THEIA:
An Advanced Scintillator Detector at LBNF

- Opportunity and Physics
- Technology and Basic Approach
- THEIA Sensitivities
- Path Forward

A Tremendous Opportunity

Evolution of LBNE into DUNE@LBNF is transformational:

US is building a world-class neutrino facility

World is coming to build DUNE

A long-baseline beam aimed at a deep underground lab is a vision it has taken many decades to realize.

(*Pace* MINOS+SOUDAN)

PHYSICAL REVIEW D VOLUME 15, NUMBER 3 1 FEBRUARY 1977

Neutrino oscillations and the number of neutrino types*

A. K. Mann and H. Primakoff
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19174
(Received 7 July 1976; revised manuscript received 27 September 1976)

A brief treatment of neutrino oscillations, generalized to an arbitrary number of neutrino types, is given as the basis for design of a feasible experiment to search for neutrino oscillations using the neutrino beam produced at a high-energy proton accelerator.

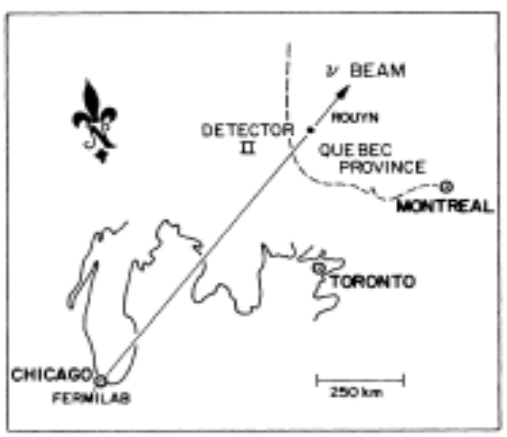


FIG. 4. Approximate geography of the proposed experiment. The present ν beam at Fermilab is directed 38°13′52″ east of north as indicated roughly.

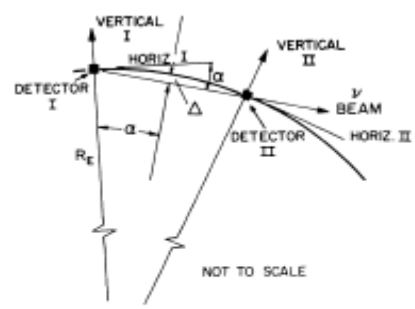
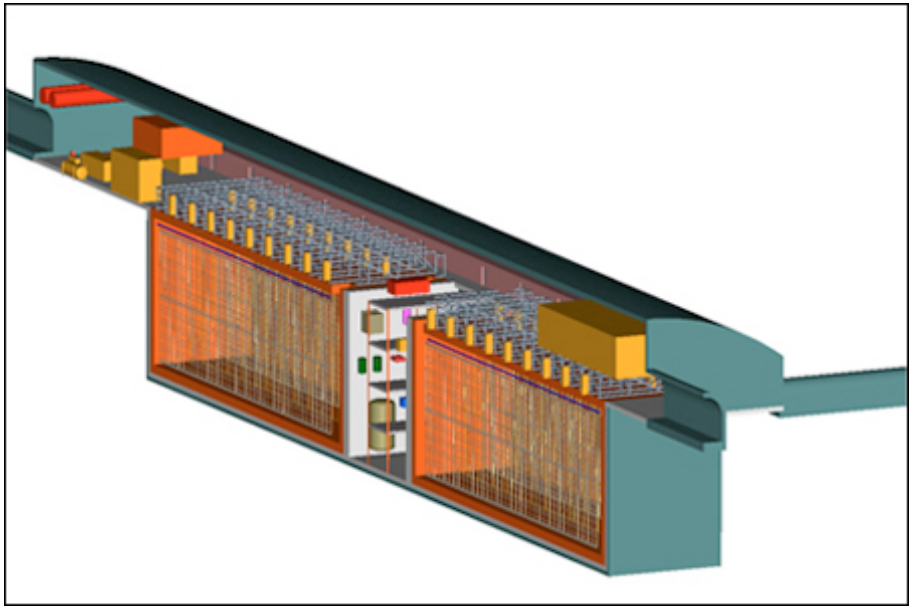


FIG. 1. Geometry of a feasible experiment. If the distance between detectors I and II is 1000 km, then $\alpha = 0.078$ rad and $\Delta = 19$ km. R_E is the radius of the earth $= 6.4 \times 10^3$ km.

DUNE Physics

- Determination of mass hierarchy
- Search for CP violation
- Precision determination of (2,3) and (1,3) mixing parameters
- Tests of the 3-flavor paradigm
- Atmospheric neutrinos (applied to all of the above)
- Nucleon decay (primarily p->K^+ +antinu)
- Supernova burst neutrinos

It is an exciting list but---gasp!---it isn't all of neutrino physics.



Beyond DUNE

Other Critical Physics of and with Neutrinos

- Majorana vs. Dirac
- Solar neutrinos
- Mixing angles and mass differences in (1,2) sector
- Geoneutrinos
- Diffuse supernova (anti)neutrino background

(Clearly this list is not exhaustive either)

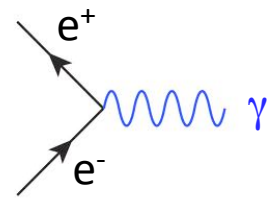
The investment in the facility makes
a broad physics program possible!

Majorana vs. Dirac

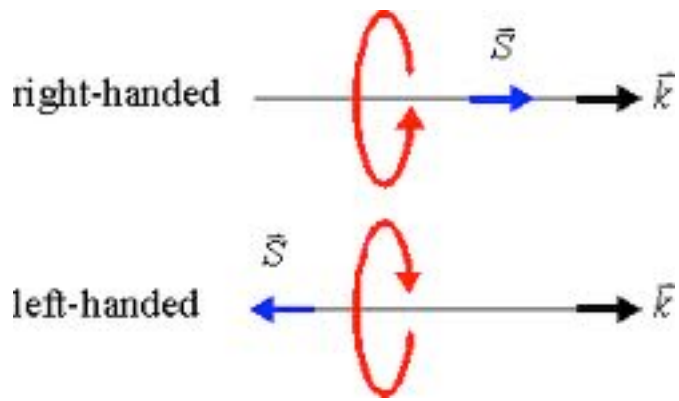
A simple conceptual model

Antimatter is easy to think about for charged particles:

$$e^- \longleftrightarrow e^+$$



But weak interaction distinguishes particles by handedness---it couples to left-handed electrons and right-handed positrons (for massless particles, this is the same as helicity).



So there are really 4 kinds of electron in nature:

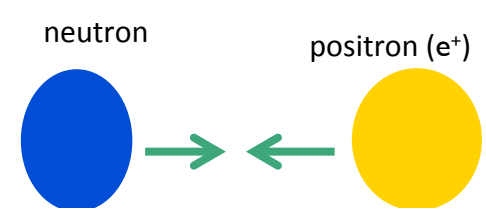
$$e^-_L, e^-_R, e^+_L, e^+_R$$

Weak+EM

EM only

Weak+EM

Nothing fundamentally "anti" about "antimatter"



Majorana vs. Dirac

A simple conceptual model

If neutrinos were massless then just two states possible:

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

(Weak interactions only)

And since:

$$\nu_L + n \rightarrow p + e_L^- \qquad \bar{\nu}_R + p \rightarrow n + e_R^+$$

particle particle particle particle particle antiparticle

we called ν_R the "antineutrino:"

But now we know neutrinos have mass, so 4 states possible:

	"Old"	"New" (Have no weak interactions)
"Dirac neutrinos"	ν_L	ν_R
	$\bar{\nu}_R$	$\bar{\nu}_L$

How are these different?

Majorana vs. Dirac

A simple conceptual model

"Old" "New" (Have no weak interactions)

"Dirac neutrinos"

$$\left\{ \begin{array}{l} \nu_L \\ \bar{\nu}_R \end{array} \right. \quad \xleftrightarrow{\text{How are these different?}} \quad \begin{array}{l} \nu_R \\ \bar{\nu}_L \end{array}$$

So maybe we only have two states after all:

$$\nu_L \quad \nu_R$$

Which basically means

$$\nu = \bar{\nu}$$ "Majorana neutrinos"

So what?

Majorana vs. Dirac

If neutrinos are Majorana, then:

1. We need a new mass-generating mechanism
   - Simplest term is dimension-5 and not renormalizable!
2. We likely have observed low-energy consequences of very high E scale physics
3. We may have an explanation for the matter/antimatter asymmetry
   - "Leptogenesis"
   - Requires Majorana CP phases

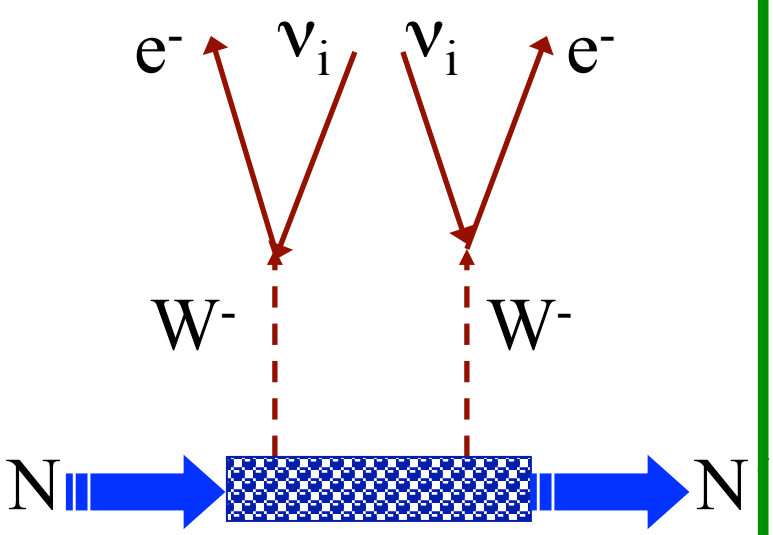
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2-i\beta} \end{pmatrix}$$

If neutrinos are Dirac, then:

1. Matter and antimatter are *fundamentally* different things
2. We have states that don't really do much

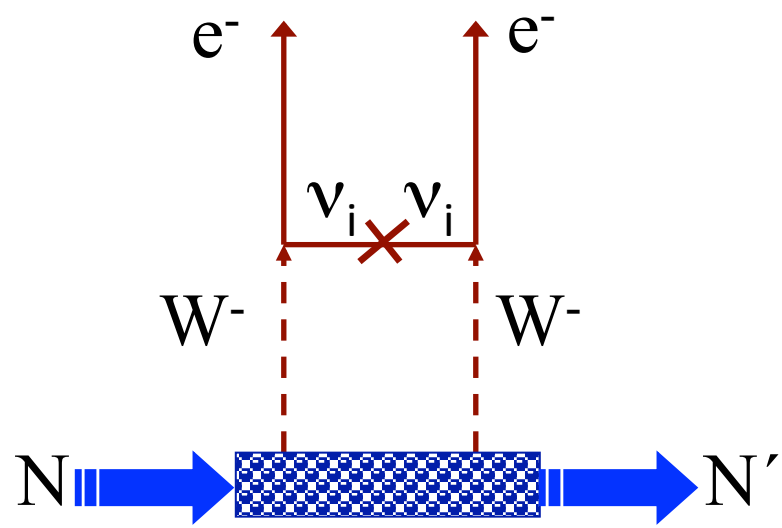
Majorana vs. Dirac

Two-neutrino double beta decay



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

Neutrinoless double beta decay



$$T_{1/2} \propto m_{\beta\beta}^2 \sim 10^{27}\,\text{years}$$

Mass is <u>mixed</u> average, including phases

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

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

Large coeffs. *Small coeff.*

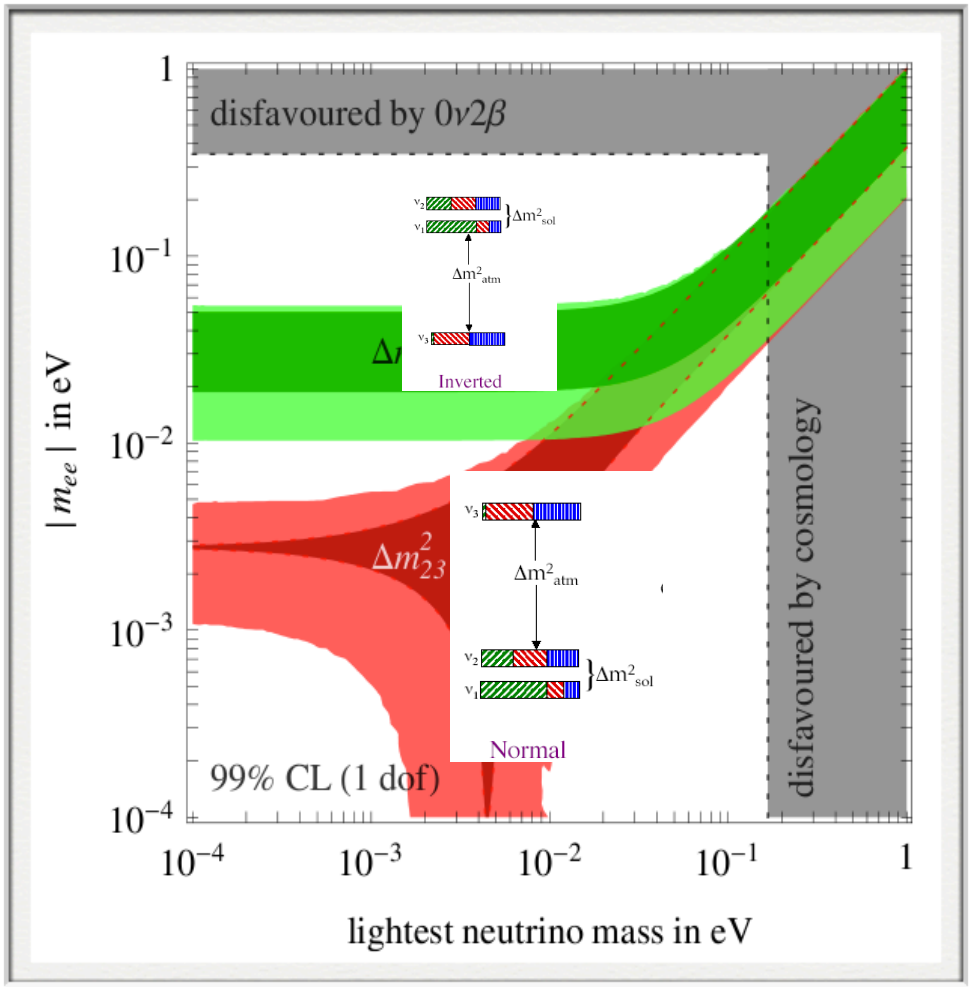
Fortunately, Avogadro's number is very big, so 10^{27} years ~ 1 tonne of isotope

Unfortunately, we don't know $m_{\beta\beta}$, or even which m_i is biggest.

Majorana vs. Dirac

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

$$\left|m_{\beta\beta}\right|^2 = \left|0.69m_1 + 0.72m_2e^{2i\lambda_2} + 0.02m_3e^{2i(\lambda_3-\delta_{CP})}\right|^2$$



If next-generation 0νββ experiments see nothing, then:

If $\Delta m^2_{23}<0$ OR $m_1>20$ meV

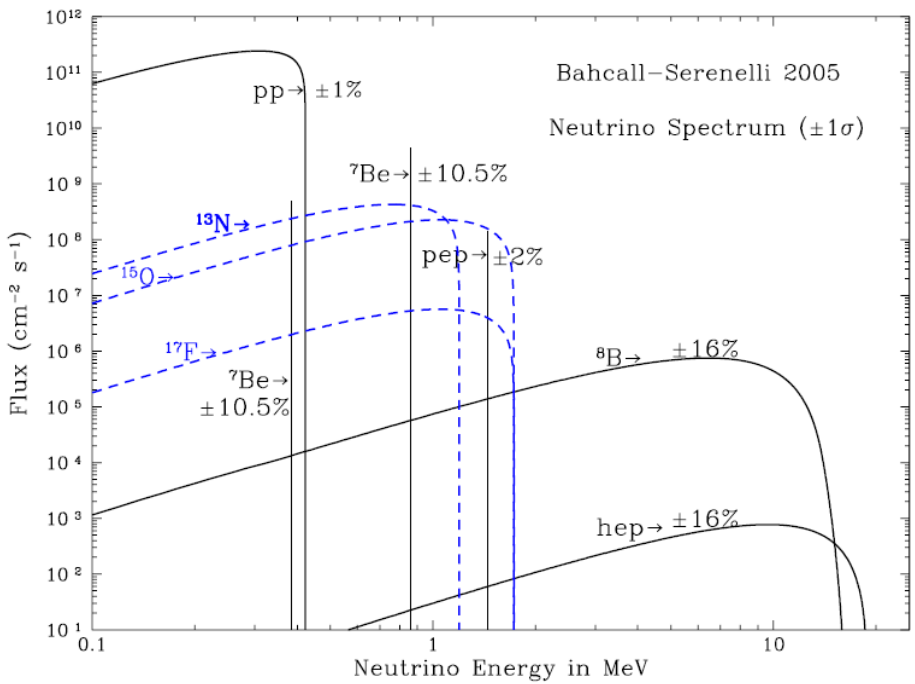
- Neutrinos are Dirac

The construction of the new Standard Model depends critically on the mass "hierarchy"

This provides the context for a long-baseline mass hierarchy determination.

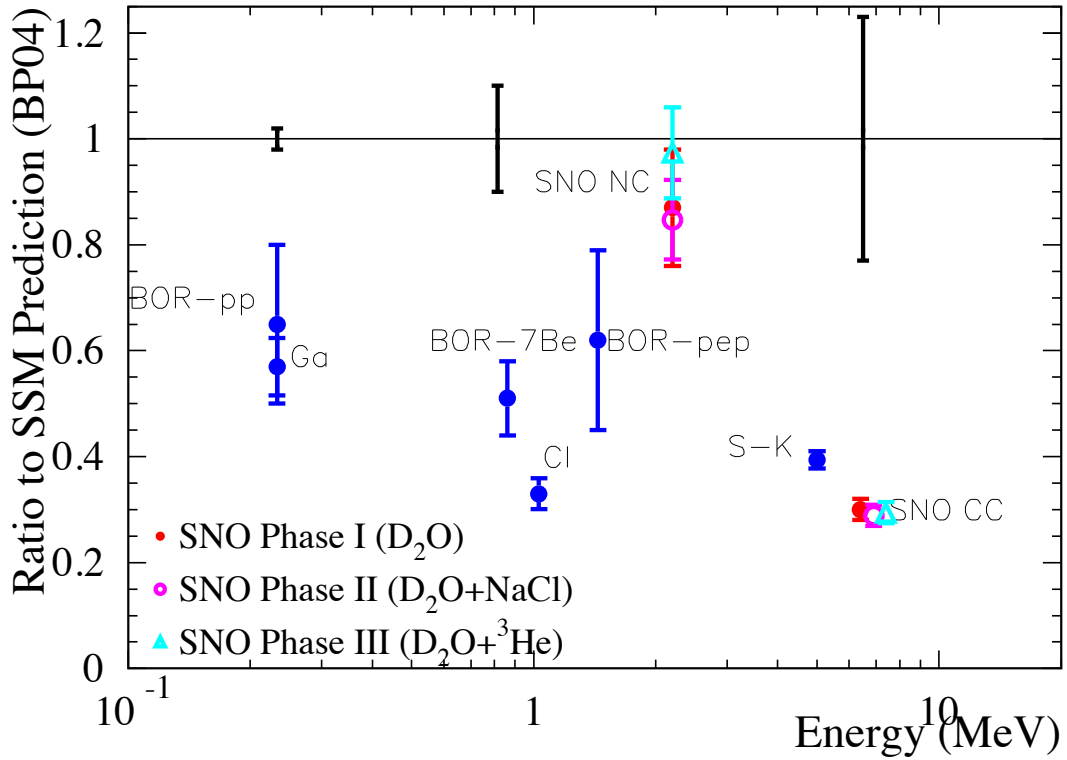
Solar Neutrinos

- Broadband and mono-energetic, background-free ν_e beam
- Flux in some cases measured as precisely as ~3%
- Flux in some cases predicted as precisely as 1%
- Matter effects are crucial and observable
- Source itself is interesting---and beam operations fits within FY2025

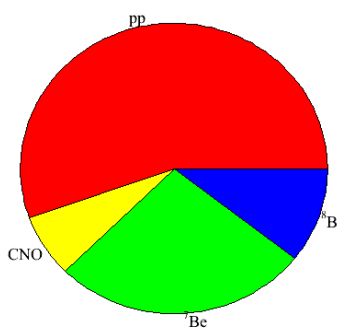


Solar Neutrinos

Measurements

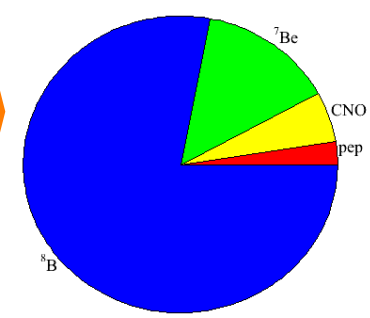


SAGE/GALLEX/GNO



Inclusive measurements

Chlorine



Aren't we done here?

Solar Neutrinos

Physics

Not really.

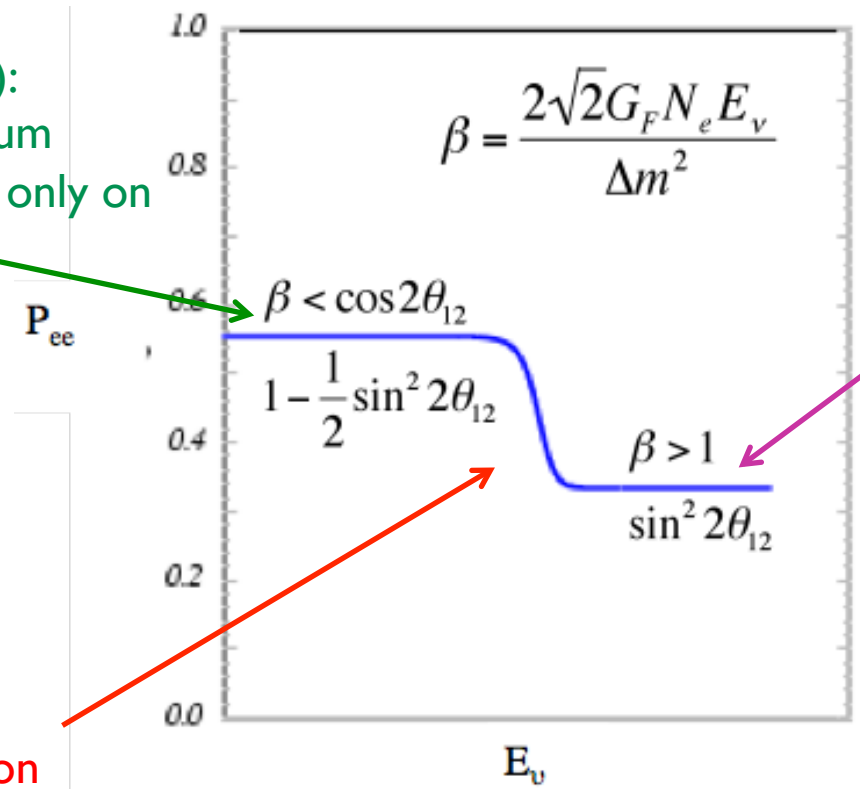
Important measurements still to make:

- Look for new physics in vacuum/matter transition region
- Understand solar system formation using…neutrinos?
- Look for new stellar energy generation/loss mechanisms
- Keep watching

Solar Neutrinos

Vacuum/Matter Transition

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



'High' energy (>5MeV): Matter-dominated conversion; depends only on θ_{12}

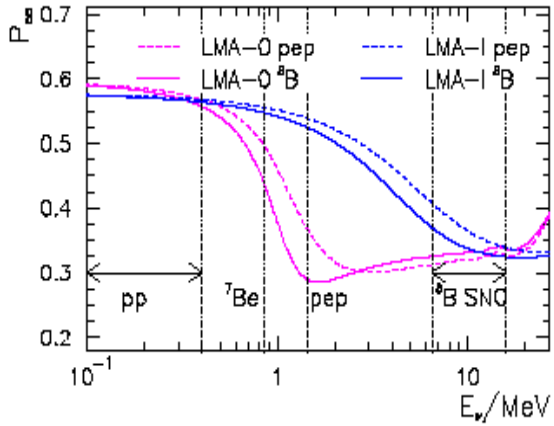
Transition region

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

Solar Neutrinos

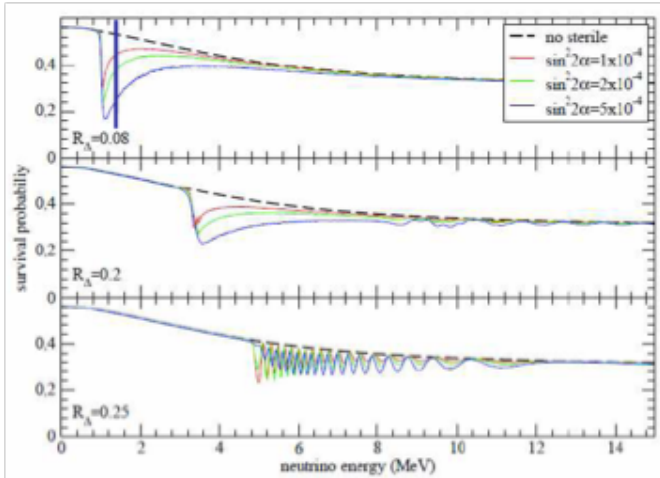
Vacuum/Matter Transition

Non-standard interactions (flavour changing NC)



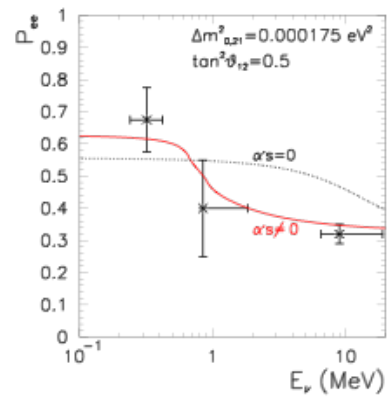
Friedland, Lunardini, Peña-Garay, PLB 594, (2004)

Sterile Neutrinos



Holanda & Smirnov
PRD 83 (2011) 113011

Mass varying neutrinos (MaVaNs)



M.C. Gonzalez-Garcia, M. Maltoni
Phys Rept 460:1-129 (2008)

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

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.

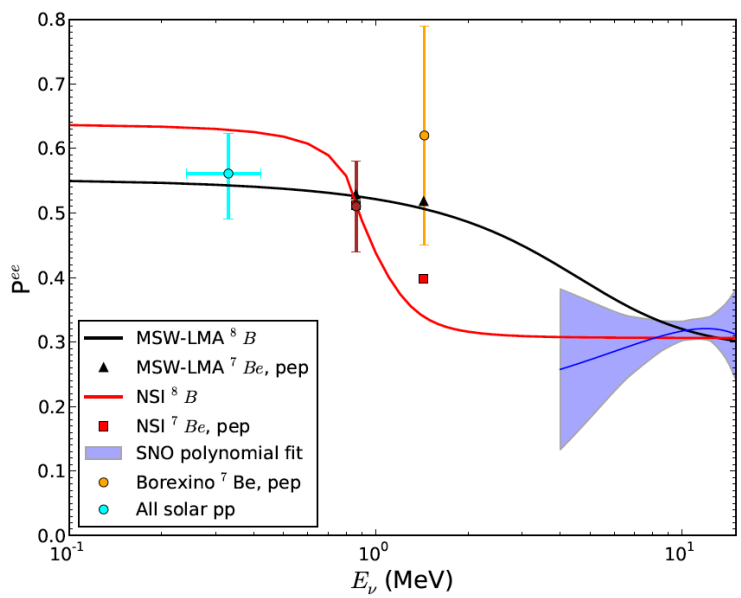
Model	Best fit	$\Delta\chi^2$	Additional d.o.f.	C.L.
MSW-LMA	$\Delta m^2_{21} = 7.462 \times 10^{-5}$ eV^2, $\sin^2\theta_{12} = 0.301$, $\sin^2\theta_{13} = 0.0242$	0	···	···
MSW-LMA (AGSS09SF2)	$\Delta m^2_{21} = 7.469 \times 10^{-5}$ eV^2, $\sin^2\theta_{12} = 0.304$, $\sin^2\theta_{13} = 0.0240$	2.8	···	···
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	$k_S = 6.73 \times 10^{-45}$, $\lambda = 1.56R_\odot$, $m_{1,0} = 0$ eV	−2.9	3	0.58
Long-range vector leptonic force	$k_V = 3.26 \times 10^{-54}$, $\lambda = 16.97R_\odot$	−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	···

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

Best fit for mass-varying neutrinos

$\Delta\chi^2 = 3.3$

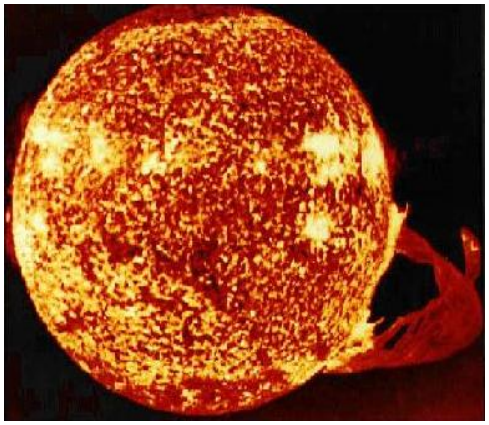
C.L. = 0.81



Sensitivity non-standard effects entirely driven by lack of precision ^{8}B data in transition region

CNO and the Sun

The solar `metallicity problem'



the ar. Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars. ---John Bahcall, PR, (1964)

- Helioseismology convinced `everyone' that SSM was correct
- Modern measurements of surface metallicity are lower than before
- Which makes SSM helioseismologic predictions wrong

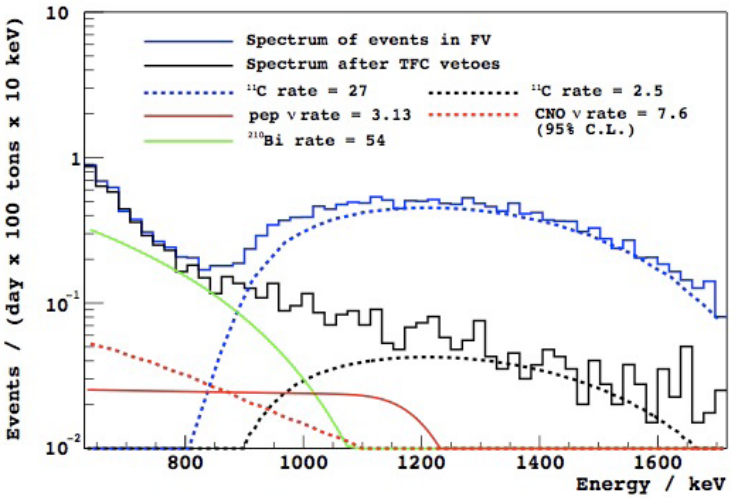
But! CNO neutrinos tell us metallicity of solar core

→ Flux may differ by factor of 2 between old/new metallicity

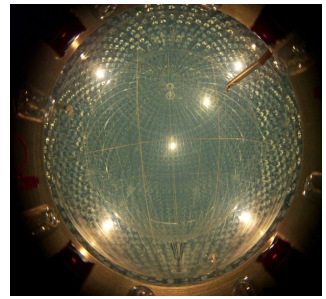
(Maybe Jupiter and Saturn `stole' metals from solar photosphere?
---Haxton and Serenelli, Astrophys.J. 687 (2008)

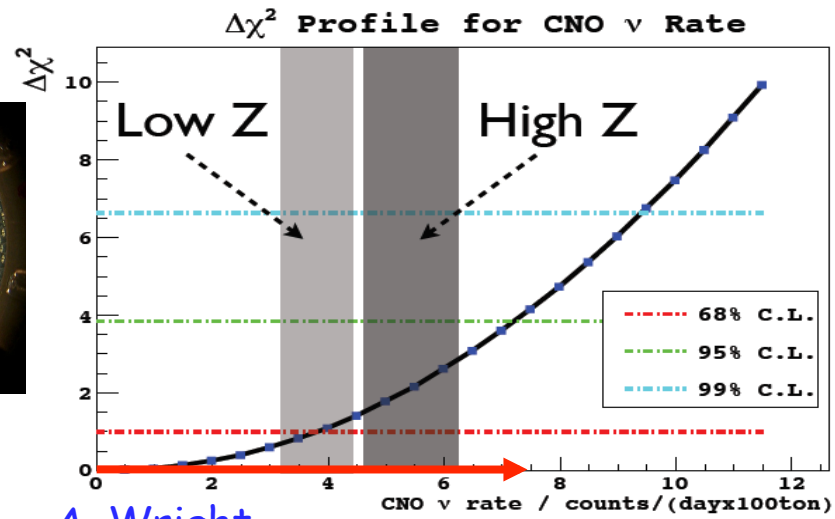
CNO Measurements

BOREXINO has placed limits but no clear signal yet



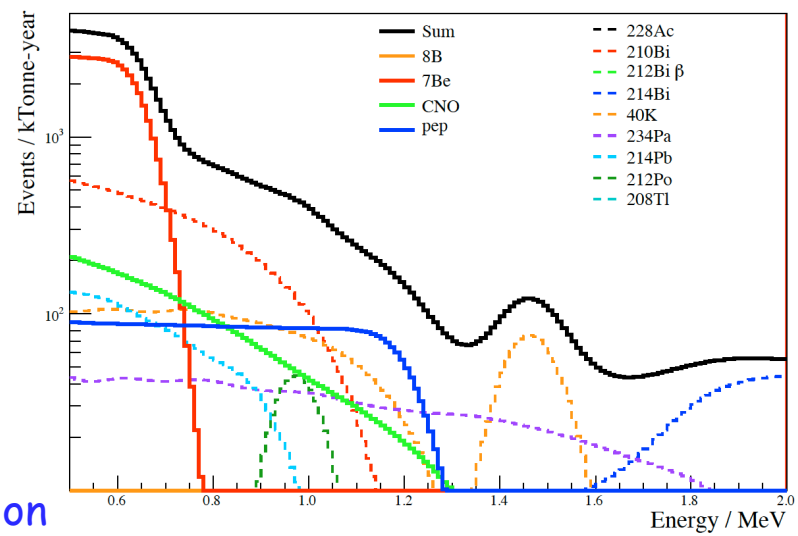
A. Wright





A. Wright

SNO+ will not have ^{11}C background but still separation of CNO from ^{210}Bi is VERY hard.



SNO+ Collaboration

pp/pep and the Sun

Are all energy generation/loss mechanisms accounted for?

