Future Advances in Photon-Based Neutrino Detectors

Josh Klein
University of Pennsylvania

White Paper

Future Advances in Photon-Based Neutrino Detectors: A SNOWMASS White Paper

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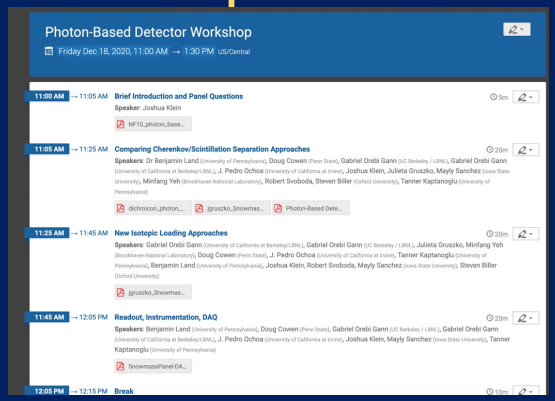
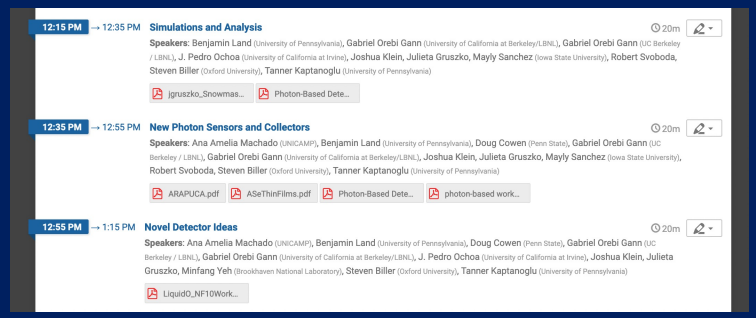
(Editors and Contributors)

+about 300 co-signers from 9 experimental collaborations

https://arxiv.org/pdf/2203.07479.pdf

Grew out of photon-based workshop held in December 2020



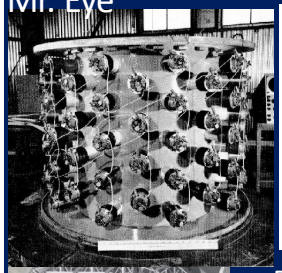


Not comprehensive! There was a bias toward “warm”, monolithic detectors

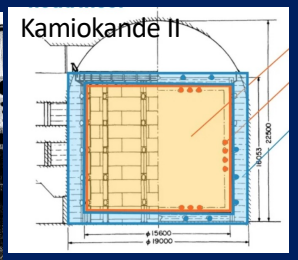
“Photon-Based”

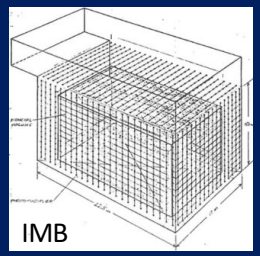
“Photon-based Neutrino Detector” is almost redundant

Mr. Eye



Kamiokande II





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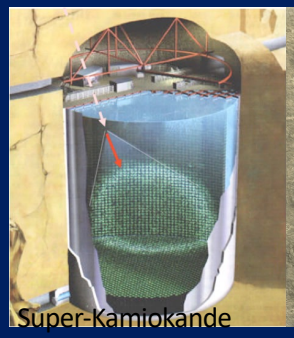
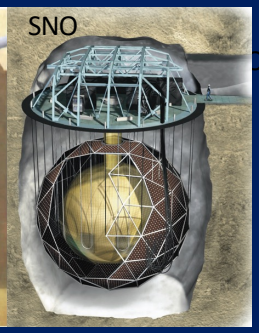
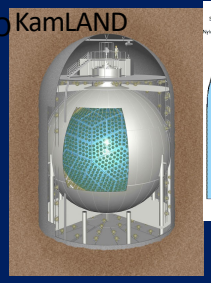


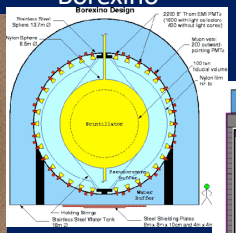
Super-Kamiokande



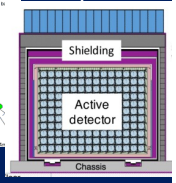
SNO



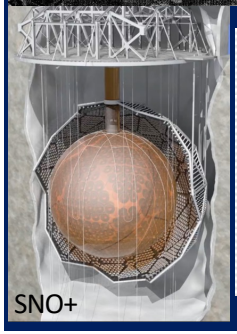
KamLAND



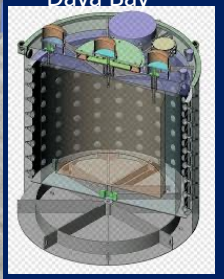
Borexino



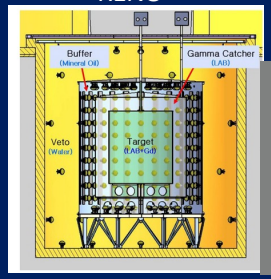
Prospect



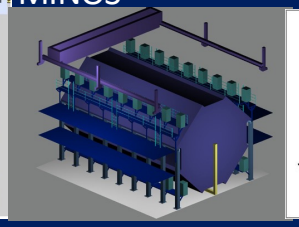
SNO+



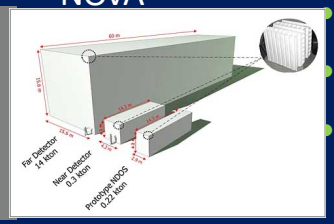
Daya Bay



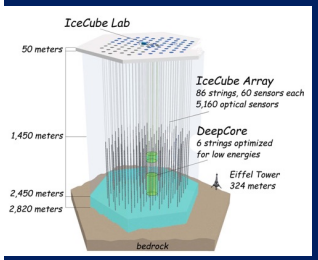
RENO



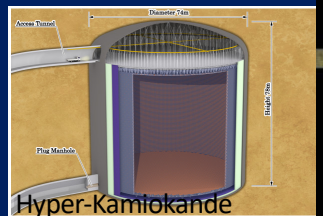
MINOS



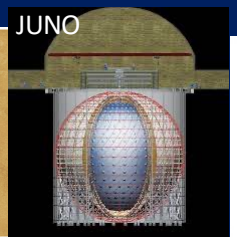
NOvA



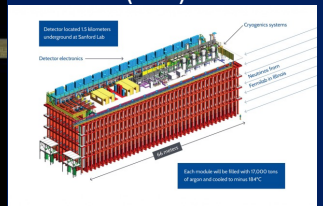
Coming soon:



Hyper-Kamiokande



JUNO



DUNE (PDS)

Discoveries/Measurements:

- The neutrino
- Neutrino oscillations
- Resolution of
  Solar Neutrino Problem
- LMA mixing
- θ_{12}, Δm^2_{12}, δm^2_{23}, θ_{23}, θ_{13}
- Supernova neutrinos
- (Exclusive) ^{8}B,pep,^{7}Be,pp solar
- Extragalatic νs

“Photon-Based”

Success to date has been driven by several factors:

- Low cost
- Scalability
- Adaptability
- Precision modeling
- Analysis simplicity

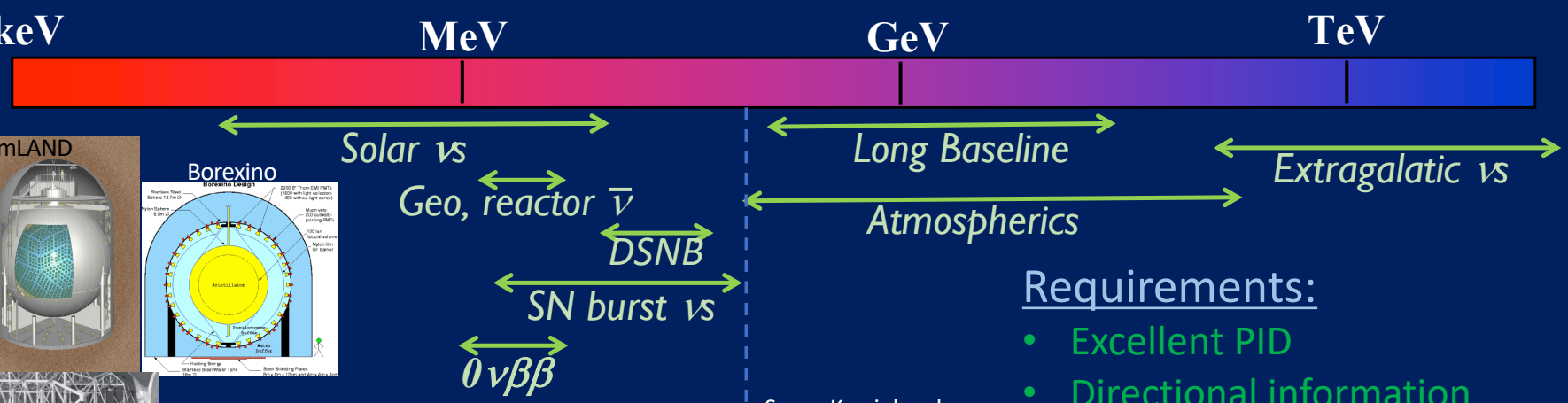
“Photon-Based”

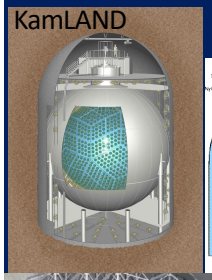
With so much success, what is left to do?

- Improve precision
  - Bigger detectors for better statistics
  - Better calibrations and simulation models
- Increase sensitivity
  - Better reconstruction (~better timing, pixelization or segmentation)
  - Better energy resolution (~better photon counting)
  - Better particle ID
- Broaden the program
  - New scintillating materials
  - Isotopic “loading” for various physics programs
  - Hybrid Cherenkov/scintillation detectors

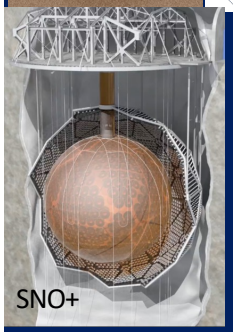
Hybrid Cherenkov/Scintillation Detectors

Goal: A very broad range of world-leading physics



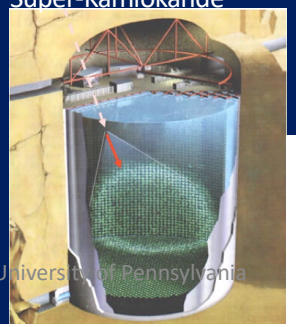

KamLAND

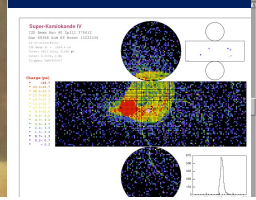
Borexino

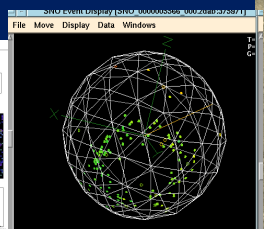

SNO+

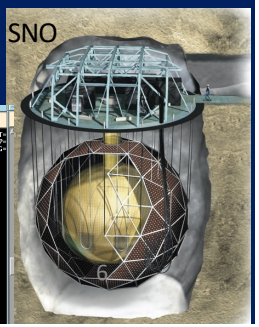
Requirements:

- Low radio backgrounds
- Excellent energy resolution
- Directional information


Super-Kamiokande





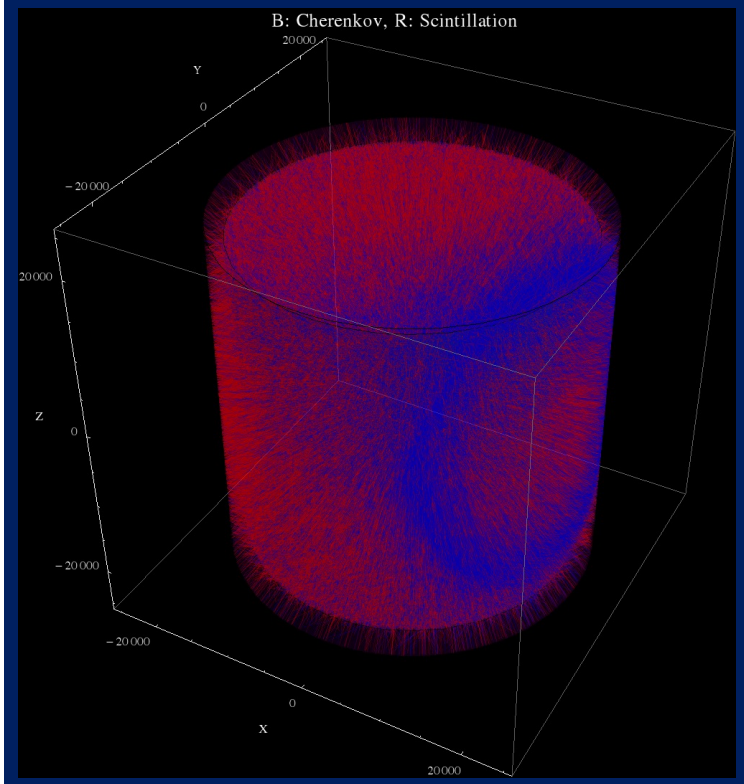

SNO

Requirements:

- Excellent PID
- Directional information
- Very big detector

Hybrid Cherenkov/Scintillation Detectors

At the last Snowmass, this was mostly an idea…



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

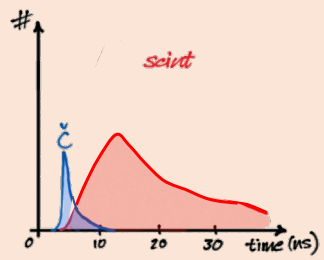
There are now many ways to do this!

