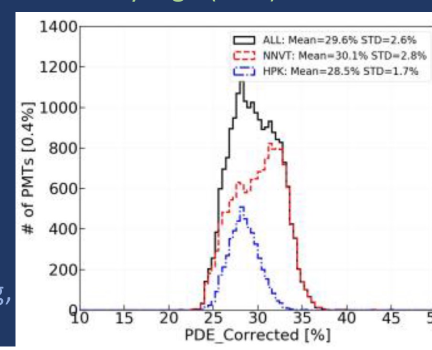
JUNO/LHAASO: 50 cm MCP-PMT





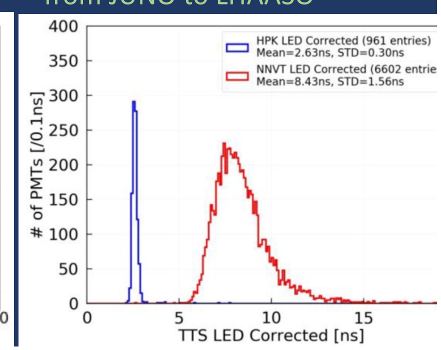
Sen.QIAN, TIPP 2023

Peak QE 32% with very high (99%) collection efficiency



Zhaoyuan Peng, TIPP 2023

Timing performance improving from JUNO to LHAASO



Technical and Instrumentation Challenges

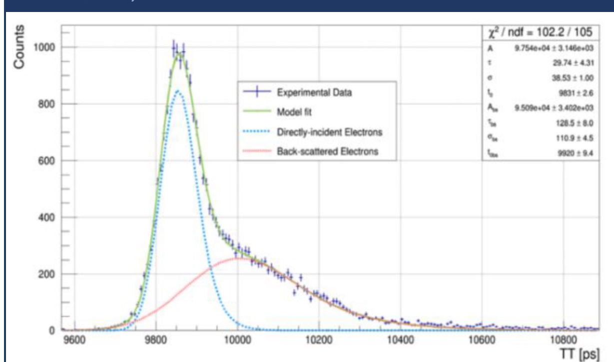
For Future Path Forward

2. Light Collection, Pixelization, and Timing

Multi-anode (2”) Fast PMTs

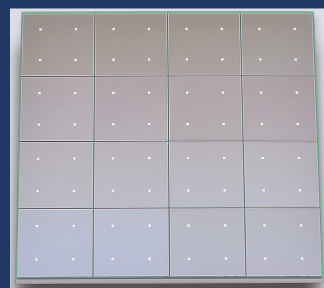
2022 JINST 17 T04002

Sen.QIAN, TIPP 2023

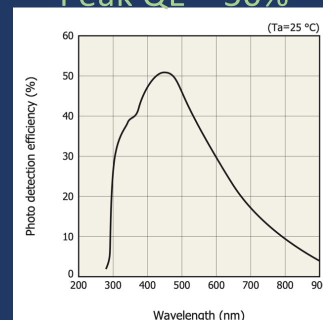


- Size is challenging

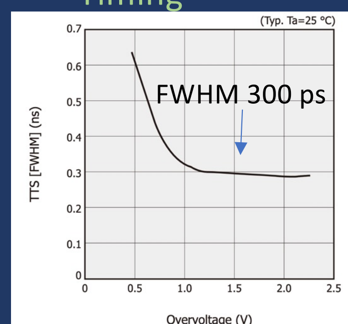
SiPMs/MPPCs (6x6 mm)



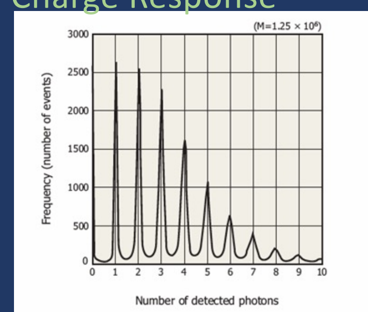
Peak QE ~ 50%



Timing

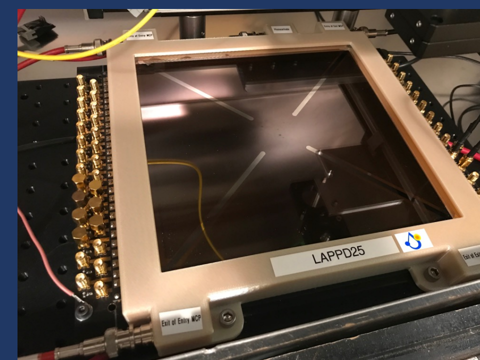


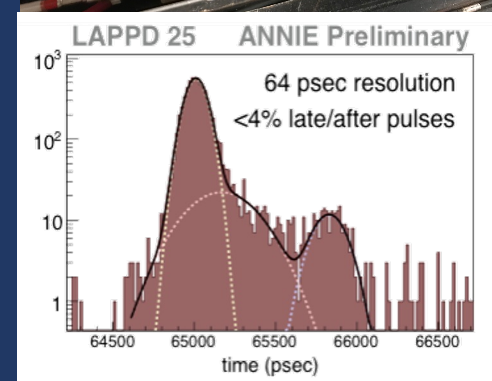
Charge Response



- But noisy when warm
- And expensive/area

LAPPDs (Incomm)





- Big but expensive
- Relatively low QE

Technical and Instrumentation Challenges

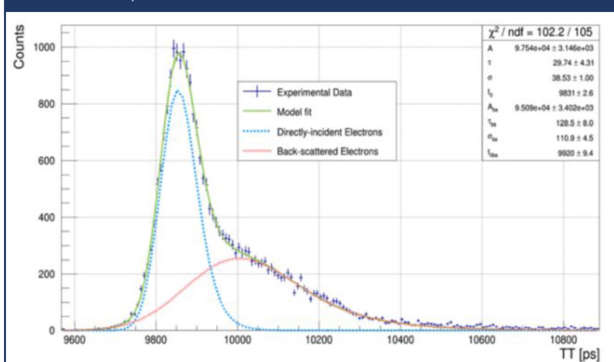
For Future Path Forward

2. Light Collection, Pixelization, and Timing

Multi-anode (2”) Fast PMTs

2022 JINST 17 T04002

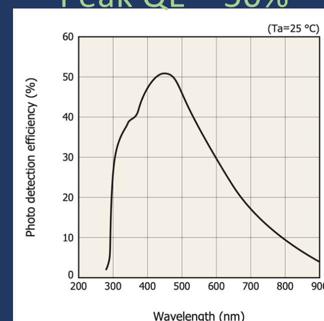
Sen.QIAN, TIPP 2023



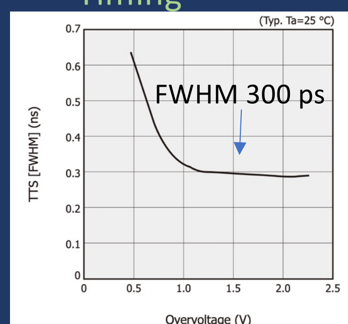
- Size is challenging

SiPMs/MPPCs (6x6 mm)

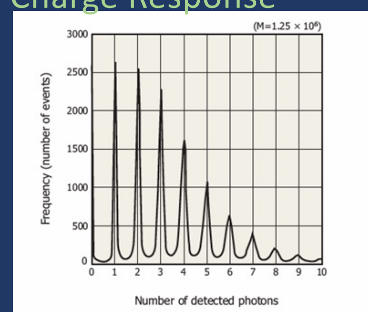
Peak QE ~ 50%



Timing



Charge Response



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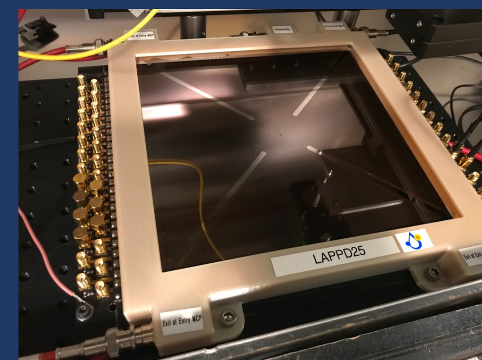
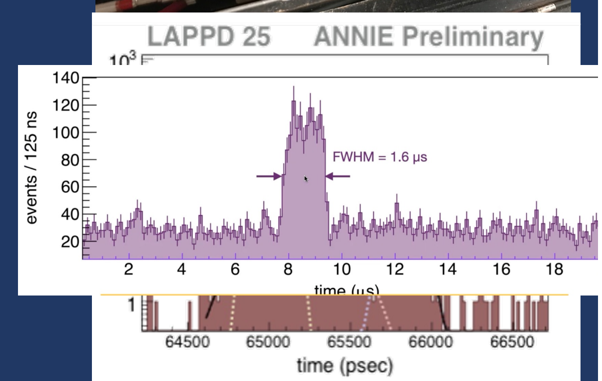
LAPPDs (Incomm)





- Big but expensive
- Relatively low QE

Technical and Instrumentation Challenges

For Future Path Forward

2. Light Collection, Pixelization, and Timing

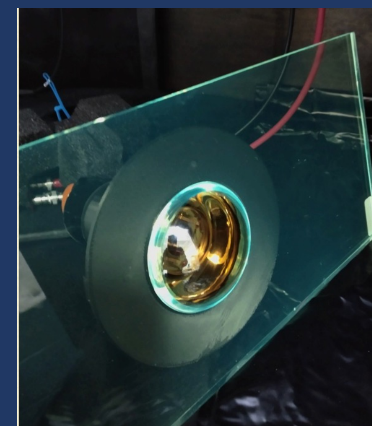
SNO/SNO+ (Truncated) Winston cone light concentrators:
~50% increase in light yield

- Field of view can be challenging
- (Or helpful)

Hyper-K light concentrators for mPMTs

Krzysztof Dygnarowicz, TIPP2203

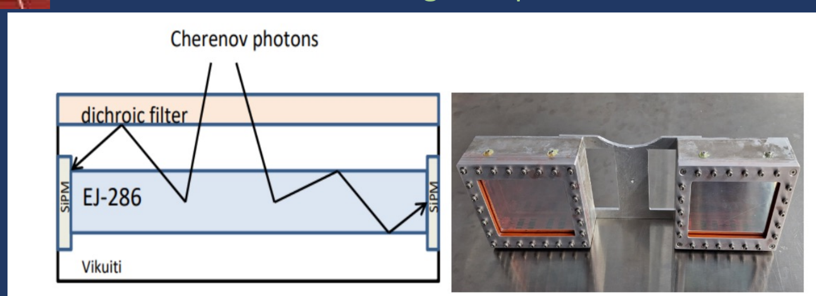
WLS plates for H-K veto



WLS plates in IMB!

