Hybrid Neutrino Detection and Spectral Photon Sorting with Dichroicons

- Neutrino reminders and some big questions
- Hybrid Cherenkov/scintillation detection
- The spectral sorting approach
- Challenges
- Physics sensitivities

Josh Klein
University of Pennsylvania

A Quick Reminder

Simple "two-flavor" oscillations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$P_{\upsilon_e \to \upsilon_e} = 1 - \sin^2 2\theta_{12} \sin^2\left(\frac{1.27\Delta m_{12}{}^2 L}{E}\right)$$

For the three known flavors of neutrinos, this is generalized <u>in analogy with</u> the quark sector:

$$\begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{3L} \end{pmatrix}$$

$$U = \begin{pmatrix} c_{12}\,c_{13} & s_{12}\,c_{13} & s_{13}\,e^{-i\delta} \\ -s_{12}\,c_{23} - c_{12}\,s_{23}\,s_{13}\,e^{i\delta} & c_{12}\,c_{23} - s_{12}\,s_{23}\,s_{13}\,e^{i\delta} & s_{23}\,c_{13} \\ s_{12}\,s_{23} - c_{12}\,c_{23}\,s_{13}\,e^{i\delta} & -c_{12}\,s_{23} - s_{12}\,c_{23}\,s_{13}\,e^{i\delta} & c_{23}\,c_{13} \end{pmatrix}$$

$c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$

Phase δ leads to differences in processes for matter and antimatter (CP Violation):

$$P(\nu_\mu \to \nu_e) \neq P(\overline{\nu}_\mu \to \overline{\nu}_e)$$

CP violation is a requirement for creating the matter/antimatter asymmetry of the Universe

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⇒

$$P_{\upsilon_e \to \upsilon_e} = 1 - \sin^2 2\theta_{12} \sin^2\left(\frac{1.27 \Delta m_{12}{}^2 L}{E}\right)$$

$$P(\nu_l \to \nu_{l'}) = \sum_j |U_{l'j}|^2 \, |U_{lj}|^2 \; + 2 \sum_{j>k} |U_{l'j} \, U_{lj}^* \, U_{lk} \, U_{l'k}^*| \cos\left(\frac{\Delta m_{jk}^2}{2p} L - \phi_{l'l;jk}\right)$$

$$\phi_{l'l;jk} = \arg\left(U_{l'j} \, U_{lj}^* \, U_{lk} \, U_{l'k}^*\right)$$

For three flavors…

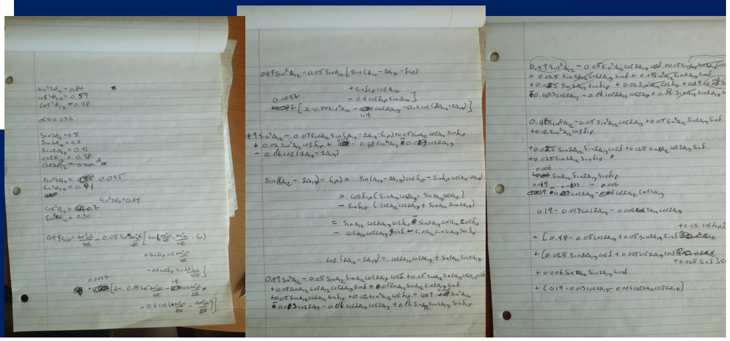
$$\begin{aligned} P_{\text{vac}}(\nu_\mu \to \nu_e) &= \sin^2 2\theta_{12} c_{23}^2 c_{13}^2 \sin^2 \alpha\Delta \\ &- \frac{1}{2} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} c_{13} \sin \alpha\Delta \Big[\sin[(\alpha - 2)\Delta - \delta_{CP}] \\ &\qquad + \sin \delta_{CP} \cos \alpha\Delta - \cos 2\theta_{12} \cos \delta_{CP} \sin \alpha\Delta \Big] \\ &+ \frac{1}{4} \sin^2 2\theta_{13} s_{23}^2 \Big[2 - \sin^2 2\theta_{12} \sin^2 \alpha\Delta - 2c_{12}^2 \cos 2\Delta - 2s_{12}^2 \cos 2(\alpha - 1)\Delta \Big] \end{aligned}$$

$$\alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2}$$

$$\Delta = \frac{\Delta m_{31}^2 L}{4E}$$

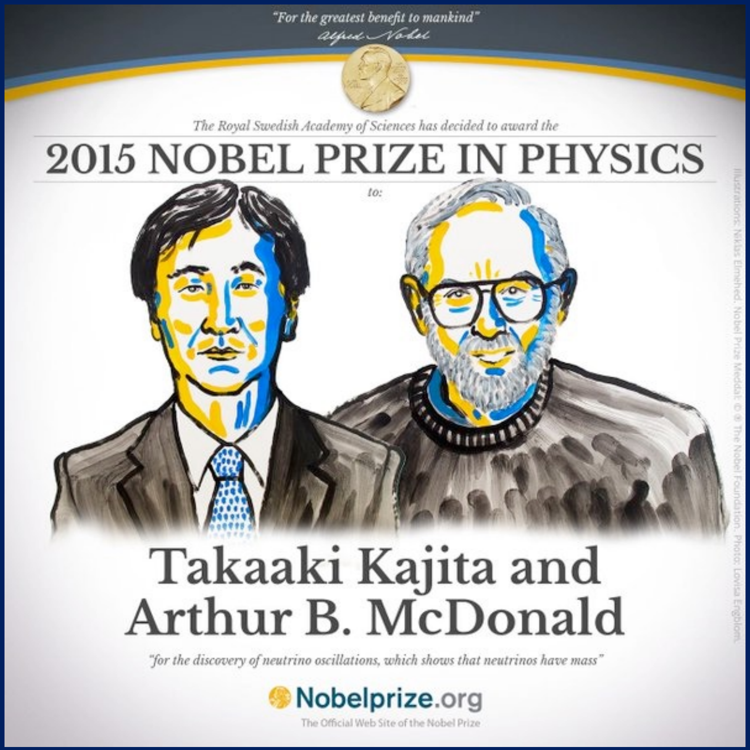
$$c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij}$$

(Don’t try this at home…)



Neutrino Mass and Oscillations

Neutrinos oscillate!



"For the greatest benefit to mankind"

Alfred Nobel

The Royal Swedish Academy of Sciences has decided to award the

2015 NOBEL PRIZE IN PHYSICS

to:

Takaaki Kajita and
Arthur B. McDonald

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

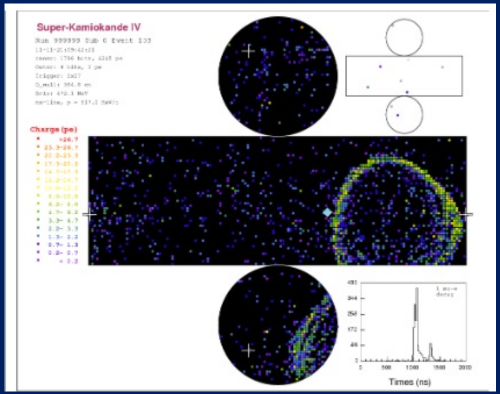
Nobelprize.org

The Official Web Site of the Nobel Prize

Illustrations: Niklas Elmehed. Nobel Prize Medal: © ® The Nobel Foundation. Photo: Lovisa Engblom.

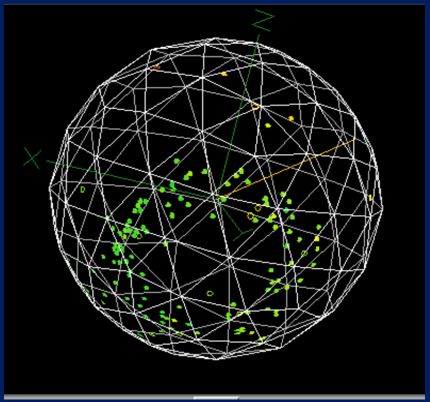
Neutrinos have mass!

Super-Kamiokande



H_2O Cherenkov (E>100 MeV)
(~6 photons/MeV)

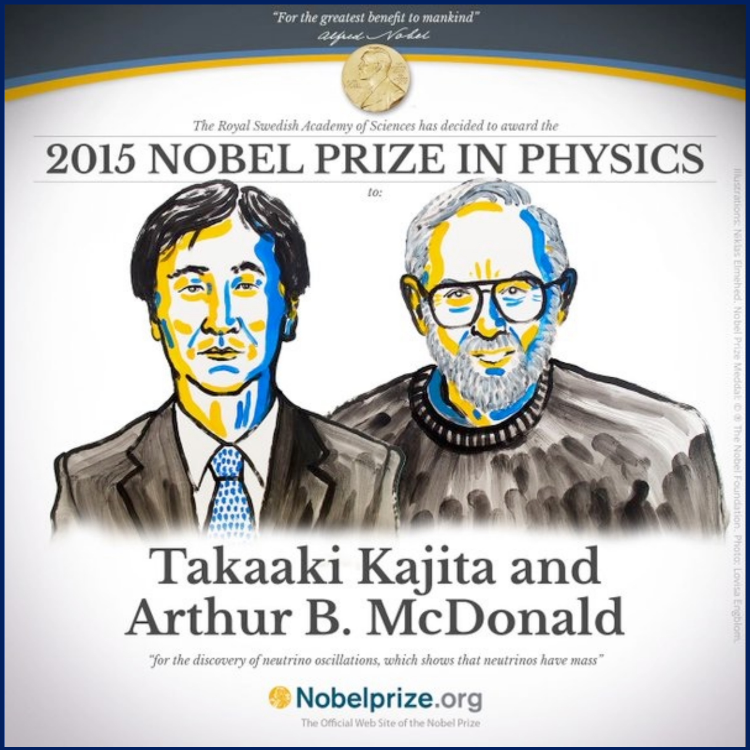
SNO



D_2O Cherenkov (E>4 MeV)
(~8 photons/MeV)

Neutrino Mass and Oscillations

Neutrinos oscillate!



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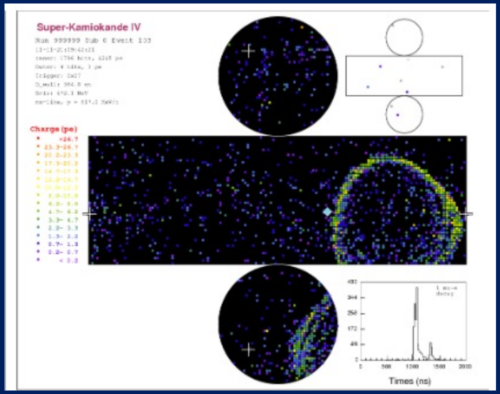

H_2O Cherenkov (E>100 MeV)

So what?

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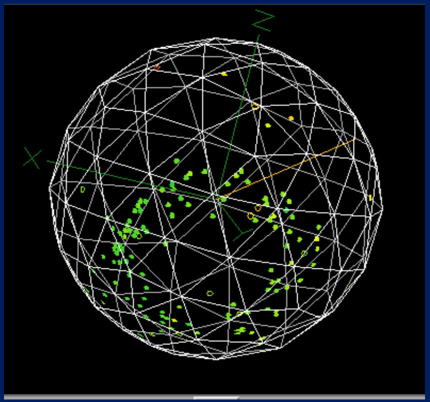


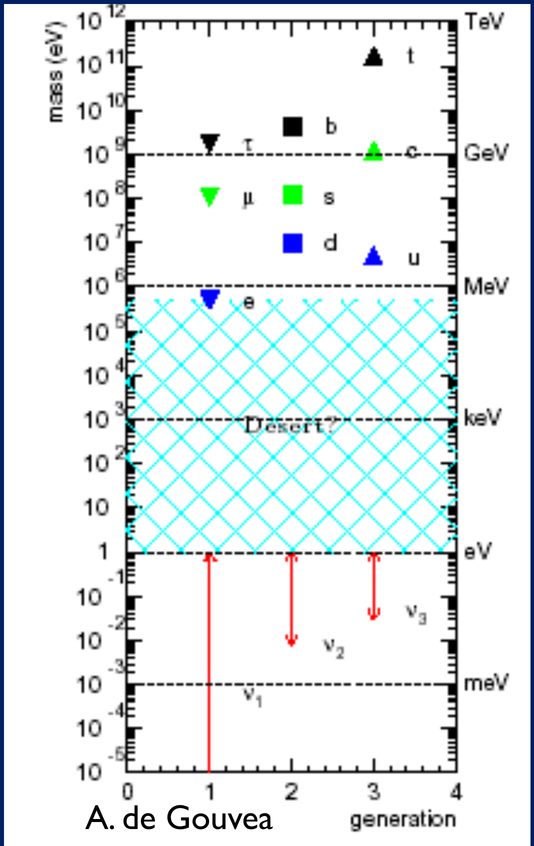
D_2O Cherenkov (E>4 MeV)

Doesn't that make them just like every other fundamental fermion…?

So What?

Doesn't this make neutrinos just like the other fundamental particles?

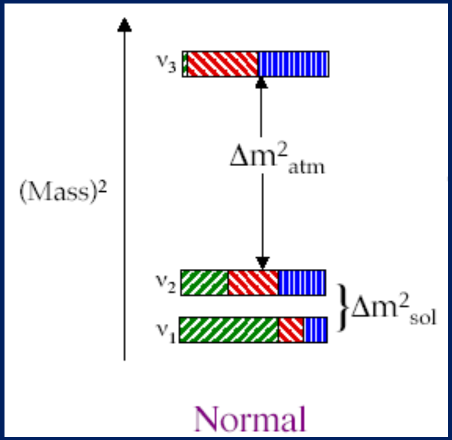
Not quite: ν masses are much smaller than other particles



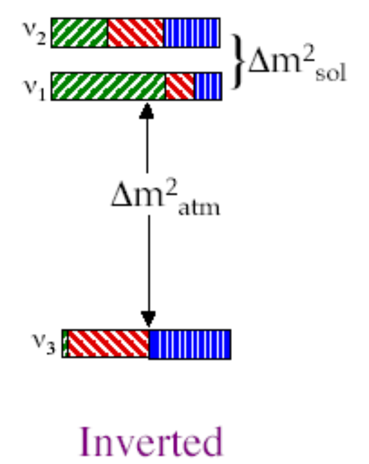
A. de Gouvea

Neutrino masses are so small, perhaps mass-generating mechanism is different?

(and we still don't know which neutrino is heaviest, or what the absolute mass scale is…)



Normal



Inverted

So What?

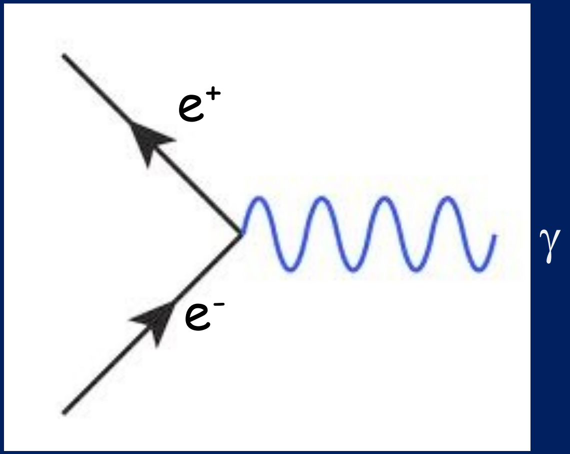
Matter and Antimatter

A quick tangent…

How is e^+ different from e^-?

Opposite charges, but otherwise identical.

When e^+ meets e^- …



Annihilation!

So What?

Matter and Antimatter

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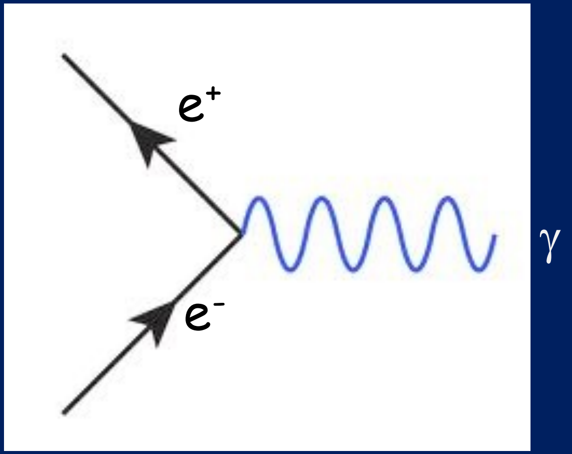
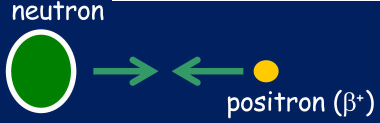


Annihilation!

But!



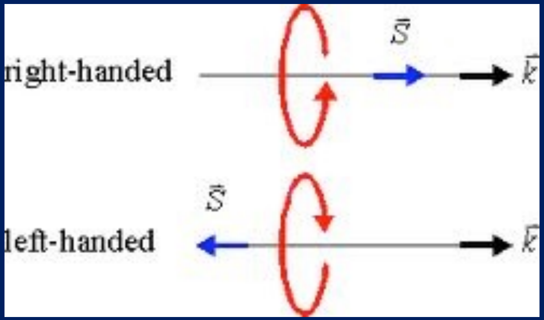
No big deal

Nothing really “anti” about antimatter….

Matter and Antimatter

OK, an important detail

Weak interaction violates parity: it makes only left-handed electrons and right-handed positrons.



But the electromagnetic interaction doesn’t care about handedness, and so we have in Nature four kinds of “electron”

$$e^-_L, e^-_R, e^+_L, e^+_R$$

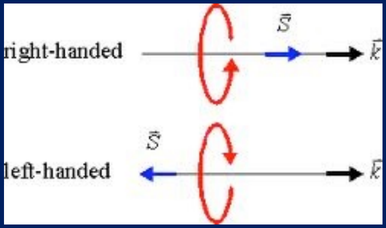
Weak+EM

EM only

Weak+EM

Matter and Antimatter

If neutrinos are massless, they are "stuck" in one chirality state:



So massless neutrinos have just two states:

$$\nu_L, \bar{\nu}_R$$

And since: $\nu_L + n \rightarrow p + e^-_L$ and $\bar{\nu}_R + p \rightarrow n + e^+_R$

particle particle particle

particle particle antiparticle

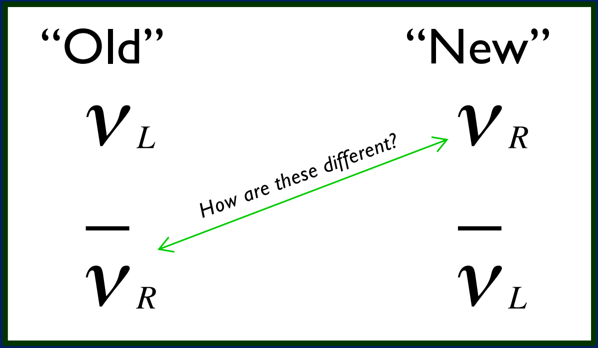
we call ν_R the "antineutrino:"

And it's all good.

So What?

Doesn't this make neutrinos just like the other fundamental particles?

But massive neutrinos can have four neutrino states ("Dirac" neutrinos):



"Old"	"New"
ν_L	ν_R
$\bar{\nu}_R$	$\bar{\nu}_L$

But what's the ***physical*** difference between (say) $\bar{\nu}_R$ and ν_R ?

They have:

Same charge (0)
Same mass
Same handedness

They differ only in their "anti"-ness…which is not a thing!

(And the new states don't interact with anything!)

So What?

Doesn't this make neutrinos just like the other fundamental particles?

Maybe there really are only two states:

$$\nu_L, \nu_R$$

So that actually:

$$\nu_{eL} + n \rightarrow p + e^-$$

$$\nu_{eR} + p \rightarrow n + e^+$$

In other words, $\nu = \bar{\nu}$ (the neutrino is its own antiparticle)

"Majorana Neutrinos"

Only way this is *not* true is if "anti-ness" (Lepton Number) is a fundamentally conserved property

Majorana or Dirac?

Which way does Ockham's razor cut?

- Neutrinos are Dirac particles, because that makes them look just like other particles, therefore a simple adjustment to the Standard Model

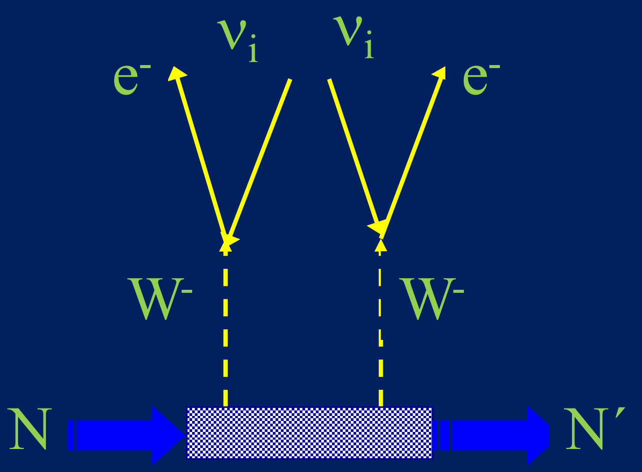
- Neutrinos are Majorana particles, because there are fewer total states, and we don't need to invent a fundamental "anti-ness" conservation law (promote a global symmetry to a fundamental symmetry)

Today, there is no `Standard' Model until this question is resolved

Majorana vs. Dirac

$2\nu\beta\beta$ vs. $0\nu\beta\beta$

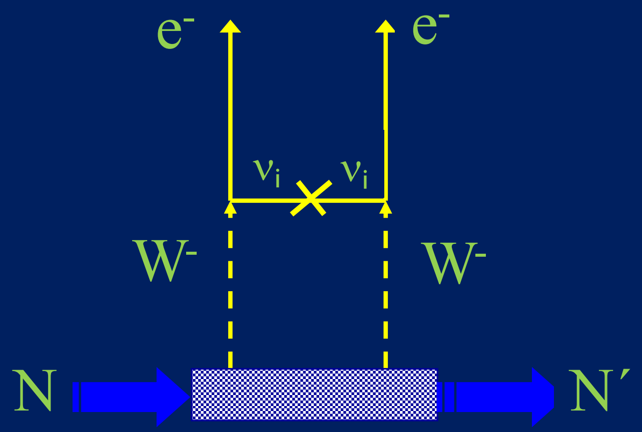
Two-neutrino double beta decay



Rare process with half-lives of ~10^{21} years

About a dozen isotopes known

Neutrino*less* double beta decay



$T_{1/2} \propto 1/m_\upsilon^2 \sim 10^{27}$ years

Mass is mixed average, including phases

$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right|$$

$$m_{\beta\beta} = \cos^2\theta_{12}\cos^2\theta_{13} m_1 + e^{2i\lambda_2}\sin^2\theta_{12}\cos^2\theta_{13} m_2 + e^{2i(\lambda_3-\delta_{CP})}\sin^2\theta_{13} m_3$$

Large coeffs.

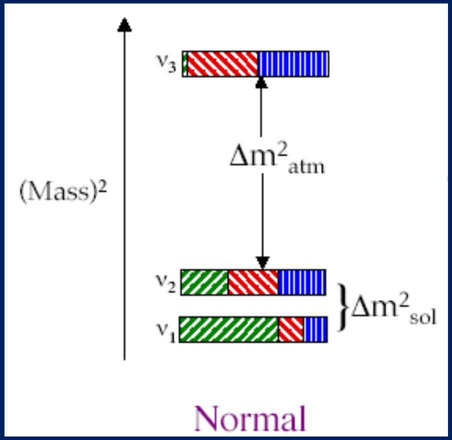
Small coeff.

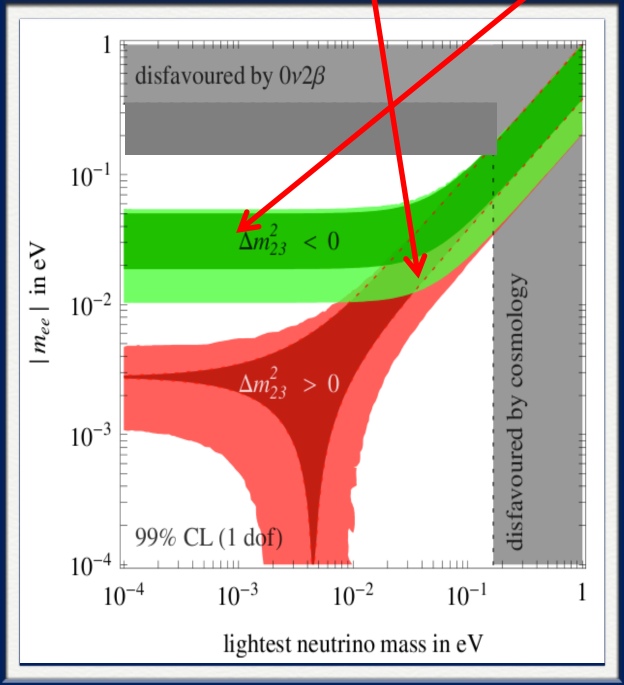
Unfortunately, neutrino mass is very small (and unknown).

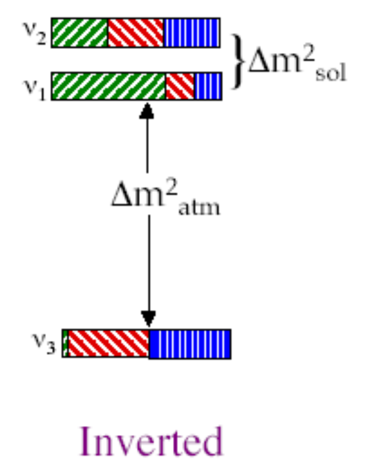
Fortunately, Avogadro's number is very big.

Majorana Nature and Neutrinoless Double Beta Decay (0νββ)

We `hope' that either mass ordering is "inverted" or masses are somewhat degenerate.