Hybrid Cherenkov/Scintillation Detectors

Ratio

Reduce number of scintons

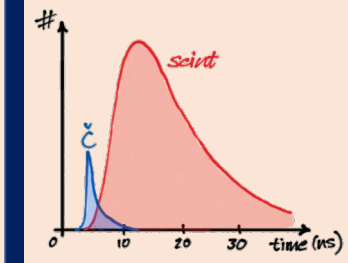
→ new materials/fluors



Timing

"instantaneous chertons" vs. delayed "scintons"

→ ns resolution or better

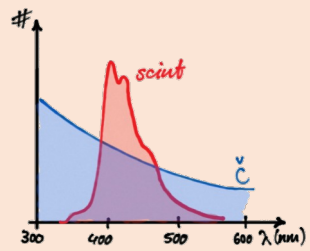


M. Wurm

Spectrum

UV/blue scintillation vs. blue/green Cherenkov

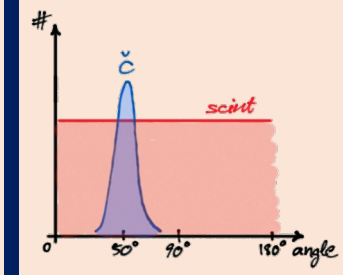
→ wavelength-sensitivity



Angular distribution

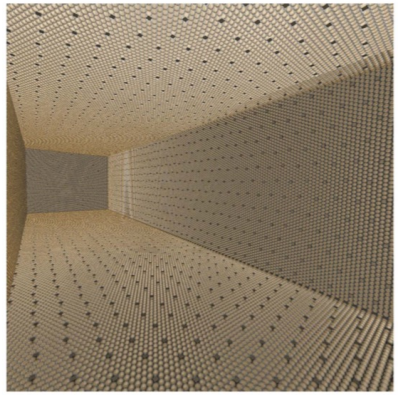
increased PMT hit density under Cherenkov angle

→ sufficient granularity

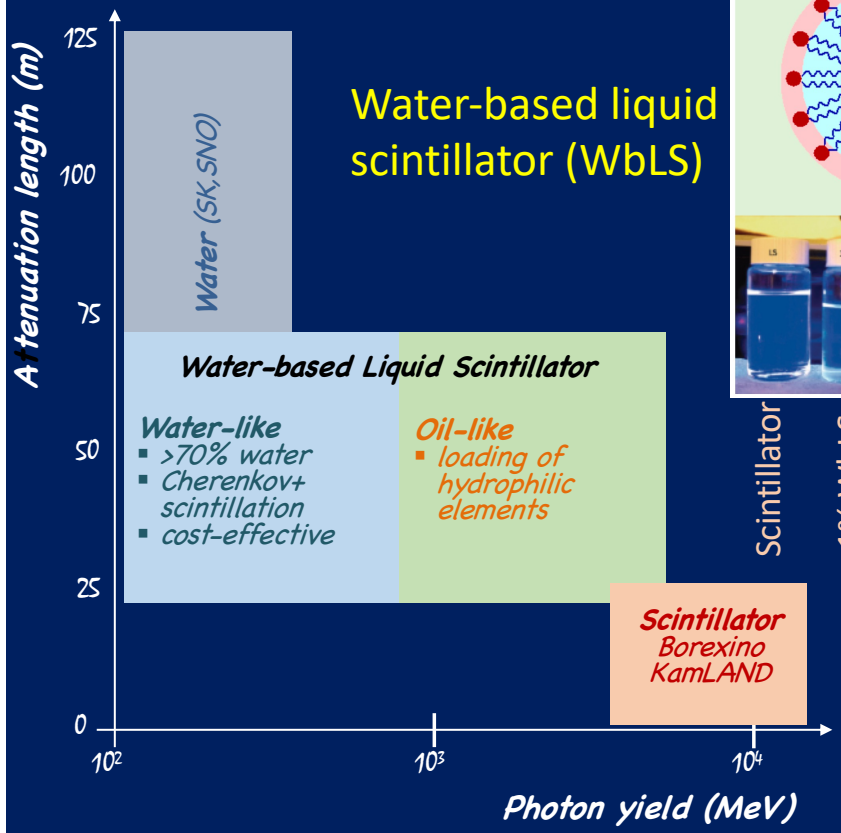


"Theia" is most well-developed concept; Could be Module 3 or 4 or DUNE?

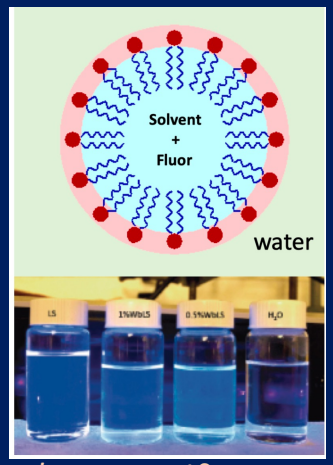
Theia25



Adjust Cher/Scint Ratio



Water-based liquid scintillator (WbLS)

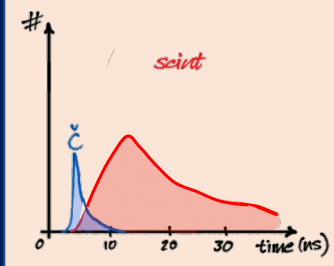


Scintillator | 1% WbLS | 0.5% WbLS | H_2O

Ratio

Reduce number of scintons

→ new materials/fluors



Other possibilities:

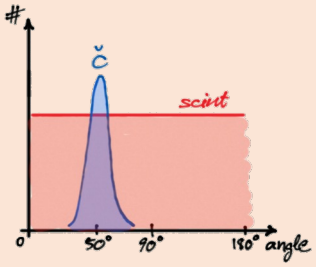
- LAB with "thin" PPO (Jinping)
- Vanilla mineral oil (MiniBooNE)
- Oil+a little scintillator
- Water+WLS?

Target can be adjusted for different physics goals

(Angular Distribution)

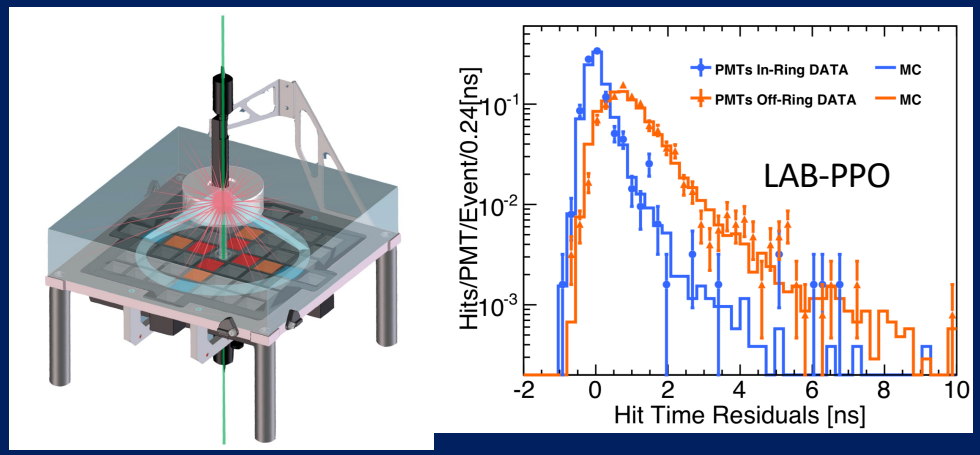
Angular distribution

increased PMT hit density under Cherenkov angle
→ sufficient granularity



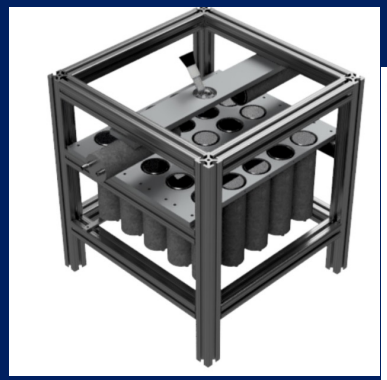
Not really instrumentation but an analysis approach---