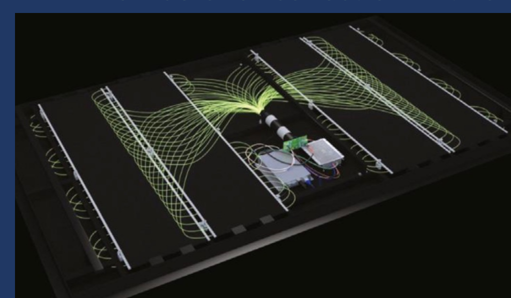
Alexander Izmaylov, TIPP2023

C-ARAPUCA light traps



Anderson Campos Fauth, ICRC 2023

WLS fibers for collection with small PMTs in LHAASO



Hao Sun, TIPP2023

Technical and Instrumentation Challenges

For Future Path Forward

3. Radiological backgrounds (at low energies)

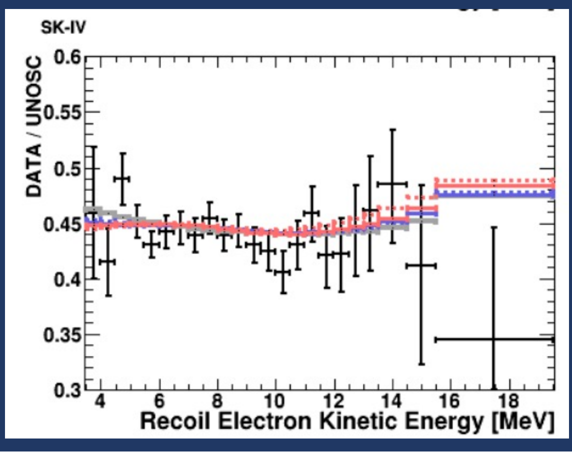
- Water washes everything…it "likes" to hold onto metals
- U and Th chains, "unsupported" Rn are primary culprits
- Photon-starved resolution means no good spectral separation
- And Cherenkov threshold prevents use of α,β coincidences

Workhorses here:

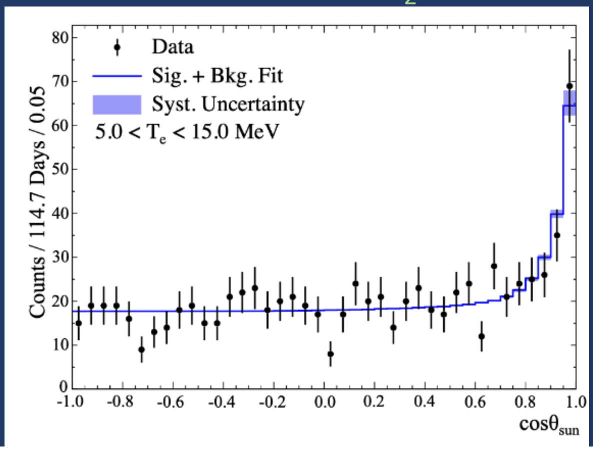
- Radon degassing
- Reverse osmosis

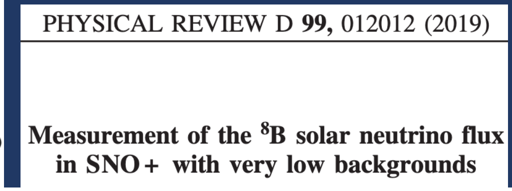
Nevertheless…

Super-Kamiokande 3.5 MeV solar ν threshold



SNO+: Lowest solar ν background levels ever achieved in H_2O




PHYSICAL REVIEW D **99,** 012012 (2019)

Measurement of the ^{8}B solar neutrino flux in SNO+ with very low backgrounds

Technical and Instrumentation Challenges

For Future Path Forward

3. Radiological backgrounds (at low energies)

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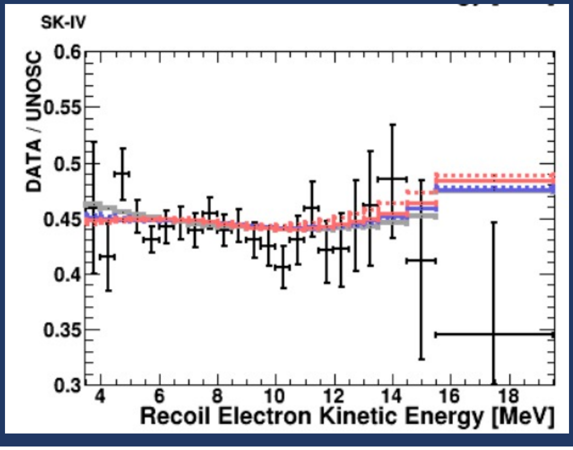
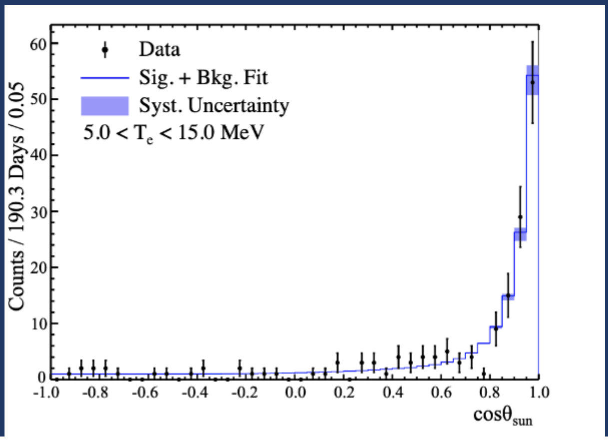
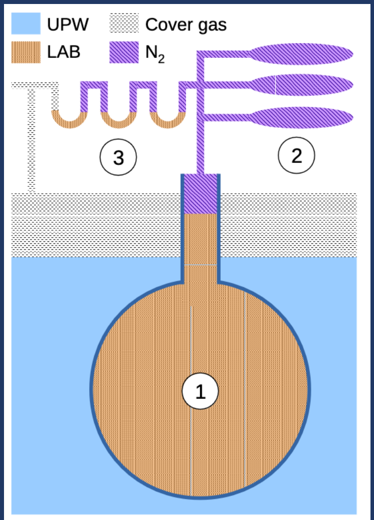
Nevertheless…

Super-Kamiokande 3.5 MeV solar ν threshold



SNO+: But with even more work on radon mitigation and purification





Technical and Instrumentation Challenges

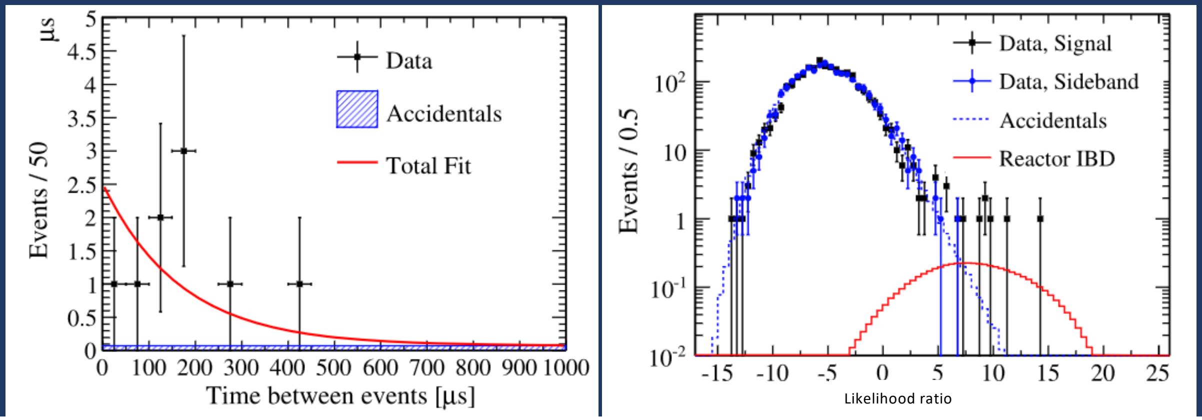
For Future Path Forward

3. Radiological backgrounds (at low energies)

- Water washes everything…it "likes" to hold onto metals
- U and Th chains, "unsupported" Rn are primary culprits
- Photon-starved resolution means no good spectral separation
- And Cherenkov threshold prevents use of α,β coincidences

Nevertheless…

SNO+: Reactor antineutrinos in water Cherenkov detector > 200 km away



$\bar{\upsilon}$+p→e^++n

~200 μs delayed neutron capture creates 2.2 MeV γ---only 12/9000 PMTs hit on average

SNO+ collaboration, PRL 130 (2023) 9, 091801

Technical and Instrumentation Challenges

For Future Path Forward

5. Threshold and Resolution

keV MeV GeV TeV

Solar νs

Geo, reactor $\bar{\nu}$

DSNB

SN burst νs

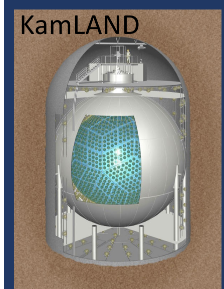
$0\nu\beta\beta$

Long Baseline

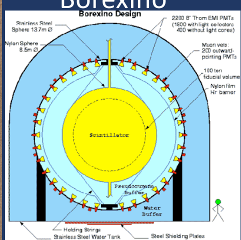
Atmospherics

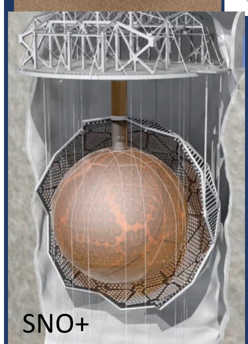
Extragalatic νs

KamLAND



Borexino



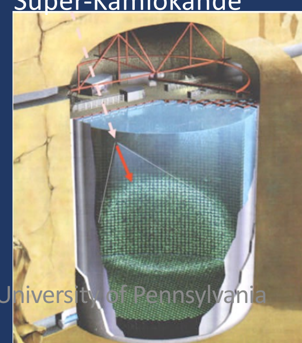


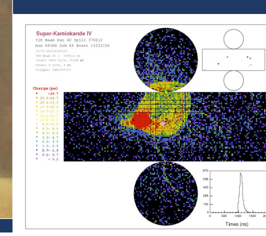
SNO+

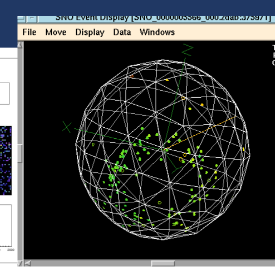
Requirements:

- Low radio backgrounds
- Excellent energy resolution
- Directional information

Super-Kamiokande



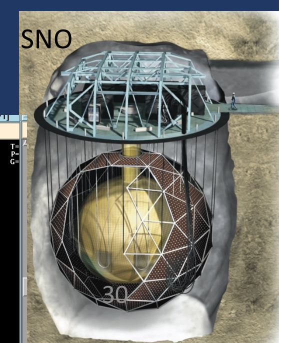




Requirements:

- Excellent PID
- Directional information
- Very big detector

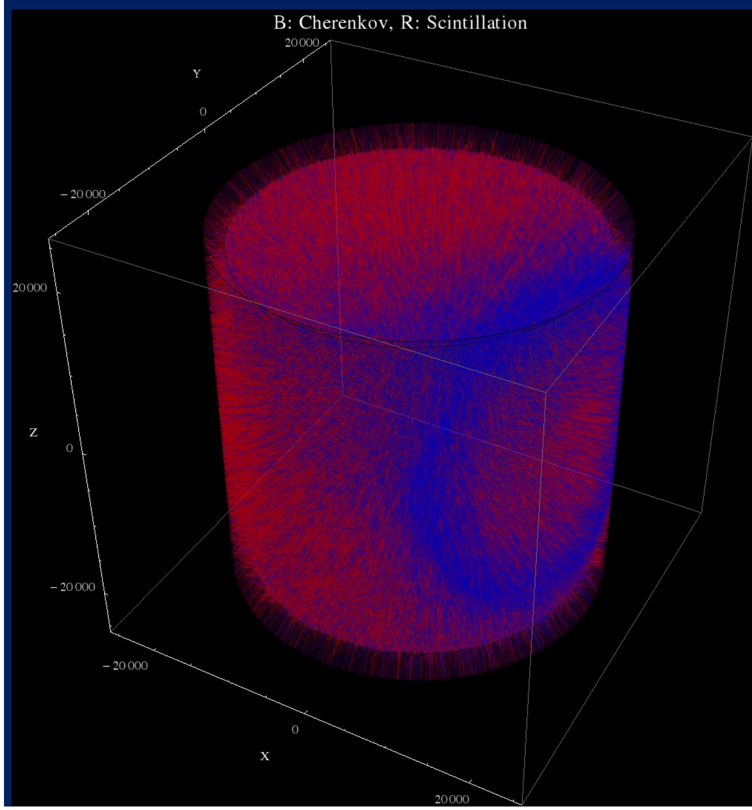
SNO



Technical and Instrumentation Challenges

For Future Path Forward

5. Threshold and Resolution
    - Add scintillation light to water detector for a “hybrid Cherenkov/scintillation detector”



High energy

- particle ID and final states from “chertons”
- Large detector mass for high statistics
- “scintons” for reconstruction of sub-Cherenkov threshold recoils

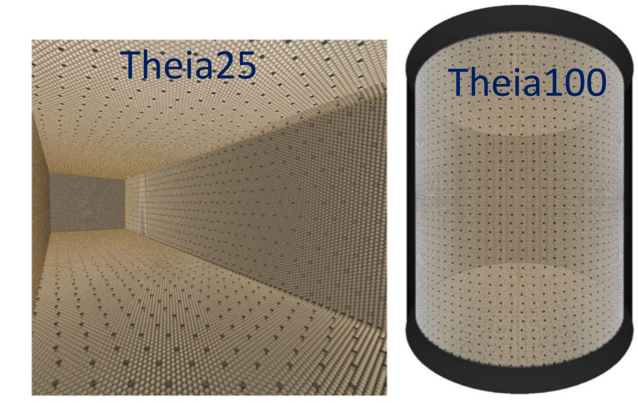
Low energy

- energy resolution from scintons for solar, reactor, $0\nu\beta\beta$…
- Direction reconstruction from chertons rejects/accepts solar νs

Hybrid Cherenkov/Scintillation Detectors

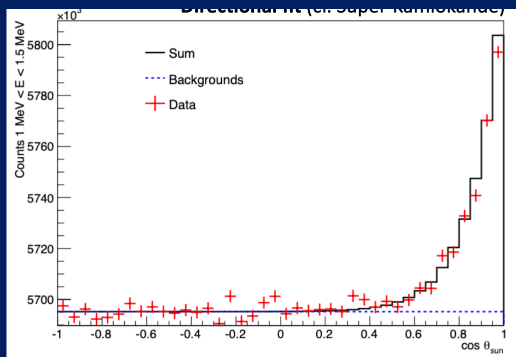
Extremely broad physics program

"Theia" is most well-developed concept;
Could be Module 4 for DUNE?

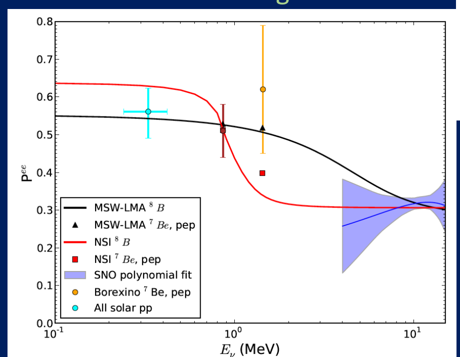


Eur. Phys. J. C 80 (2020)

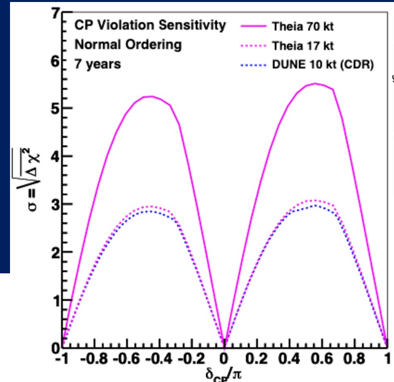
World-leading precision on pep and CNO solar νs (1-1.5 MeV)



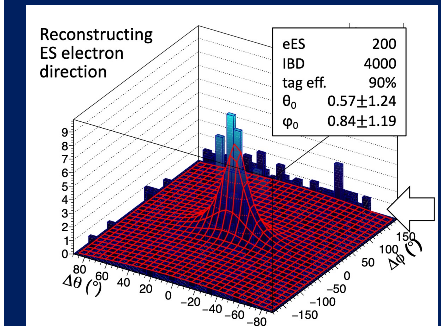
Only experiment capable of seeing MSW ^{8}B transition region



CP sensitivity comparable to one DUNE module (with ND changes)

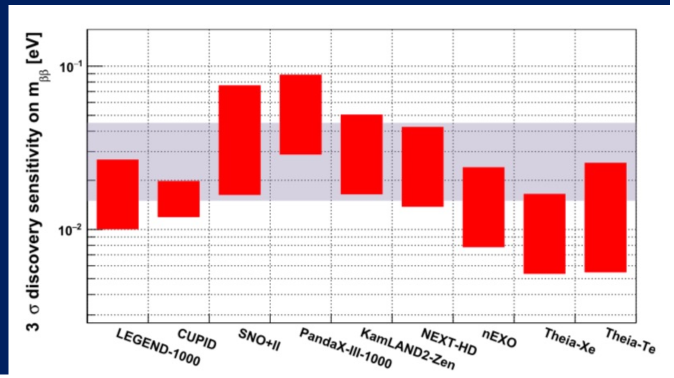


Lighter nucleus to check cross section systematics



Complementary (anti-ν vs ν) to DUNE with pointing resolution < 2°

0νββ sensitivity into normal hierarchy region with ***natural*** Te—direction removes ^{8}B background



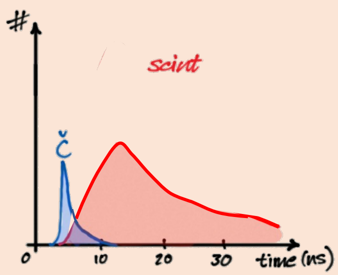
Hybrid Cherenkov/Scintillation Detectors

Many Ways of Doing This

Ratio

Add just a little scintillation

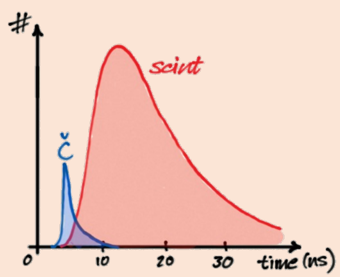
→ new materials/fluors



Timing

"instantaneous chertons" vs. delayed "scintons"