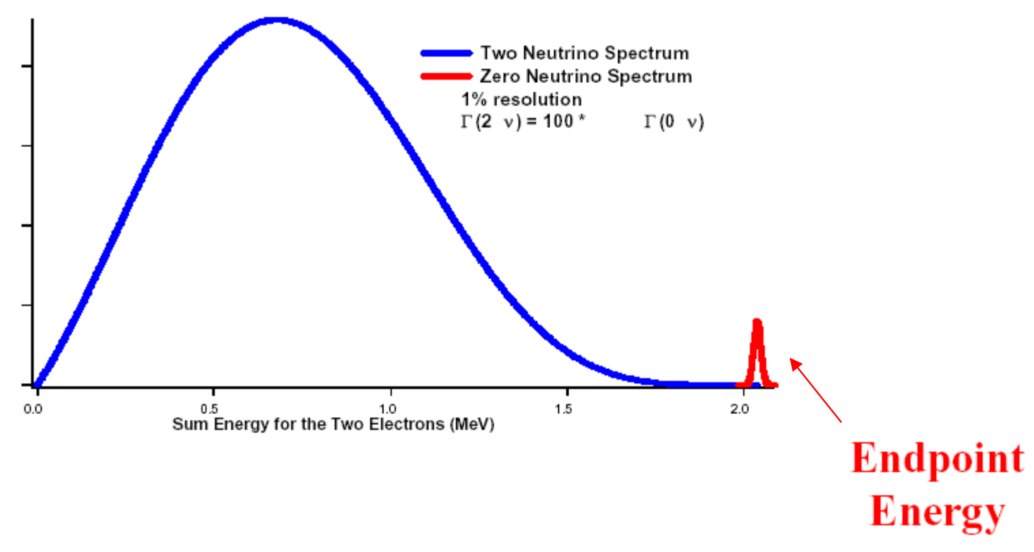




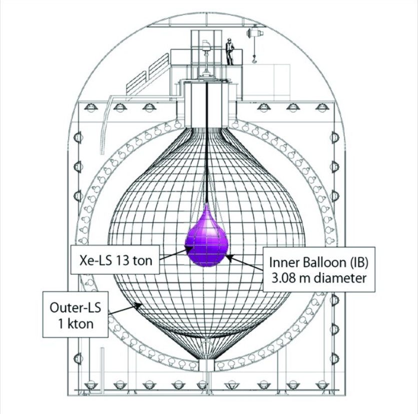


Majorana Nature and Neutrinoless Double Beta Decay (0νββ)

Experimental Challenges

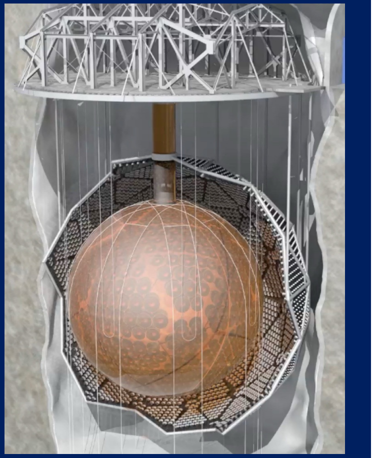


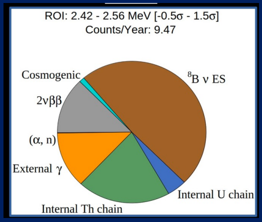
KamLAND-Zen
Xe dissolved in scintillator



Currently best limits of any approach

SNO+
Te loaded in scintillator





Biggest background are ^{8}B solar νs!

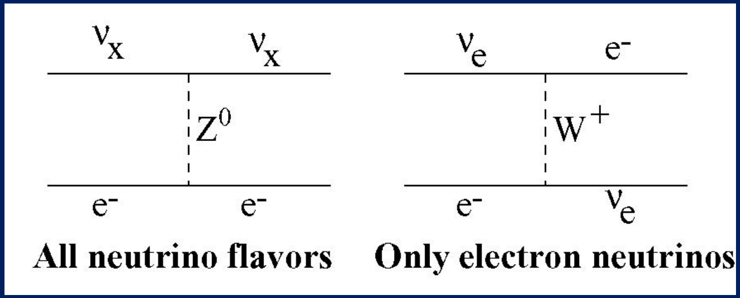
- Big mass for lifetime sensitivity
- Low radioactive backgrounds
- Deep underground site to get away from cosmic rays
- Good energy resolution to avoid 2νββ `background'

Liquid scintillator has high light yield and can be made very radio-clean and big

So What?

Solar neutrino oscillations have quantum effects on the scale of the Sun

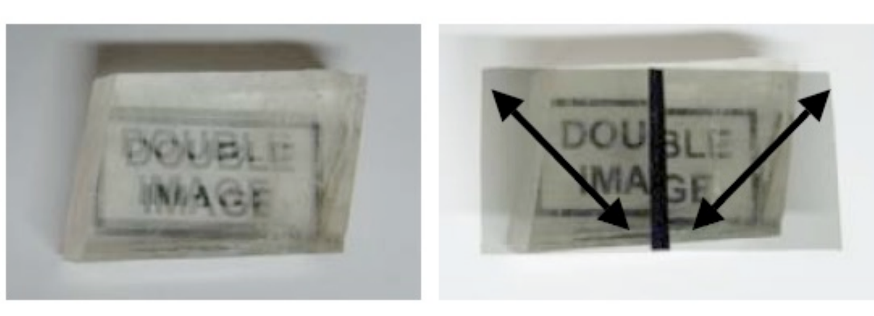
"Mikheyev-Smirnov-Wolfenstein" (MSW) effect



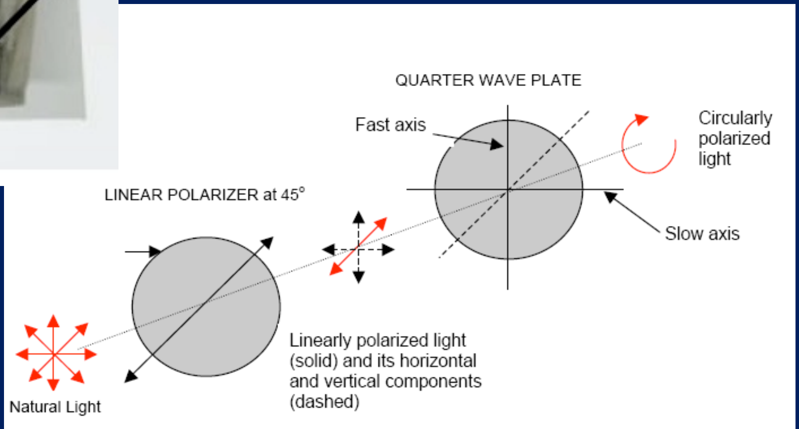
All neutrino flavors **Only electron neutrinos**

These can be coherent forward scattering—"diffractive"

This makes the Sun birefringent to neutrinos!



A ν_e turns into ν_2 like the way linearly polarized light becomes circular.

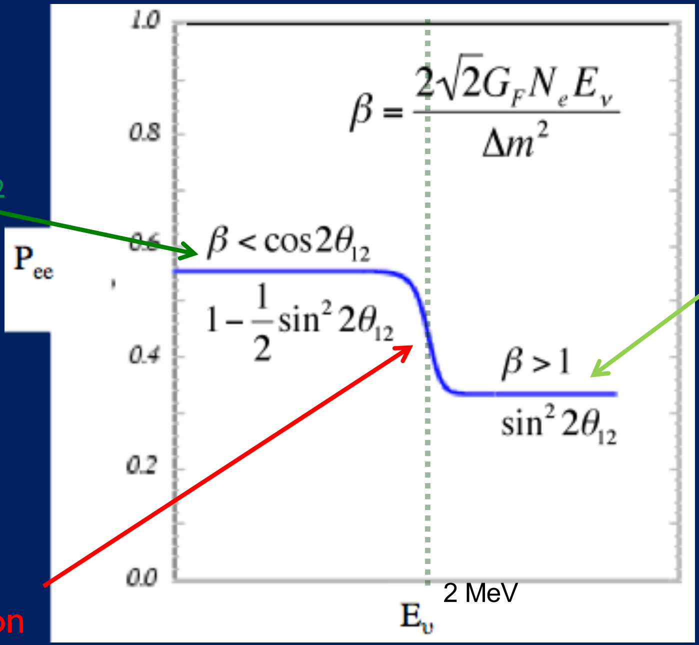


Transformation probability can be much higher than vacuum oscillations alone and happens just inside the Sun.

So What?

Solar neutrino oscillations have quantum effects on the scale of the Sun

Low energy (<1MeV):
Phase-averaged vacuum
oscillations; depends only on θ_{12}



'High' energy (>5MeV):
Matter-dominated conversion

$$\tan 2\theta_m = \frac{\frac{\Delta m^2}{2E}\sin 2\theta}{\frac{\Delta m^2}{2E}\cos 2\theta - \sqrt{2}G_F N_e}$$

Transition region

Interferometry on top of interferometry…
Anything that distinguishes flavor or mass states
changes position and width of transition region

So What?

Data cannot yet exclude lots of other models:

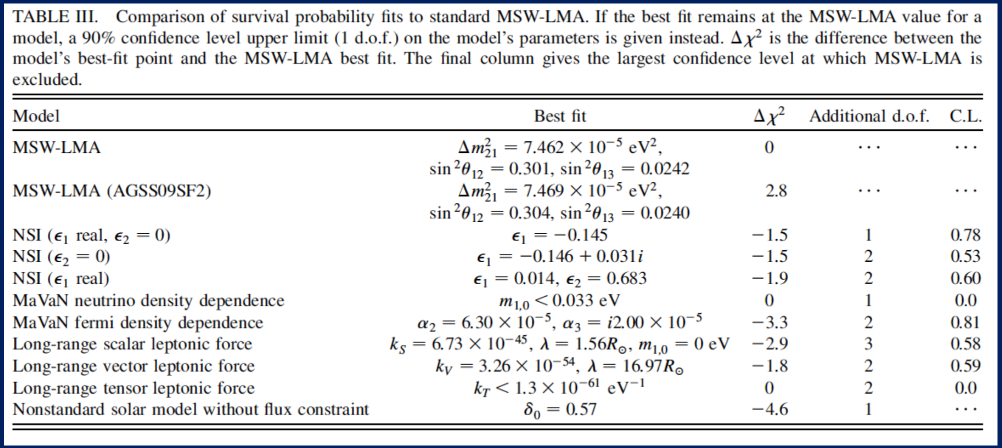


TABLE III. Comparison of survival probability fits to standard MSW-LMA. If the best fit remains at the MSW-LMA value for a model, a 90% confidence level upper limit (1 d.o.f.) on the model's parameters is given instead. $\Delta\chi^2$ is the difference between the model's best-fit point and the MSW-LMA best fit. The final column gives the largest confidence level at which MSW-LMA is excluded.

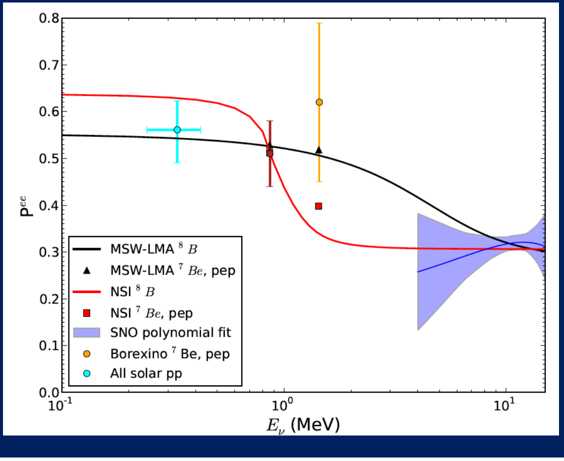
Model	Best fit	$\Delta\chi^2$	Additional d.o.f.	C.L.
MSW-LMA	$\Delta m^2_{21} = 7.462 \times 10^{-5}$ eV^2, $\sin^2\theta_{12} = 0.301$, $\sin^2\theta_{13} = 0.0242$	0	$\cdots$	$\cdots$
MSW-LMA (AGSS09SF2)	$\Delta m^2_{21} = 7.469 \times 10^{-5}$ eV^2, $\sin^2\theta_{12} = 0.304$, $\sin^2\theta_{13} = 0.0240$	2.8	$\cdots$	$\cdots$
NSI (ϵ_1 real, $\epsilon_2 = 0$)	$\epsilon_1 = -0.145$	-1.5	1	0.78
NSI ($\epsilon_2 = 0$)	$\epsilon_1 = -0.146 + 0.031i$	-1.5	2	0.53
NSI (ϵ_1 real)	$\epsilon_1 = 0.014$, $\epsilon_2 = 0.683$	-1.9	2	0.60
MaVaN neutrino density dependence	$m_{1,0} < 0.033$ eV	0	1	0.0
MaVaN fermi density dependence	$\alpha_2 = 6.30 \times 10^{-5}$, $\alpha_3 = i2.00 \times 10^{-5}$	-3.3	2	0.81
Long-range scalar leptonic force	$k_S = 6.73 \times 10^{-45}$, $\lambda = 1.56 R_\odot$, $m_{1,0} = 0$ eV	-2.9	3	0.58
Long-range vector leptonic force	$k_V = 3.26 \times 10^{-54}$, $\lambda = 16.97 R_\odot$	-1.8	2	0.59
Long-range tensor leptonic force	$k_T < 1.3 \times 10^{-61}$ eV^{-1}	0	2	0.0
Nonstandard solar model without flux constraint	$\delta_0 = 0.57$	-4.6	1	$\cdots$

Bonventre, LaTorre, *et al*, Phys. Rev. D 88 (2013) 053010

Best fit for mass-varying neutrinos

$\Delta\chi^2 = -3.3$

C.L. = 0.81

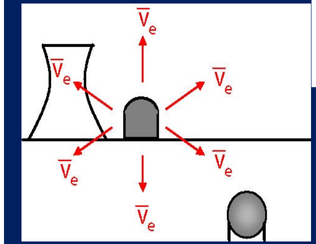


Sensitivity to non-standard effects entirely driven by lack of precision data in transition region

So What?

Doesn't this make neutrinos just like the other fundamental particles?

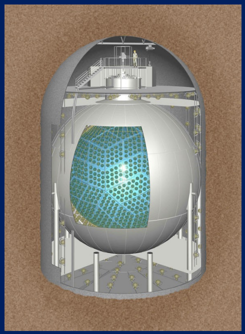
Terrestrial and solar do not yet agree on Δm^2_{21} because no clear transition region in data



$$P_{\upsilon_e \to \upsilon_e} = 1 - \sin^2 2\theta_{12} \sin^2\left(\frac{1.27\Delta m_{12}{}^2 L}{E}\right)$$

$\bar{\upsilon}_e$

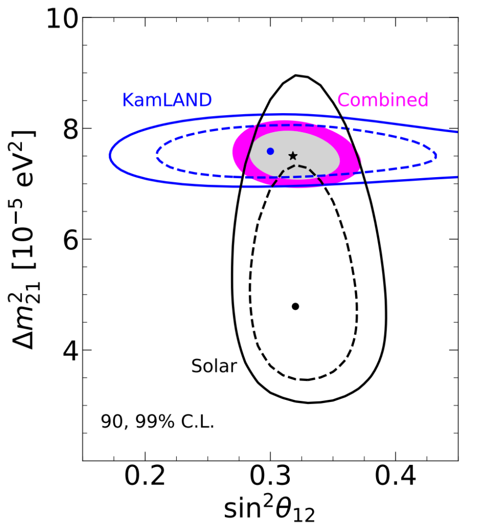
KamLAND



1000 tons of liquid scintillator: $\bar{\upsilon}_e + \mathrm{p} \rightarrow n + e^+$

(200 photons/MeV)

Reactor "vacuum" oscillations and solar "matter" oscillations agree well on θ_{12} but not on Δm^2_{12}



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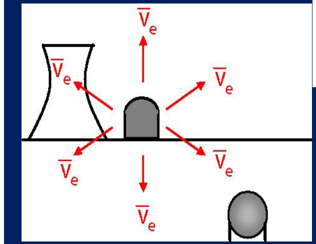

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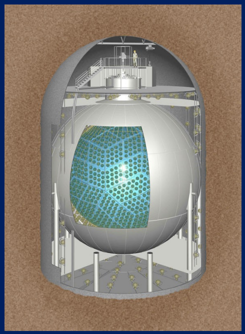
$\bar{\upsilon}_e$

KamLAND



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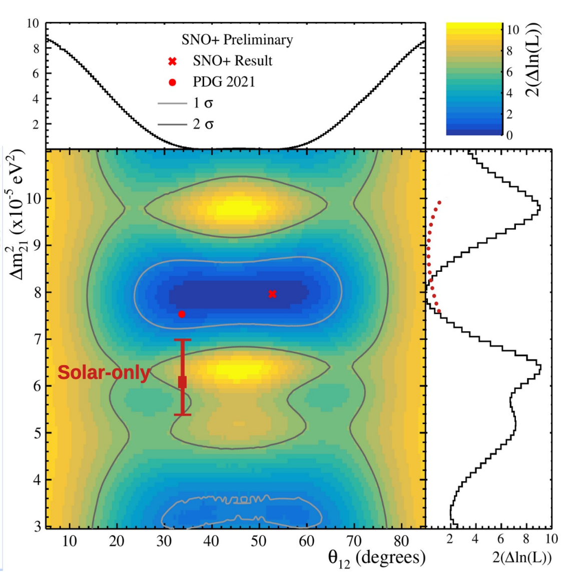
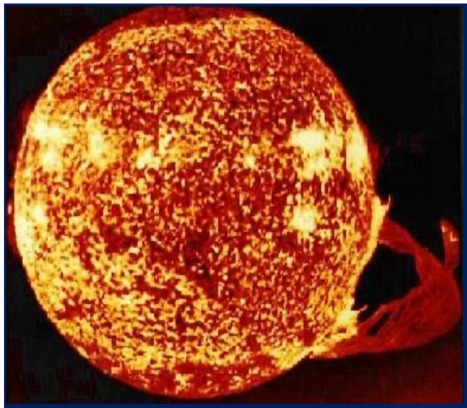
(200 photons/MeV)

Reactor "vacuum" oscillations and solar "matter" oscillations agree well on θ_{12} but not on Δm^2_{12}



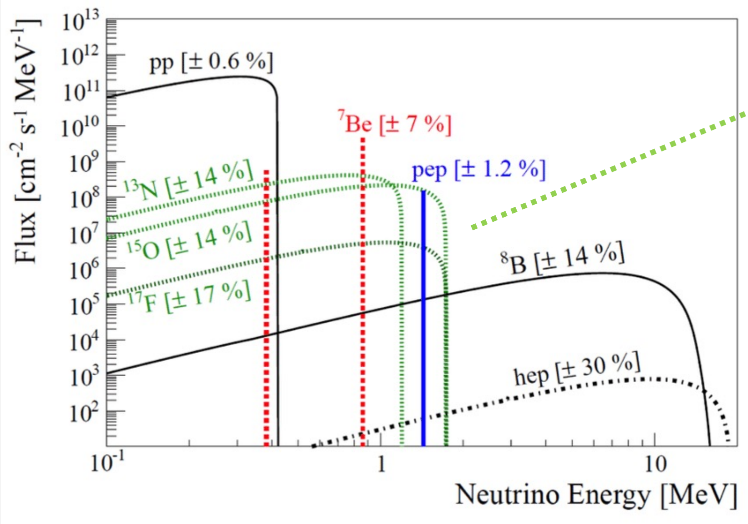
Submitted soon

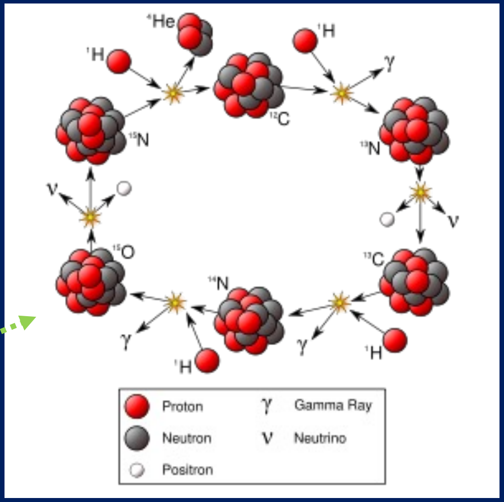


So What?

Can go back to using neutrinos to understand the Sun

Many different ν sources from Sun

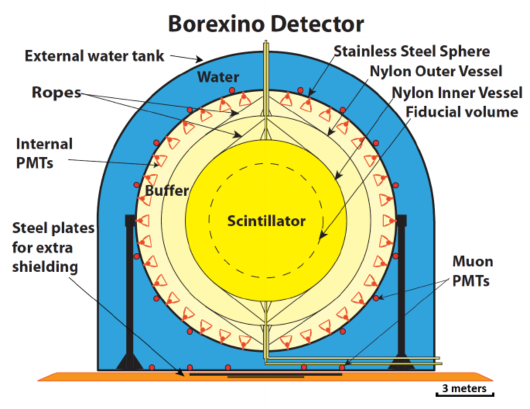


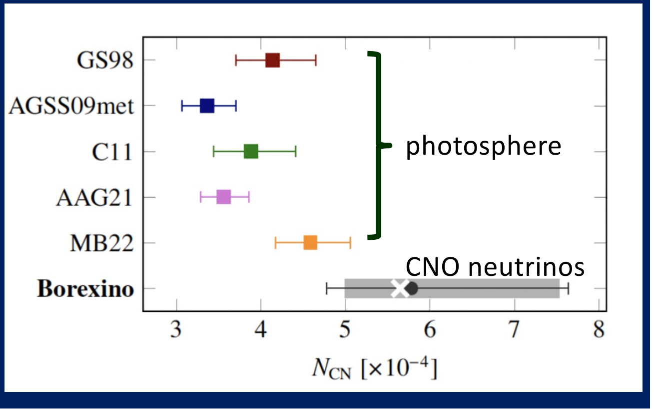


“Carbon-Nitrogen-Oxygen” (CNO) νs tell us metallicity of solar core—

Why does it look like more metals (C,N) in core than on photosphere?

280 tonnes of liquid scintillator





So What?

“Charge-Parity” (CP) Violation

Full 3-flavor appearance probability includes matter effects:

$$\begin{aligned} P(\nu_\mu \to \nu_e) = & 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2\Phi_{31} \\ & +8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos\Phi_{32} \cdot \sin\Phi_{31} \cdot \sin\Phi_{21} \end{aligned}$$

CP violating term

$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{32} \cdot \sin\Phi_{31} \cdot \sin\Phi_{21}$$

`Solar term

$$+4S_{12}^2 C_{13}^2 \left(C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\right) \sin^2\Phi_{21}$$

Matter term

$$-8C_{13}^2 S_{13}^2 S_{23}^2 \left(1 - 2S_{13}^2\right) \frac{aL}{4E_\nu} \cos\Phi_{32} \sin\Phi_{31} .$$

$$\Phi_{ij} \equiv \Delta m_{ij}^2 L / 4E_\nu$$

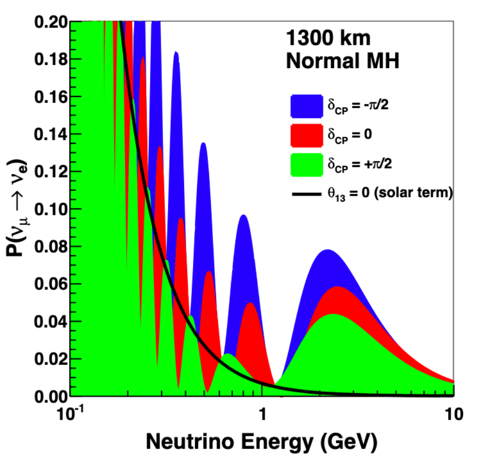
$$c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij}$$

Ambiguities can be resolved with long-baselines and “wideband” beam

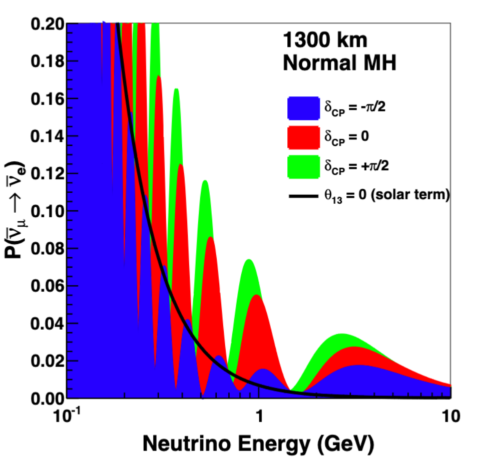
So What?

“Charge-Parity” (CP) Violation

$P(\nu_\mu \rightarrow \nu_e)$

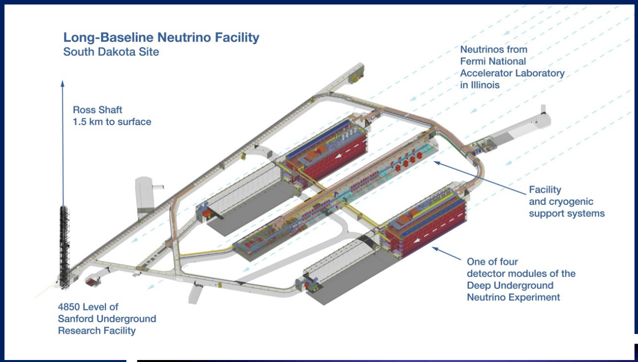


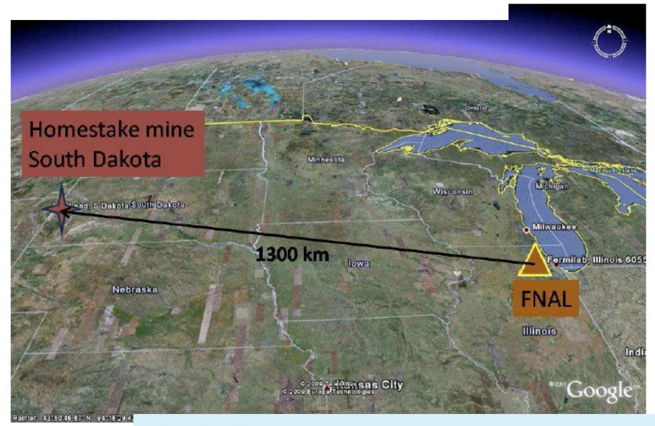
$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

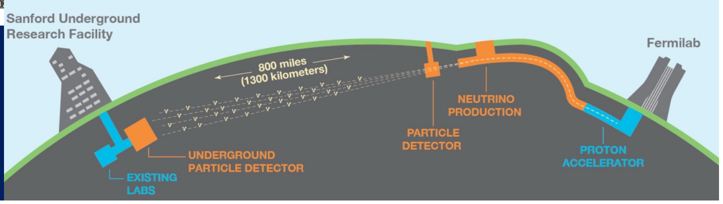


Most “easily” done with high-energy neutrinos and a baseline of 100s to 1000s of km

Deep Underground Neutrino Experiment (DUNE)







Breadth and Detectors

100 keV--10 Gev

Typically scintillator

Typically Cherenkov

keV

MeV

GeV

Solar νs

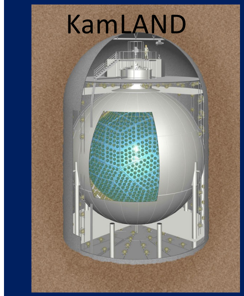
CP Violation

Reactor $\bar{\nu}$

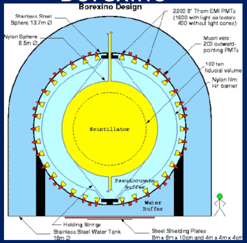
Atmospheric ν oscillations

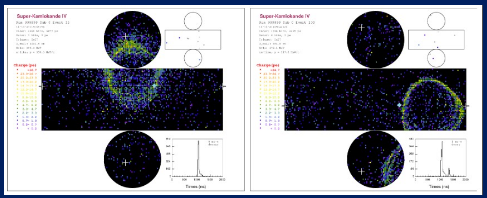
SN burst νs

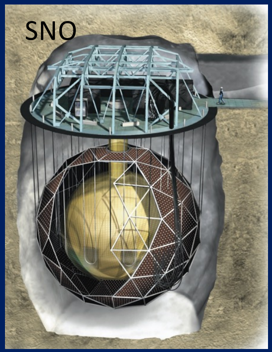
$0\nu\beta\beta$

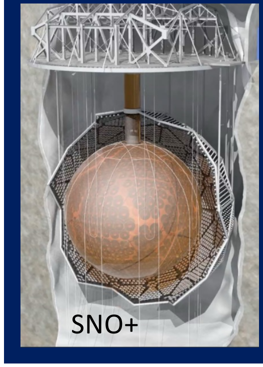


Borexino









Requirements:

- Low radio backgrounds
- Excellent energy resolution
- Directional information

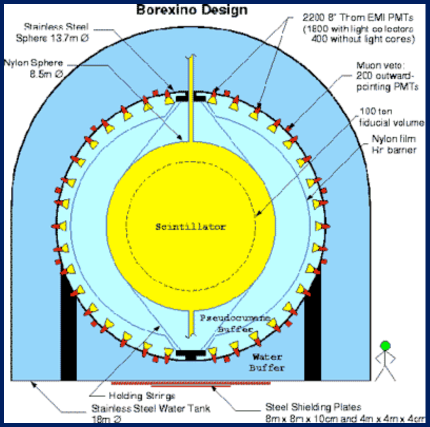
Requirements:

- Excellent particle ID
- Directional information
- Very big detector

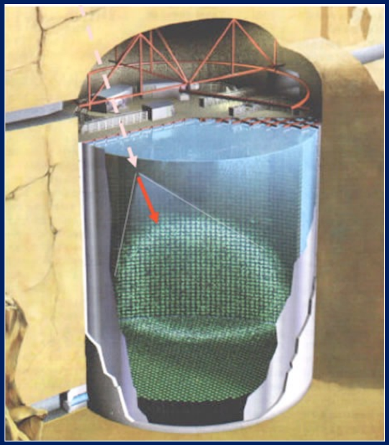
Super-Kamiokande

Hybrid Detection

Why Not do Both?