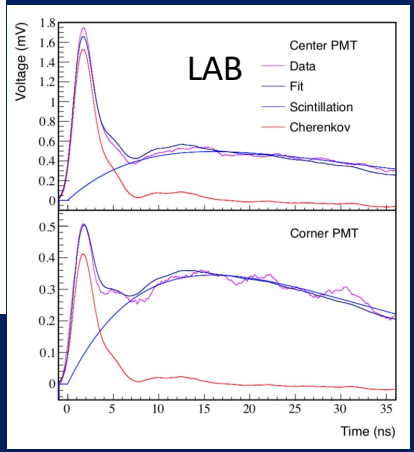
CHESS at LBNL Measurements



Caravaca et al, EPJC (2017) 77:811

"FlatDOT"





Gruszko et al, JINST 14 (2019) 02, P02005

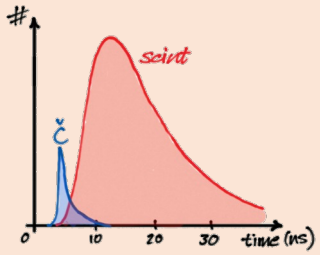
Timing

Two choices:

- Improve sensor timing
  - Lots of other benefits, like better reconstruction
  - But increases cost, in some cases dramatically
  - Dispersion in big detector helps!
  - But scattering hurts
- Slow down scintons with slow fluor
  - Relatively easy and inexpensive
  - Broadens reconstruction resolution
  - May have impact on overall light yield

Timing

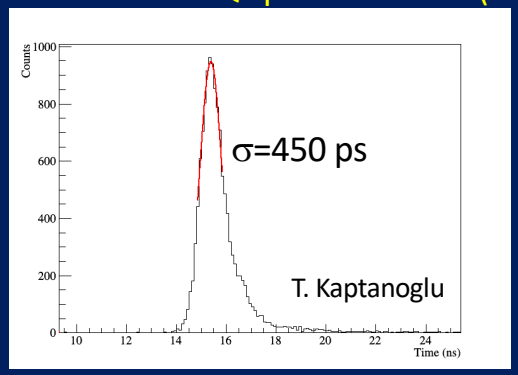
"instantaneous chertons"
vs. delayed "scintons"
→ ns resolution or better

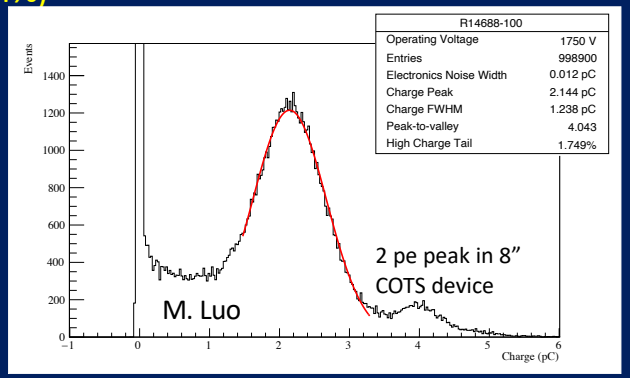


Timing

Fast(er) Sensors

R14668 new **8”** PMT from Hamamatsu---HQE photocathode (~34%)





Timing

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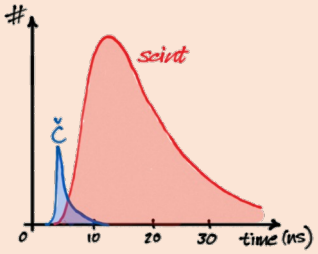
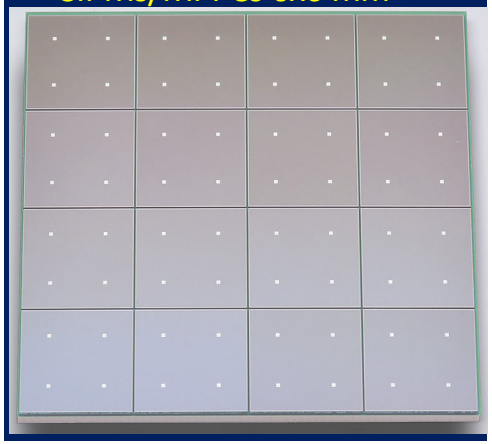
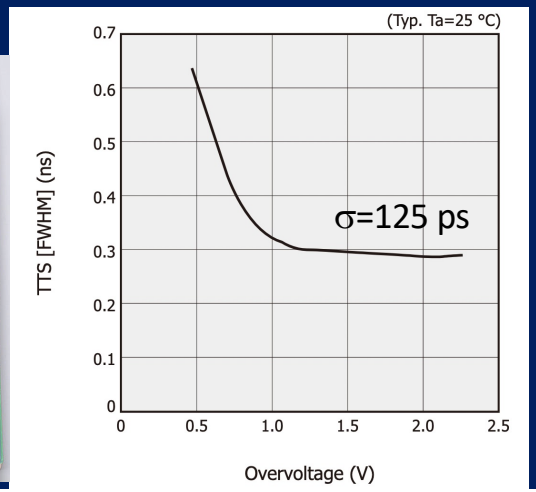
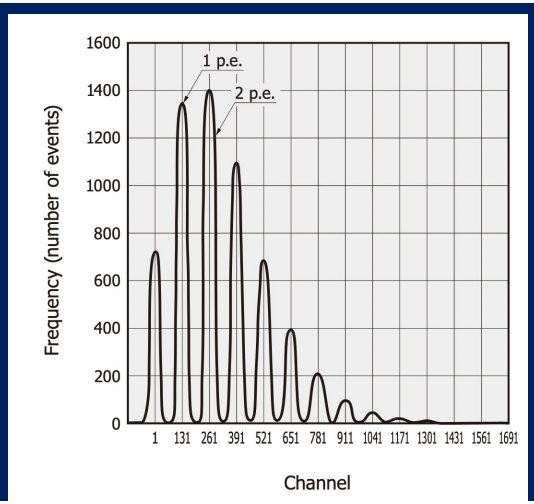