→ ns resolution or better

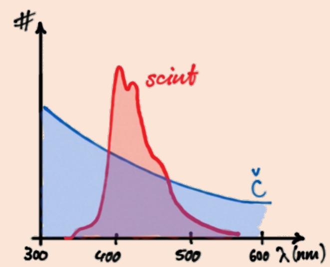


M. Wurm

Spectrum

UV/blue scintillation vs. blue/green Cherenkov

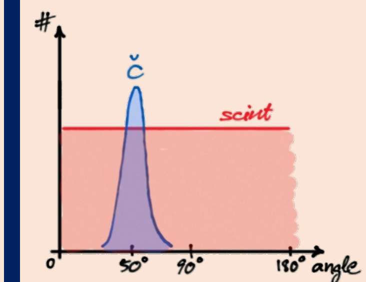
→ wavelength-sensitivity



Angular distribution

increased PMT hit density under Cherenkov angle

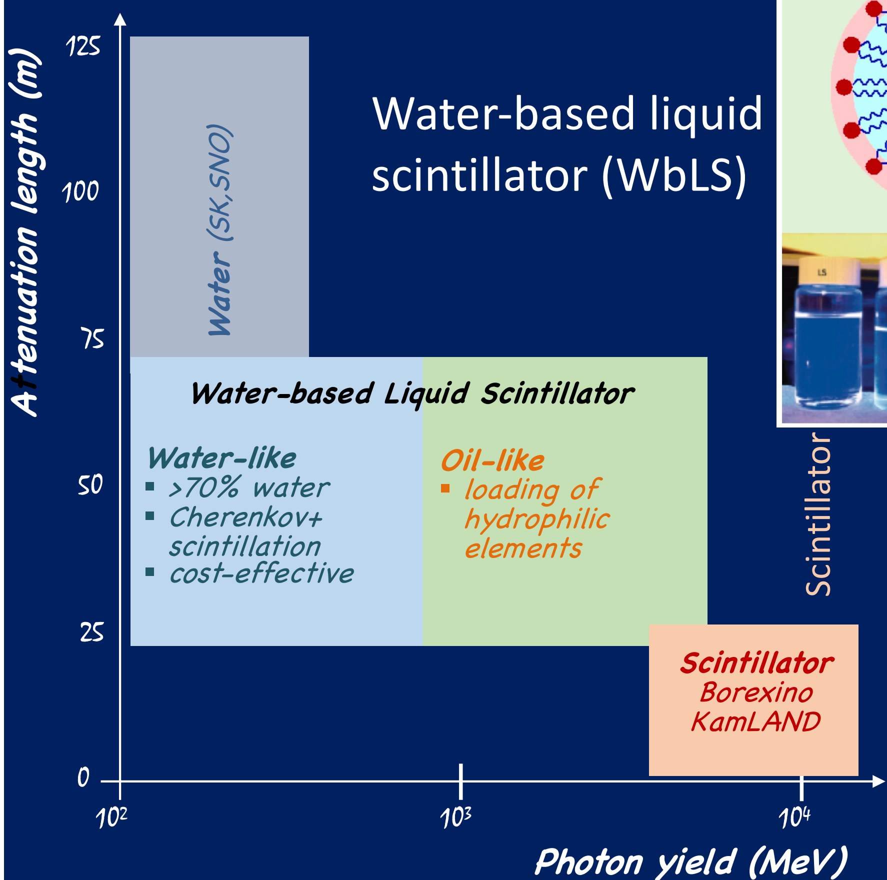
→ sufficient granularity



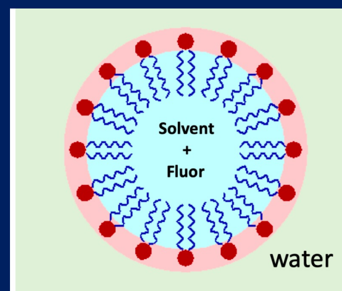
Eur. Phys. J. C 80 (2020)

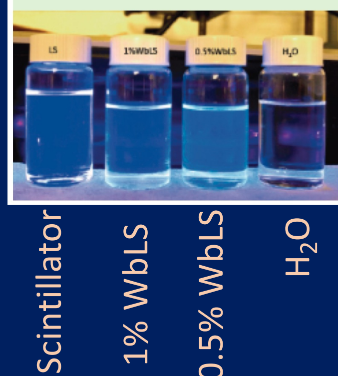
Adjust Cher/Scint Ratio

5. Threshold and Resolution



Water-based liquid scintillator (WbLS)



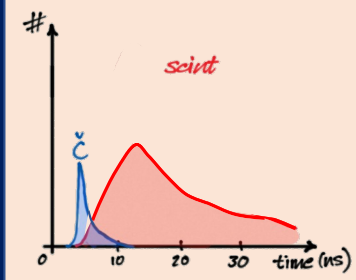


M. Yeh, BNL

Ratio

Add just a little scintillation

→ new materials/fluors



Isotopes easily loaded into WbLS

Target	Loading (mass)	Potential Applications
Indium	>8% In	Solar ν
Tellurium	> 6% Te	$0\nu\beta\beta$
Lithium	0.1% ^{6}Li >0.2% ^{6}Li	Reactor $\bar{\nu}$; excellent PSD Reactor $\bar{\nu}$; super PSD with improved optics
Boron	>0.5%	Dark Matter veto, reator $\bar{\nu}$
Potassium	>1%	Calibration for LS detectors
Iron, Strontium	ppm to 1%	Nuclear waste management, enviromental tracers
Gadolinium	0.1% Gd	Dark matter veto Reactor monitoring Reactor $\bar{\nu}$ oscillations
High-Z elements	10-15%Pb	Solar ν Calorimeters Medical QA/AC

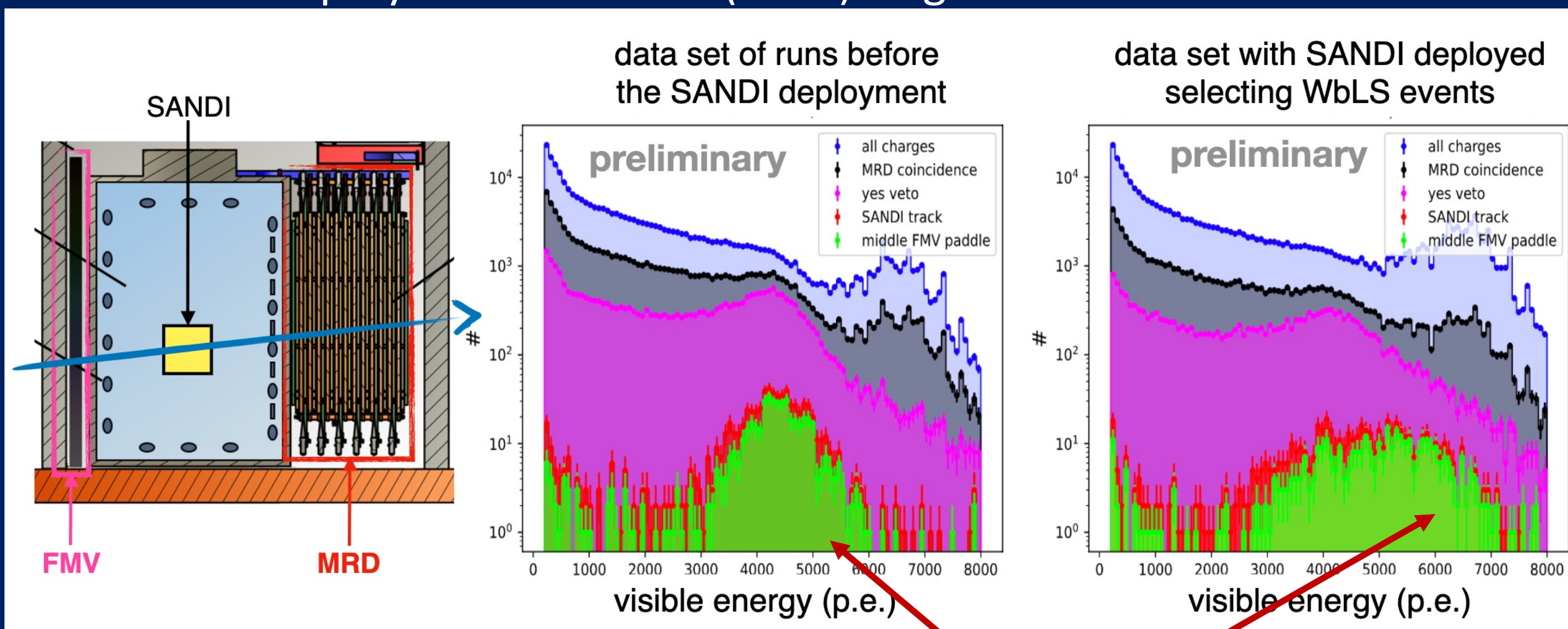
Target can be adjusted for different physics goals

M. Yeh, BNL

Adjust Cher/Scint Ratio

5. Threshold and Resolution

First deployment of WbLS (0.5%) target in ANNIE

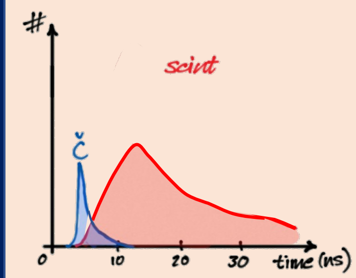


Increase in μ response through WbLS target

Ratio

Add just a little scintillation

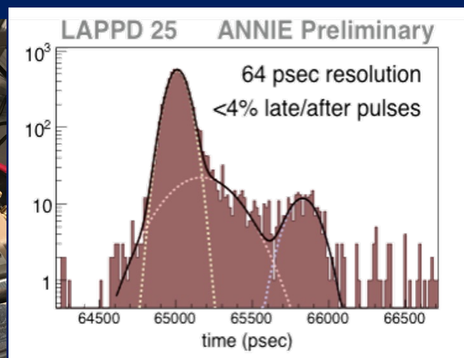
→ new materials/fluors

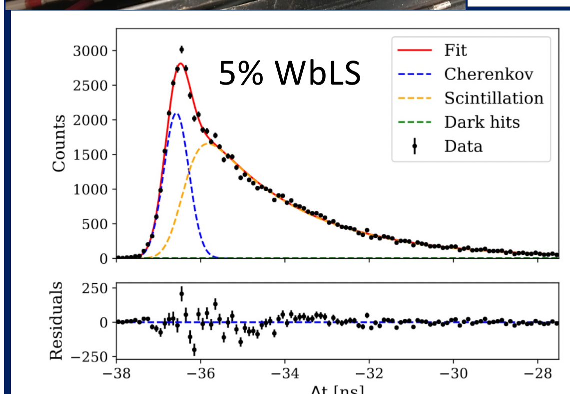


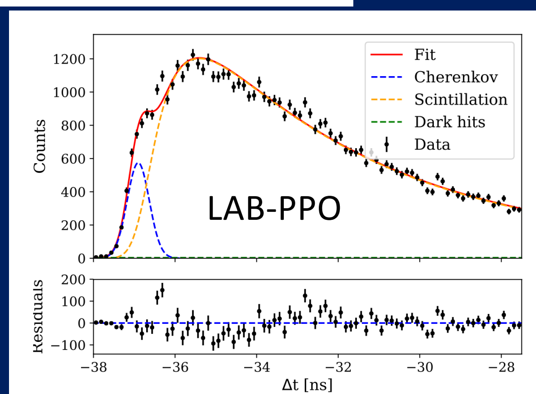
M. Wurm
TAUP 2023

Timing

5. Threshold and Resolution







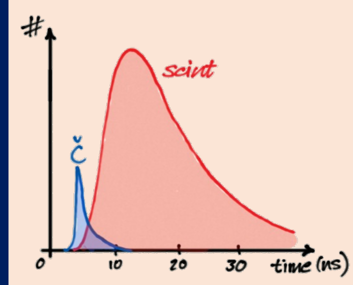
T. Kaptanoglu, LBNL

Cherenkov peak easy to pick out even in pure scintillator

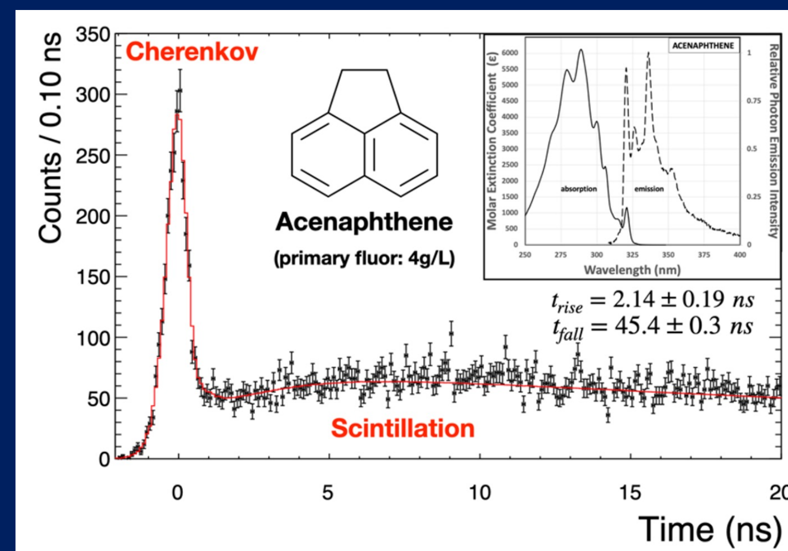
Timing

“instantaneous chertons” vs. delayed “scintons”