+



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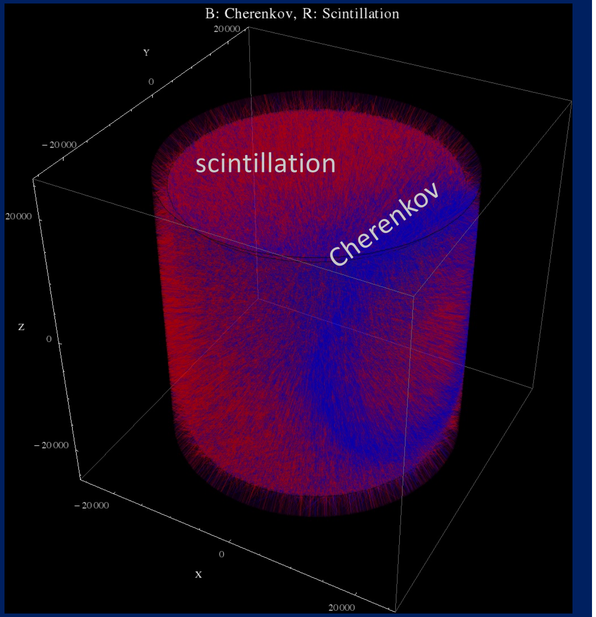
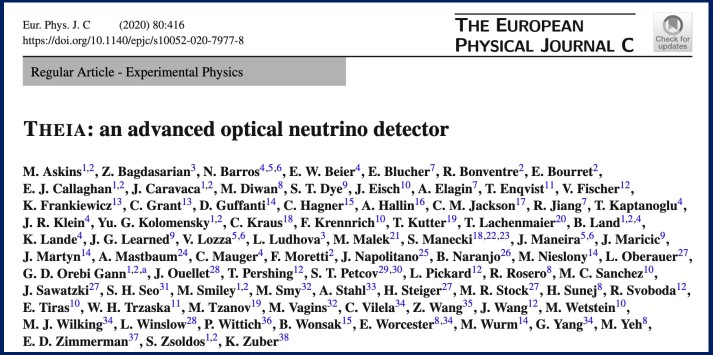


But:

- 100x more scintillation light in scintillator than Cherenkov light
- `Chertons’ are buried by `scintons’
- And need detector to be very big…

THEIA

- Low-energy physics using scintons
- High-energy with chertons
- Exploit *both* to do otherwise very difficult physics



Eur. Phys. J. C (2020) 80:416
https://doi.org/10.1140/epjc/s10052-020-7977-8

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

THEIA: an advanced optical neutrino detector

M. Askins[1,2], Z. Bagdasarian[3], N. Barros[4,5,6], E. W. Beier[4], E. Blucher[7], R. Bonventre[2], E. Bourret[2], E. J. Callaghan[1,2], J. Caravaca[1,2], M. Diwan[8], S. T. Dye[9], J. Eisch[10], A. Elagin[7], T. Enqvist[11], V. Fischer[12], K. Frankiewicz[13], C. Grant[13], D. Guffanti[14], C. Hagner[15], A. Hallin[16], C. M. Jackson[17], R. Jiang[7], T. Kaptanoglu[4], J. R. Klein[4], Yu. G. Kolomensky[1,2], C. Kraus[18], F. Krennrich[10], T. Kutter[19], T. Lachenmaier[20], B. Land[1,2,4], K. Lande[4], J. G. Learned[9], V. Lozza[5,6], L. Ludhova[3], M. Malek[21], S. Manecki[18,22,23], J. Maneira[5,6], J. Maricic[9], J. Martyn[14], A. Mastbaum[24], C. Mauger[4], F. Moretti[2], J. Napolitano[25], B. Naranjo[26], M. Nieslony[14], L. Oberauer[27], G. D. Orebi Gann[1,2,a], J. Ouellet[28], T. Pershing[12], S. T. Petcov[29,30], L. Pickard[12], R. Rosero[8], M. C. Sanchez[10], J. Sawatzki[27], S. H. Seo[31], M. Smiley[1,2], M. Smy[32], A. Stahl[33], H. Steiger[27], M. R. Stock[27], H. Sunej[8], R. Svoboda[12], E. Tiras[10], W. H. Trzaska[11], M. Tzanov[19], M. Vagins[32], C. Vilela[34], Z. Wang[35], J. Wang[12], M. Wetstein[10], M. J. Wilking[34], L. Winslow[28], P. Wittich[36], B. Wonsak[15], E. Worcester[8,34], M. Wurm[14], G. Yang[34], M. Yeh[8], E. D. Zimmerman[37], S. Zsoldos[1,2], K. Zuber[38]

See also:
"Advanced Scintillator Detector Concept," arXiv 1409.5864

THEIA-100 (kt)

Named for Titaness of Light

Mother of Eos (Dawn), Helios (Sun), and Selene (Moon)

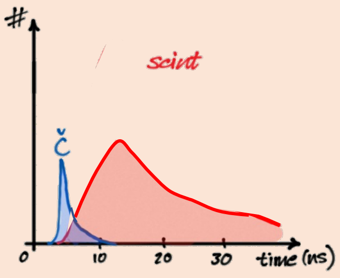
Hybrid Cherenkov/Scintillation Detectors

Many Ways of Doing This

Ratio

Add just a little scintillation

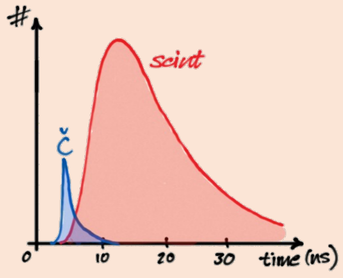
→ new materials/fluors



Timing

“instantaneous chertons” vs. delayed “scintons”

→ ns resolution or better

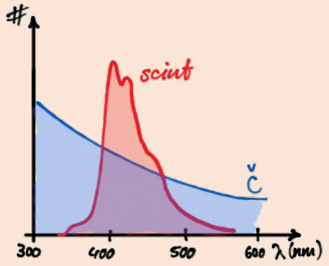


M. Wurm

Spectrum

UV/blue scintillation vs. blue/green Cherenkov

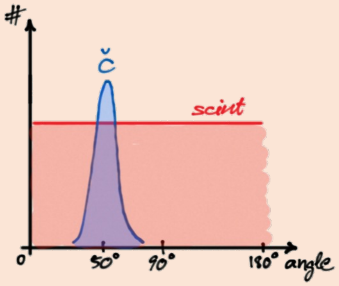
→ wavelength-sensitivity



Angular distribution

increased PMT hit density under Cherenkov angle

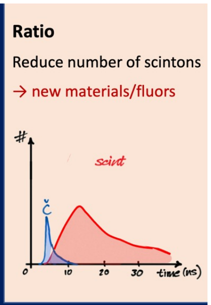
→ sufficient granularity



Past 5-10 years has seen rapid growth in exploring these approaches.

Adjust Cher/Scint Ratio

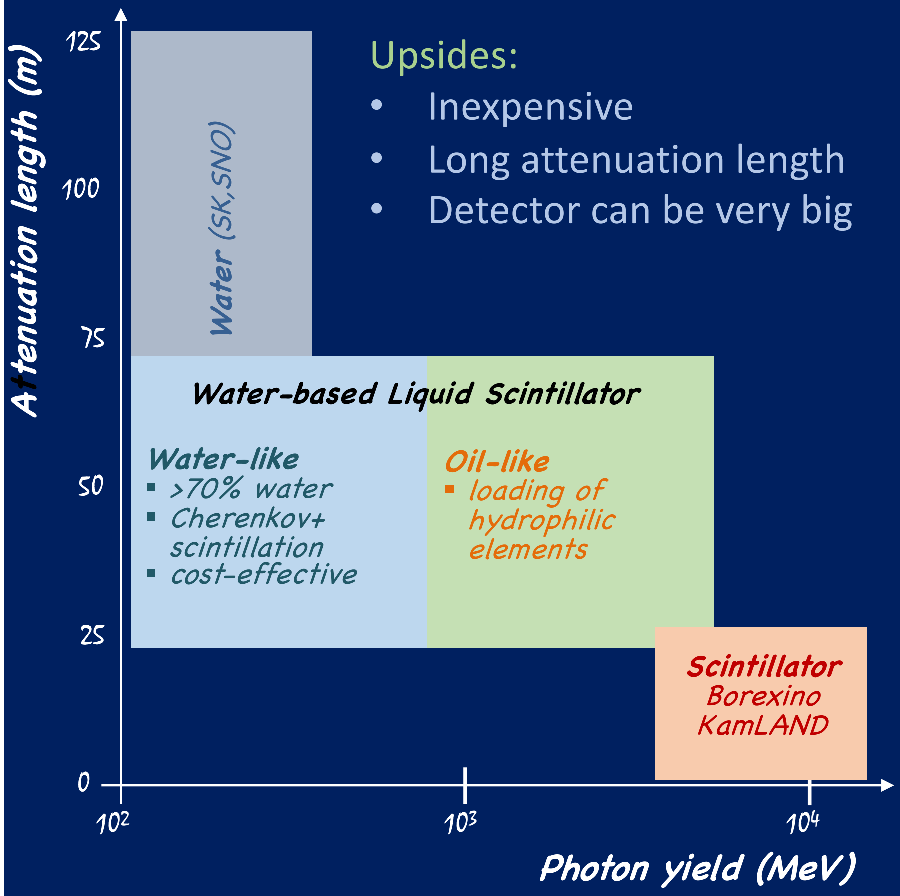
Water-based liquid scintillator (WbLS)



Ratio

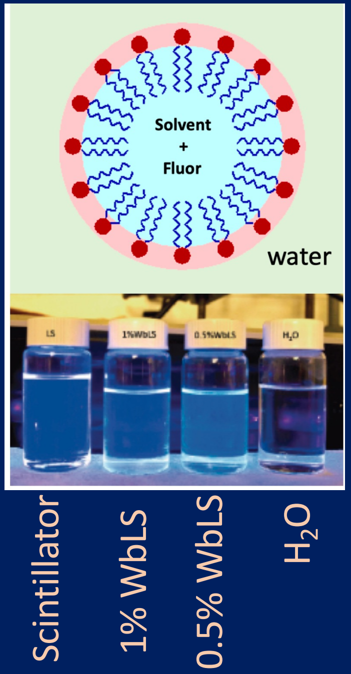
Reduce number of scintons

→ new materials/fluors



Upsides:

- Inexpensive
- Long attenuation length
- Detector can be very big



Downsides:

- Production quantities
- Radiological backgrounds
- Fewer scintillation photons! (than pure scintillator)
- And fewer Cherenkov photons (than pure scintillator)

Other possibilities:

- LAB with “thin” PPO (Jinping)
- Vanilla mineral oil (MiniBooNE)
- Oil+a little scintillator
- Water+Wavelength shifter?

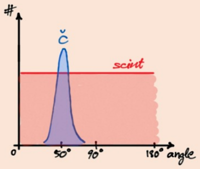
Target can be adjusted for different physics goals

Angular Distribution

Basically an analysis approach---

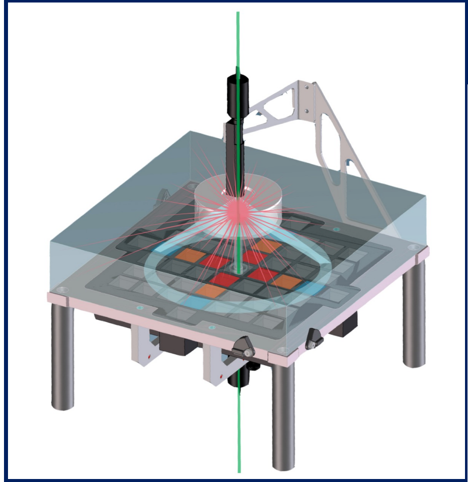
Angular distribution

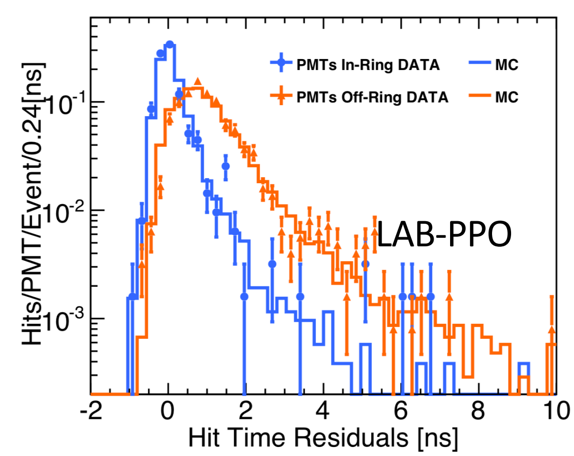
increased PMT hit density under Cherenkov angle
→ sufficient granularity



Time profile of photons in Cherenkov ring is separated from scintillation light

CHESS at LBNL Measurements

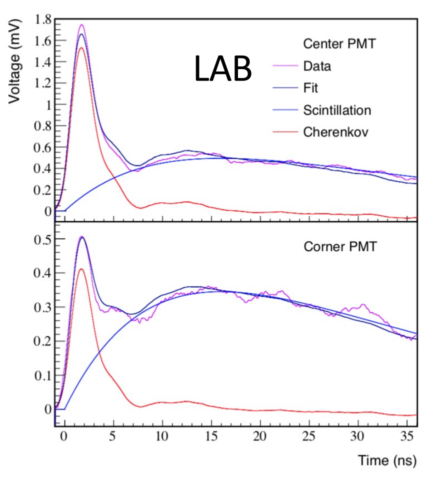




Caravaca et al, EPJC (2017) 77:811

"FlatDOT" (MIT/UNC)

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



Upsides:

- Easy to do
- Can be used in any configuration

Downsides:

- Separation is not good enough by itself
- Need high pixelization to see ring well

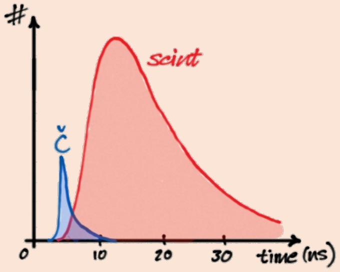
Timing

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

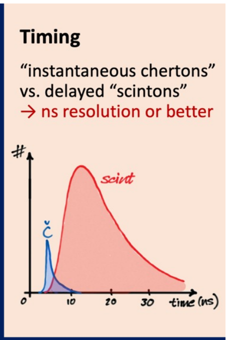
Timing

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



Timing

Improving photosensor timing has lots of benefits

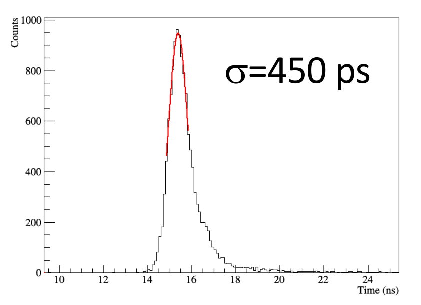


Timing

“instantaneous chertons” vs. delayed “scintons”

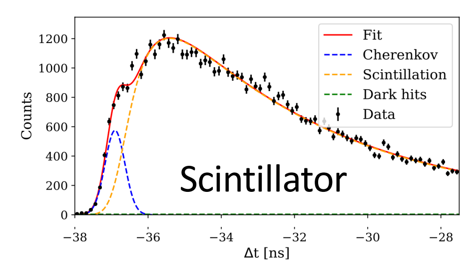
→ ns resolution or better

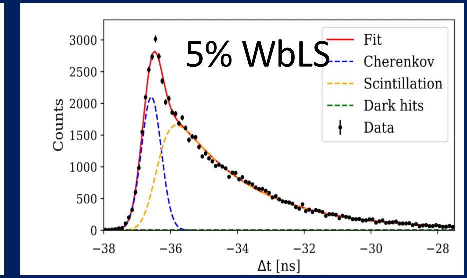
R14668 new **8”** PMT from Hamamatsu
Quantum efficiency = 34%



But: small, not cheap

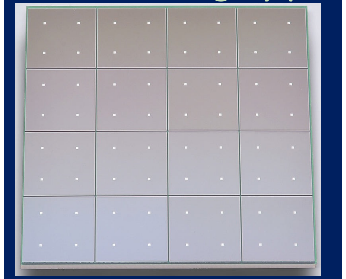
Can do separation even in full light-yield scintillator

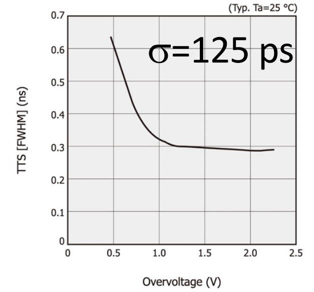




LBNL

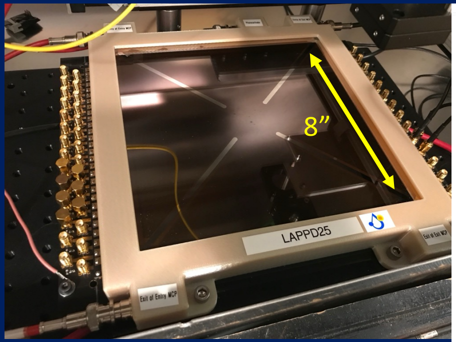
Silicon photomultiplier arrays (6x6 mm)
QE = 50%, highly pixellated

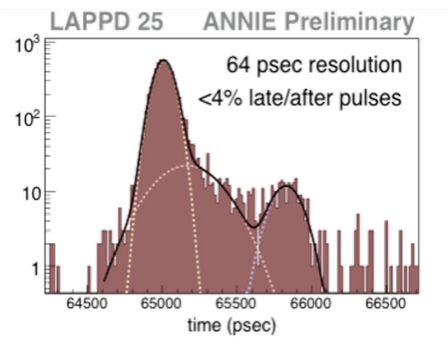




But: noisy, expensive

Large Area Picosecond Photodetector
QE = 20%

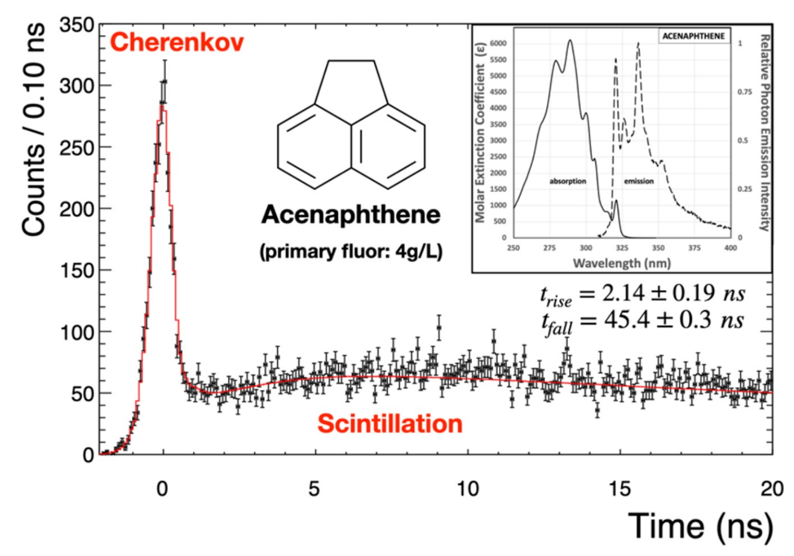




But: VERY expensive

Timing

Slow(er) Scintillator



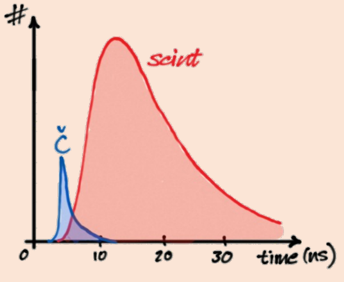
Biller, Leming, Paton, NIM A 972 (2020) 164106

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

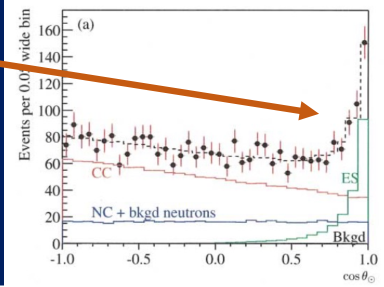
(Jinping, SNO+ "partial fill")

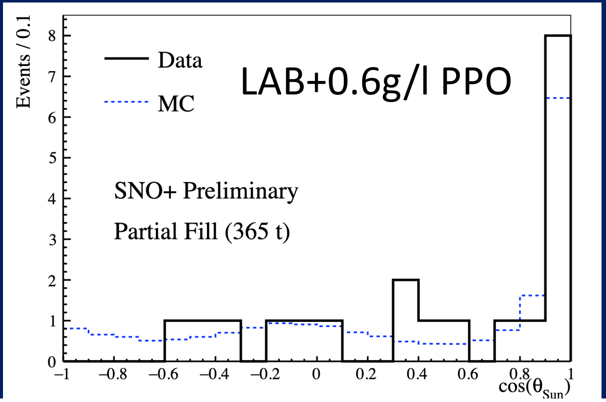
Timing

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



SNO D_2O Cherenkov



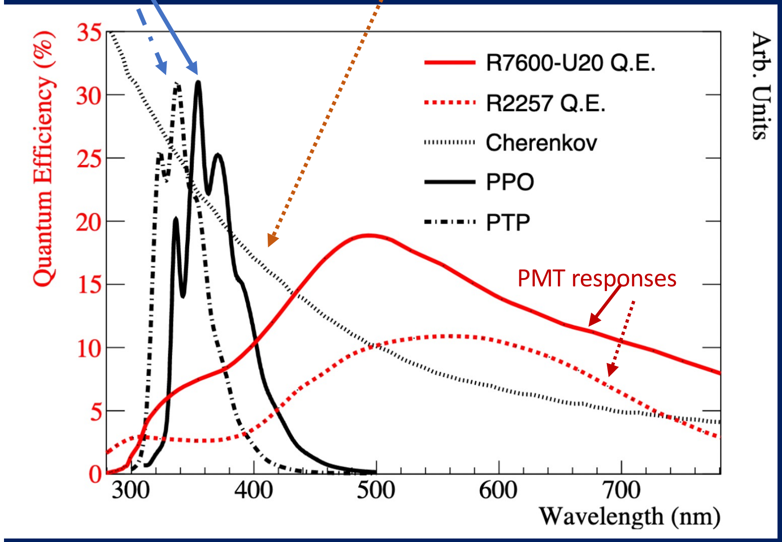


Solar peak in scintillator event-by-event!