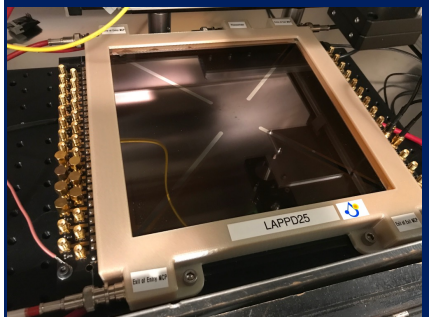
SiPMs/MPPCs 6x6 mm

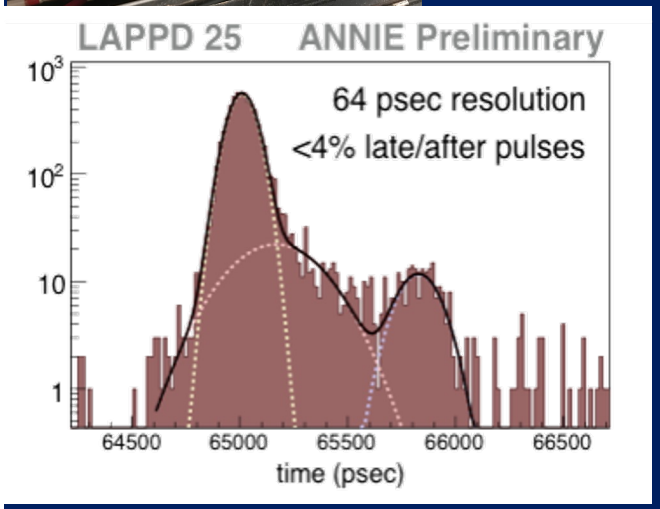






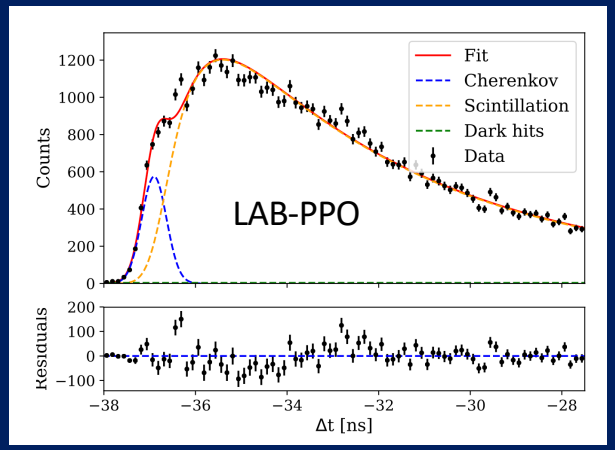
Fast(er) Sensors

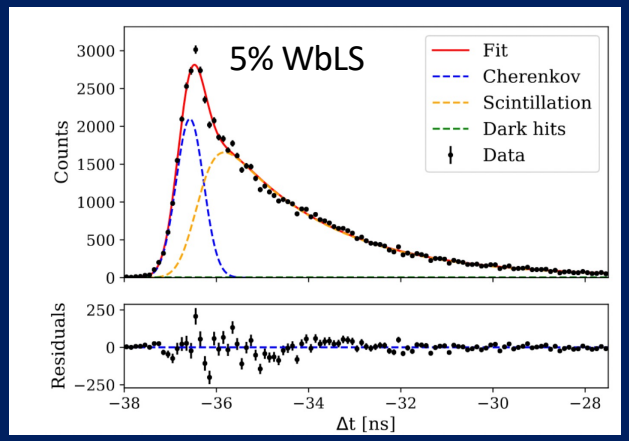




Timing

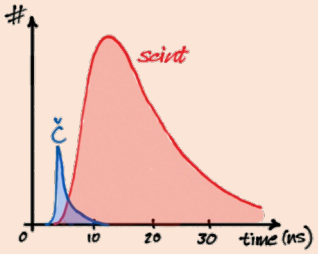
CHESS (LBNL)





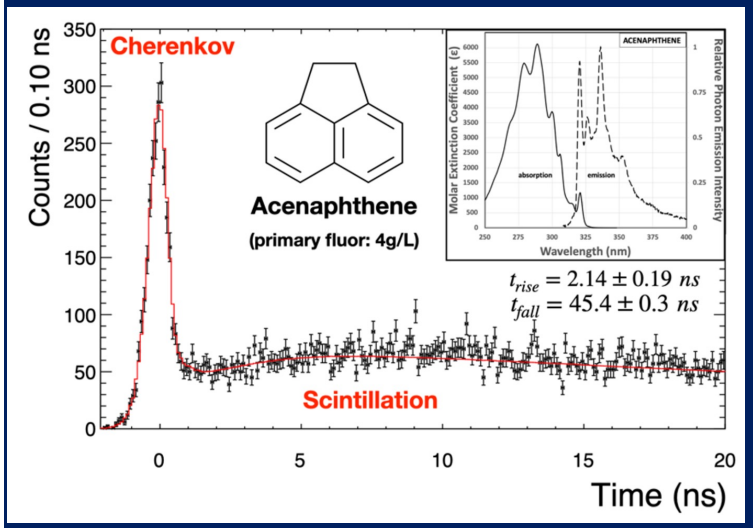
Timing

"instantaneous chertons"
vs. delayed "scintons"
→ ns resolution or better



Timing

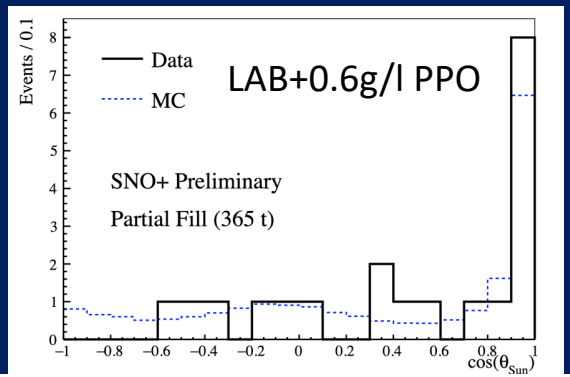
Slow(er) Scintillator



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

Can also slow down scintillator by using a small amount of fluor---
Also (obviously) increases Cher/Scint ratio

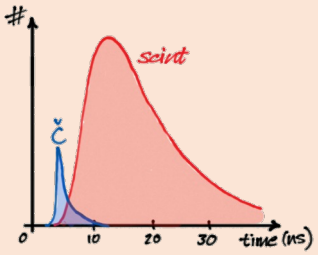
(Jinping, SNO+ "partial fill")



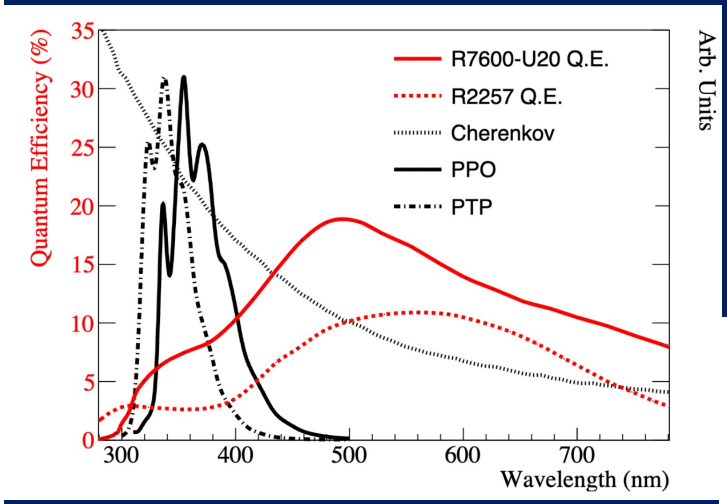
Solar peak in scintillator event-by-event!