With luminosity constraint:

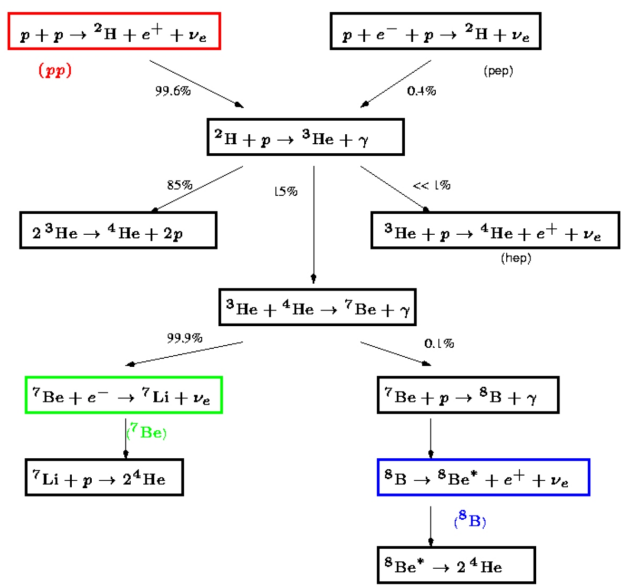
Exp. Uncs. Theory Uncs.

$$\phi(\mathrm{pp})_{\mathrm{measured}} = (1.02 \pm 0.02 \pm 0.01)\phi(\mathrm{pp})_{\mathrm{theory}}$$
$$\phi(^8\mathrm{B})_{\mathrm{measured}} = (0.88 \pm 0.04 \pm 0.23)\phi(^8\mathrm{B})_{\mathrm{theory}}$$
$$\phi(^7\mathrm{Be})_{\mathrm{measured}} = (0.91^{+0.24}_{-0.62} \pm 0.11)\phi(^7\mathrm{Be})_{\mathrm{theory}}$$

Bahcall and Pinsonneault

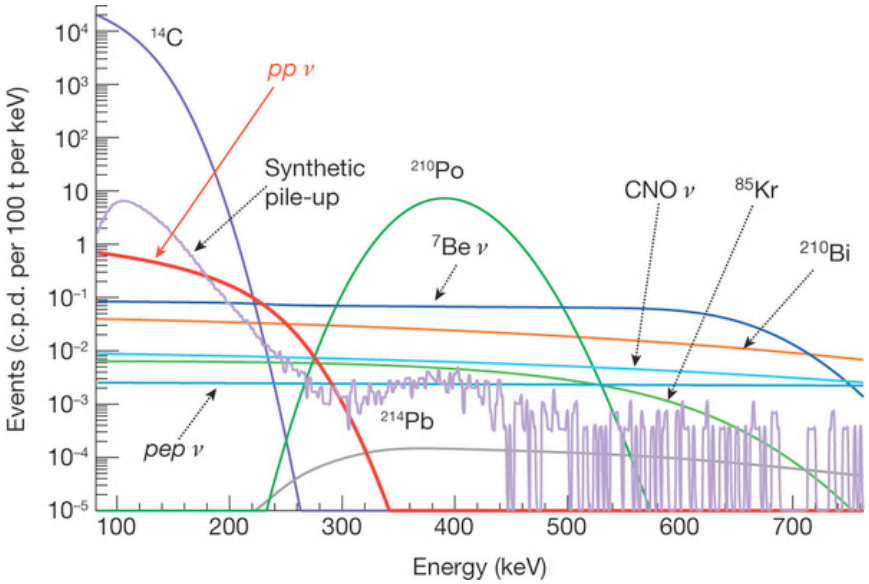
But without constraint: $L_\nu/L_\odot$ known only to 20-40%

→ `Unitarity' test that integrates over a lot of new physics



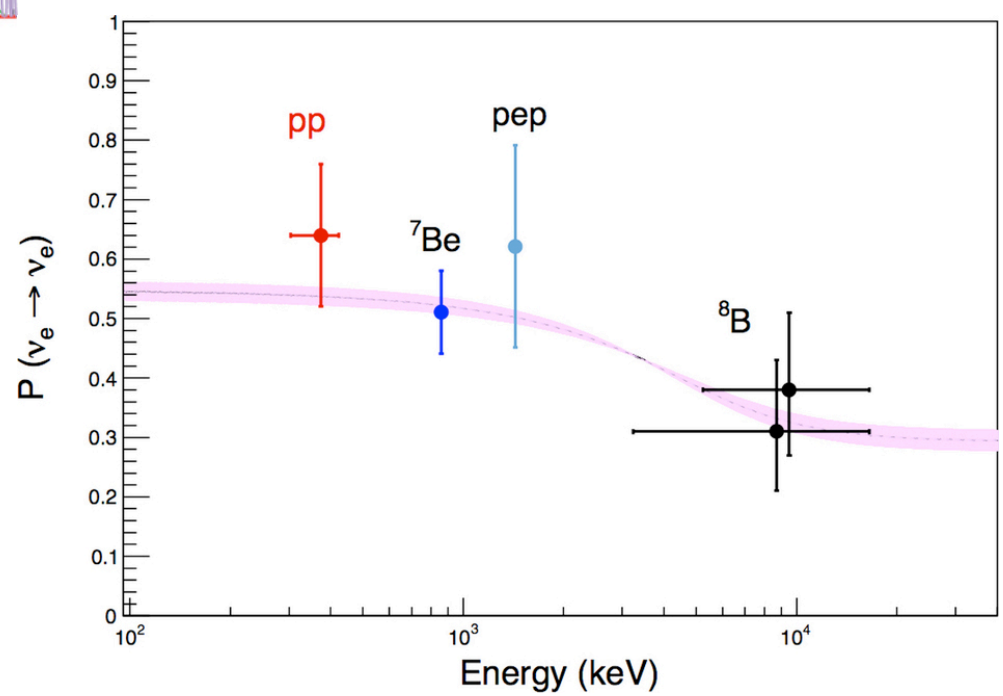
pp Measurements

BOREXINO spectacularly clean…first *exclusive* pp measurement!



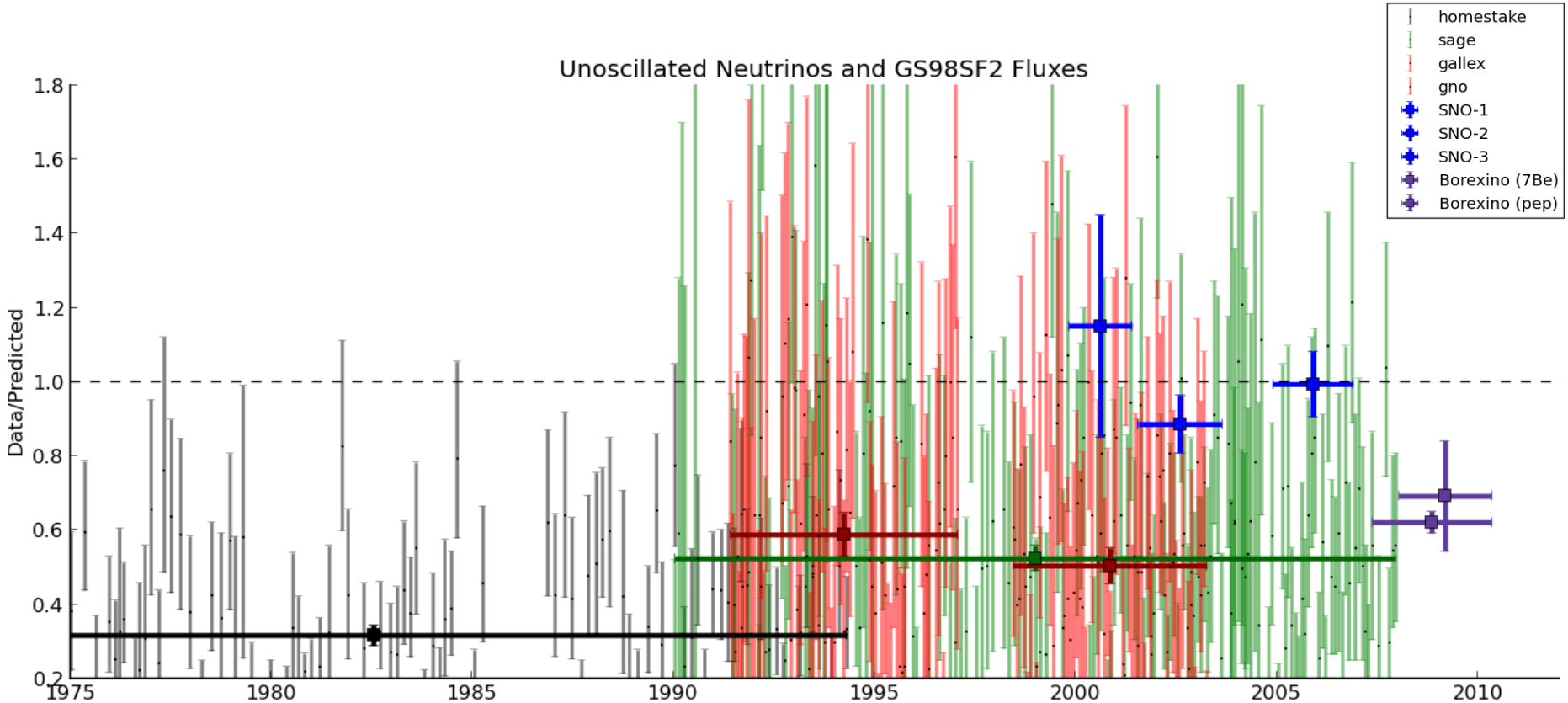
Precision comparable to inclusive Ga experiments

But far from what is needed for precision luminosity test.



The (Very) Recent History of the Solar Core

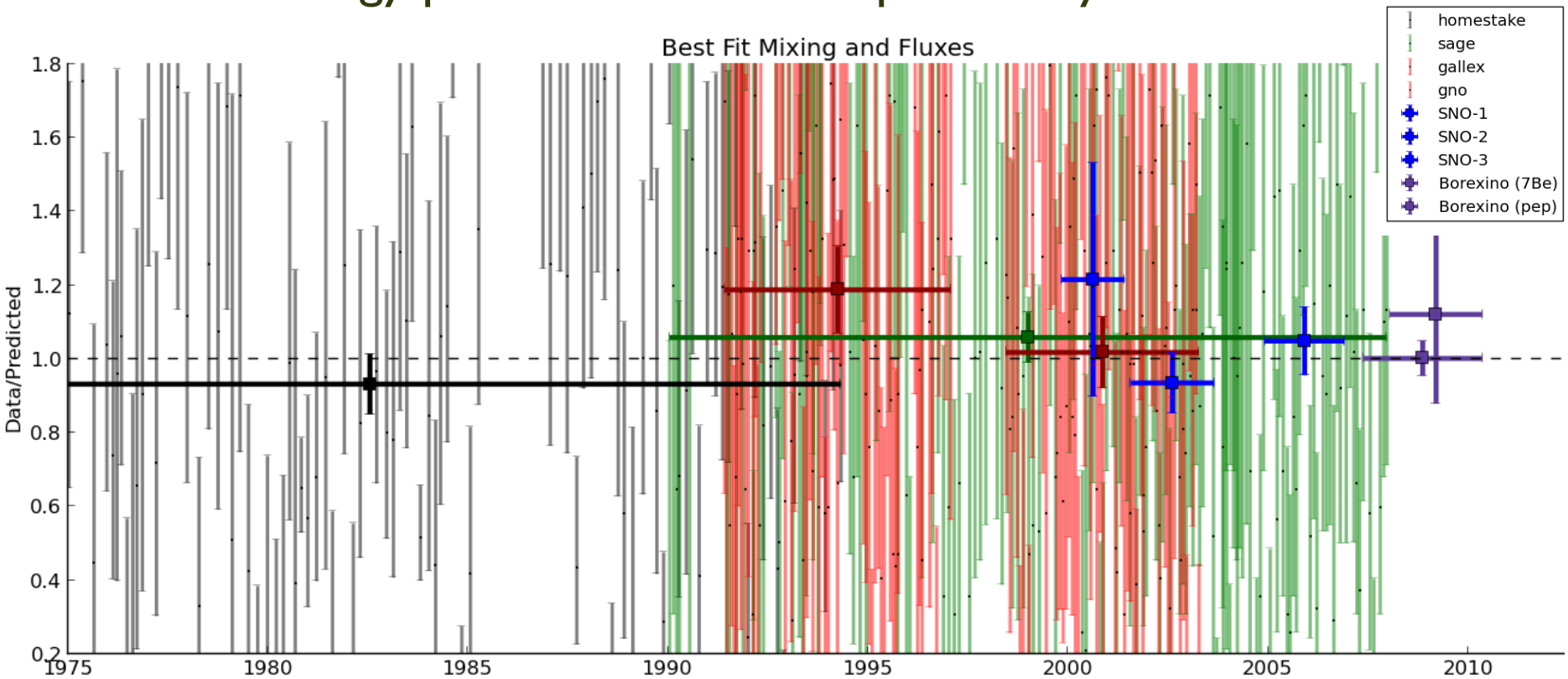
Without mixing correction, this is a history of the Solar Neutrino Problem



A. LaTorre

The (Very) Recent History of the Solar Core

Correcting for mixing angles, this is the stability of solar energy production over the past 45+ years.