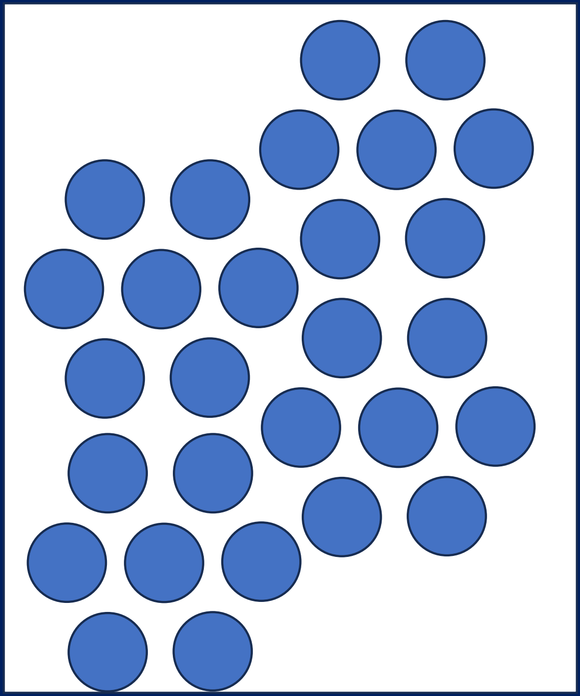
Spectrum

Scintillation emission

$N^{\gamma}_{cer} \sim 1/\lambda^2$



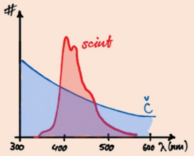
Spectral differences allow separation---could use filters or red-sensitive PMTs:



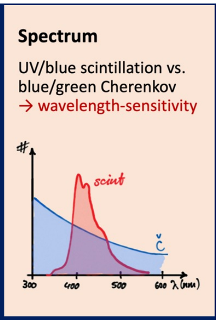
Spectrum

UV/blue scintillation vs. blue/green Cherenkov

→ wavelength-sensitivity

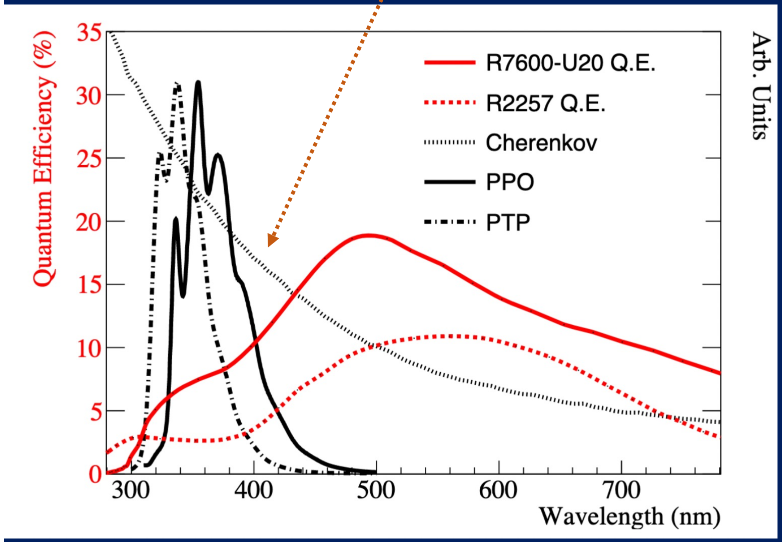


Spectrum

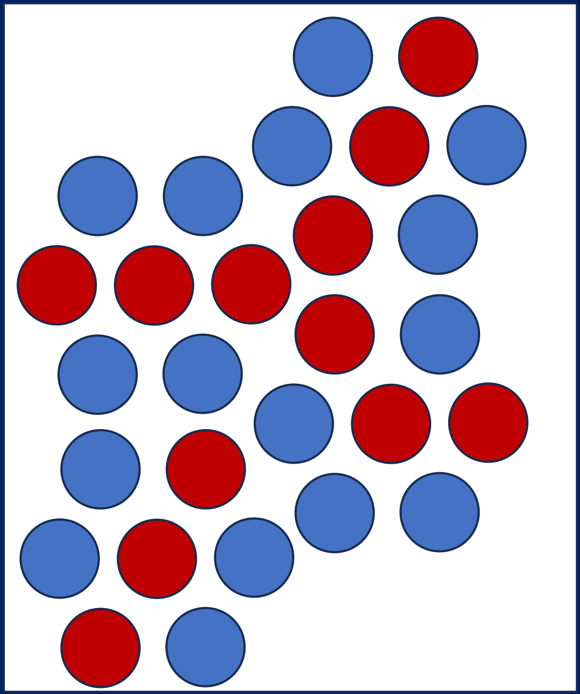

Spectrum

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

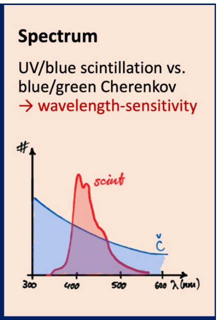
$N^{\gamma}_{cer} \sim 1/\lambda^2$



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



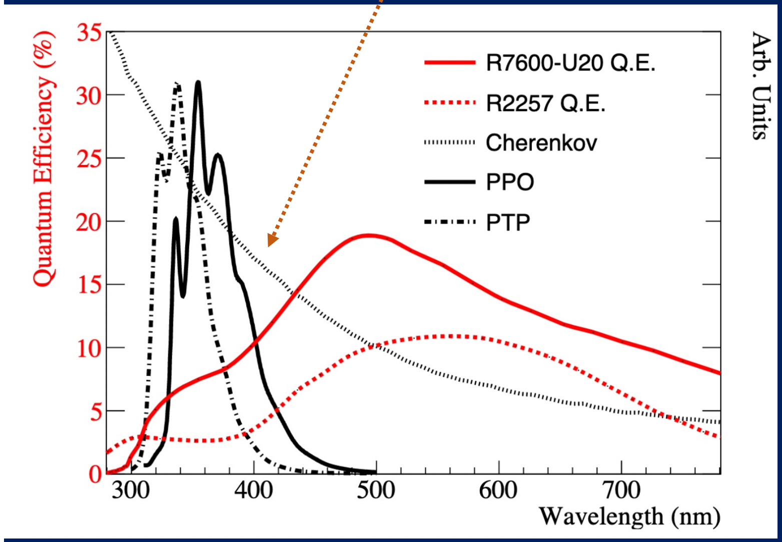
Spectrum



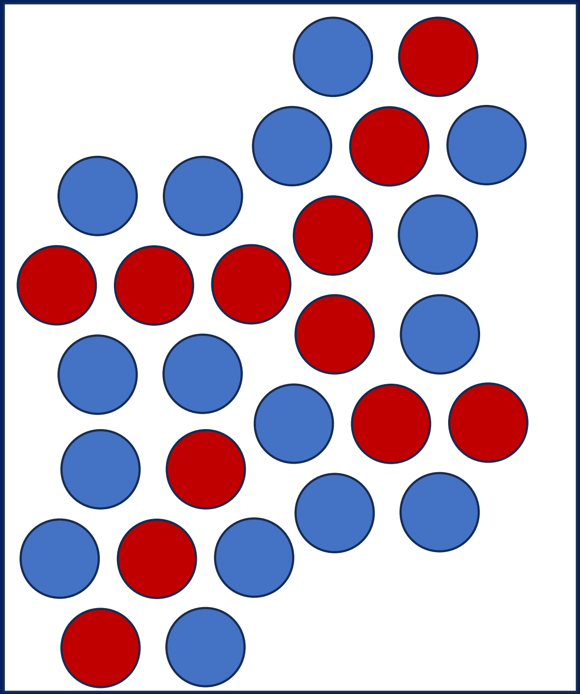
Spectrum

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

$N^{\gamma}_{cer} \sim 1/\lambda^2$



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



But now we have lost a lot of our scintillation photons---can we instead ***sort*** the photons so they go to the right sensors…?

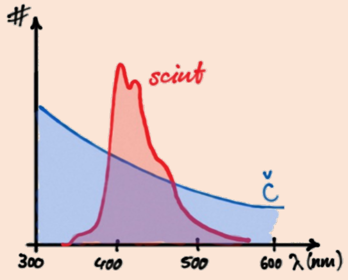
Spectral Photon Sorting

If we *sort* photons efficiently:

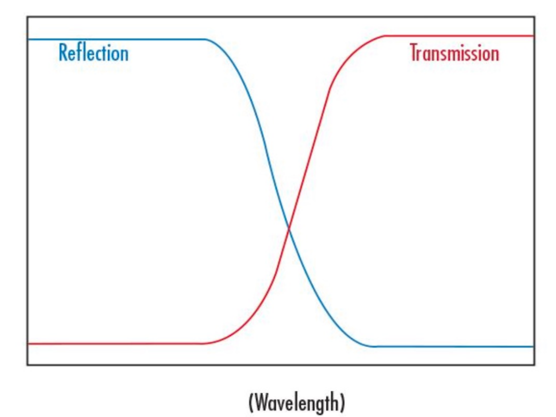
- Can preserve most of the different signals
- Possibly increase overall light yield by viewing a broad-band spectrum by relevant sensor

Spectrum

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

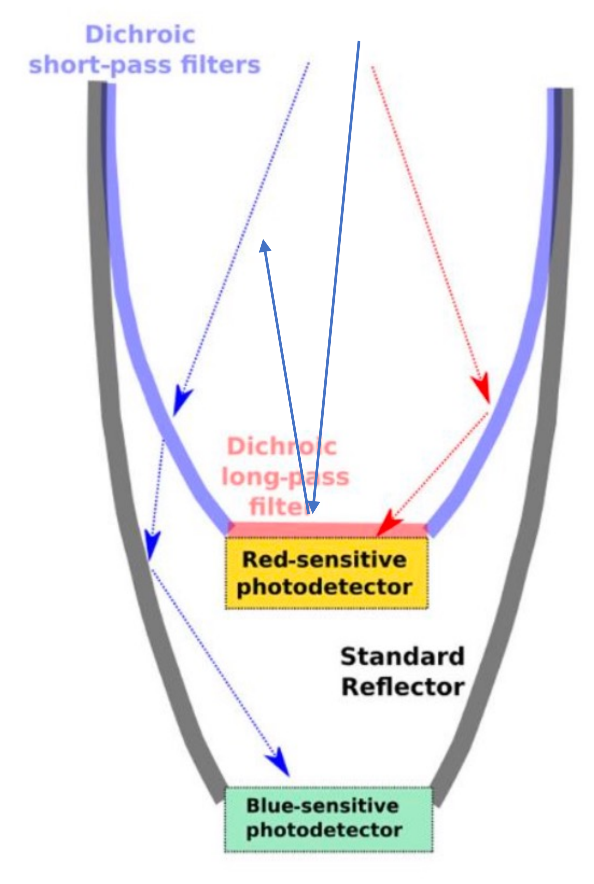


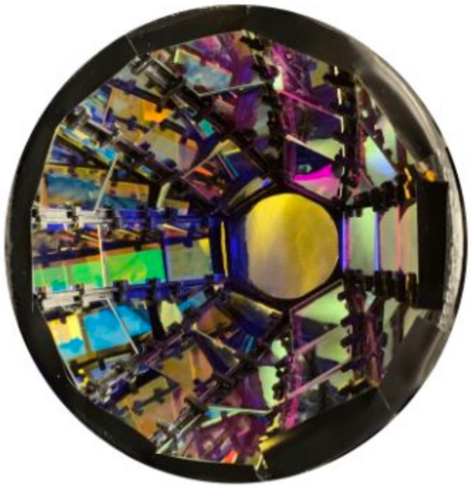
Dichroic filters provide a sorting mechanism---how do we use this in a large detector?



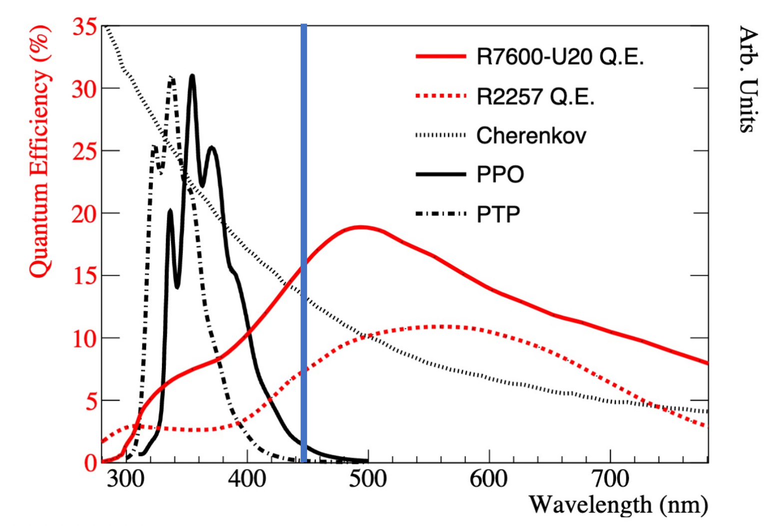
Dichroicons

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





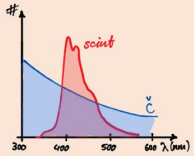
Cut-on wavelength depends on QE curve of sensors and emission of scintillation light and physics



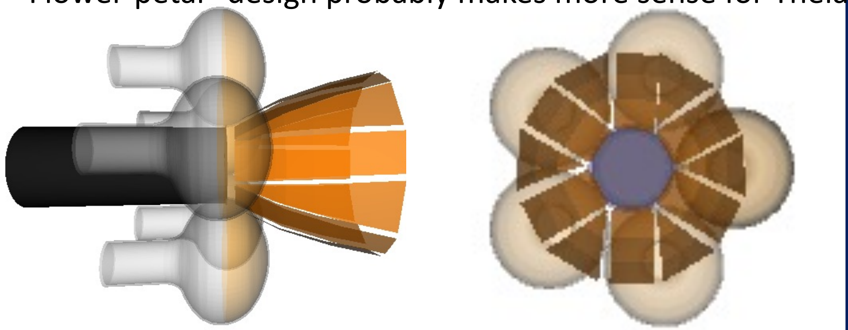
Spectrum

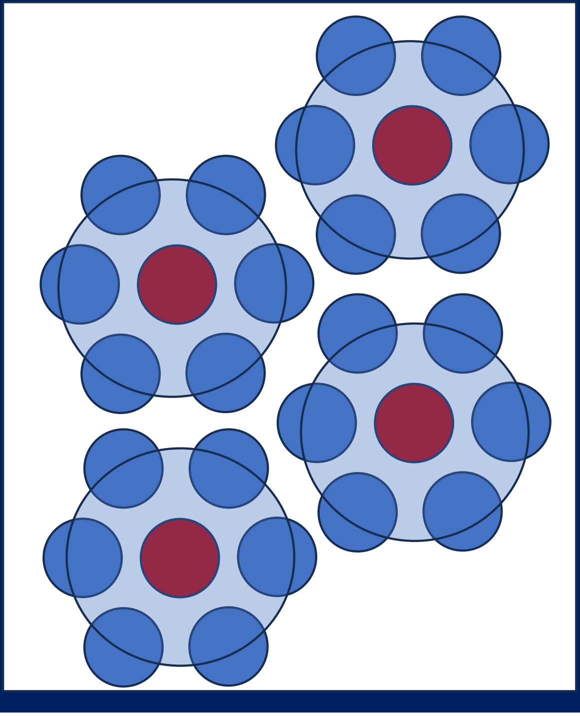
Spectrum

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



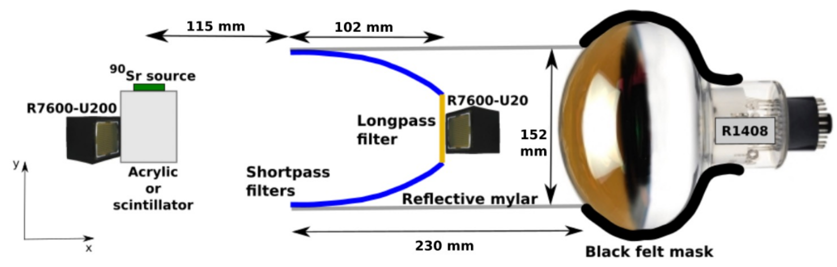
“Flower-petal” design probably makes more sense for Theia

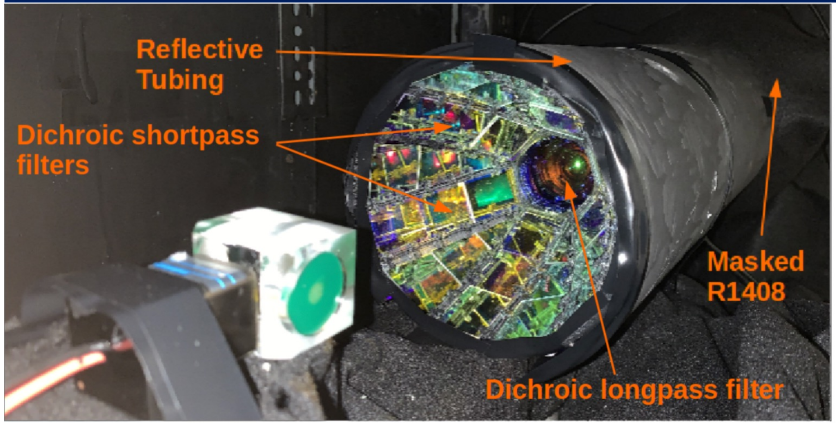


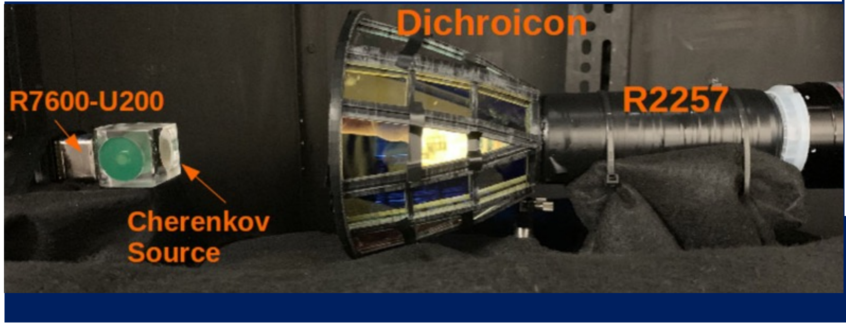


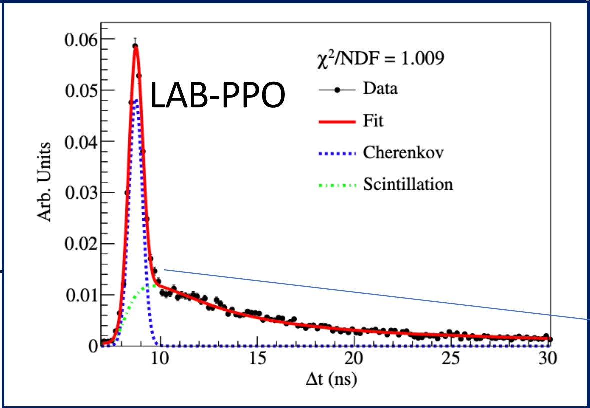
Dichroicons

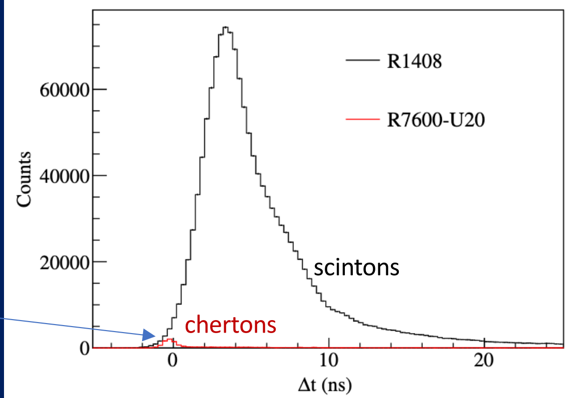
^{90}Sr/^{90}Y source (~2.3 MeV β)



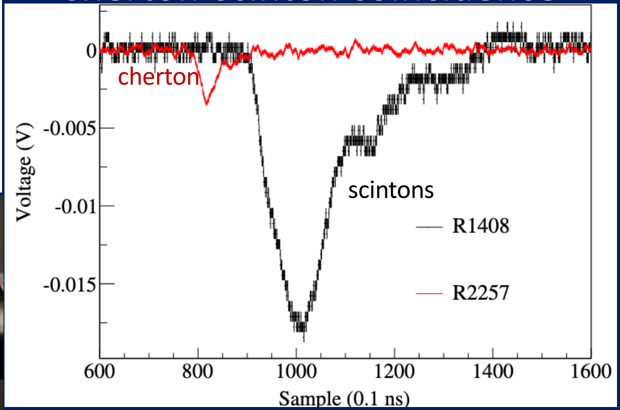




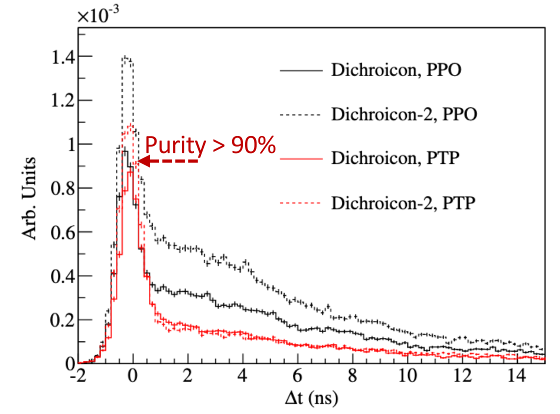




Cherton-scinton coincidence



PPO vs. PTP



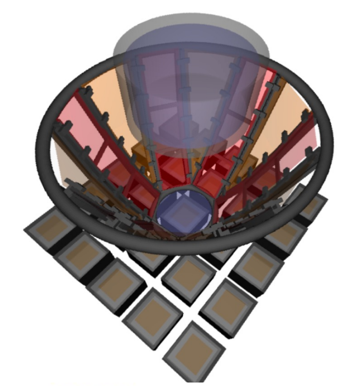
Phys. Rev. D 101, 072002

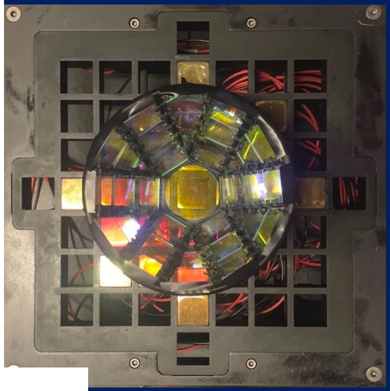
T. Kaptanoglu

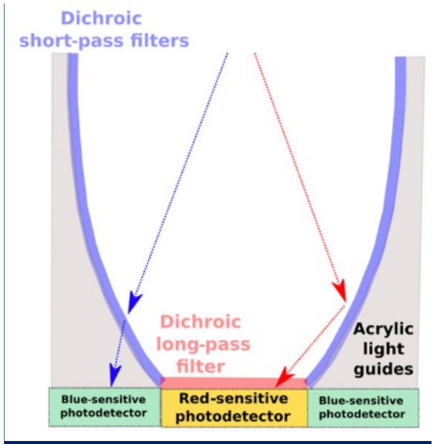
Dichroicons

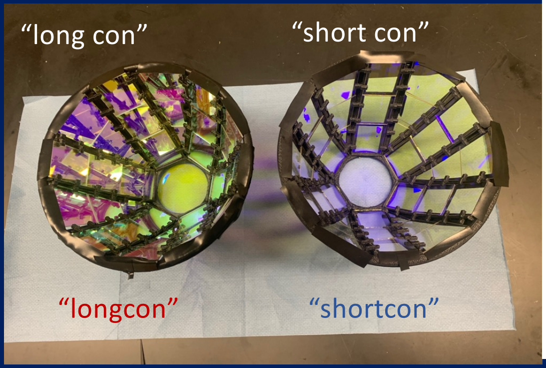
Pixellated sensors and high-energy source

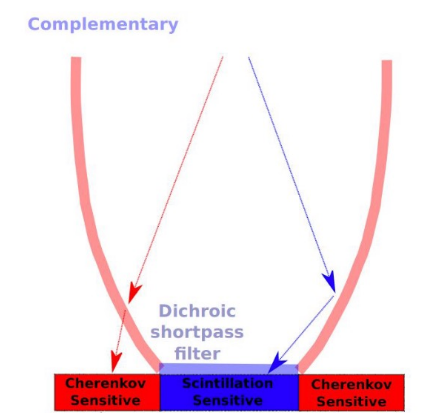
Dichroicon at CHESS (LBNL)

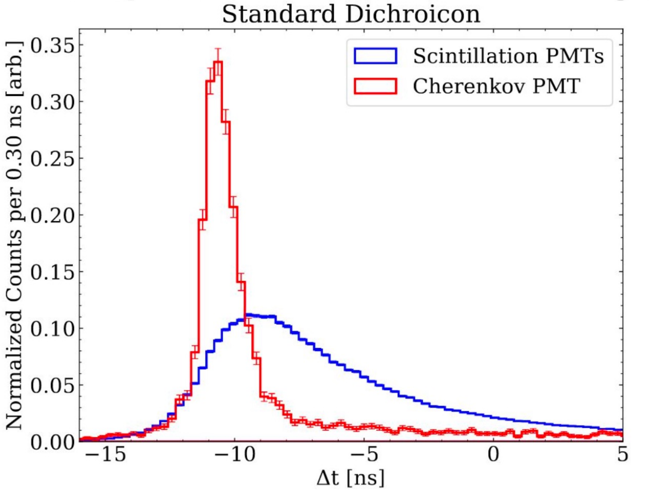




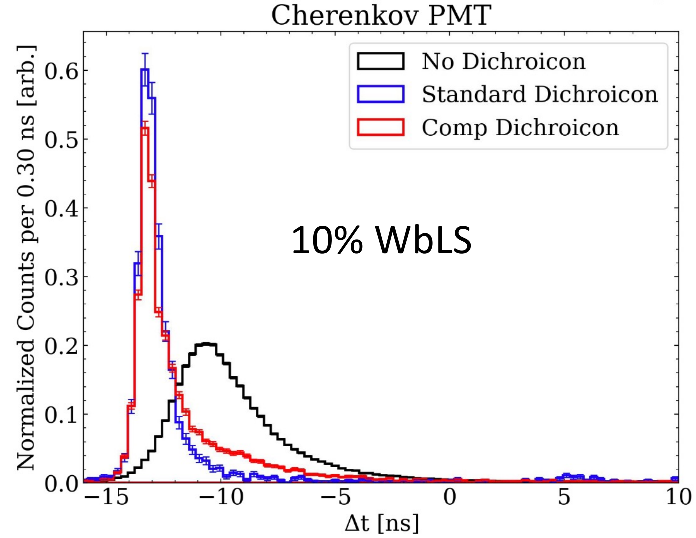








Atmospheric Muons Incident on LABPPO Target
Standard Dichroicon



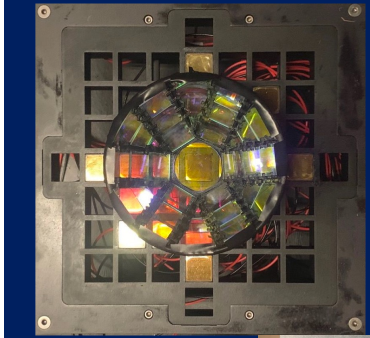
Atmospheric Muons Incident on WbLS Target
Cherenkov PMT

S. Naugle

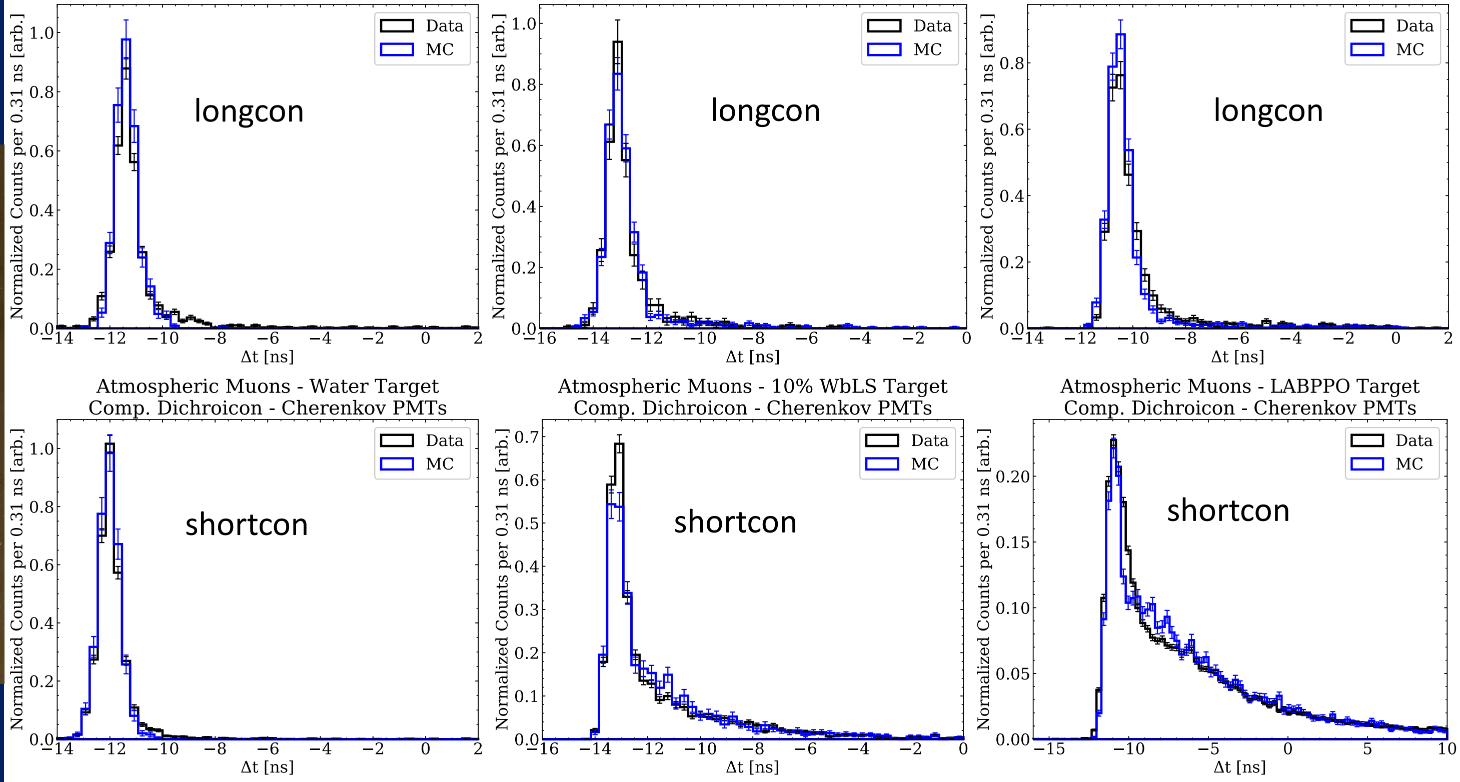
Dichroicons

Pixellated sensors and high-energy source

Dichroicon at CHESS (LBNL)