→ ns resolution or better

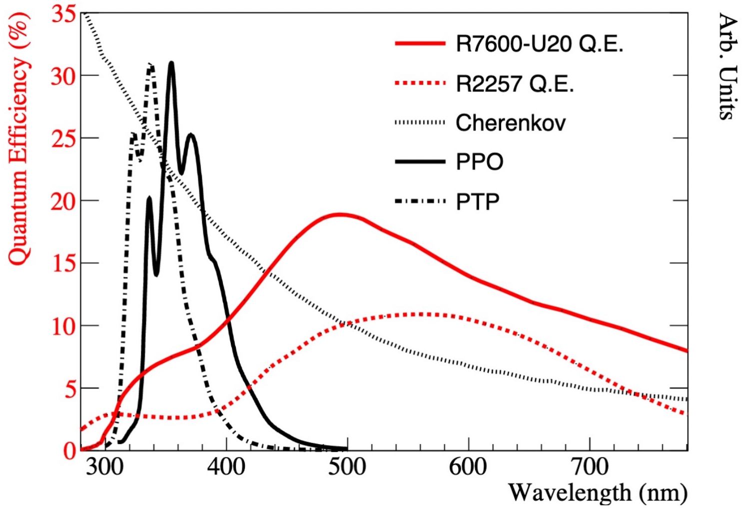


Slower scintillator



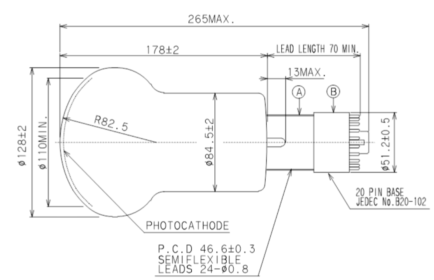
Biller, Leming, Paton, NIM A 972 (2020) 164106

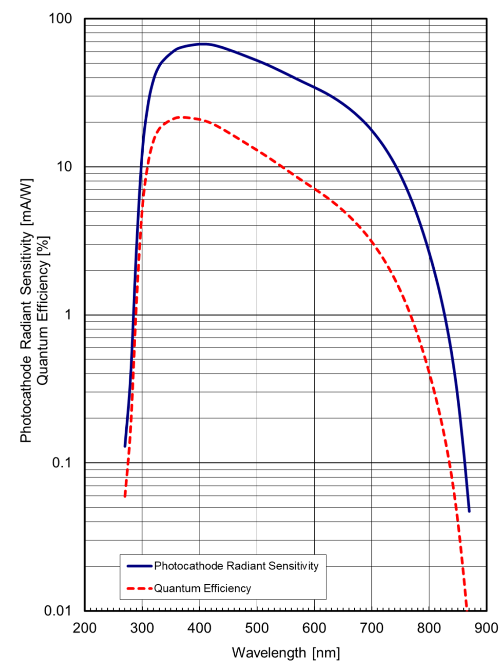
Spectral Sorting



Spectral differences may allow separation---could use filters or red-sensitive PMTs:

R6954 (S20) [5”]

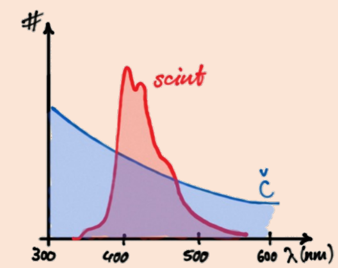




Spectrum

UV/blue scintillation vs. blue/green Cherenkov

→ wavelength-sensitivity

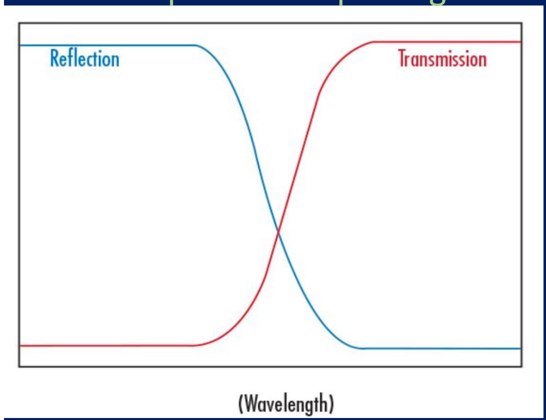


Although this means each spot taken up by filter or “red” PMT is lost scintillation light---Is there a way to keep both even at high photocathode coverage?

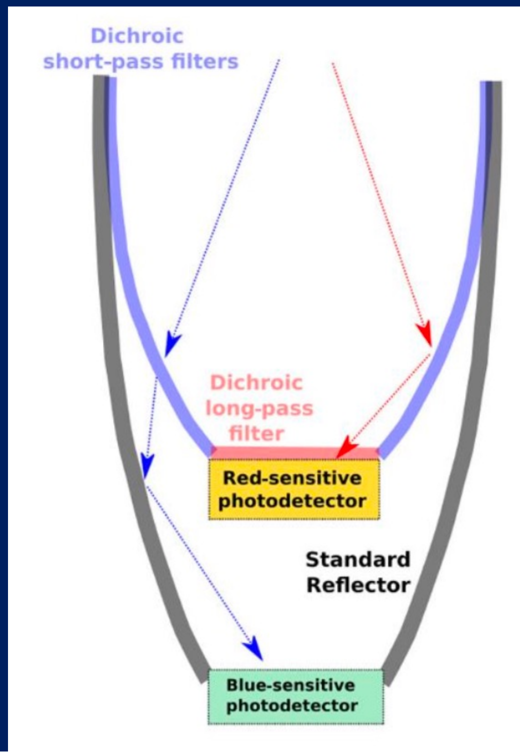
Spectral Sorting

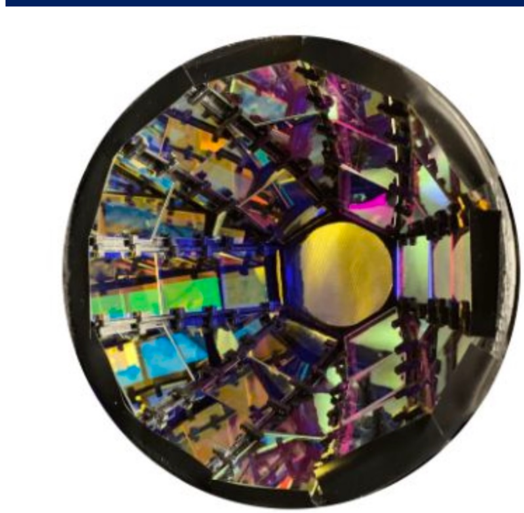
5. Threshold and Resolution

Dichroic filters already used in ARAPUCA photon-trap design



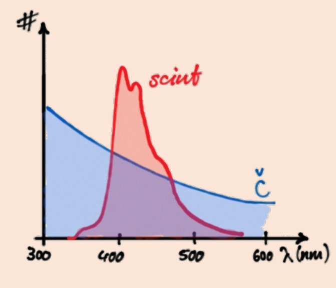
Winston-style light concentrator made out of dichroic mirrors can concentrate long-wavelength and pass short wavelength light (a "dichroicon")





Spectrum

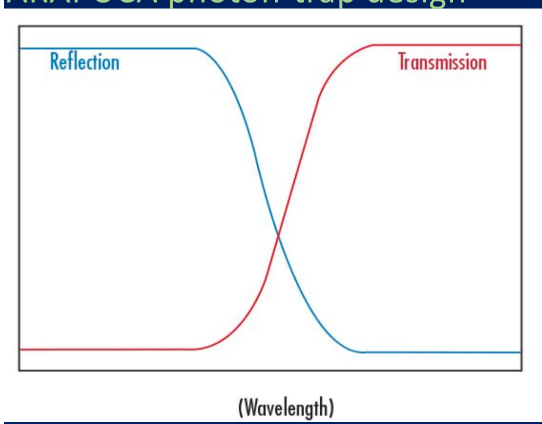
UV/blue scintillation vs. blue/green Cherenkov
→ wavelength-sensitivity



Spectral Sorting

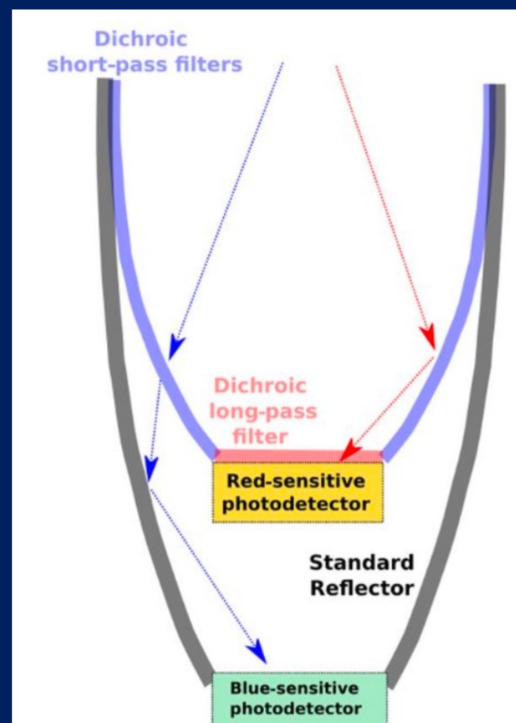
5. Threshold and Resolution

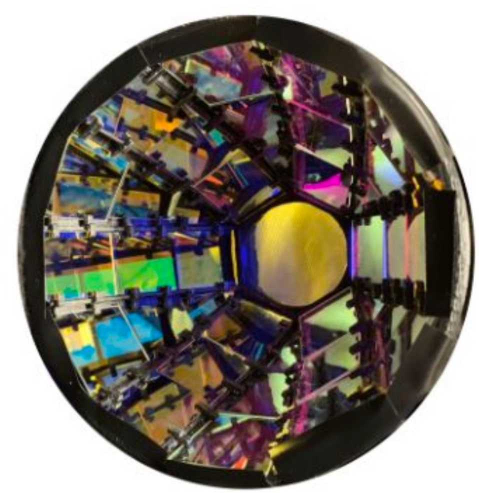
Dichroic filters already used in ARAPUCA photon-trap design