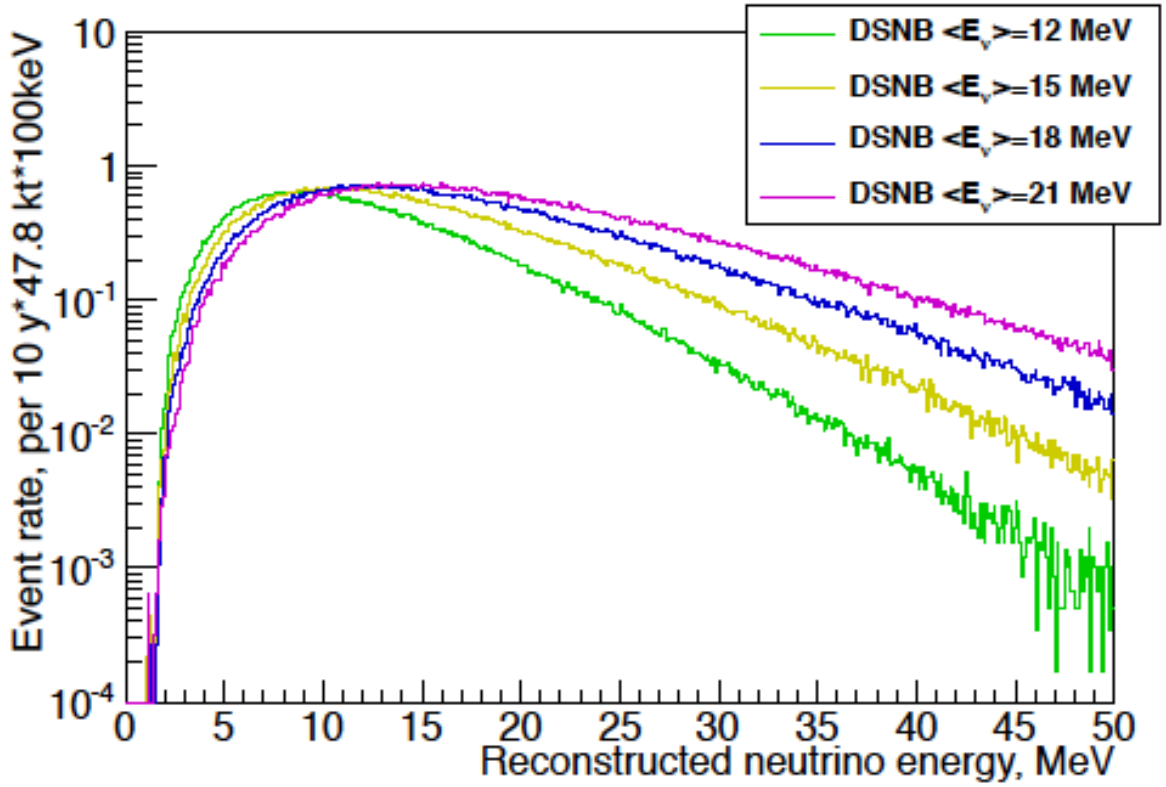


A. LaTorre

Diffuse Supernova (Anti)Neutrino Background

"Guaranteed" relic neutrinos from all the supernovas…

Many detailed studies from LENA Collaboration



Geoneutrinos

Electron antineutrinos from U, Th, K decay in the Earth

Assay the Earth by looking at the "antineutrino glow"

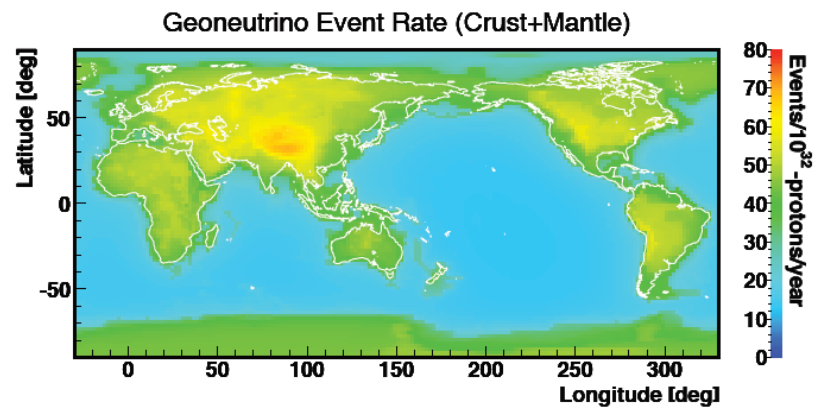


Image: S. Enomoto

Current total geo-n exposure < 10 kt-yr (KamLAND+BOREXINO)

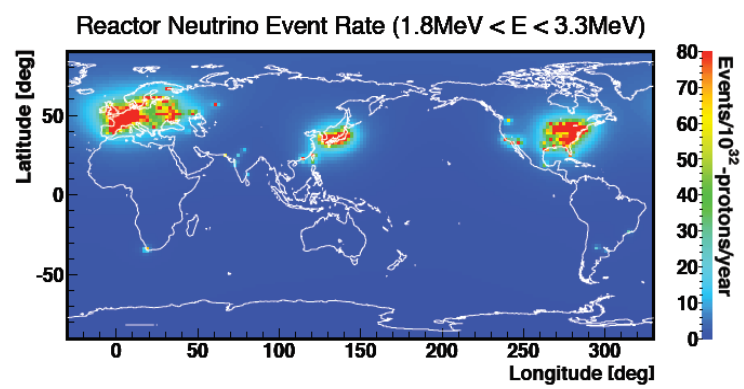


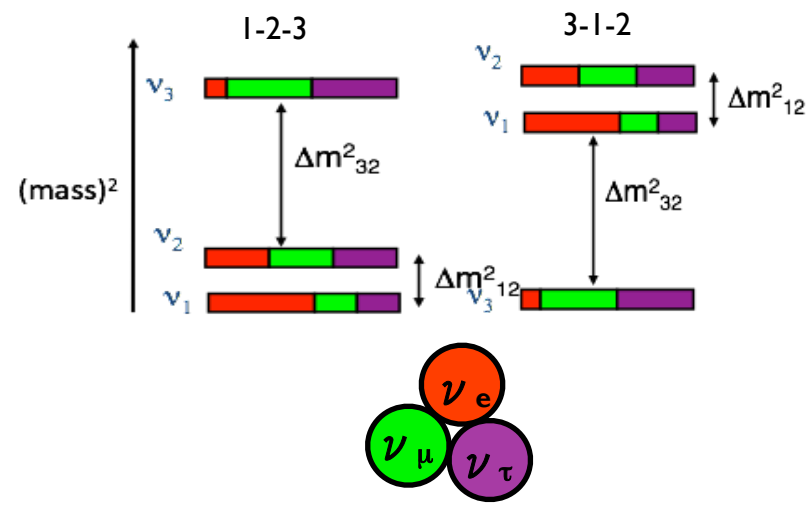
Image: S. Enomoto

Long Baseline Physics

T2K's observation of ν_e appearance was the real herald of the "3-flavor era"

The goals of future experiments are now very clear:

- Determination of the Mass Hierarchy
- CP Violation (and δ)
- Searches for new physics
- "Octant" of θ_{23}



$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times U_{\mathrm{Maj}}^{\mathrm{diag}}$$

Broadening the Program

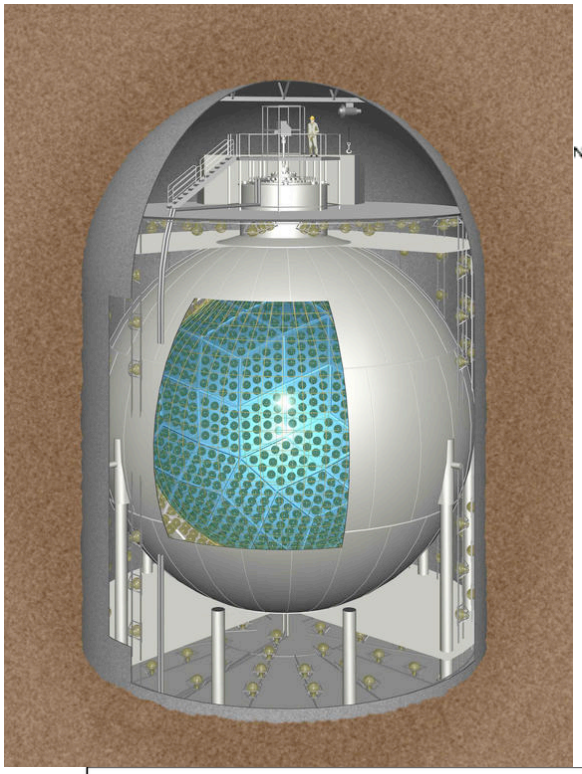
Would like a detector that can access a broad physics program, leveraging investment in LBNF, and enhancing the long-baseline program as well.