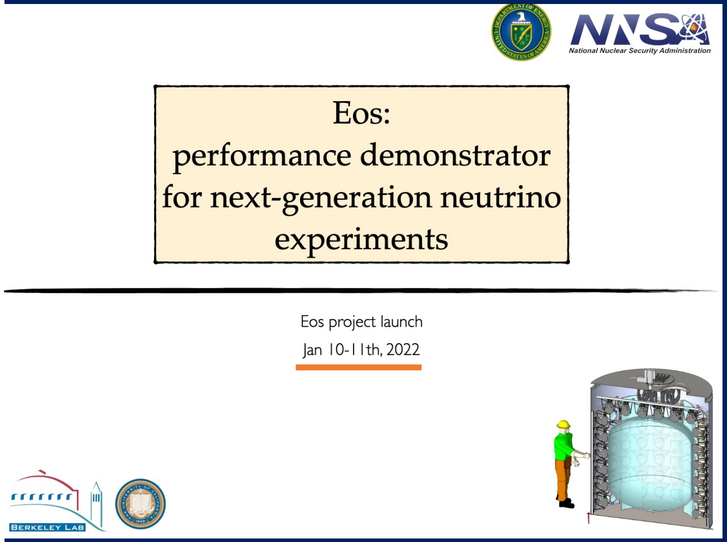


Chroma model does well reproducing data



S. Naugle

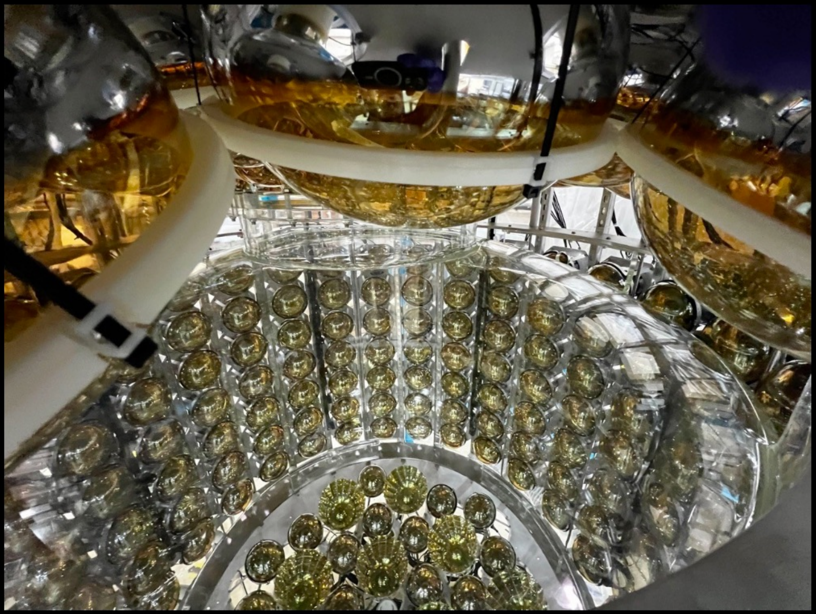
Eos Demonstrator



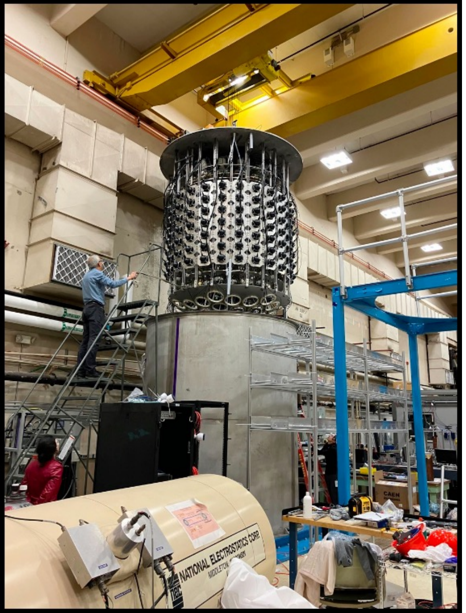
Eos:
performance demonstrator
for next-generation neutrino
experiments

Eos project launch
Jan 10-11th, 2022

Designed to test multiple approaches to hybrid Cherenkov/scintillation detection



Dec. 2023



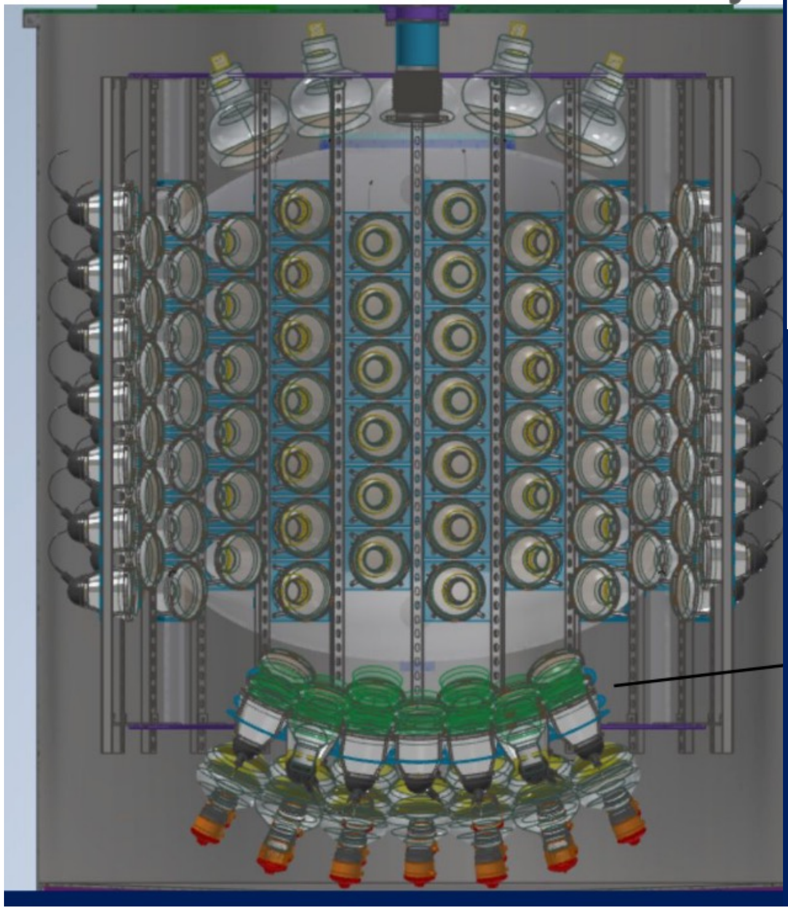
Jan. 2024

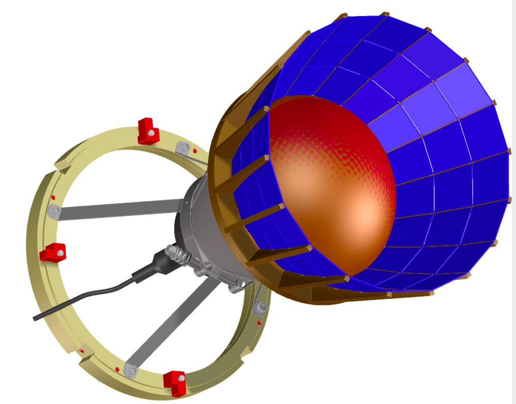
- Water-based liquid scintillator
- Fast (~450 ps) 8” PMTs
- 12 dichroicons

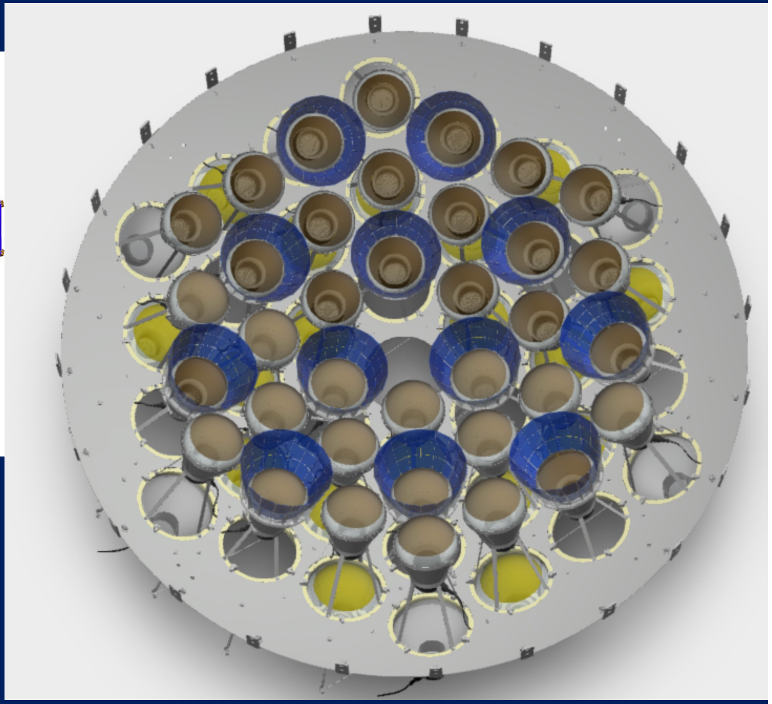
Dichroicons

Eos at LBNL

12 dichroicons at bottom





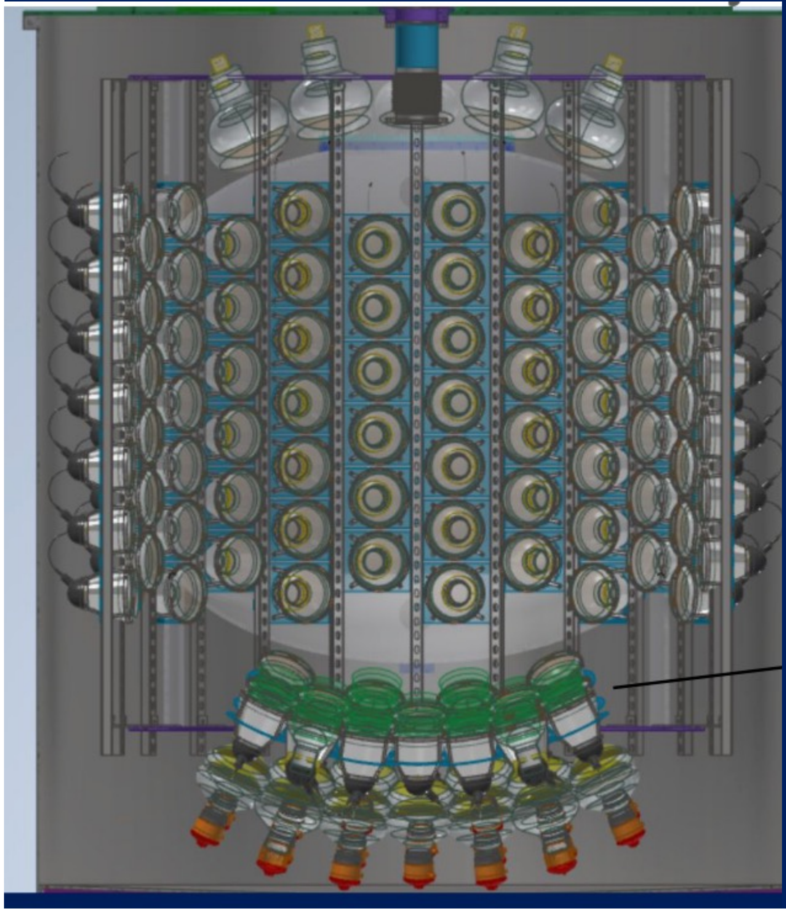


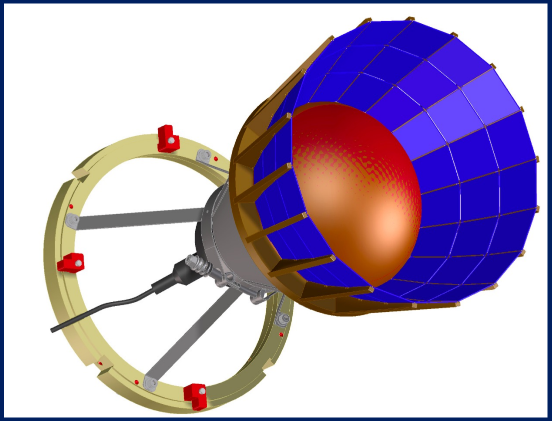
- Demonstrate Cherenkov/scintillation separation for variety of sources in tonne-scale detector
- Develop reconstruction methods leveraging scintons+chertons
- Test model of response

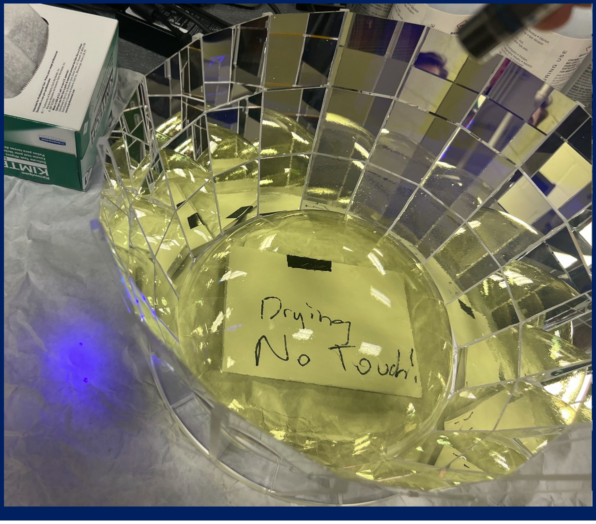
Dichroicons

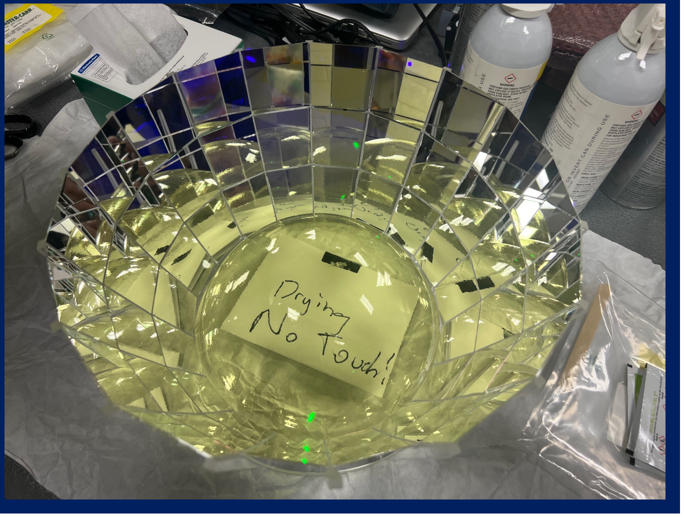
Eos at LBNL

12 dichroicons at bottom





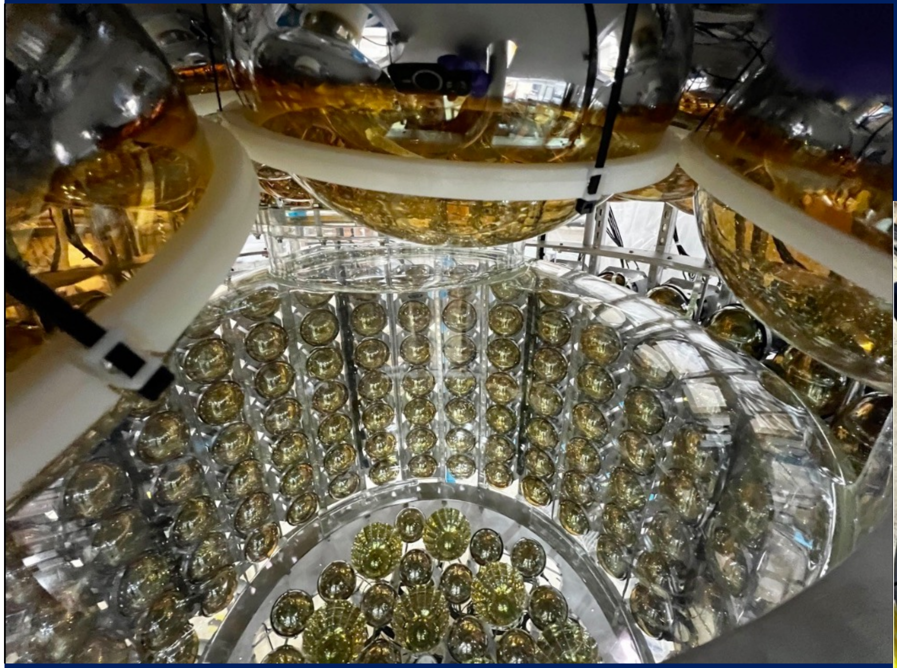




Dichroicons

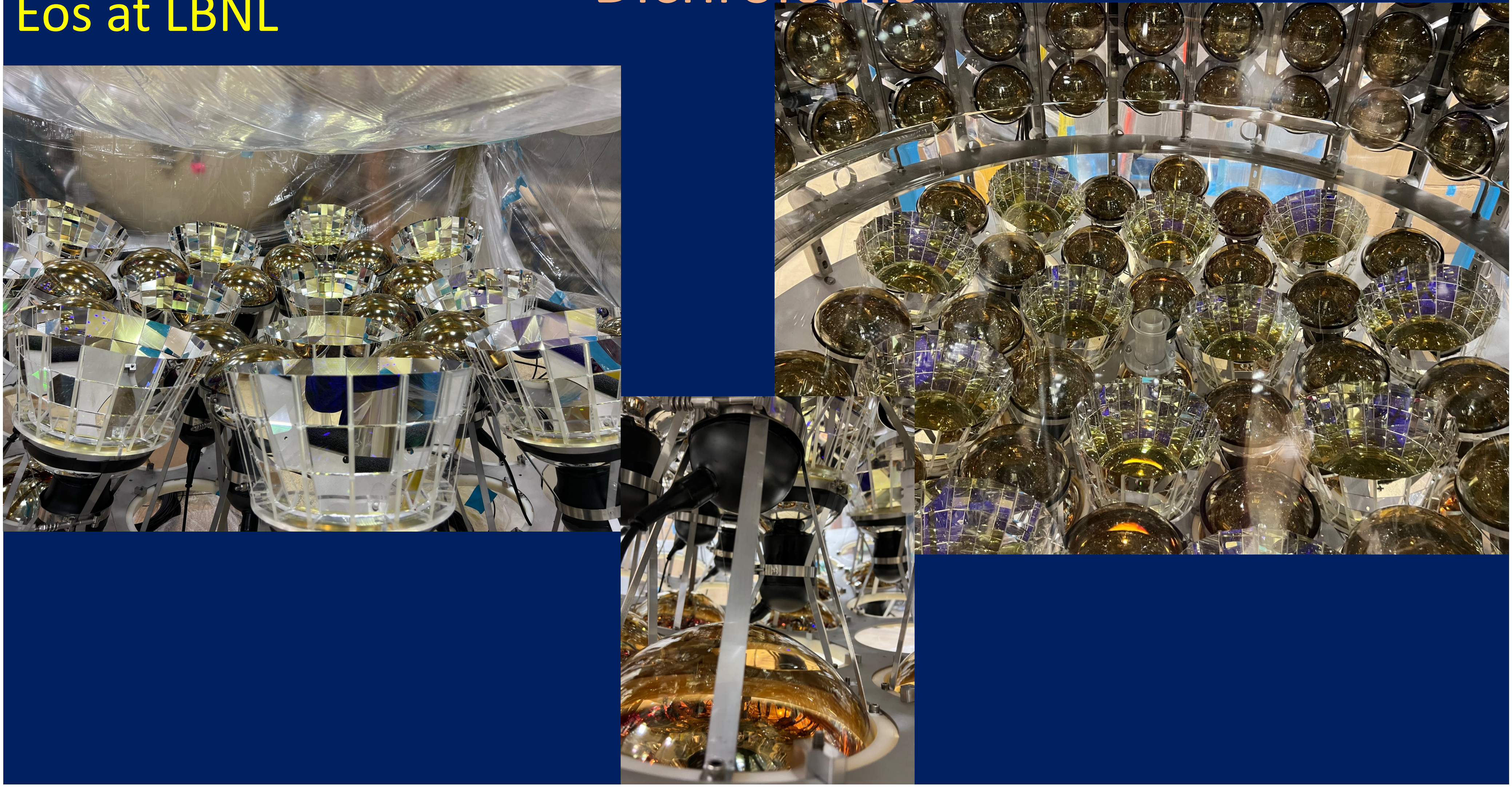
Eos at LBNL

12 dichroicons at bottom

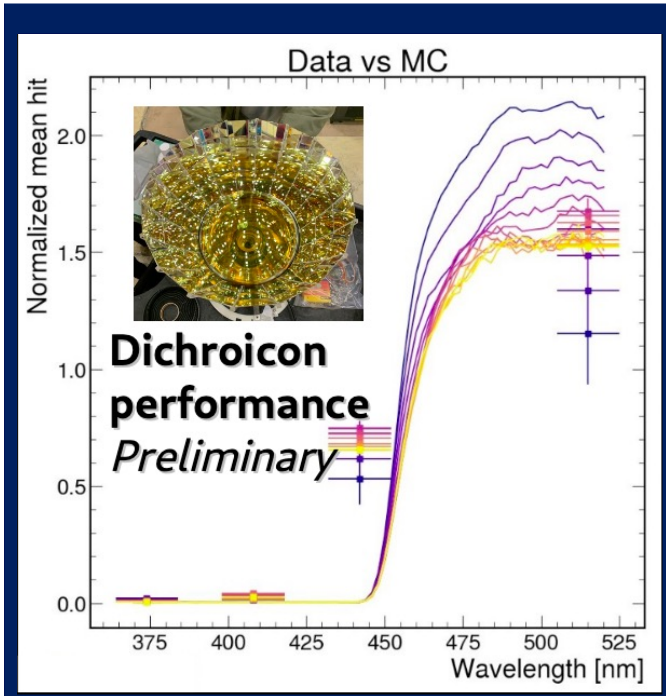


Dichroicons

Eos at LBNL

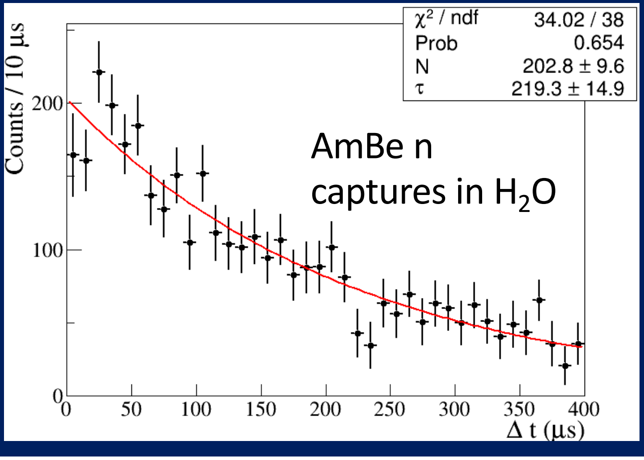


Eos at LBNL



Dichroicon performance

Preliminary

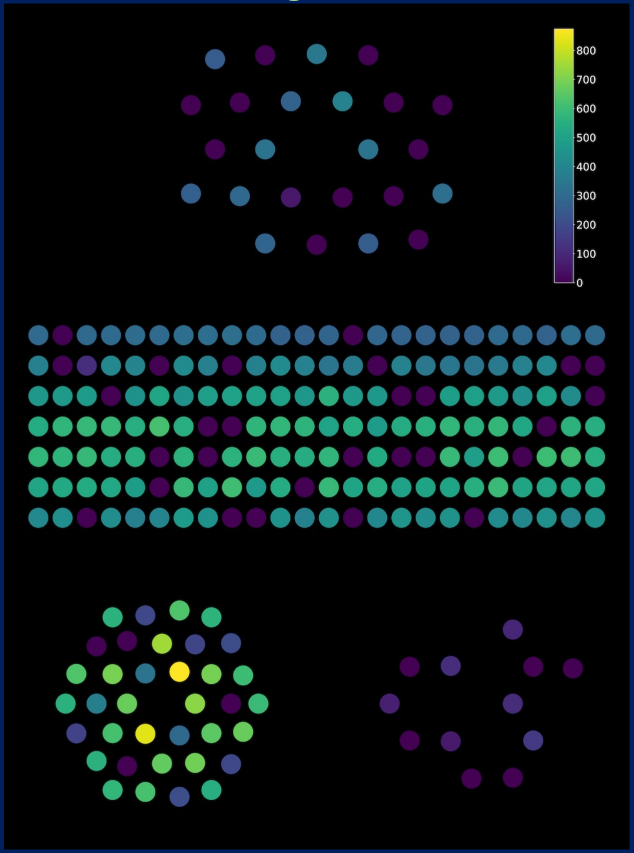


χ^2 / ndf 34.02 / 38
Prob 0.654
N 202.8 ± 9.6
τ 219.3 ± 14.9

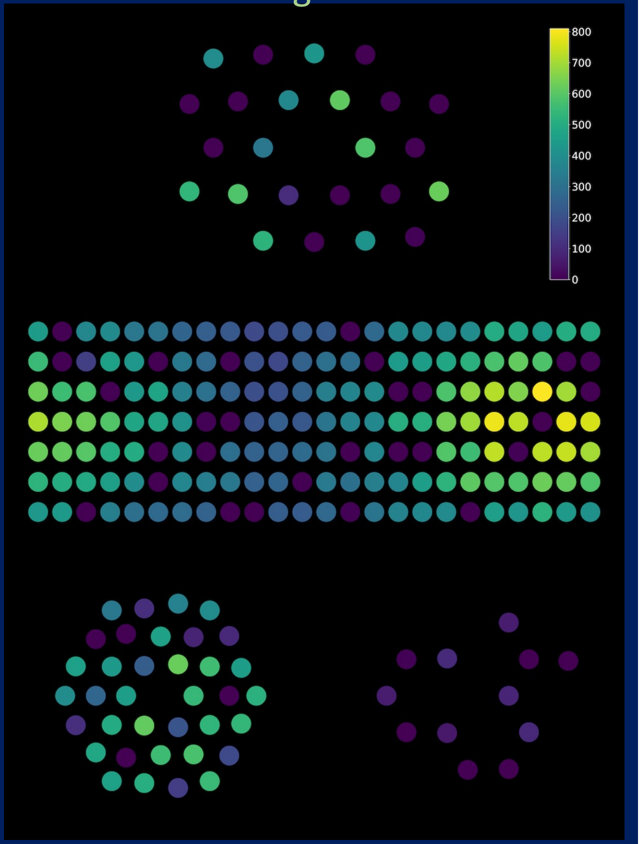
AmBe n captures in H_2O

Directional source (^{90}Sr) in 1% WbLS

Pointing down



Pointing sidewaus

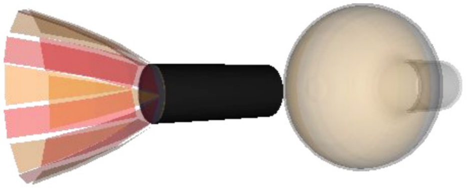


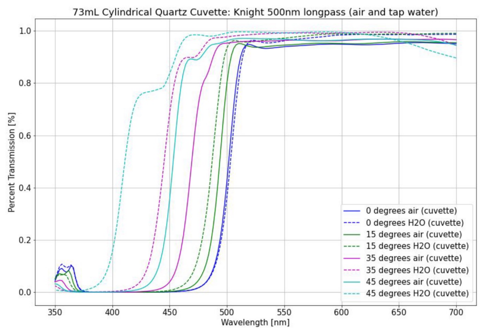
Dichroicons

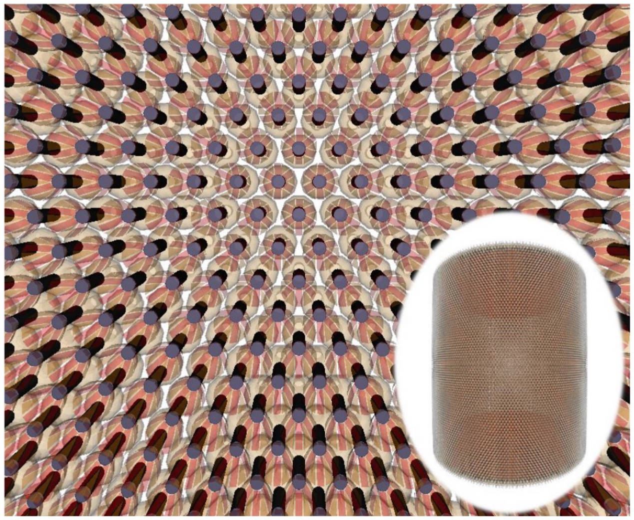
Theia

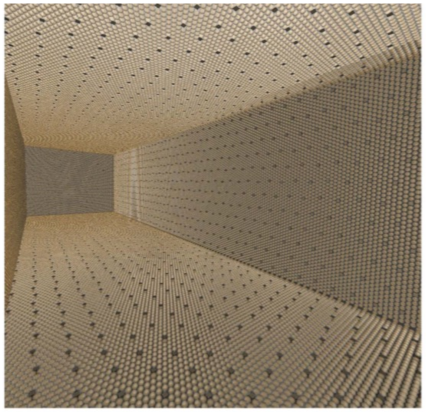
- Using full dichroicon model, implemented in Chroma GPU ray-tracer
- Developed simple timing and angular reconstruction for vertex and direction