Also useful for measuring dispersion of photons in water—new way of reconstruction in very large detectors.
(And scattering is lower for big λ)

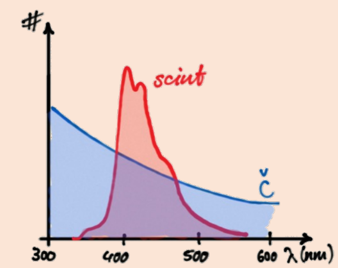
Winston-style light concentrator made out of dichroic mirrors can concentrate long-wavelength and pass short wavelength light (a “dichroicon”)





Spectrum

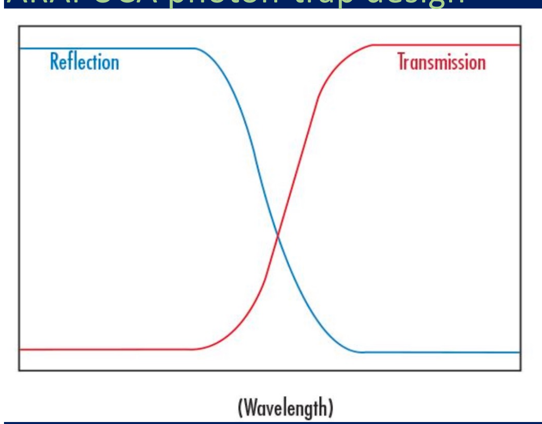
UV/blue scintillation vs. blue/green Cherenkov
→ wavelength-sensitivity



Spectral Sorting

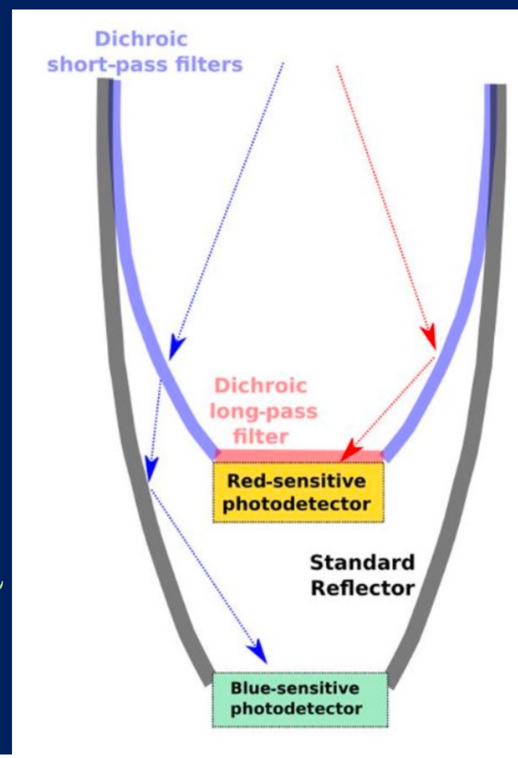
5. Threshold and Resolution

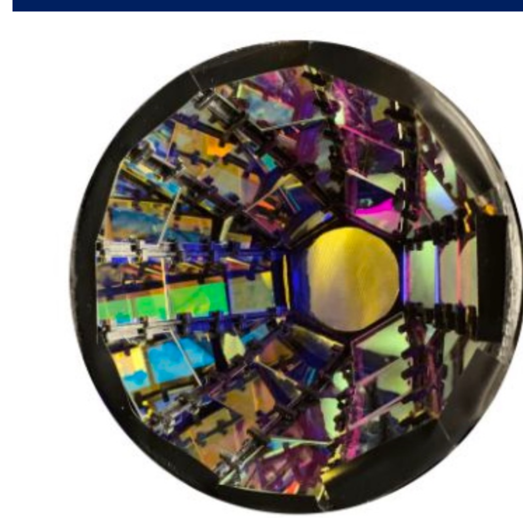
Dichroic filters already used in ARAPUCA photon-trap design



And in principle can increase light collection by sorting photons to sensors with better QE for a given λ

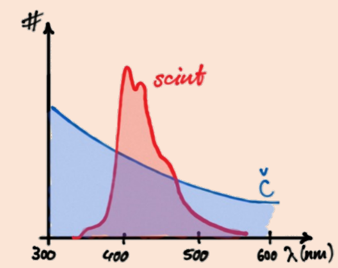
Winston-style light concentrator made out of dichroic mirrors can concentrate long-wavelength and pass short wavelength light (a "dichroicon")





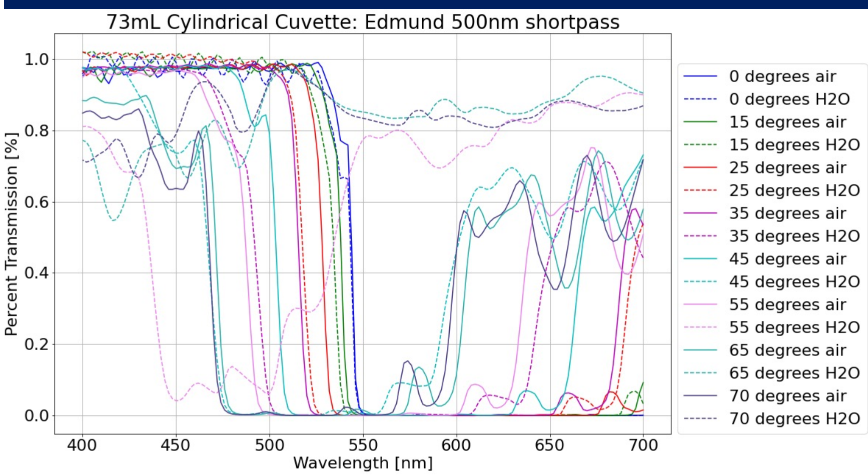
Spectrum

UV/blue scintillation vs. blue/green Cherenkov
→ wavelength-sensitivity



Spectral Sorting

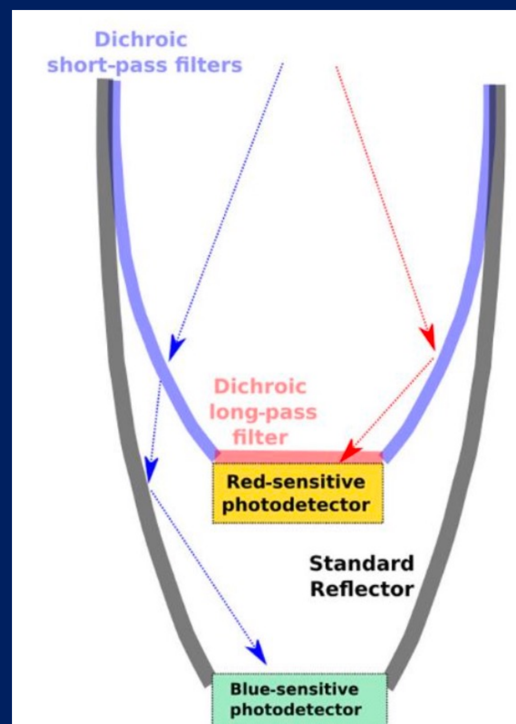
5. Threshold and Resolution

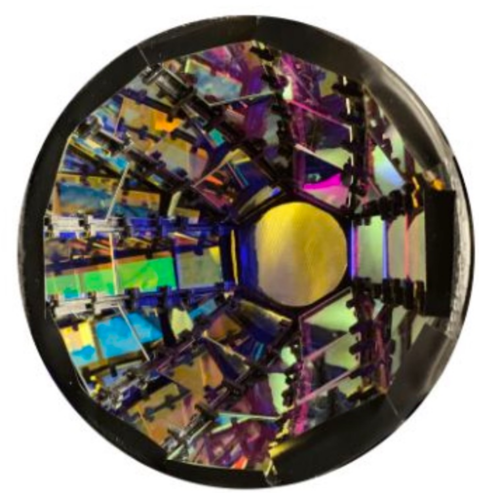


A. Bacon, Penn

(But actual response is more complex than basic concept)

Winston-style light concentrator made out of dichroic mirrors can concentrate long-wavelength and pass short wavelength light (a "dichroicon")





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UV/blue scintillation vs. blue/green Cherenkov
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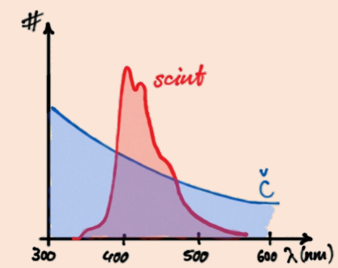