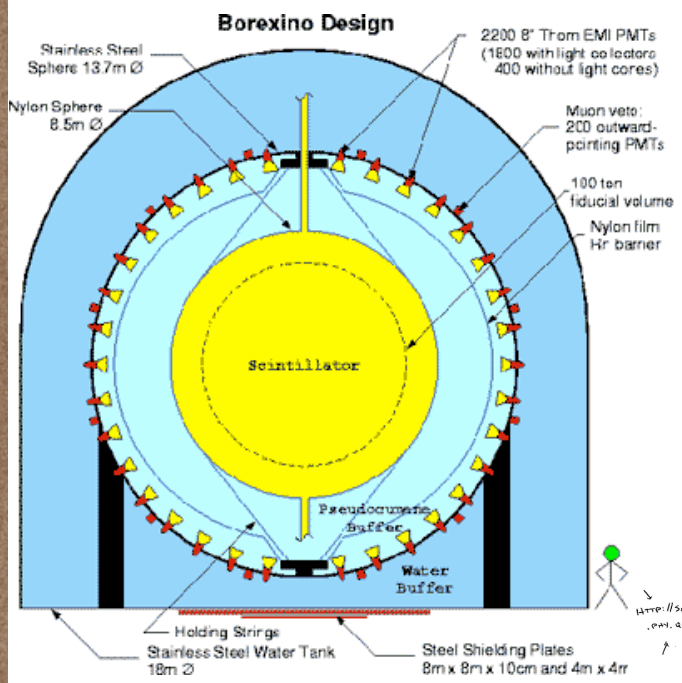
Basic Requirements:

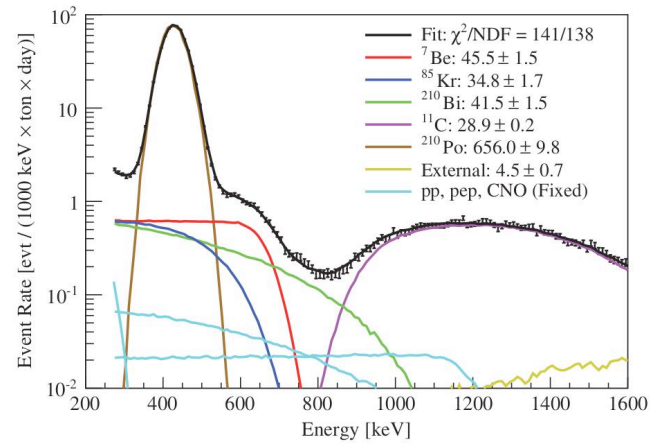
- Size >= 50 ktonne (fiducial)
- Depth (4850 ft would be fine)
- Cleanliness (U, Th, Kr, ^{14}C comparable to BOREXINO)
- Narrow energy resolution even at MeV energies
- Fast timing to detect coincident signal from anti-nus and reject bkds
- Direction determination of secondaries for signal/background ID
- Flexibility to allow different physics to be pursued with same detector
- Upgradability to improve performance as new technologies arrive

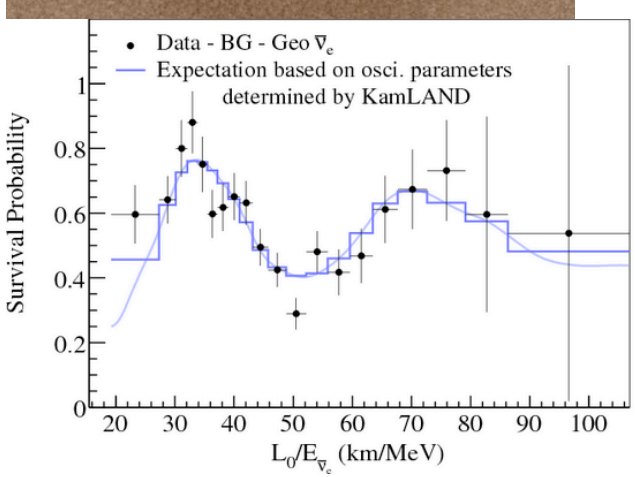
Broadening the Program

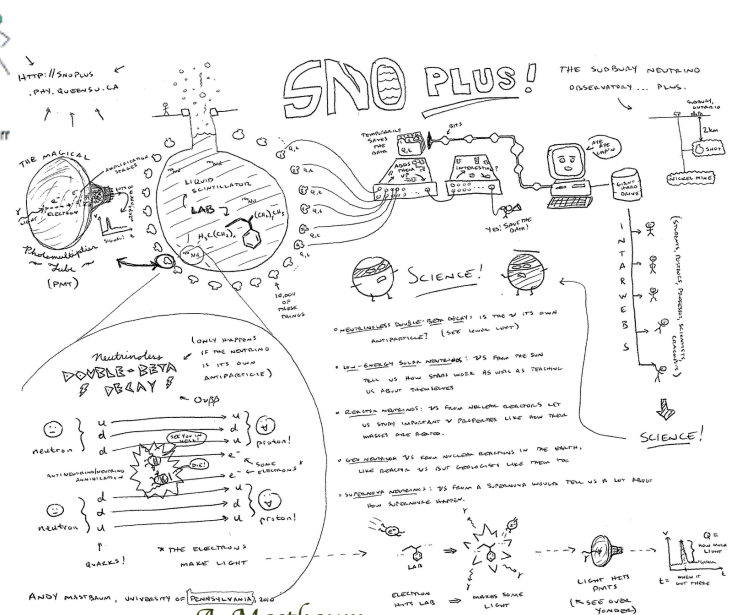
A large-scale scintillation detector clearly has access to low-E physics:





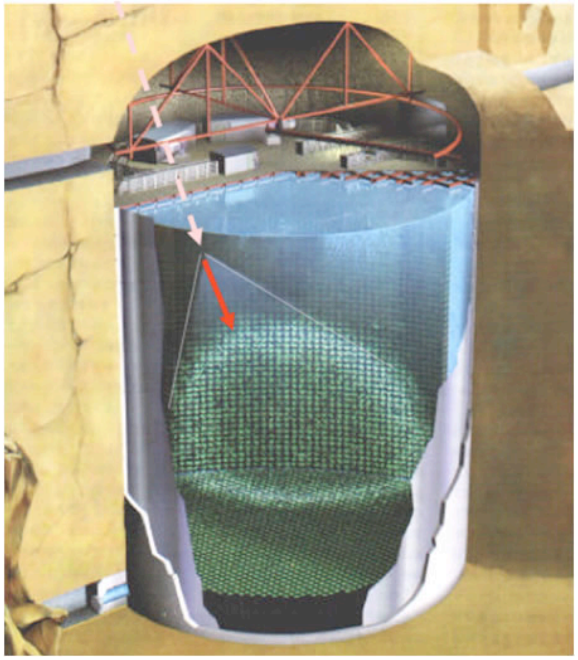


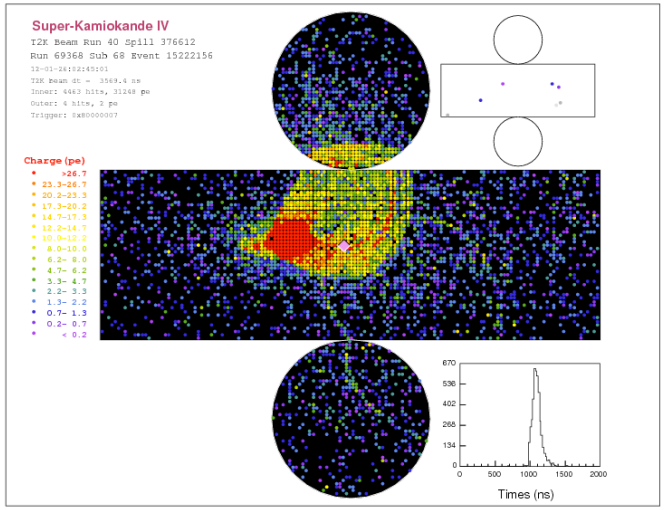


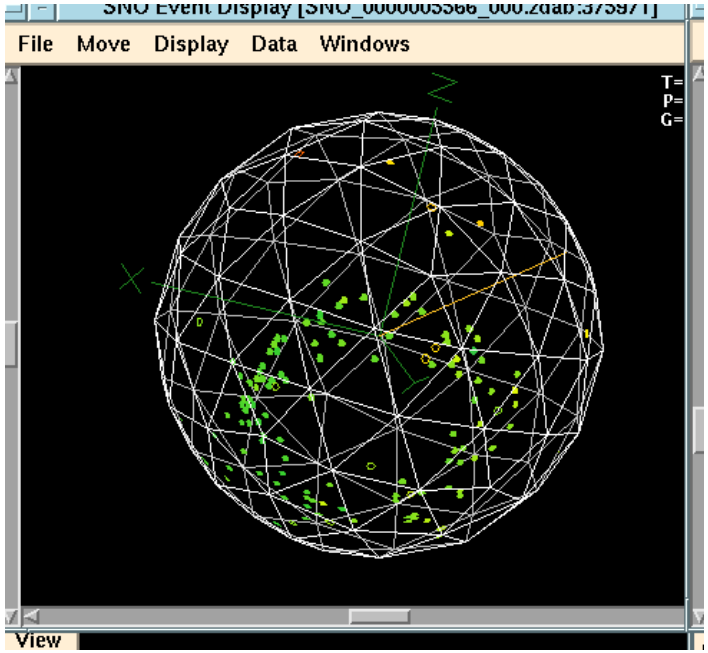


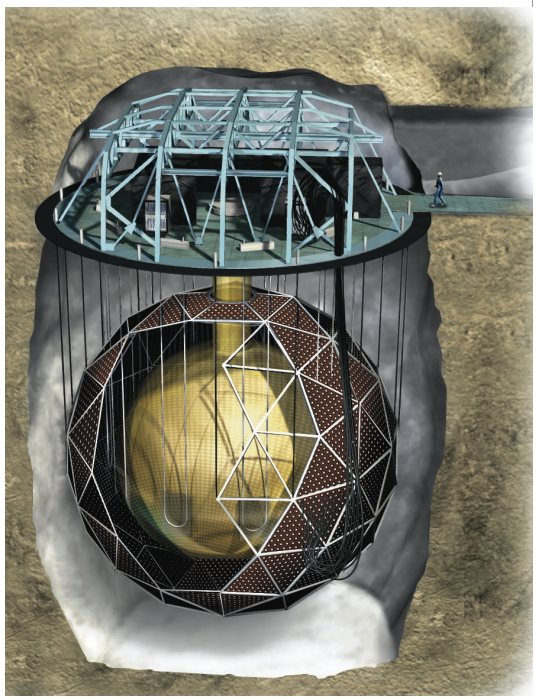
Broadening the Program

And big Cherenkov detectors to high-energy physics:









Broadening the Program

But requirements for various physics goals are in tension:

Physics	Size	Cherenkov Priority	Scintillation Priority	Cleanliness Priority
$0\nu\beta\beta$	~few ktonne	Medium	Very high	Very High
Low E Solar νs (< 1MeV)	~10 ktonne	High	Very high	Very High
High E Solar νs (> 1 MeV)	>50 ktonne	High	Low	High
Geo/reactor anti-νs	~10 ktonne	Low	High	Medium
DSNB anti-ns	>50 ktonne	Low	High	Medium
Long-baseline νs	> 50 ktonne	Very high	Low	Low
Nucleon decay (K+ anti-ν)	> 100 ktonne	High	High	Low

- Low-energy physics wants a clean detector with a lot of light
- High-energy physics wants a big detector with direction reconstruction

Broadening the Program

But requirements for various physics goals are in tension:

Scintillation Detectors:

- Limited in size because scintillator absorbs light
- Have high scattering making direction reconstruction difficult
- Are expensive even if they could be made large

Water Detectors:

- No access to physics below Cherenkov threshold
- Low light yield makes E & vtx resolution poor even at ~10 MeV
- Are hard to make ultra-clean

THEIA

- New materials (water-based liquid scintillator)

+

- New technologies (ultra-fast PMTs, LAPPDs…)

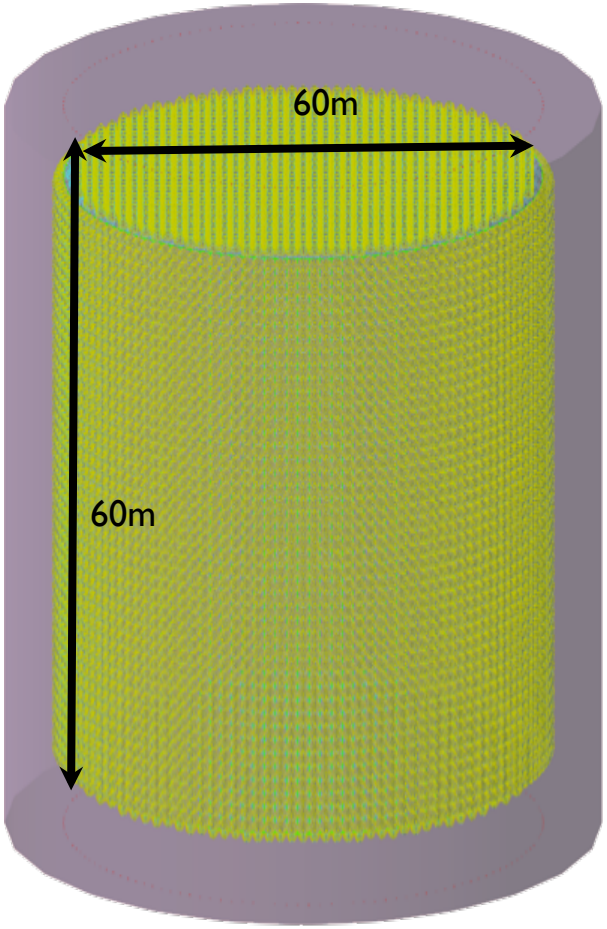
+

- Flexible design

May satisfy conflicting requirements.