A. Bacon







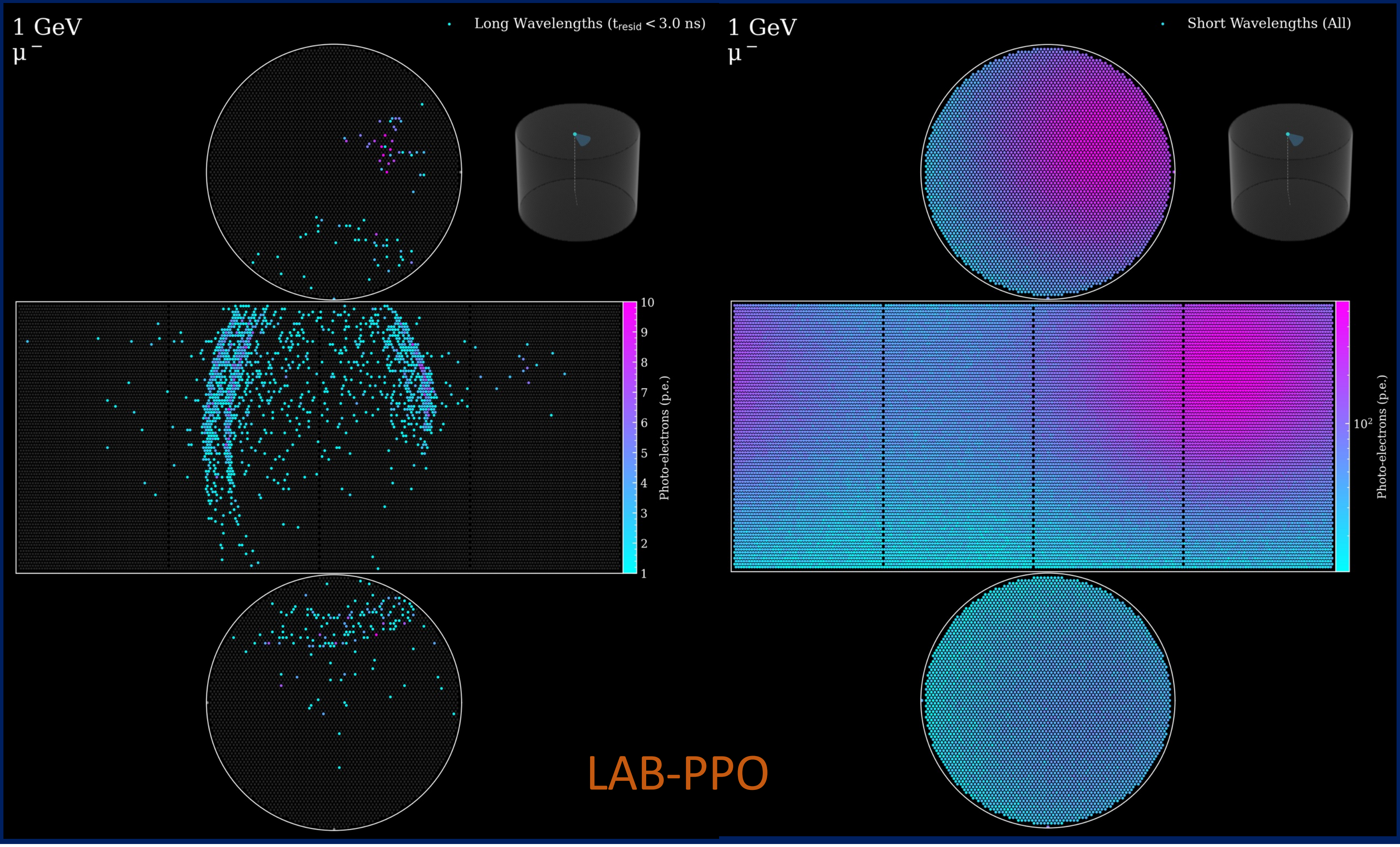


- *Implemented measured dichroic filter transmission and reflection curves in Chroma model*
- *Have full PMT QE curves*
- *Complete PMT timing response*
- *Optical isolation of long-wavelength PMT*

Theia

Dichroicons

One Detector

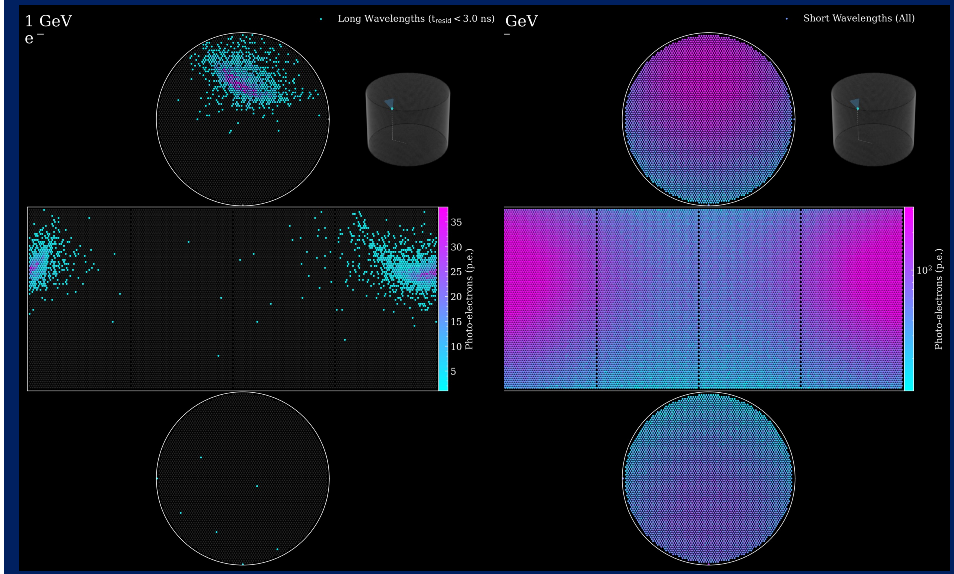


LAB-PPO

S. Young

Dichroicons

Theia (100kt)



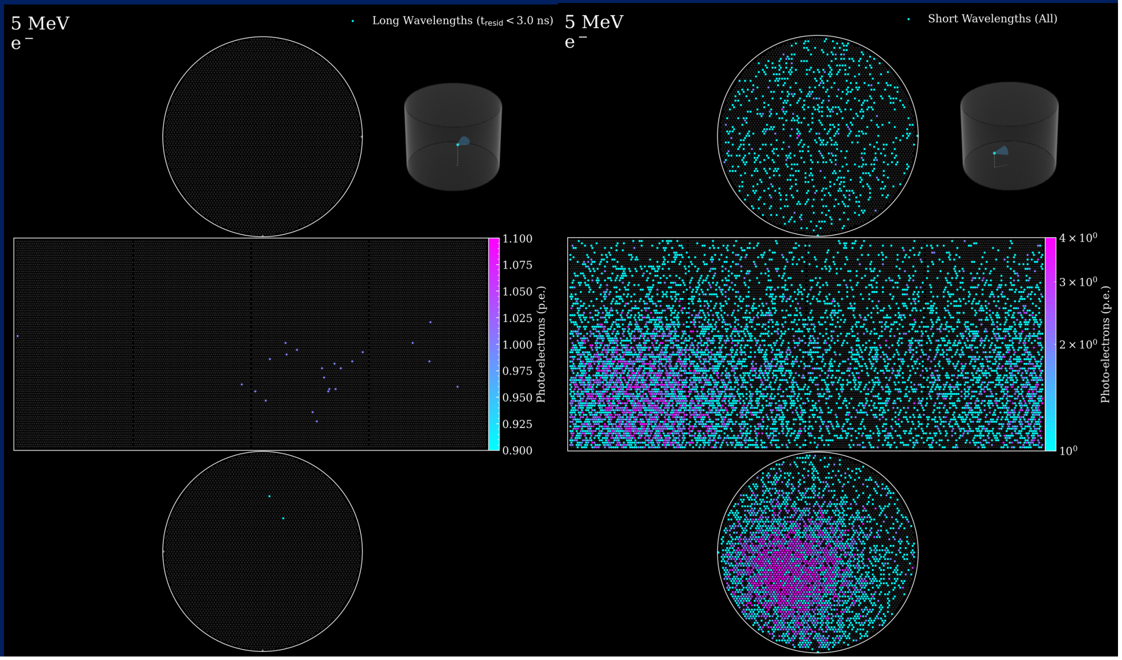
$\cos\theta_{ch} = 1/\beta n$

So $m = E\,\frac{\sqrt{n^2 cos^2\theta - 1}}{n \cos\theta}$

→ New PID handle if uncertainty on $\cos\theta_{ch}$ is small enough (~1 degree can do e, μ, K, p but not μ/π)

LAB-PPO, JUNO-level coverage

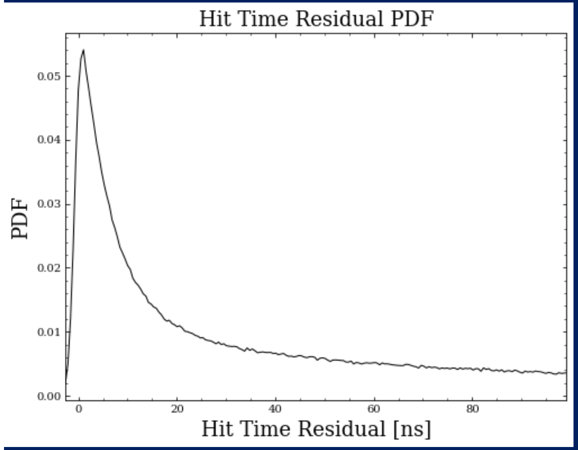
About 10,000pe≅
1% energy resolution
At 5 MeV

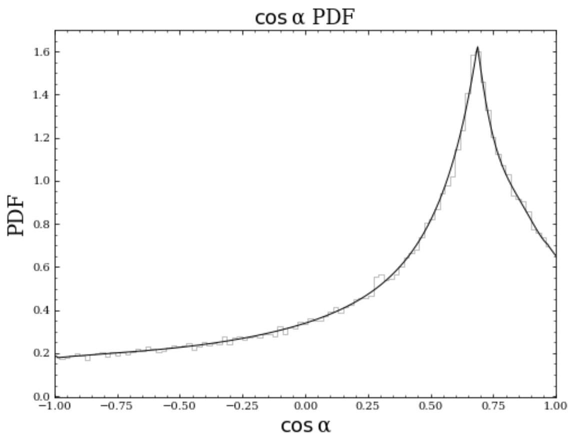


Dichroicons

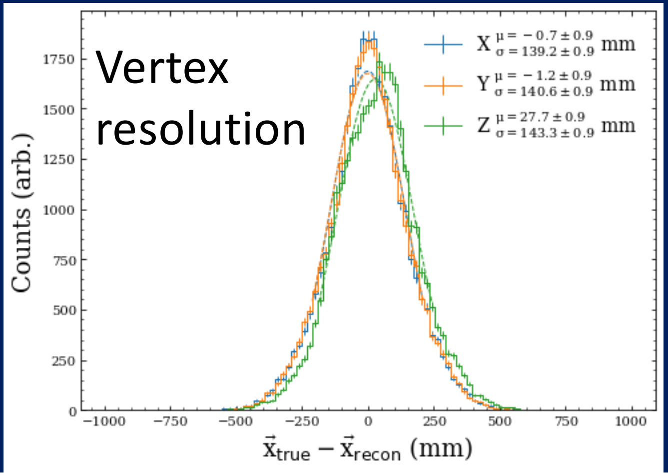
Reconstruction at 5 MeV

Simple likelihood-based reconstruction so far

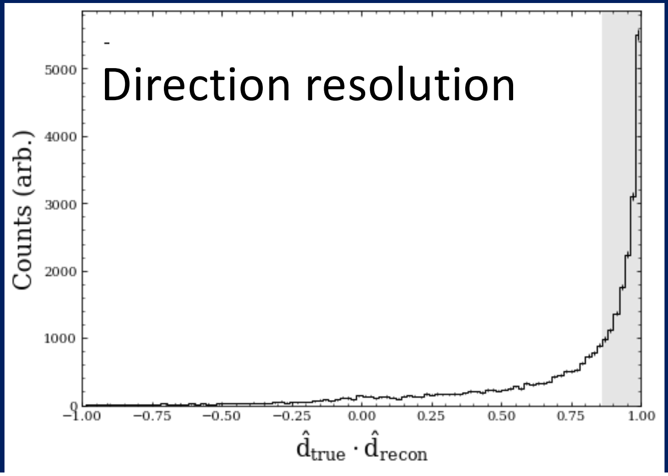




- 2D PDFs for both chertons and scintons will do better
- Energy should be included, too
- Bayesian approach may help with scintillation leakage
- Machine learning?



Vertex resolution



Direction resolution

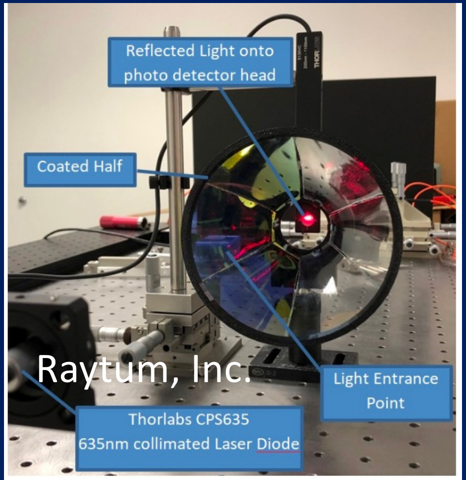
Only the surface has been scratched here---many other interesting problems

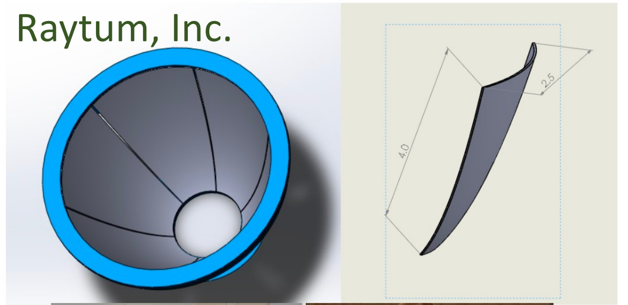
S. Young

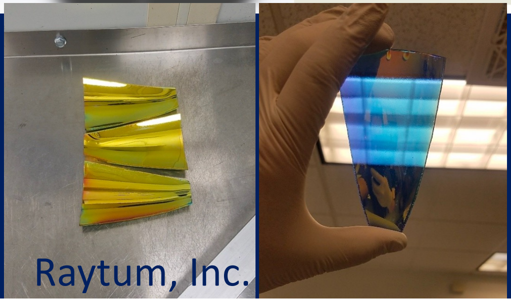
Dichroicons

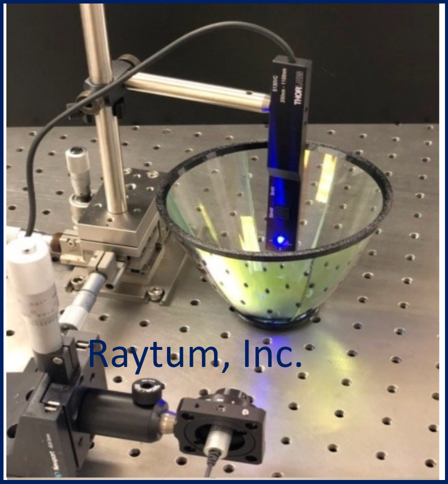
Challenges

1. Cost: Filters are not cheap! (Full dichroicon for a 5” PMT is ~cost of PMT)
    - But costs vary by x10 between vendors
    - New approach by Raytum Inc+Brookhaven SBIR grant using atomic-layer deposition may lead to much cheaper and better filters
    - With dichroic layers on non-flat surfaces!







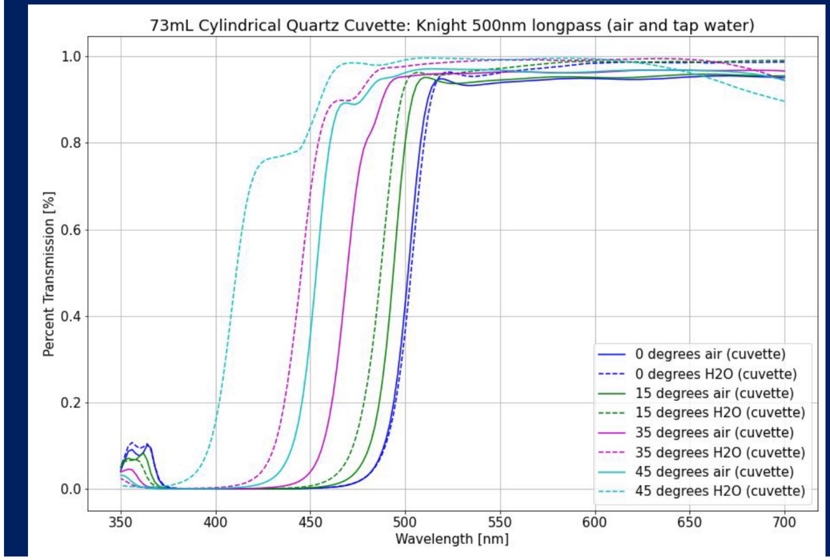


Dichroicons

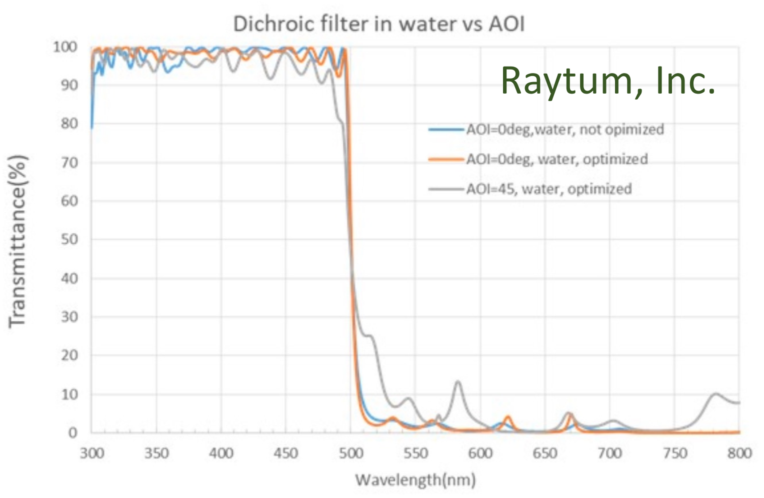
Challenges

2. Filter response (in media): Dichroicon has high-incidence illumination
   And cut-on wavelength shifts in media
   - But can design (e.g. Raytum) better matched angular response
   - And tune critical angle for better illumination

A. Bacon



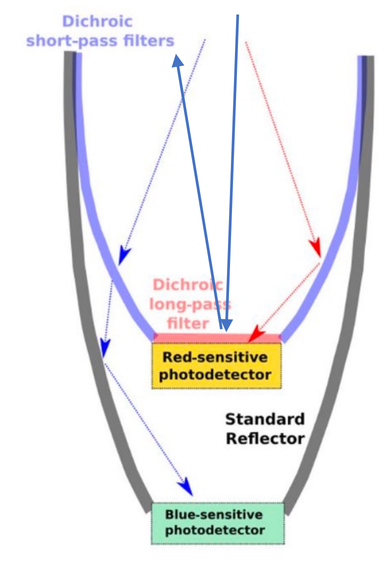
Dichroic filter optimized in water at AOI=0° and 45°



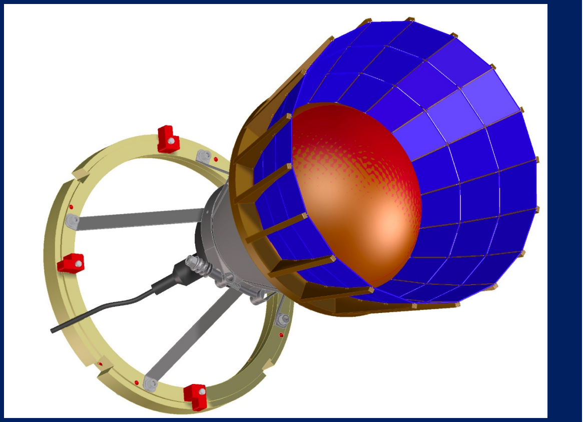
Dichroicons

Challenges

3. Field-of-view: Winston sees only part of the volume in a cylinder/shoebox
    - "Truncated" Winston cone like SNO loses few% light but much better FOV
    - Insertion of PMT into cone doubles Cherenkov yield



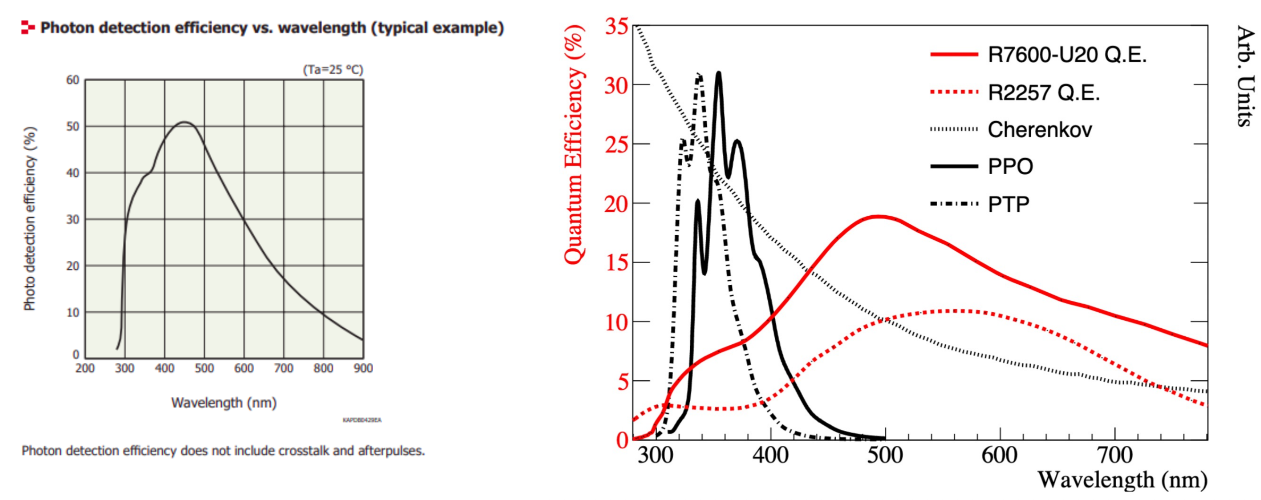
But this makes short-wavelength bounce back into detector harder---need a curved filter



Dichroicons

Challenges

3. Long-wavelength sensors: Vendors do not make green or red PMTs in >5” sizes with good timing yet
    - 8” SBA PMTs are already pretty good
    - SiPMs have almost “ideal” response
    - But they have high dark rates and are small

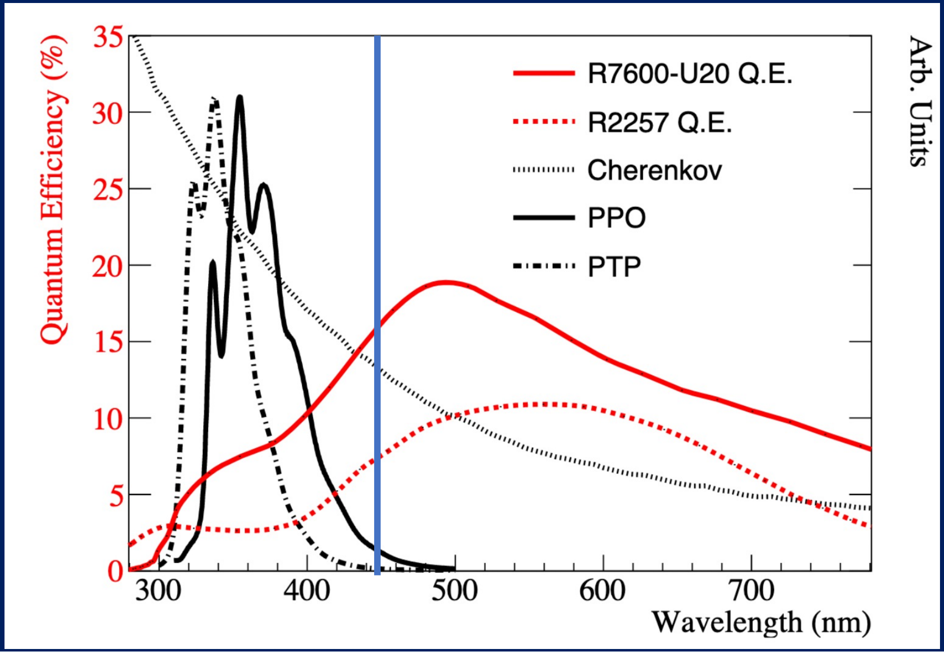


Photon detection efficiency does not include crosstalk and afterpulses.