Timing

"instantaneous chertons" vs. delayed "scintons"
→ ns resolution or better

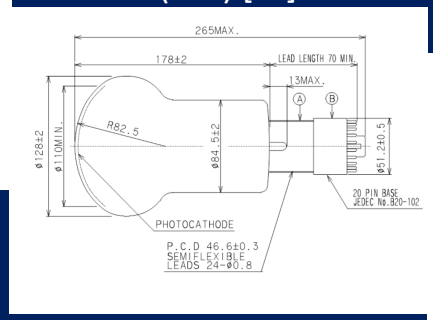


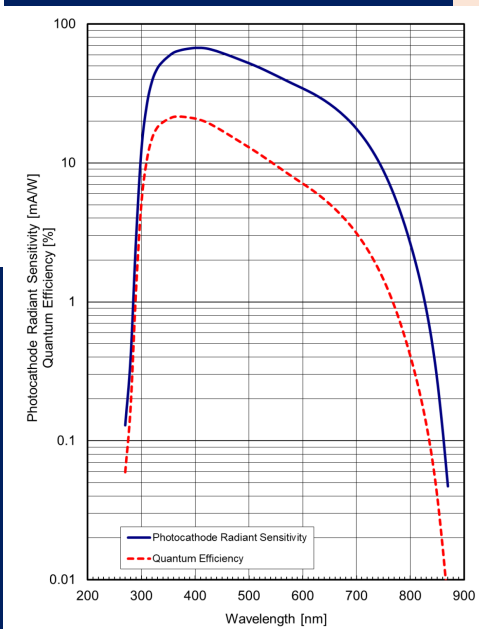
Spectrum



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

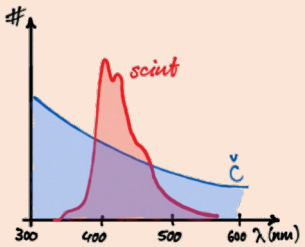
R6954 (S20) [5”]





Spectrum

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

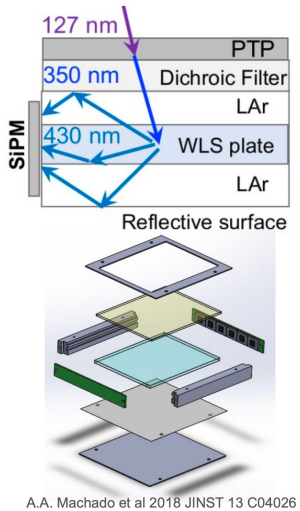


Although this means each spot taken up by filter or “red” PMT is lost scintillation light---

Is there a way to keep both even at high photocathode coverage?

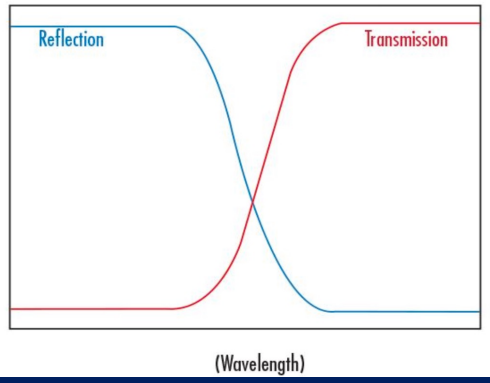
Spectrum

H.V. Souza, arXiv:2112.02967



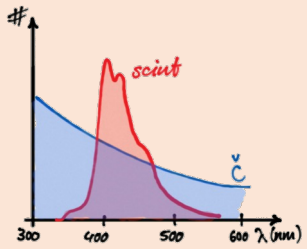
A.A. Machado et al 2018 JINST 13 C04026

Dichroic filters already used in ARAPUCA photon-trap design

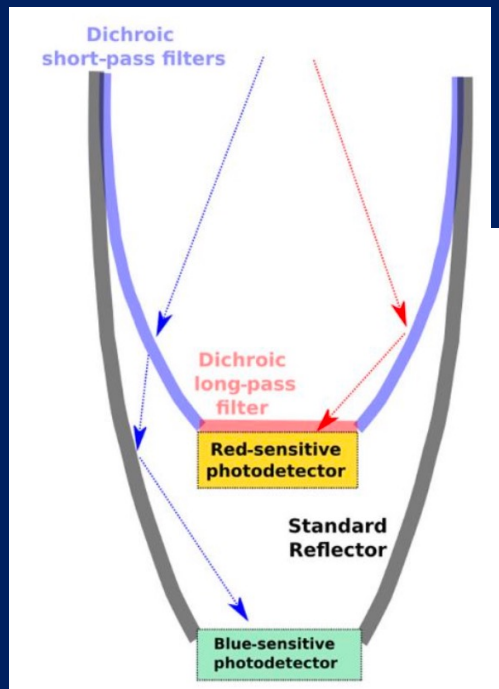


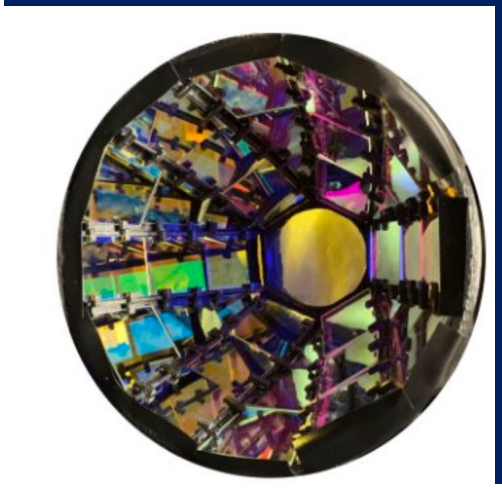
Spectrum

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



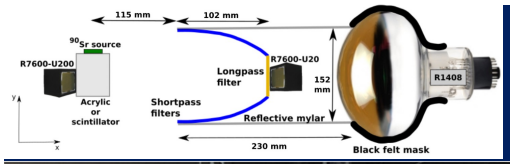
Spectral Photon Sorting

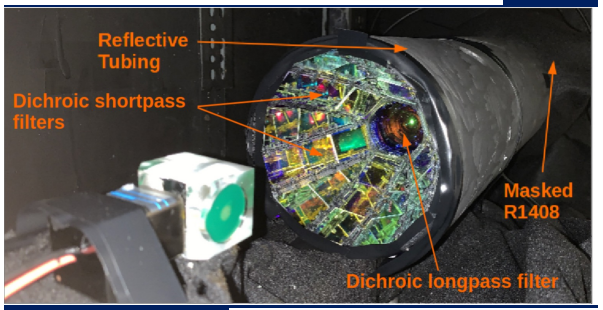




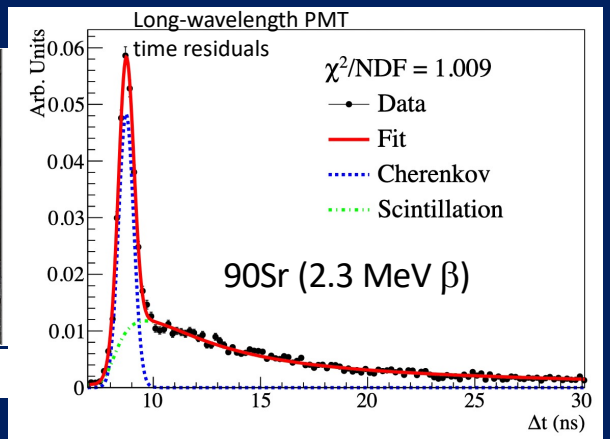
Winston-style light concentrator made out of dichroic mirrors can concentrate long-wavelength and pass short wavelength light
(a “dichroicon”)