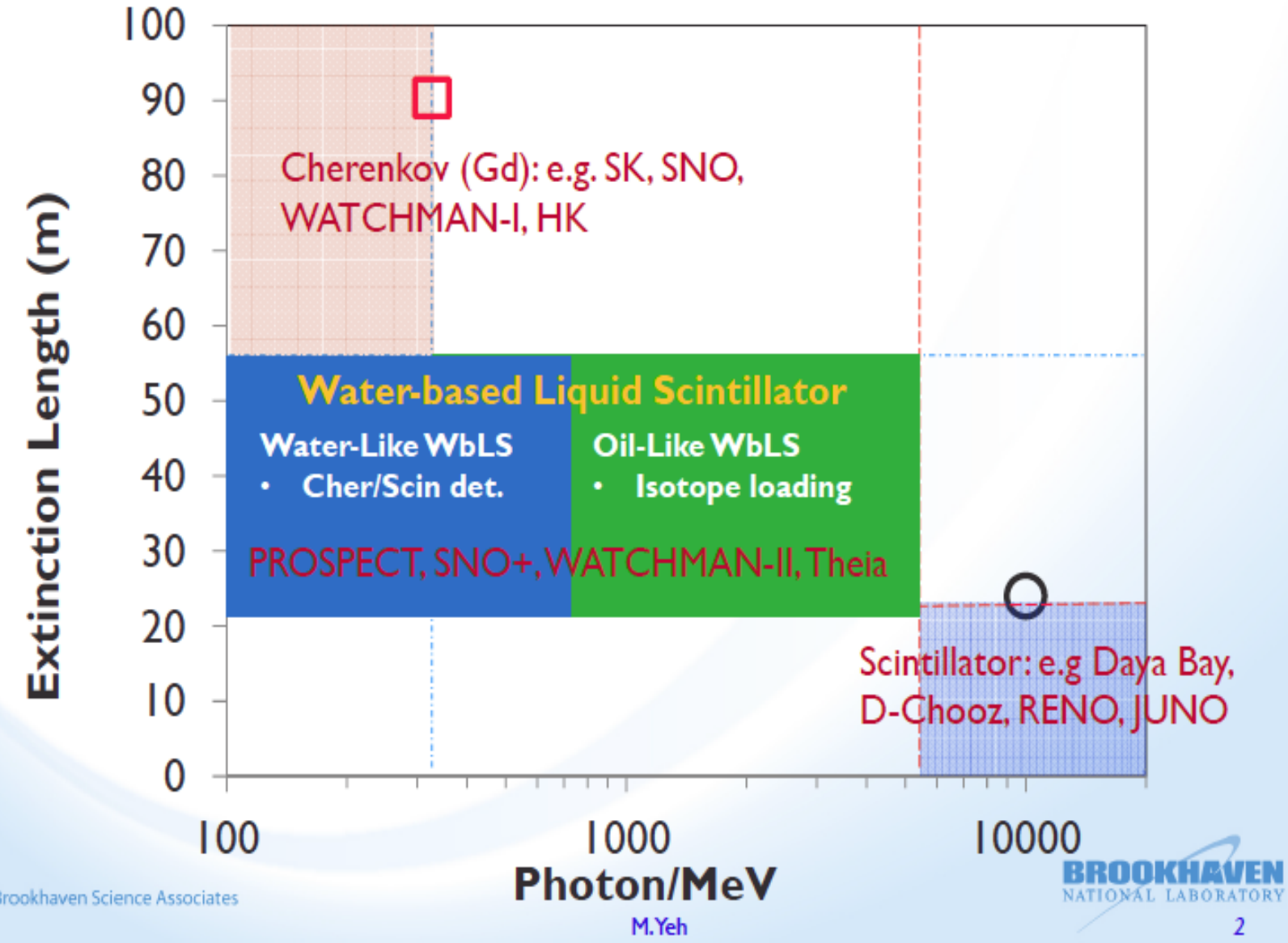
Reference Design:

- 50-100 ktonnes WbLS
- Cylindrical geometry
- >80% coverage with photon sensors
- 4800 mwe underground
- Loading of various isotopes (Gd, Li, Te)
- Ability to deploy inner "bag"

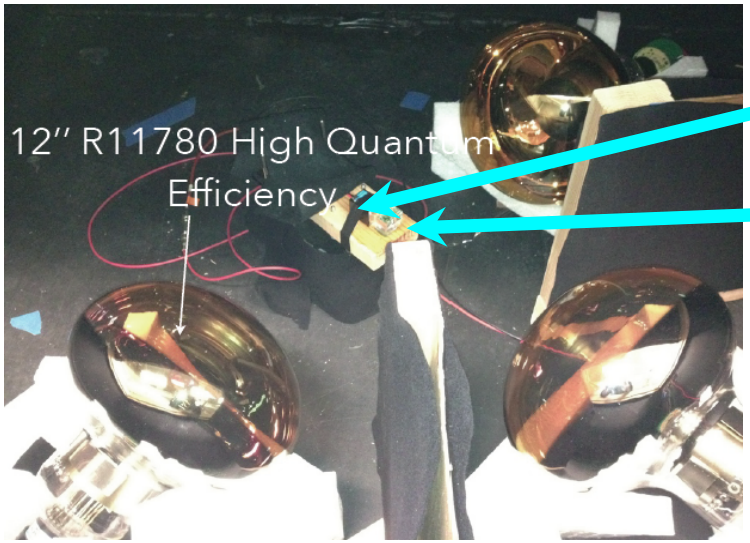


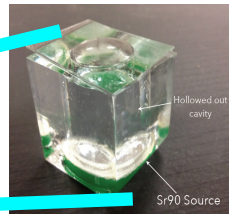
Water-based Liquid Scintillator

Developed at Brookhaven National Lab



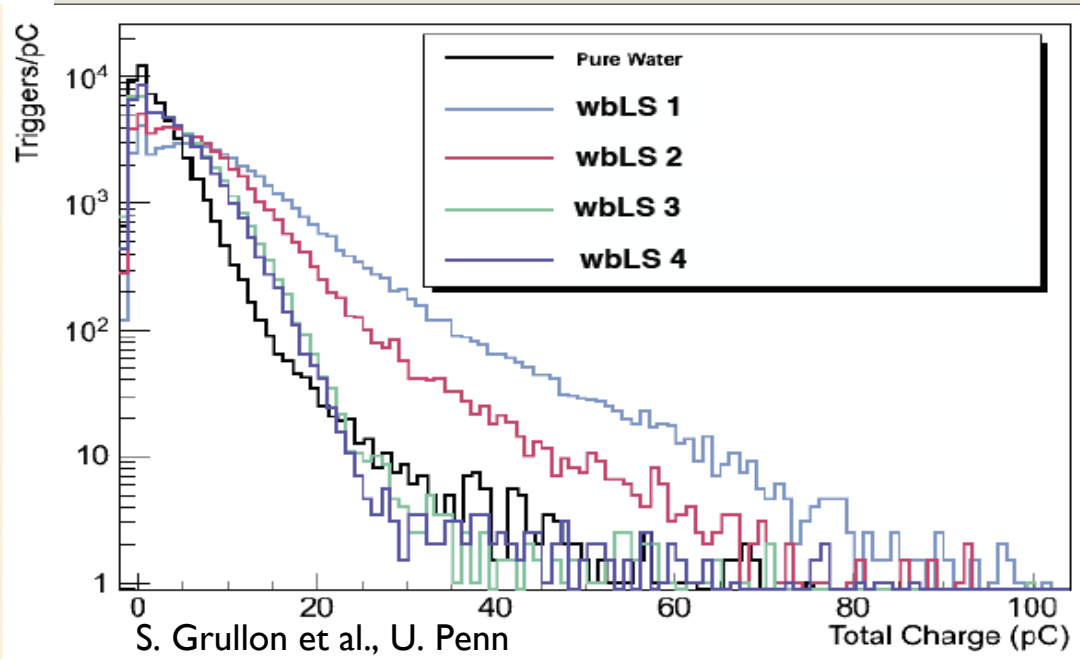
Water-based Liquid Scintillator





SAMPLE	MEASURED P.E. : WBLS/WATER	SCINTILLATION LIGHT YIELD
WbLS1	4.00 ± 0.06	~300 photons/MeV
WbLS2	2.71 ± 0.07	~200 photons/MeV
WbLS3	1.68 ± 0.09	~110 photons/MeV
WbLS4	1.52 ± 0.08	~100 photons/MeV
WbLS5	1.9 ± 0.09	~125 photons/MeV

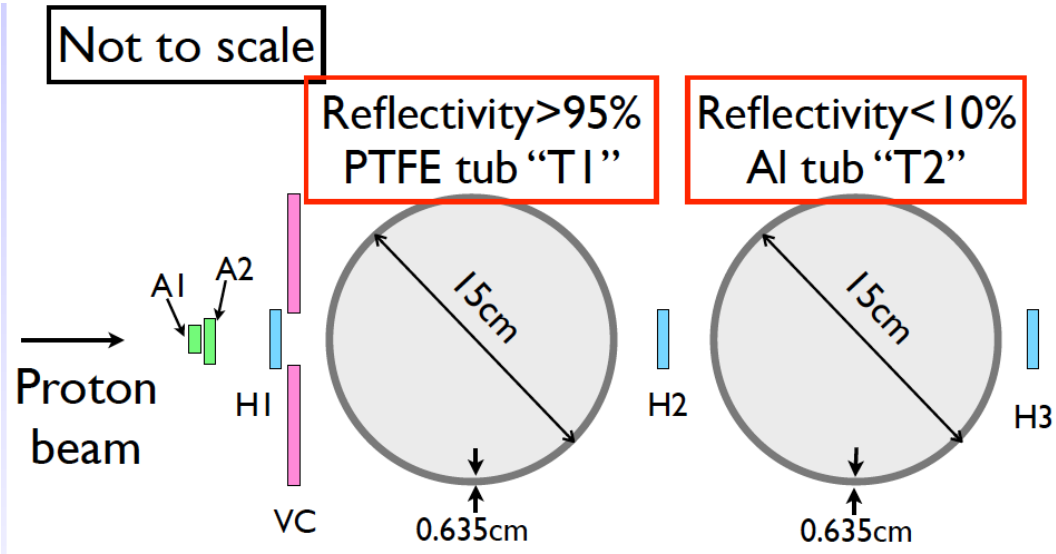
At low energies, intrinsic light yield scales with scintillator fraction.