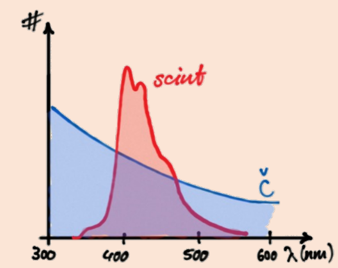
Spectral Sorting

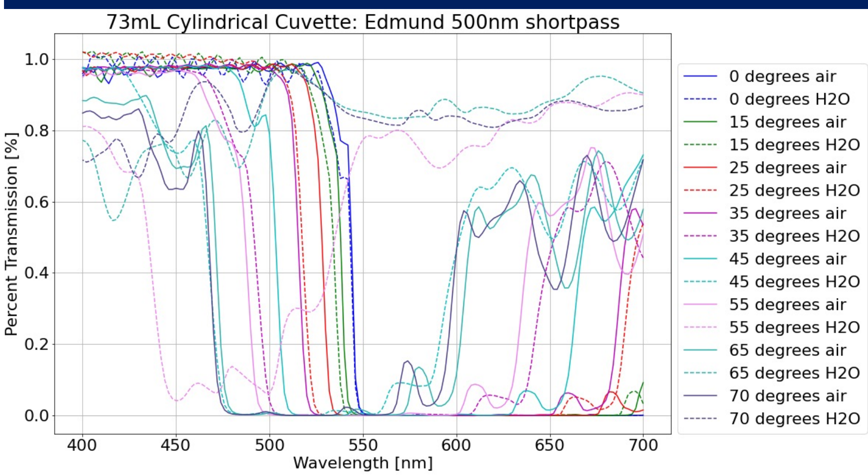
5. Threshold and Resolution

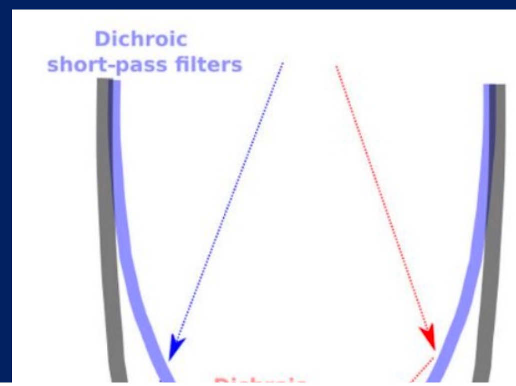
Winston-style light concentrator made out of dichroic mirrors can concentrate long-wavelength and pass short wavelength light (a “dichroicon”)

Spectrum

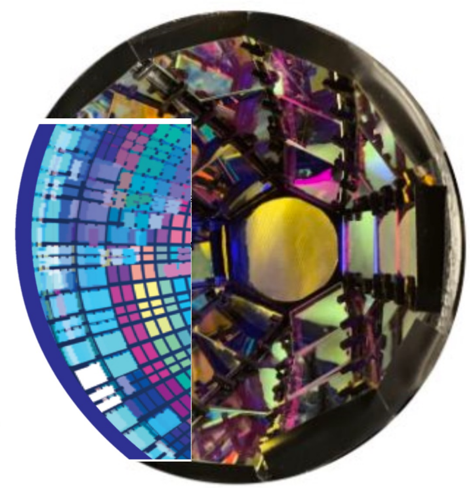
UV/blue scintillation vs. blue/green Cherenkov
→ wavelength-sensitivity





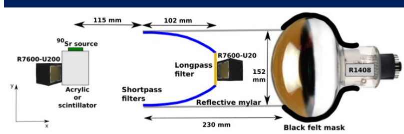


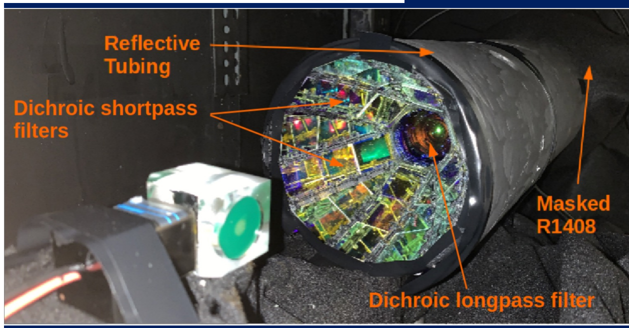
A. Bacon, Penn



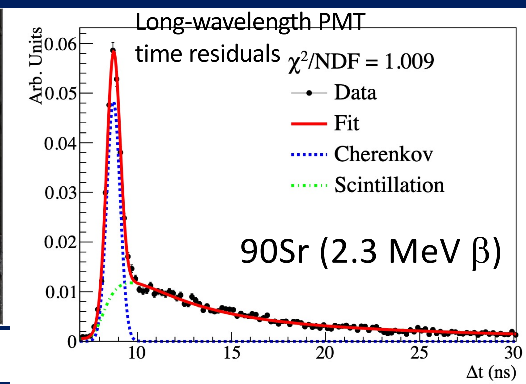
Spectral Sorting

5. Threshold and Resolution

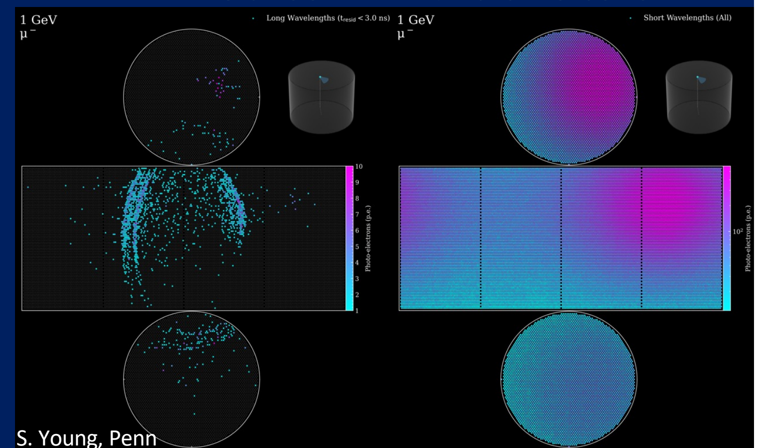




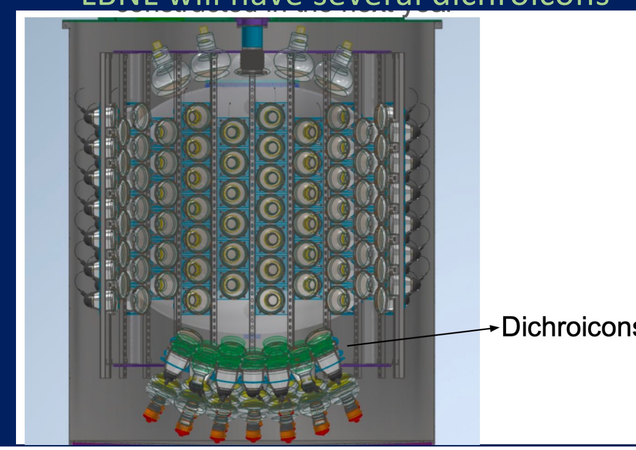
Phys. Rev. D 101, 072002



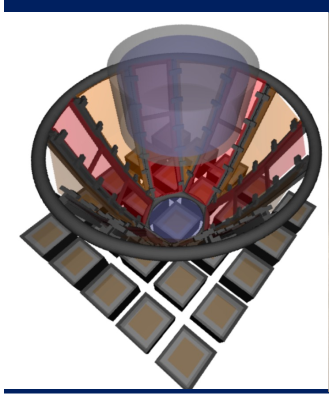
Theia100 MC with dichroicons

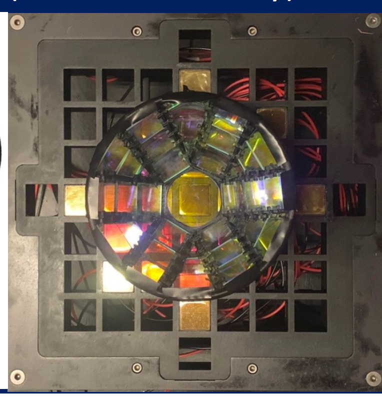


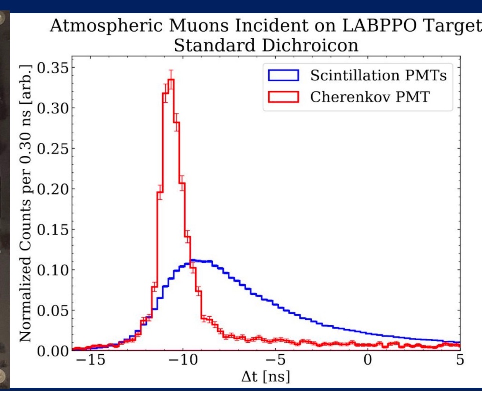
Eos demonstrator (~5 t WbLS) at LBNL will have several dichroicons



Dichroicon at CHESS (R7600 PMT array) at LBNL





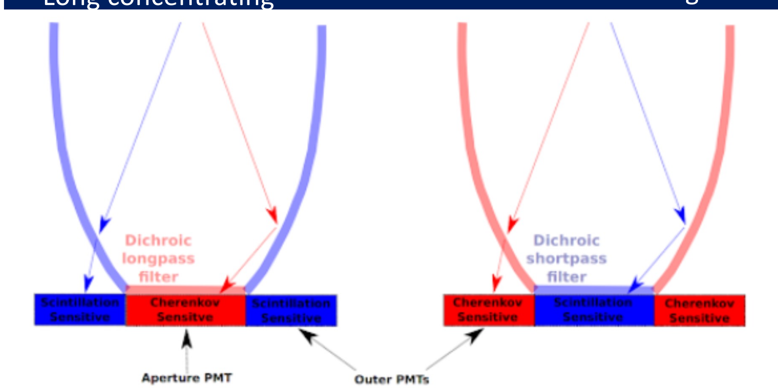


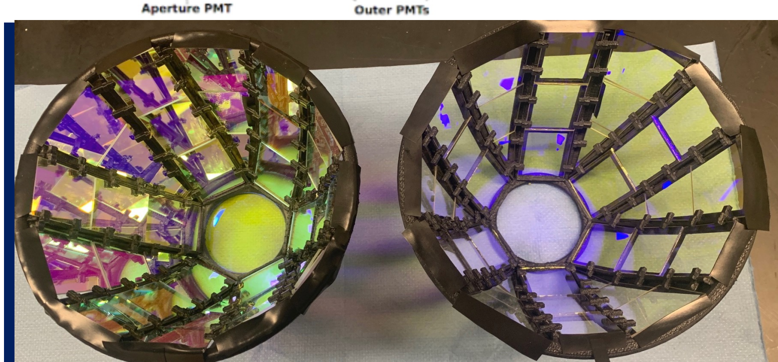
S. Naugle, Penn

Spectral Sorting

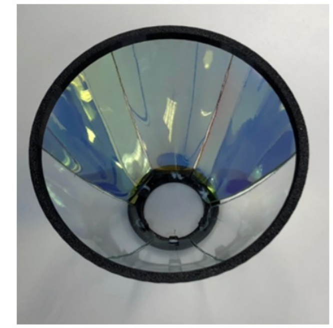
5. Threshold and Resolution

“Long concentrating” “Short concentrating”



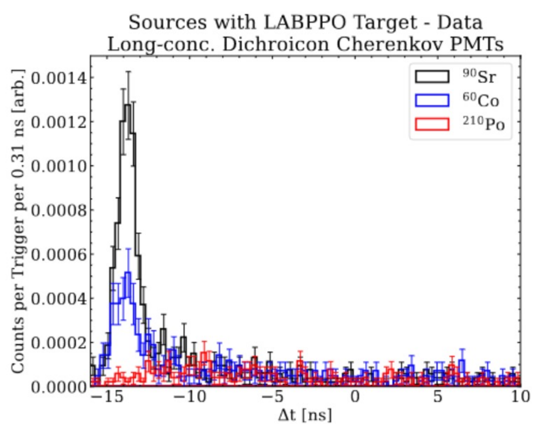


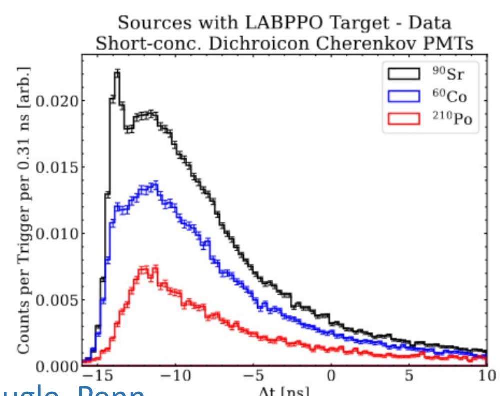
Atomic layer deposition (ALD) allows larger filters at lower cost, and on non-flat surfaces →



RAYTUM, Inc.