Spectrum



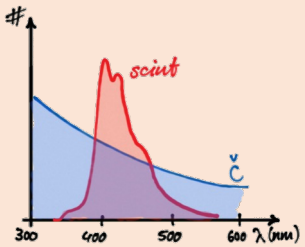


Phys. Rev. D 101, 072002

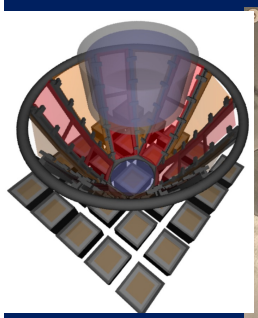


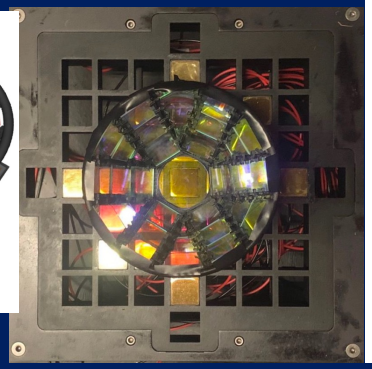
Spectrum

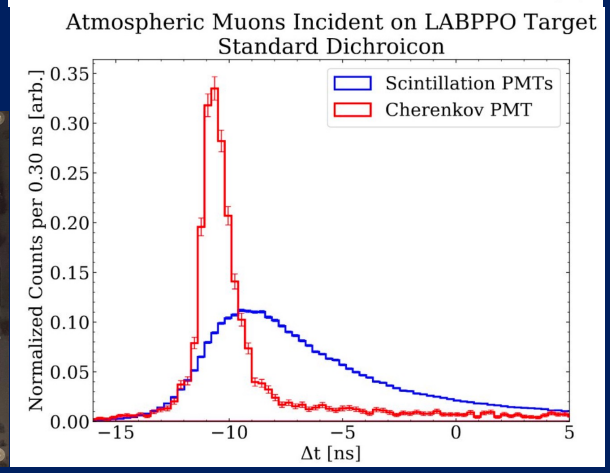
UV/blue scintillation vs. blue/green Cherenkov
→ wavelength-sensitivity



Dichroicon at CHESS

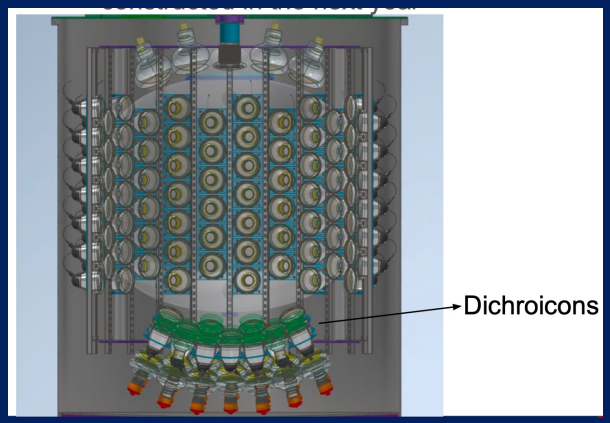






S. Naugle; see talk in NF+IF session 21g on July 23

Eos demonstrator (~5 t) at LBNL will have several of these



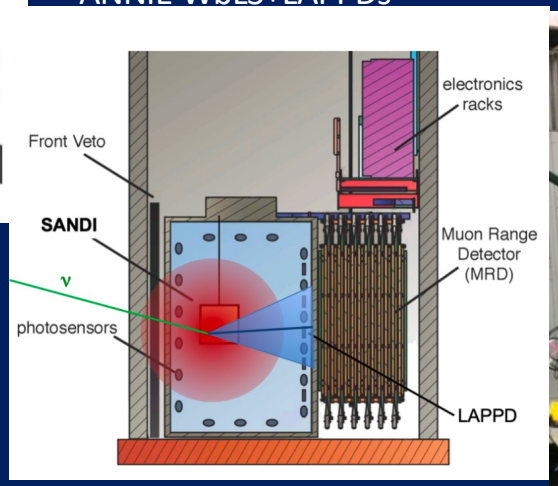
See T. Kaptanoglu talk in Session 20j July 24

Hybrid Cherenkov/Scintillation Detectors

Existing and upcoming demonstrators:

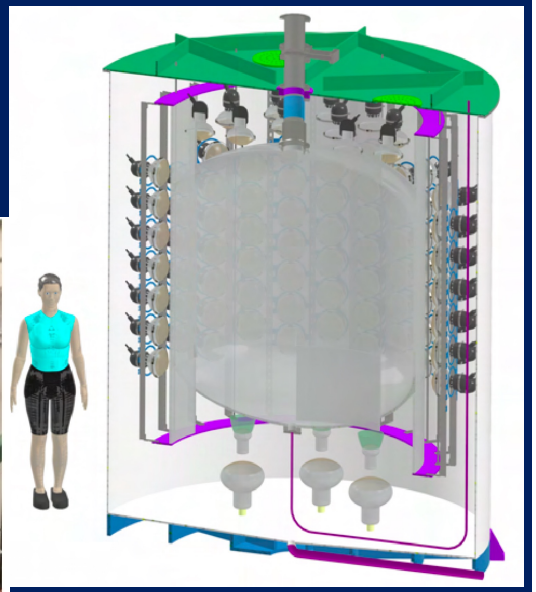
BNL 30 t WbLS

ANNIE WbLS+LAPPDs



NuDOT

Eos

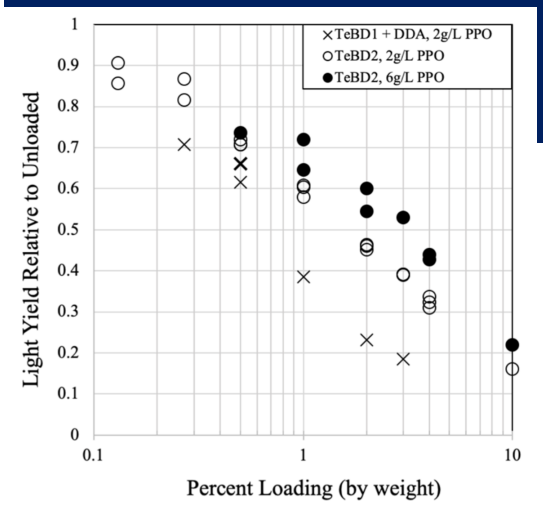


Isotopic Loading

Physics programs of these detectors is substantially broadened by adding isotopes