Dichroicons

Challenges

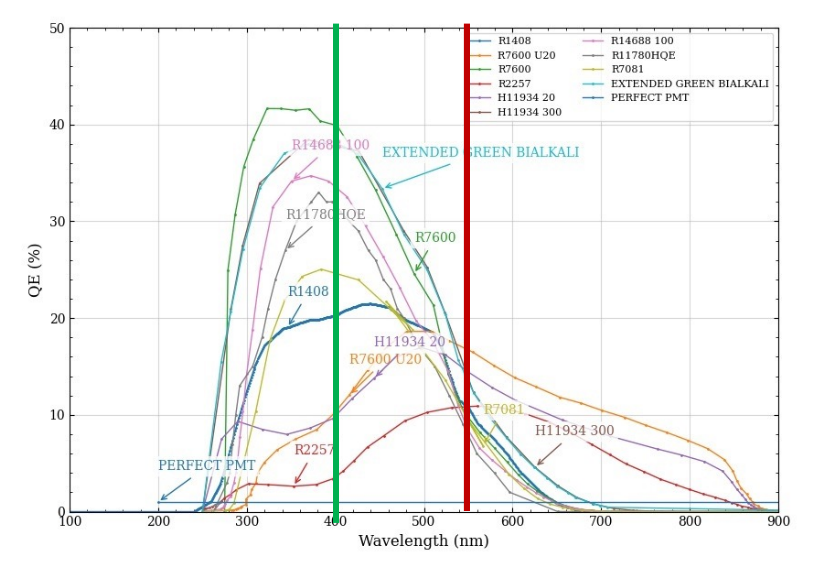
5. Cherenkov yield: Cut-off wavelengths at 450 nm miss plenty of chertons
    - Development of narrow-band fluor (perovskites? quantum dots?) would allow lower cut-offs, increasing chertons without leaking scintons

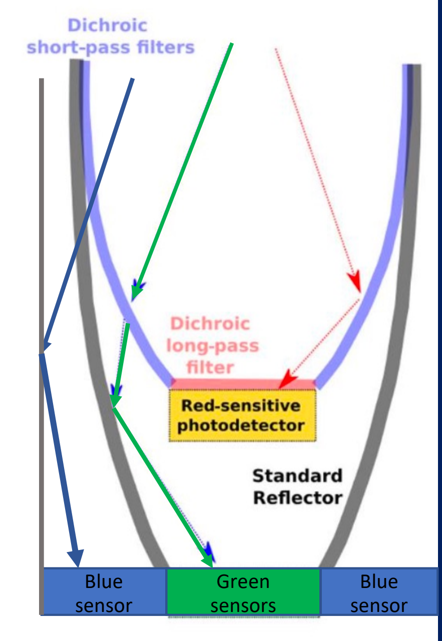


Trichroicons…?

Three distinct QE regimes---blue, green, red

Can stack dichroicons to direct photons to best collector





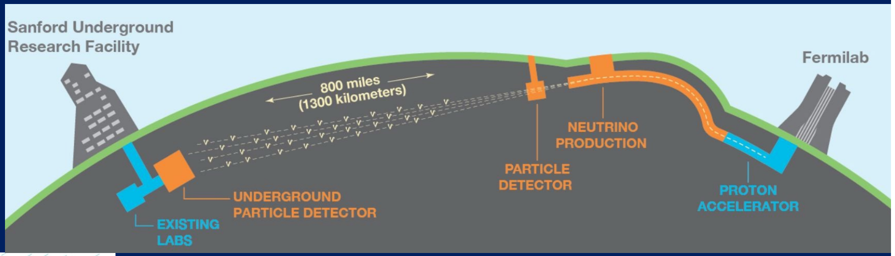
Increases light yield in a broadband, *very* photon-starved detector (e.g, low-energy Cherenkov)

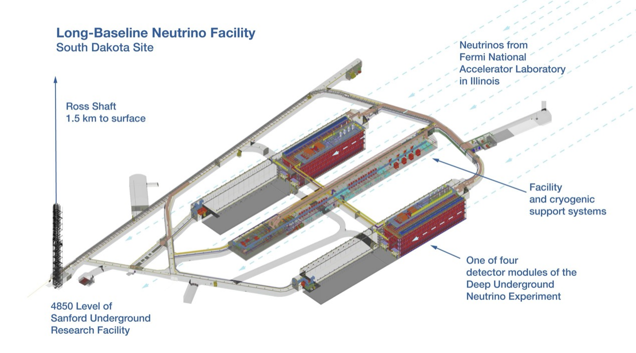
Theia

Where to put it?

Need:

- Neutrino beam for CP violation and neutrino oscillation physics
- Deep underground site for solar neutrinos and 0νββ search
- Big space for large detector





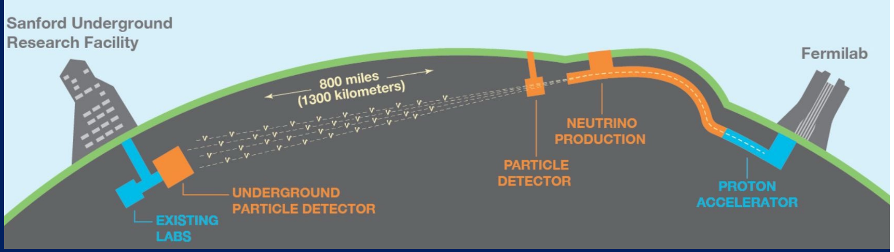
- 4 detector caverns for DUNE
- 2-3 will be liquid argon detectors
- 4th Cavity could house Theia
- (Also new space planned)

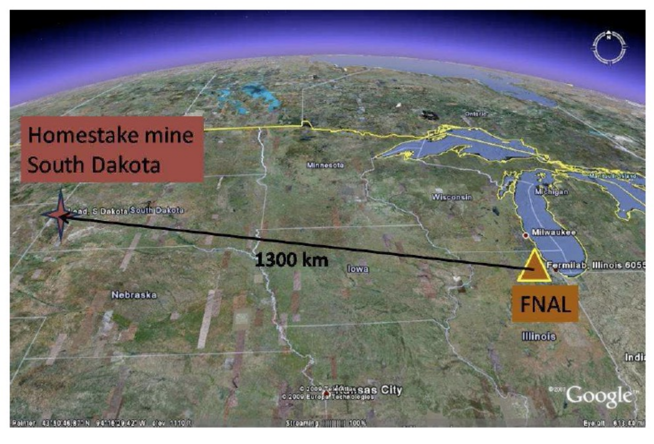
Theia

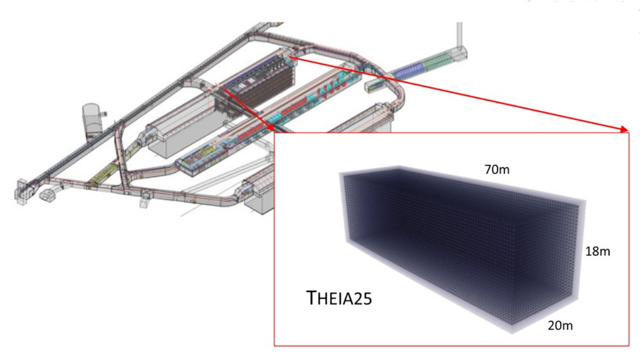
Where to put it?

Need:

- Neutrino beam for CP violation and neutrino oscillation physics
- Deep underground site for solar neutrinos and 0νββ search
- Big space for large detector





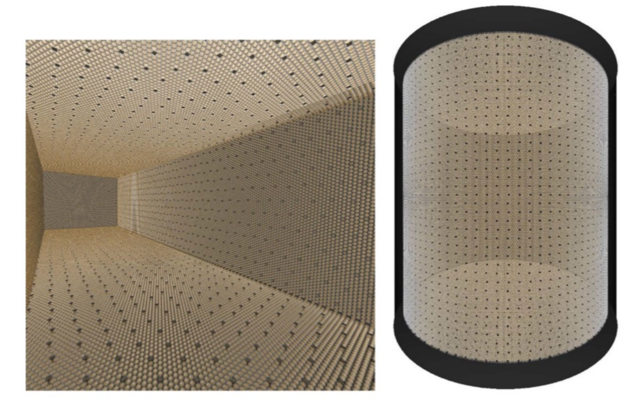


- 4 detector caverns for DUNE
- 2-3 will be liquid argon detectors
- 4th Cavity could house Theia
- (Also new space planned)

Theia
Sensitivities

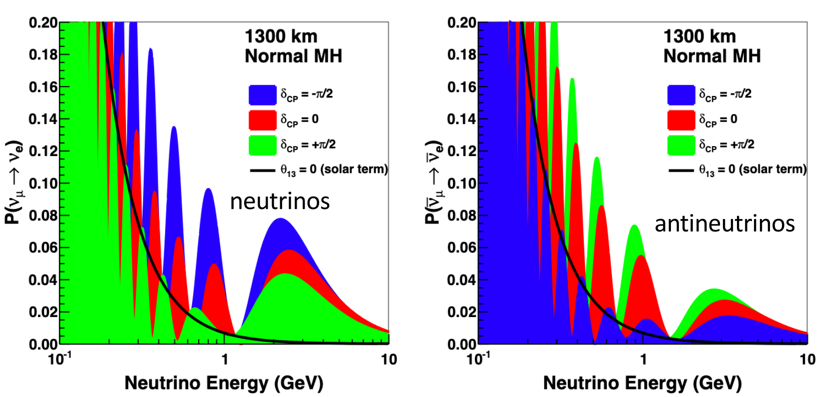
Two cases

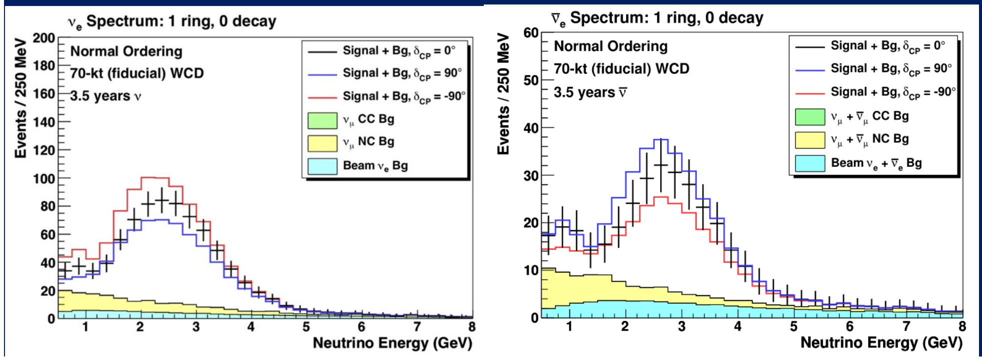
Theia-25kt Theia-100kt

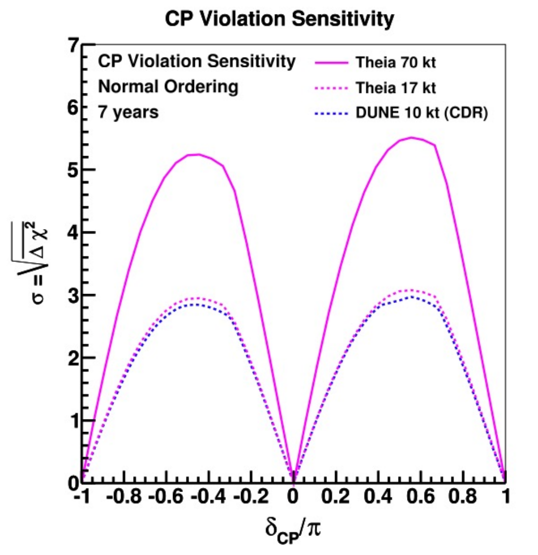


CP Violation: $P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$?

- Assume scintillation light not used for anything
- Low photosensor coverage







Theia

Sensitivities

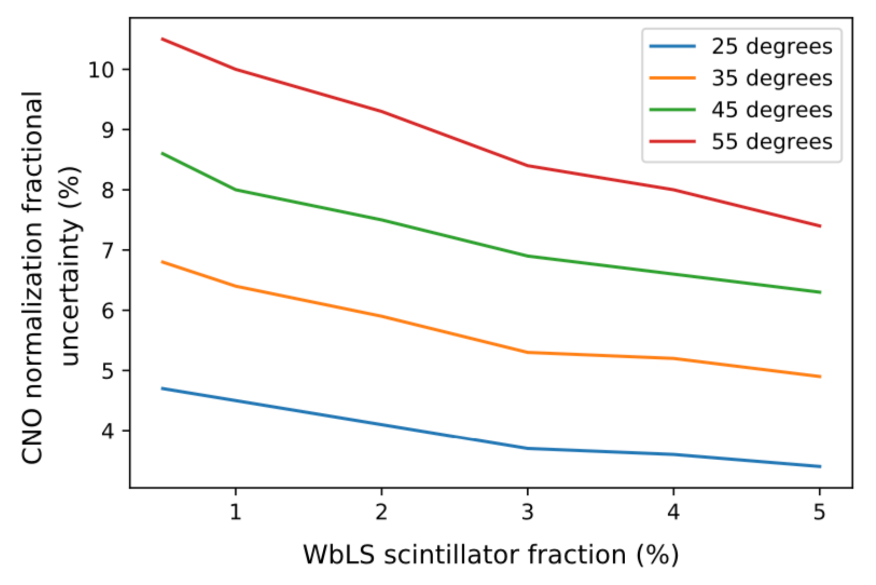
Solar CNO Neutrinos

- 5% water-based liquid scintillator
- Assume radioactivity levels like SNO water
- 90% photosensor coverage

Final BOREXINO uncertainties:

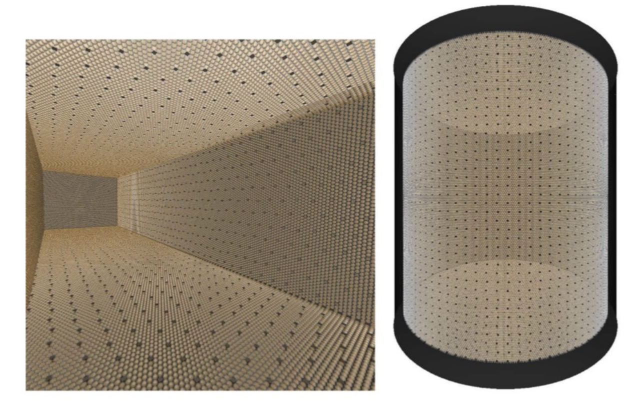
+20%
-13%

CNO uncertainty for different angular resolutions

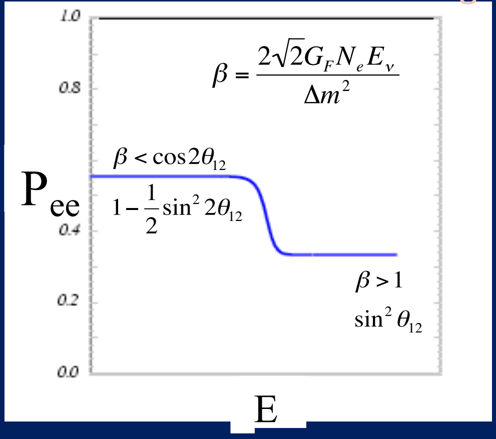


Two cases

Theia-25kt Theia-100kt



What about MSW transition region?



Expect 1000s of interactions

Theia

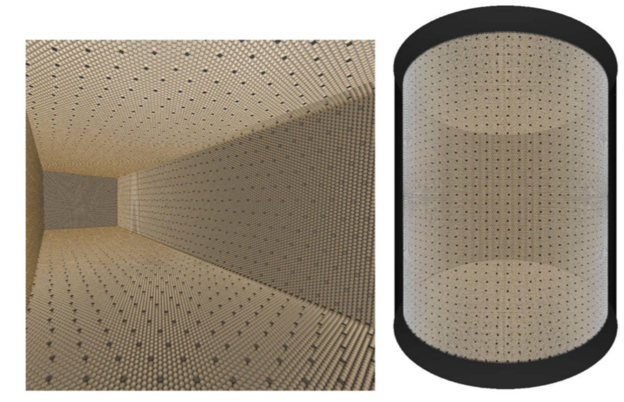
Sensitivities

0νββ and Majorana

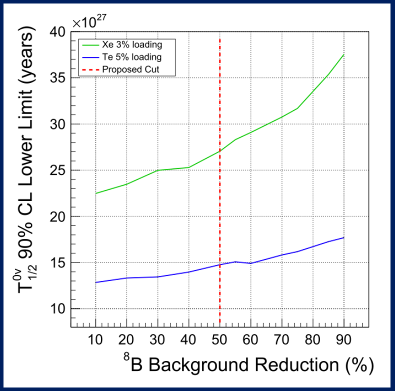
- Inner vessel filled with scintillator (WbLS outside)
- Assume radioactivity levels like BOREXINO
- 90% photosensor coverage
- Cherenkov light rejects solar neutrinos (no dichroicons)

Two cases

Theia-25kt Theia-100kt

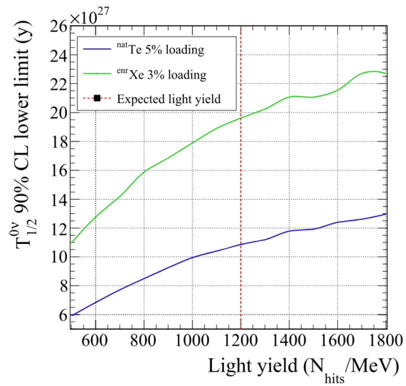


Half-life limit vs. solar neutrino rejection

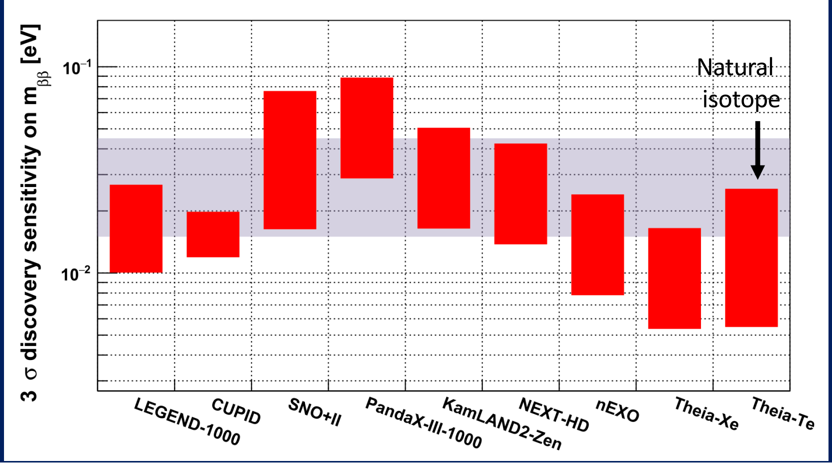


Solar νs are biggest background

Half-life limit vs. Light yield



Compared to other planned experiments

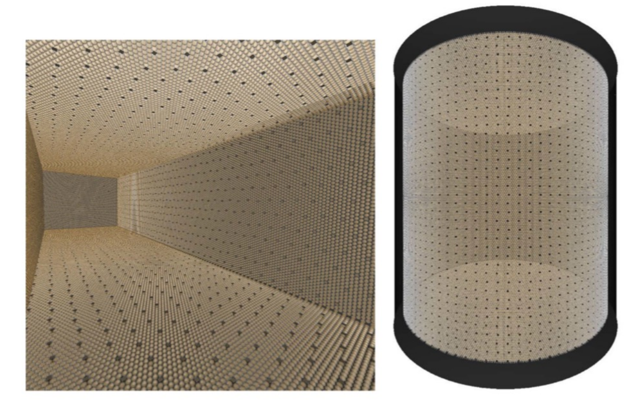


Theia

Sensitivities

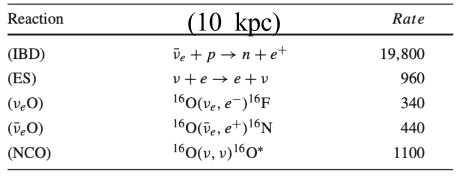
Two cases

Theia-25kt Theia-100kt



Other Physics…

Supernova burst neutrinos



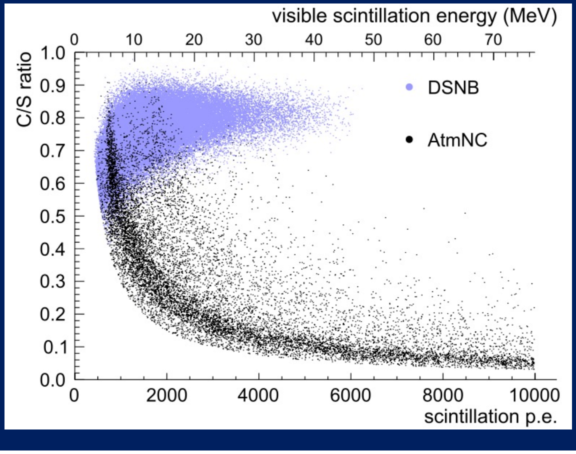
Reaction	(10 kpc)	*Rate*
(IBD)	$\bar{\nu}_e + p \rightarrow n + e^+$	19,800
(ES)	$\nu + e \rightarrow e + \nu$	960
$(\nu_e O)$	$^{16}O(\nu_e, e^-)^{16}F$	340
$(\bar{\nu}_e O)$	$^{16}O(\bar{\nu}_e, e^+)^{16}N$	440
(NCO)	$^{16}O(\nu, \nu)^{16}O^*$	1100

Literally complementary to DUNE

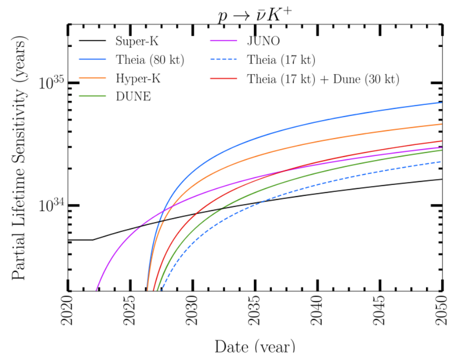
Diffuse supernova background neutrinos

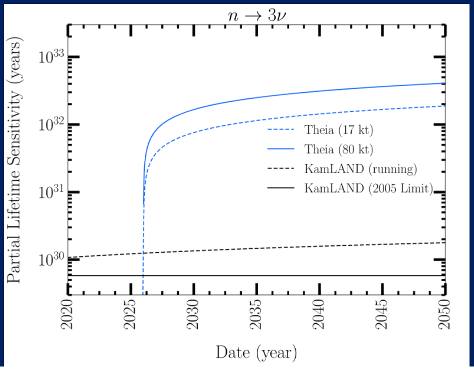
Leftover neutrinos from all the supernovae since Big Bang

Detection exploits cherton/scinton ratio



- Nucleon Decay





Summary

- Plenty of interesting neutrino questions left to answer
- Hybrid technique can address many of these in a single detector
- Lots of ways to do this
- Spectral sorting with dichroicons have some advantages
- (And some challenges)
- Big hybrid detector like Theia could have a very exciting program

Community Interest (US)

8

Instrumentation Frontier

P. Barbeau, P. Merkel, J. Zhang

Dichroicons : Dichroicons, which are Winston-style light concentrators made from dichroic mirrors, allow photons to be sorted by wavelength thus directing the long-wavelength end of broad-band Cherenkov light to photon sensors that have good sensitivity to those wavelengths, while directing narrow-band short-wavelength scintillation light to other sensors. Dichroicons are particularly useful in high-coverage hybrid Cherenkov/scintillation detectors.

SNOWMASS NEUTRINO FRONTIER:
NF10 TOPICAL GROUP REPORT
NEUTRINO DETECTORS

3.1.4 Spectral Sorting and Dichroicons

One approach to separating Cherenkov and scintillation light is by discriminating photons by wavelength, as scintillation is typically within a narrow emission band, while Cherenkov is a broad spectrum of light, falling as roughly $1/\lambda^2$.