Can concentrate short-wavelength light but this leads to more leakage into long-wavelength sensors





S. Naugle, Penn

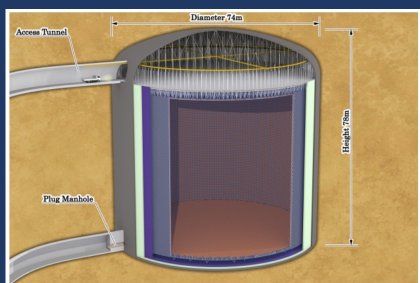
Technical and Instrumentation Challenges

For Future Path Forward

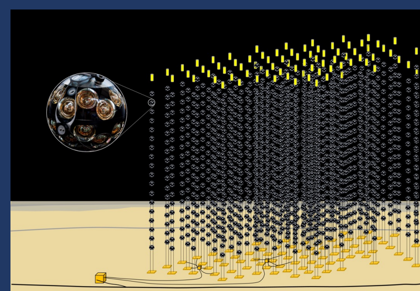
6. Electronics, Trigger, and DAQ

- Experimental sizes (100 m to 10 km) mean digitization must be done locally

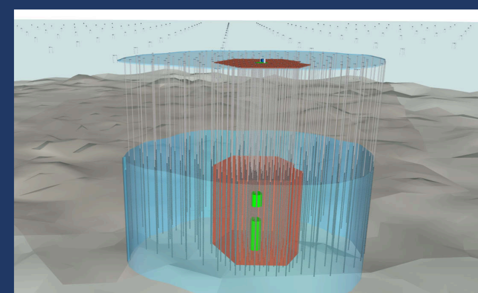
Hyper-Kamiokande



KM3NET



ICECUBE-GEN2



- Which places requirements on reliability: electronics are wet or cold and inaccessible
- And also places requirements on long-distance synchronization
    - May be the most complex, long-distance synchronized networks
    - Channel-to-channel around 1 ns
    - Absolute timing for astrophysics ~1 μs
- Solutions include White Rabbit (KM3NET) also custom designs
- Triggering typically very inclusive: N_{pmt} above threshold (can be analog, firmware, or software)

Technical and Instrumentation Challenges

For Future Path Forward

6. Electronics, Trigger, and DAQ

- Local digitization is self-triggered: need to limit data rate

Hyper-Kamiokande:
~50,000 channels

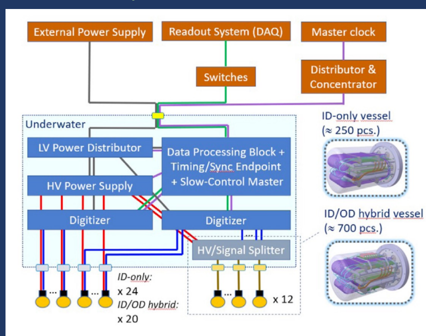
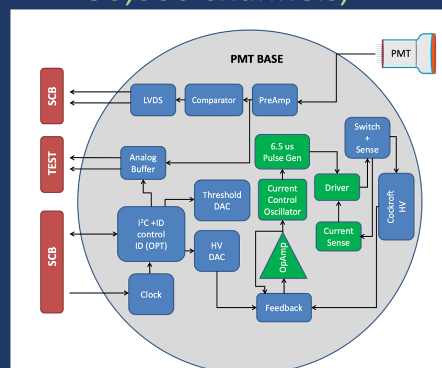


Fig. 5. Block diagram of H-K electronics.

- \\
- Want 0.1-0.3 ns precision
- 100 MSPS@14 bits

KM3NET:~
50,000 channels,



- ~1 ns resolution
- 250 MHzx4 @14 bits

ICECUBE-GEN2
~10000 channels

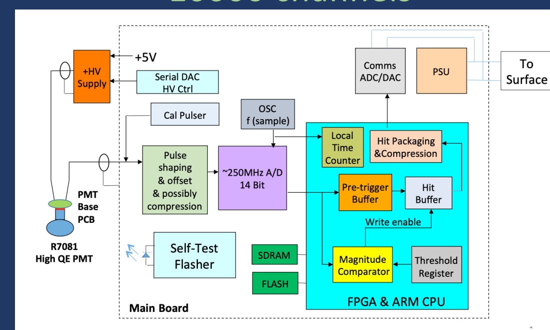


Figure 2: Block diagram of the of the Gen2 DOM mainboard.

- Want ~ 1 ns precision
- 250 MHz @14 bits

- Higher dynamic ranges likely as arrays get denser or PMTs get larger
  - Typically aiming now for 12-14 bits or > 11 or 12 ENOB
- Desire for faster timing means ADC sampling rates also pushing faster > 250 MSPs
- Data volumes can get big; ADCs and FPGAs more expensive

Technical and Instrumentation Challenges

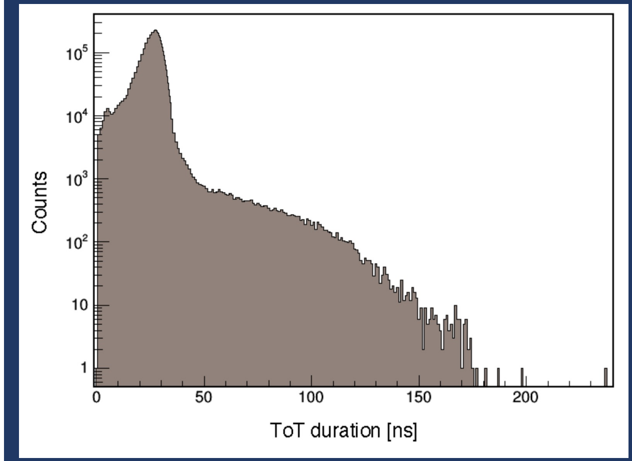
For Future Path Forward

6. Electronics, Trigger, and DAQ

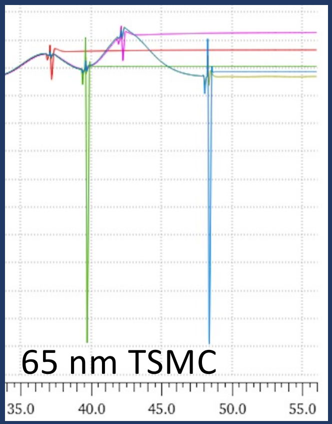
- Signals are very prompt, so full waveforms not necessarily useful
  - For hybrid detectors, late-time photons do matter, but still mostly single pe
- Only observables are $N_{photons}$ and t_i
- Typically “feature extraction” done, sometimes in local FPGA, sometimes in offline
- Analog feature extraction?

Features can be extracted via analog techniques and then digitized… Peaks/inflection points, time, time-over-threshold, integral (“Analog Photon Processor”)

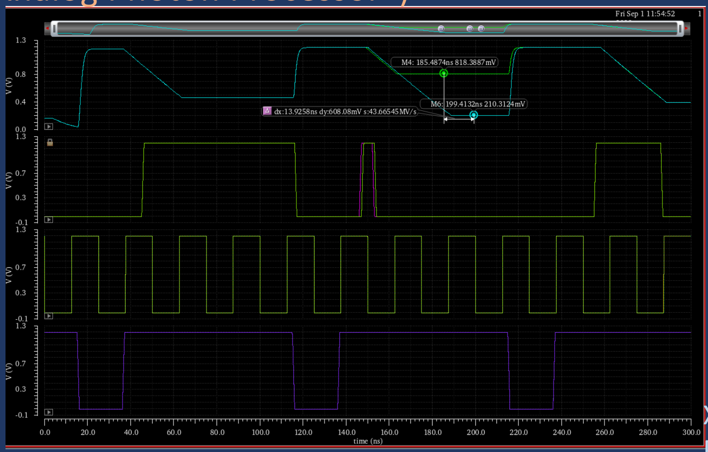
KM3NET time-over-threshold



N.Dressnandt, Penn



Peaks/inflection points via differentiation



X. Ma, Penn

Time via time-to-amplitude (TAC) ramps

Other Challenges

- PMT protection for underwater and ice operation
- Simulation --- every photon is simulated and big detectors make this slow
  - GPU accelerated ray tracers like Optiks or Chroma
  - Generative AI models
- Advanced reconstruction methods
  - High multiplicity events in Hyper-K
  - Hybrid detector reconstruction

Instrumentation Wish List

- Fast, high-photon detection efficiency, large-area, low-cost sensors
  - 500 ps FWHM
  - 40% QE
  - 50 cm diameter but…pixelated? (Hyper-K mPMTs pretty close!)
  - < $2500/device…?
- Nano-filtration for radiologicals in water or WbLS
- Dichroic filters on shaped surfaces (for lower cost/area)
- Narrow-band fluors for hybrid detectors and spectral sorting
- Large-area photon sensors with better long-wavelength sensitivity
- Real direction sensitivity via lensing?
- Polarization?

Summary

- Water Cherenkov detectors continue to be very successful!
- Size, low-cost, simplicity and dynamic range are major reasons for success
- New detectors being built or expanding (Hyper-K, ICE-GEN2, KM3NET, B-GVD)
- Future efforts will push on size, timing, photon collection, and threshold
- Hybrid detectors are a big area for detectors beyond Hyper-K, ICECUBE-GEN2, KM3Net