- Gd loading in LS for neutron detection
- Xe loading in LAr to shift UV light (and increase light yield)
- ^{6}Li loading in LS for excellent neutron pulse-shape discrimination
- Xe loading in LS for 0νββ

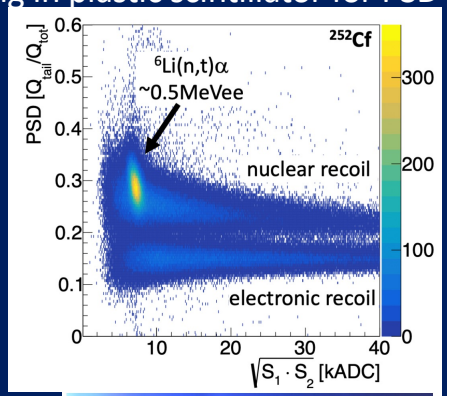
Te loading in LAB-PPO for 0νββ

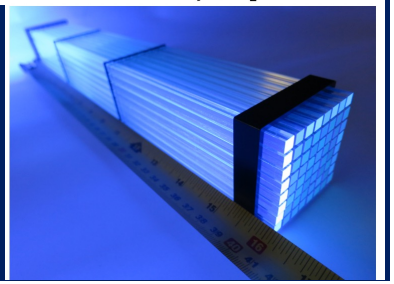


Isotopes easily loaded in WbLS and LS

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

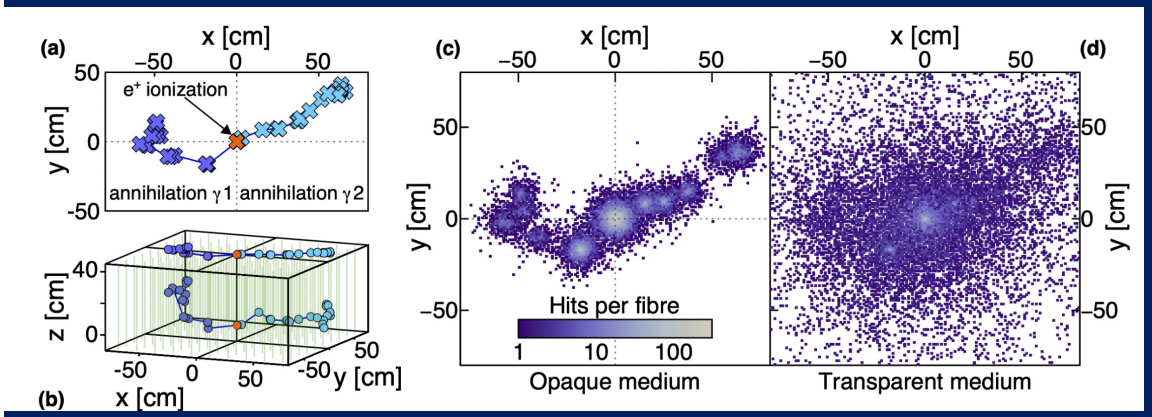
^{6}Li loading in plastic scintillator for PSD



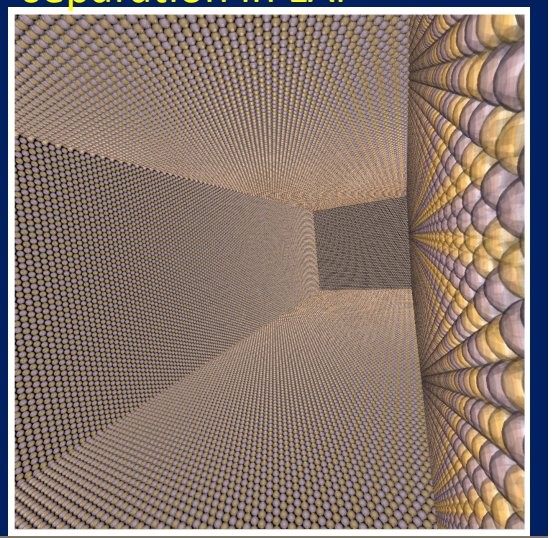


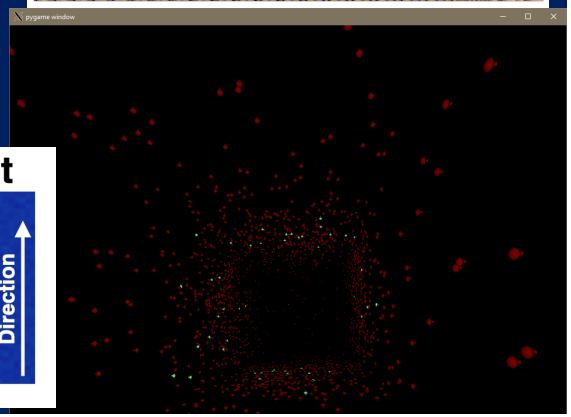
Other Ideas

LiquidO---tracking using ”opaque” scintillator+fibers



Artemis: Cher/scint separation in LAr





SLIPS---suspend LS on glycol

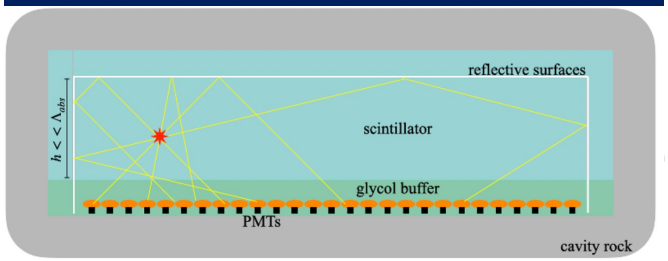
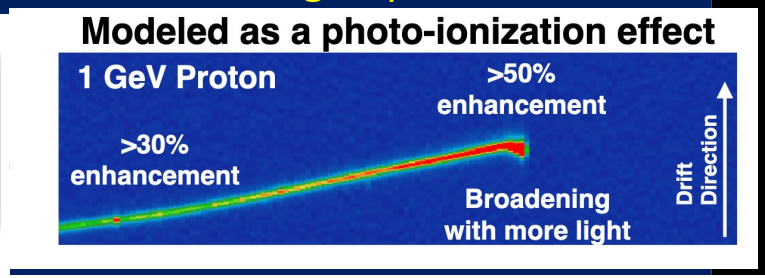


Photo-ionizing dopants in LAr+Xe



Instrumentation Wish List

- Fast, high-photon detection efficiency, large-area, low-cost sensors (duh)
- Narrow-band fluors (e.g., nanoparticles? Perovskites?)
- Dichroic filters on curved surfaces and for lower-cost
- Large-area photon sensors with better long-wavelength sensitivity
- SiPMs/MPPCs with lower warm dark rates
- High light-yield scintillators with longer attenuation lengths
- Ultra-filtration for radiologicals in WbLS