2

Photon Detectors

C. O. Escobar, J. Estrada, C. Rogan

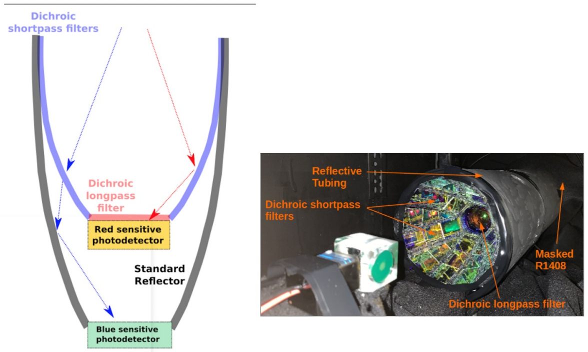


Figure 2-2. *Example of photon detector development for neutrinos: the dichroicon, from arXiv:2203.07479*

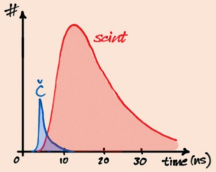
Timing

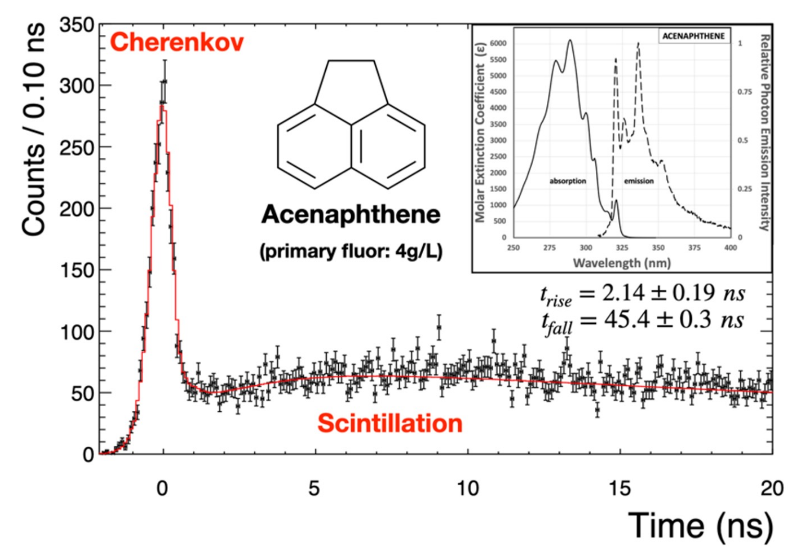
Slow(er) Scintillator

Timing

“instantaneous chertons” vs. delayed “scintons”

→ ns resolution or better



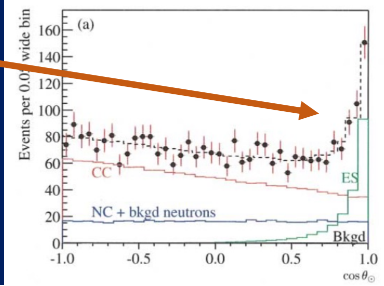


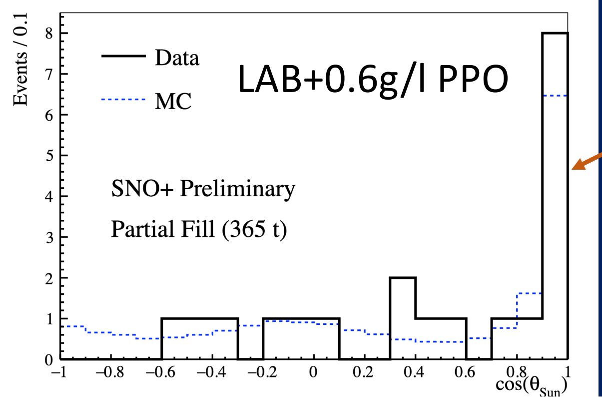
Biller, Leming, Paton, NIM A 972 (2020) 164106

But: position reconstruction degraded

Can also slow down scintillator by using a small amount of fluor

SNO D_2O Cherenkov





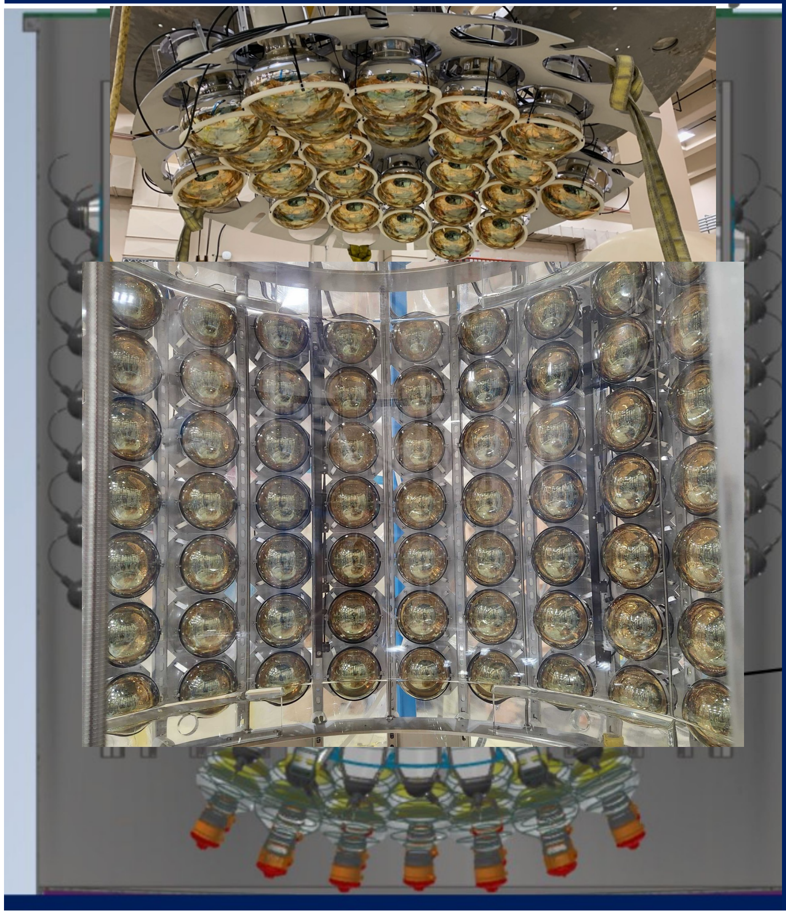
Solar peak in scintillator event-by-event

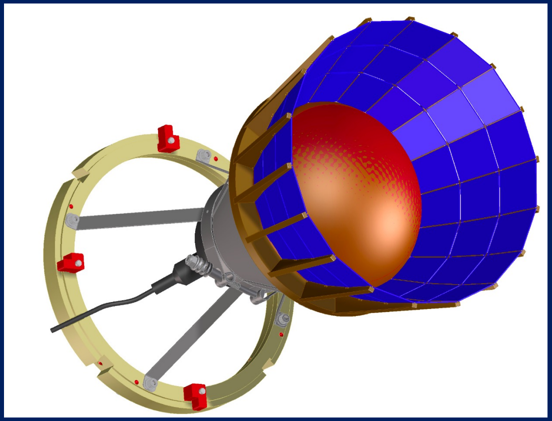
But: light yield reduced (poorer resolution)

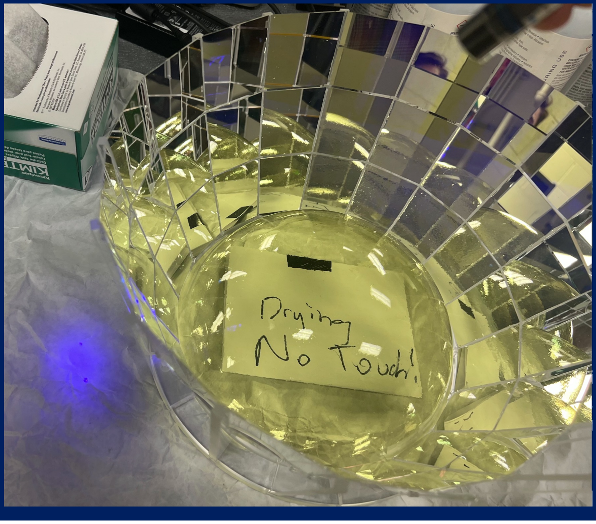
Dichroicons

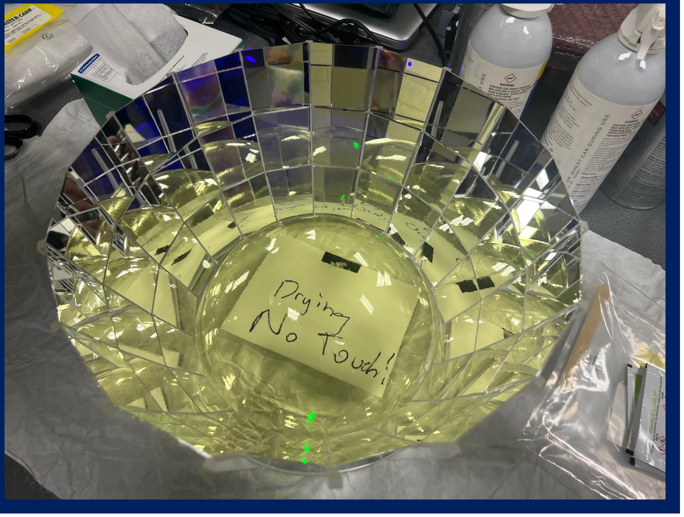
Eos at LBNL

12 dichroicons at bottom









A Quick Reminder

Neutrinos are produced as weak interaction (flavor) eigenstates (ν_e, ν_μ, …) but propagate as physical eigenstates (ν_1, ν_2, …):

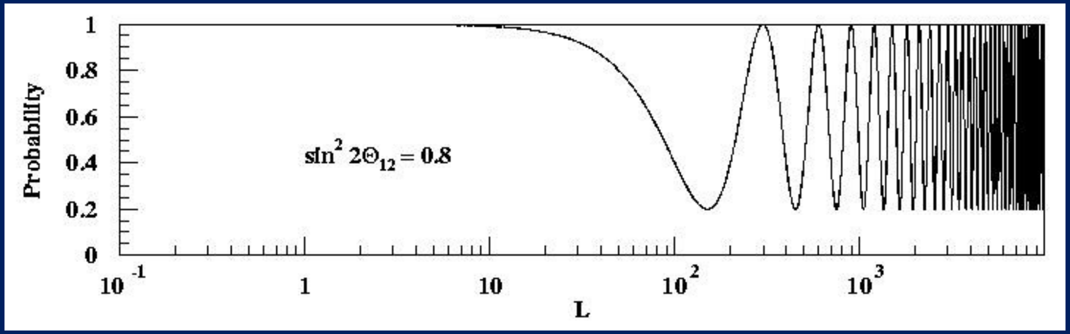
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Depends on (m_1^2-m_2^2)

“survival probability”

$$P_{\upsilon_e \to \upsilon_e} = 1 - \sin^2 2\theta_{12} \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

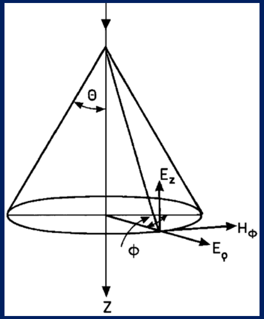
(vacuum only)



Photon Information

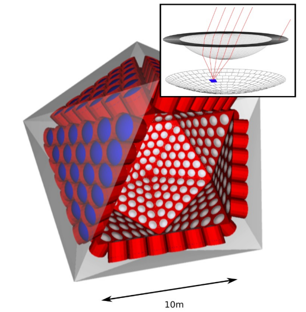
Photons also have:

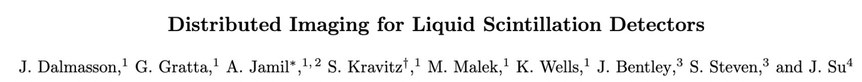
- Polarization



These have never been exploited in a large-scale detector---

- Direction





Distributed Imaging for Liquid Scintillation Detectors

J. Dalmasson,[1] G. Gratta,[1] A. Jamil*,[1,2] S. Kravitz†,[1] M. Malek,[1] K. Wells,[1] J. Bentley,[3] S. Steven,[3] and J. Su[4]

- Wavelength

Photon Information

To date nearly all these detectors use only

- Photon time-of-arrival
- Photon sensor position
- Total photon count

These allow reconstruction of

- (x,y,z,t) for vertex
- (u,v,w) usually for Cherenkov detectors
- Energy from calorimetry and/or Cherenkov angle
- Particle ID at high energy (ring imaging)
- Particle ID at low energy (scintillation time profile)

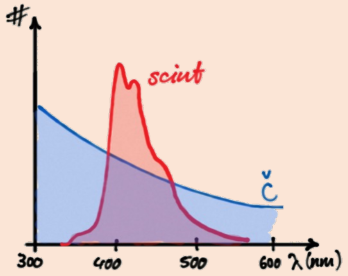
But photons carry a lot more information…

Physics Cases

- Photon Dispersion
  - Time-of-flight difference between 400 nm and 600 nm over 60 m is
    - 0.5 ns for LAr
    - 1.5 ns for H_2O
    - 5 ns for LAB-PPO
  - Measuring difference allows new handle on position reconstruction
  - And more precise timing
- Photon Collection
  - Trapping (e.g. ARAPUCAs)
  - Detecting broader spectrum than single device can see
- Particle ID
  - LAr triplet state re-emitted by Xe
  - Wavelength dependence of LS tail…?
- Cherenkov/scintillation separation (e.g., Theia)

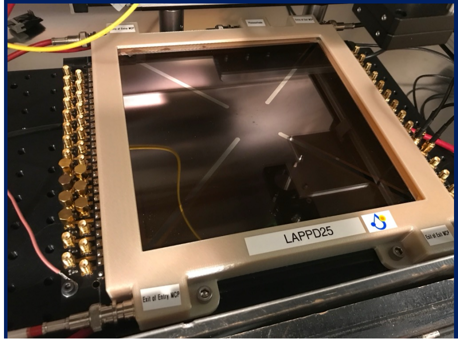
Spectrum

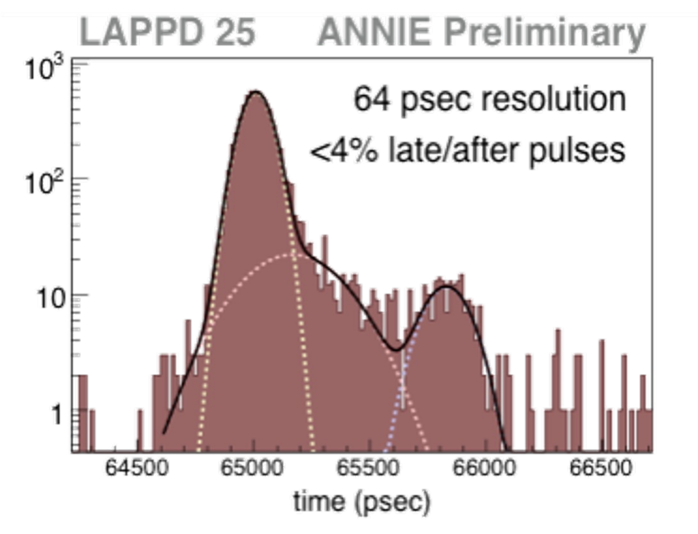
UV/blue scintillation vs.
blue/green Cherenkov
→ wavelength-sensitivity



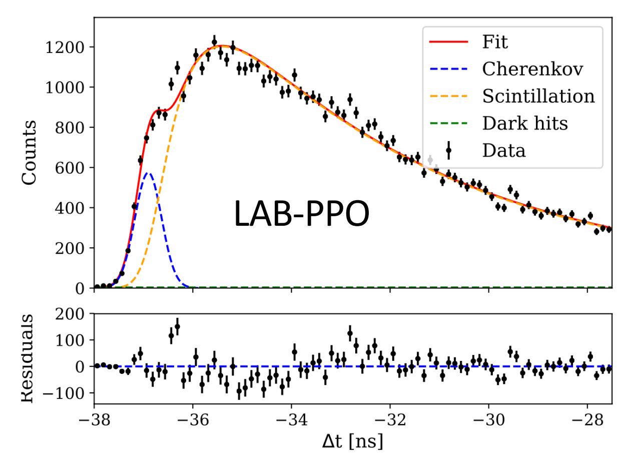
Timing

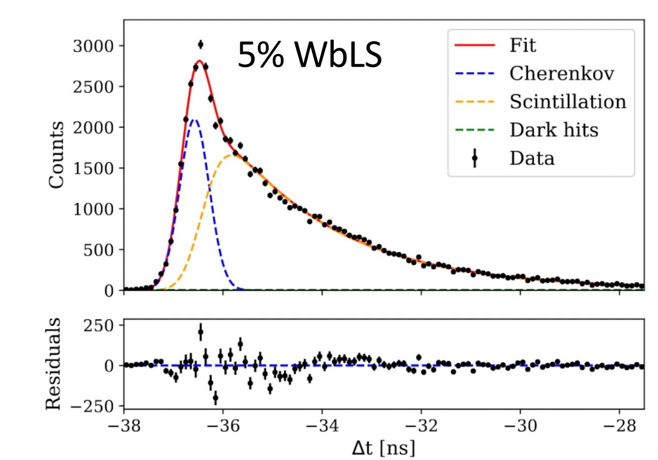
Fast(er) Sensors





CHESS (LBNL)

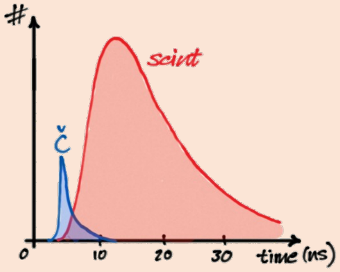




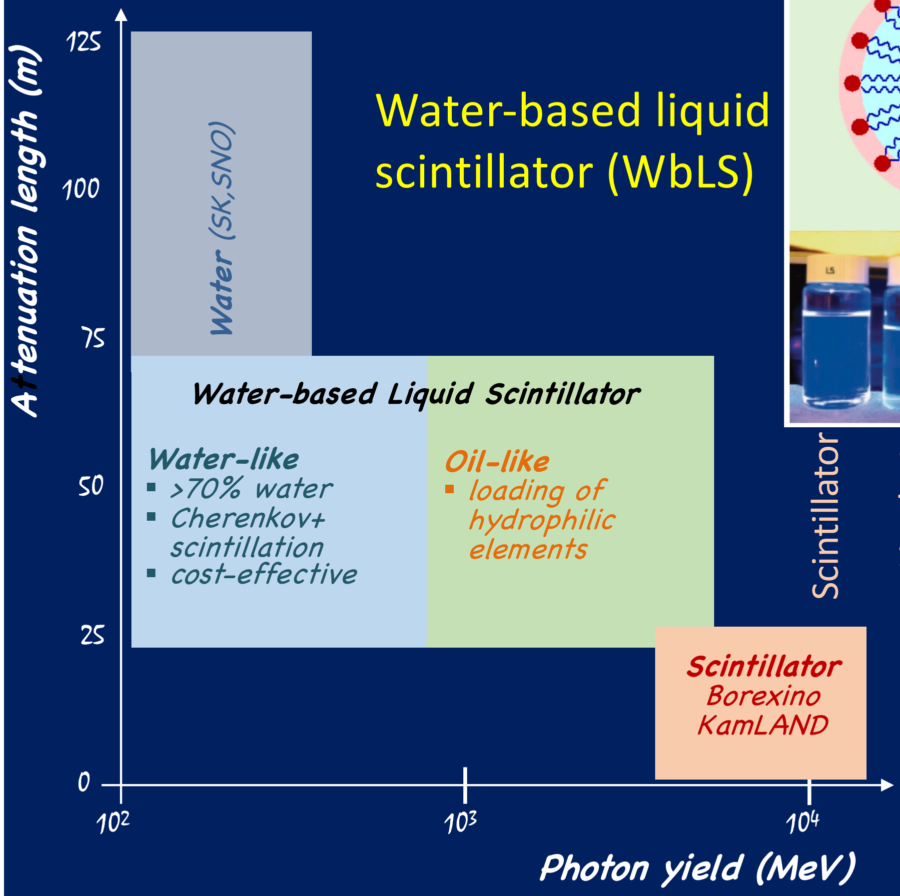
Timing

“instantaneous chertons” vs. delayed “scintons”

→ ns resolution or better



Adjust Cher/Scint Ratio



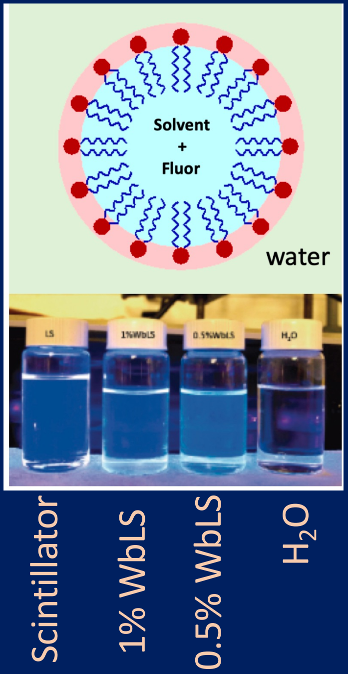
Water-based Liquid Scintillator

Water-like
- >70% water
- Cherenkov+ scintillation
- cost-effective

Oil-like
- loading of hydrophilic elements

Scintillator
Borexino
KamLAND

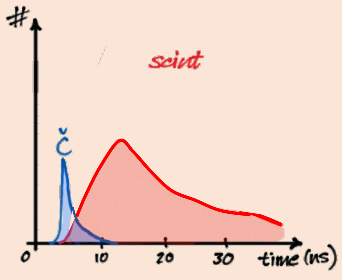
Water-based liquid scintillator (WbLS)



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?

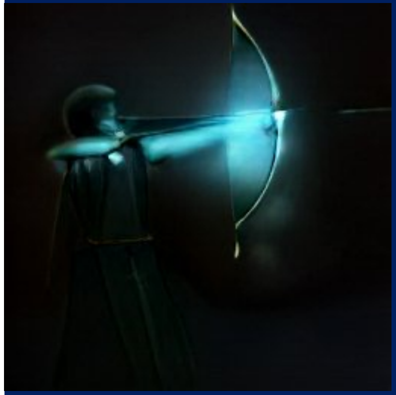
Target can be adjusted for different physics goals

Spectral Sorting in LAr?

Probably not necessary…

Scintillation light in LAr is such a different band, Cherenkov/scintillation separation comes for ”free”

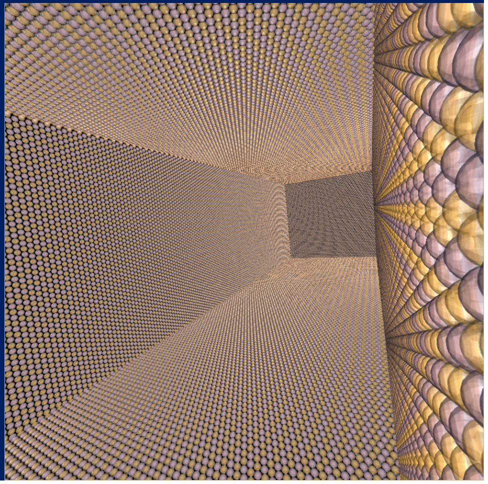
ArCherS=Argon Cherenkov and Scintillation



- LAr all-photon detector (DEAP, MiniCLEAN, CCM)
- Chertons detected by ”bare” PMTs (e.g., SBND)
- UV scintillation via ARAPUCAs or TPB-covered PMTs
- Scinton yield with no E-field is 40,000 photons/MeV (produced)
- With ¼ of scinton sensors still competitive with LS detectors
- Remaining “60%” of space can be used for Cherenkov detection
- Only need spectral sorting if WLS is dissolved in LAr (Xe?)
- Cherenkov light gives excellent timing

But:

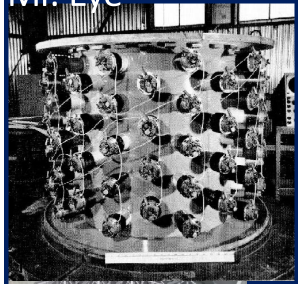
- For low-energy physics, still need to shield neutrons and use u/g argon
- ”High”-Z nucleus increases multiple scattering, affecting direction resolution
- ”High”-Z nucleus lowers crit. energy, affecting energy resolution (see Michel paper)
- ”High”-Z nucleus has complex neutrino interactions (e.g., neutrons)
- High-ish density shortens tracks at low-energies

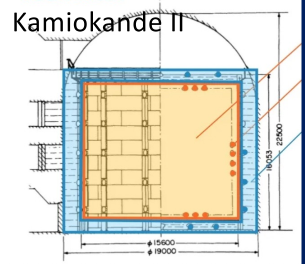


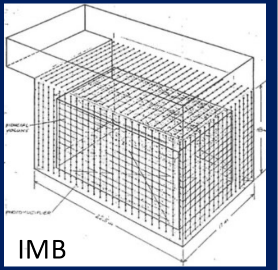
Logan Lebanowski, LBNL

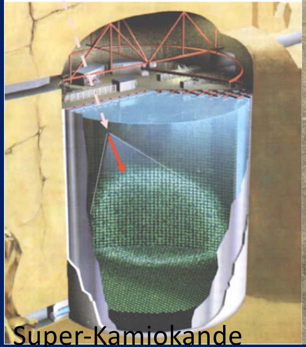
“Photon-Based”

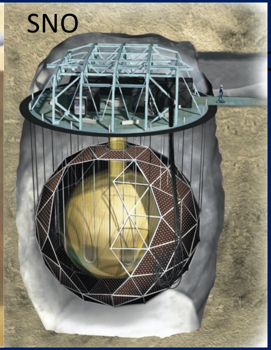
“Photon-based Neutrino Detector” is almost redundant

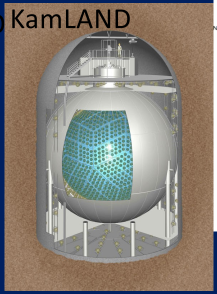

Mr. Eye


Kamiokande II


IMB


Super-Kamiokande


SNO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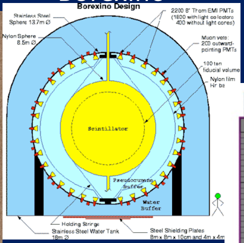
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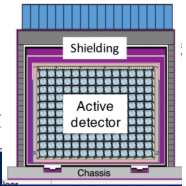
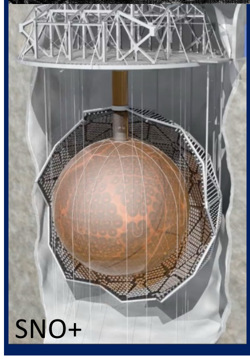

Prospect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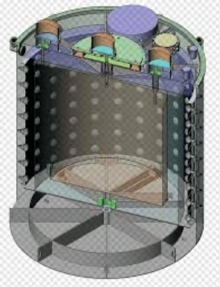
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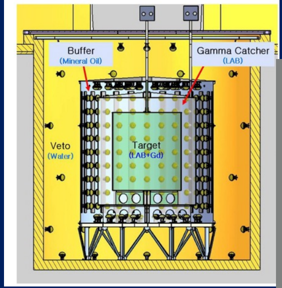
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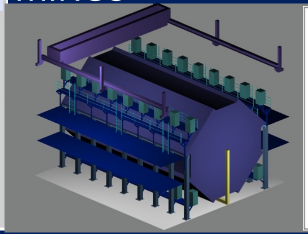
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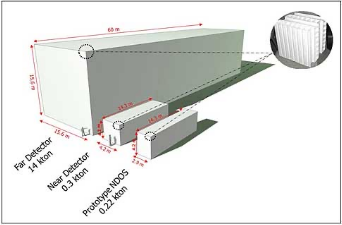
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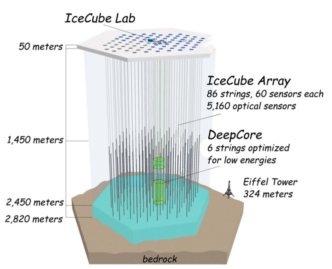
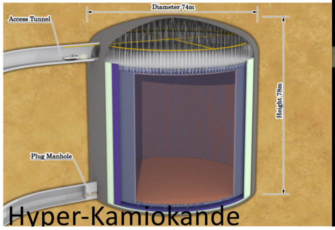
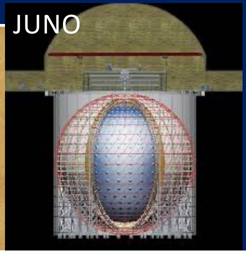


Coming soon:


Hyper-Kamiokande


JUNO

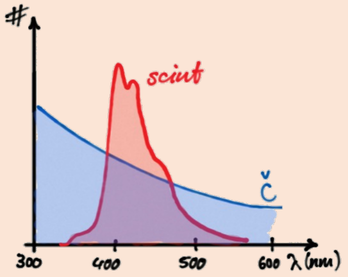
Discoveries/Measurements:

- 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

Cherenkov/Scintillation Separation with Wavelength

Spectrum

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



- “Obvious” solution would just filter x% of photon sensors

And use (e.g.) red sensitive devices

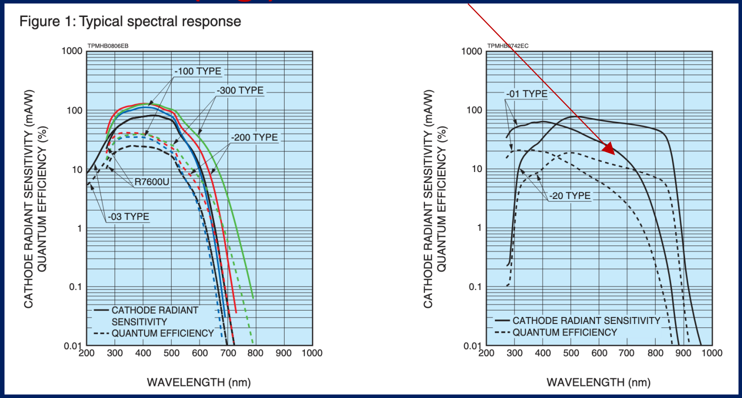


Figure 1: Typical spectral response

- But low-energy physics is photon-starved! Don’t want to lose x% of light
- And what if sensor coverage is already very high?
- Or what if detection area is already constrained (e.g., segmented like PROSPECT)