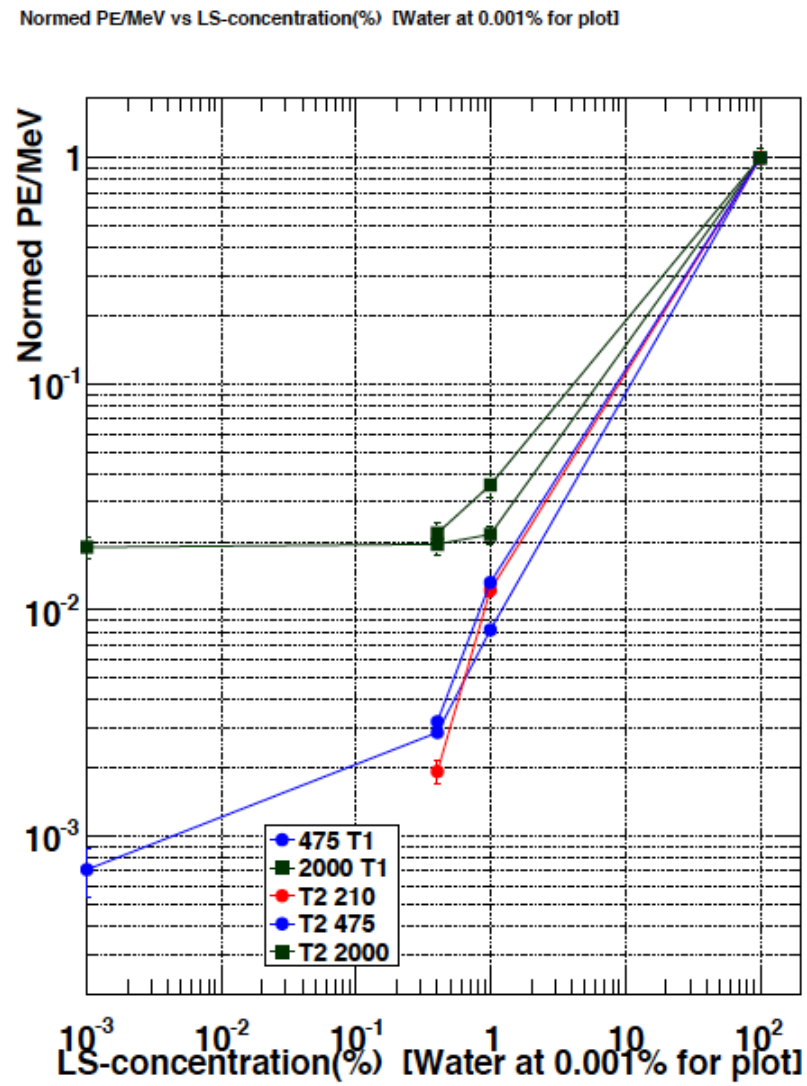


S. Grullon et al., U. Penn

Water-based Liquid Scintillator

And at high energies, until Cherenkov contribution becomes large.

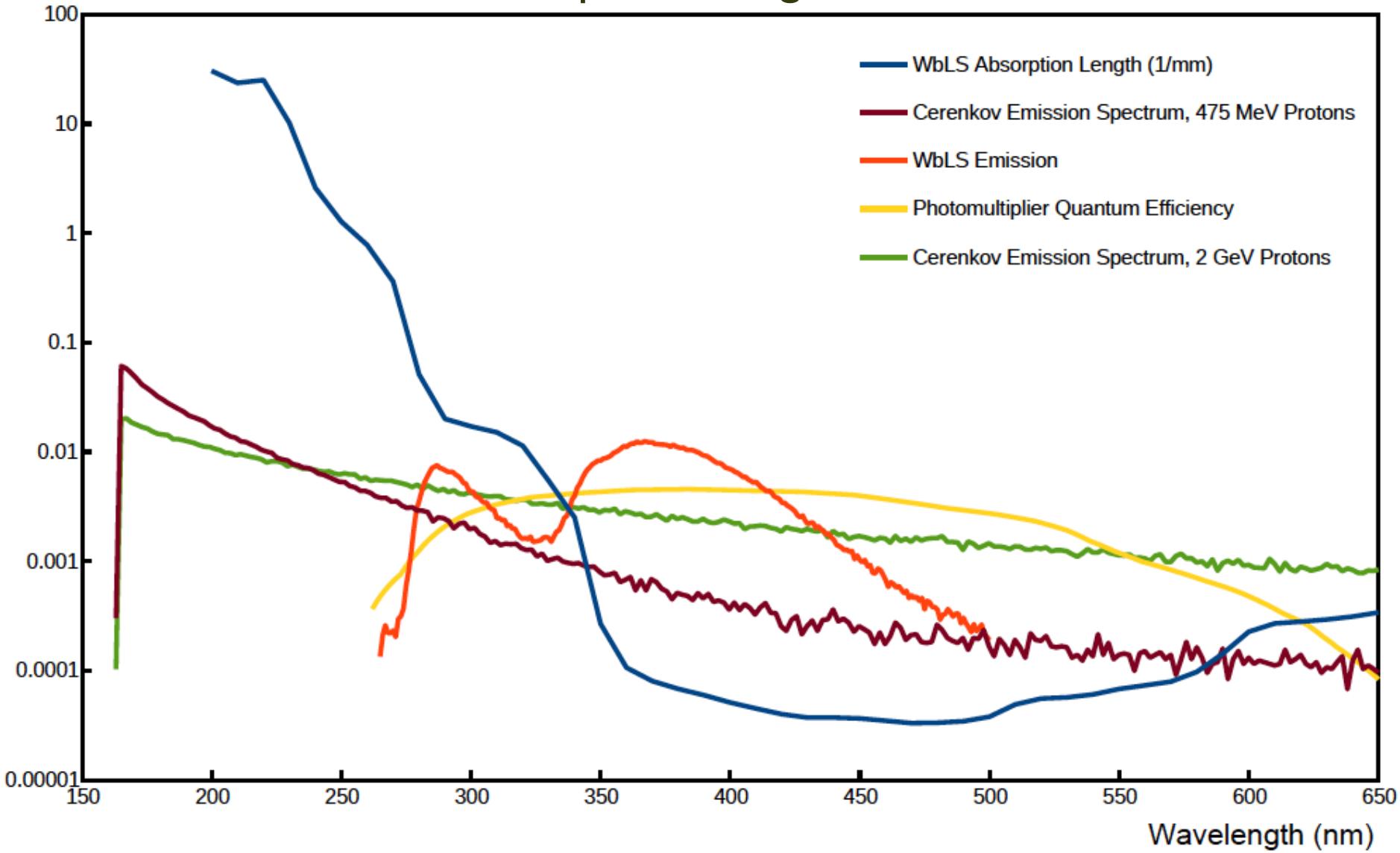




D. Jaffe, BNL

Water-based Liquid Scintillator

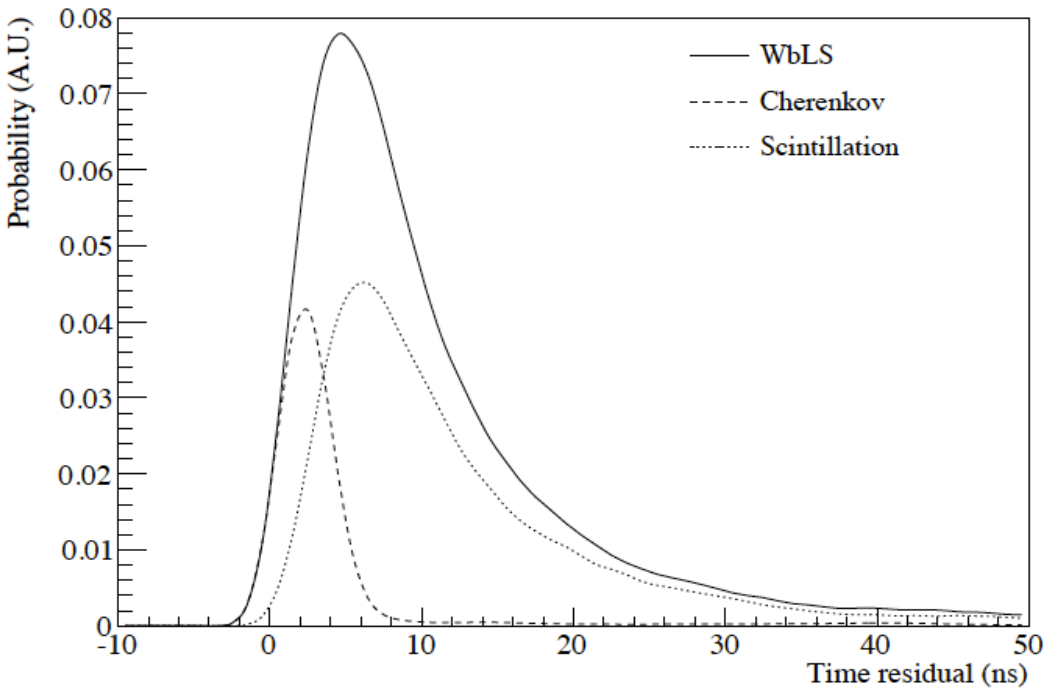
Optics look good



D. Jaffe, BNL

Cherenkov/Scintillation Separation

- Long extinction length means detector can be large
- About ½ of Cherenkov light absorbed or scattered
- But separation of two components still possible



A. Mastbaum, Penn

Cherenkov ID scales like

$$R_{s/c} \sim \frac{\gamma_C}{\gamma_S} \frac{t_{jitt}}{\tau_{sc\,\mathrm{int}}} \rho(\cos\alpha_C) R(\lambda)$$

t_{jitt} = transit time spread of PD
τ_{scint} = scintillation time constant
γ_C=number of Cherenkov photons
γ_S=number of scintillation photons
$\rho(\cos\alpha_c)$ = angular weighting function
$R(\lambda)$=spectral response function

So for a 4% scintillation fraction, standard PMTs, no use of angular information, and equal spectral response for C and S, $R_{s/c} \sim 0.25$

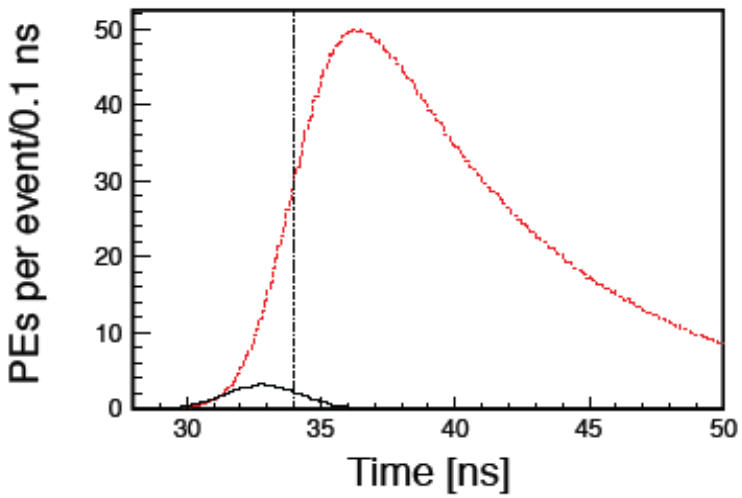
Cherenkov/Scintillation Separation

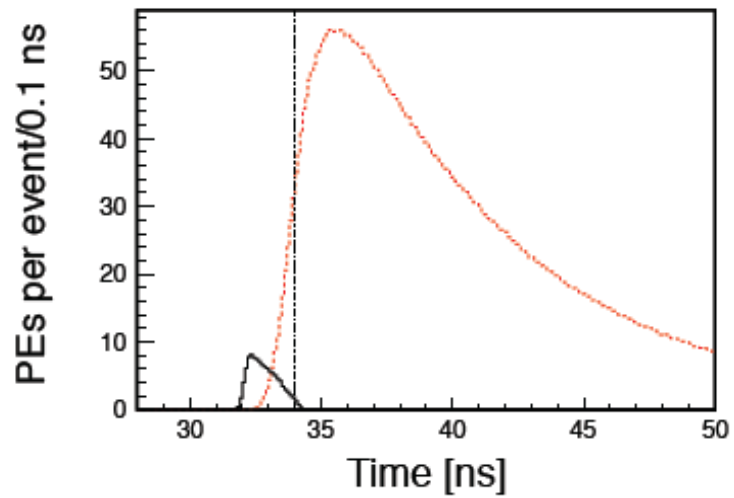
Separation via Timing

Simulation of 5MeV electrons in KamLAND-like detector

Cherenkov (prompt, scarce)

Scintillation (delayed, abundant)





1.3 ns timing of standard PMT

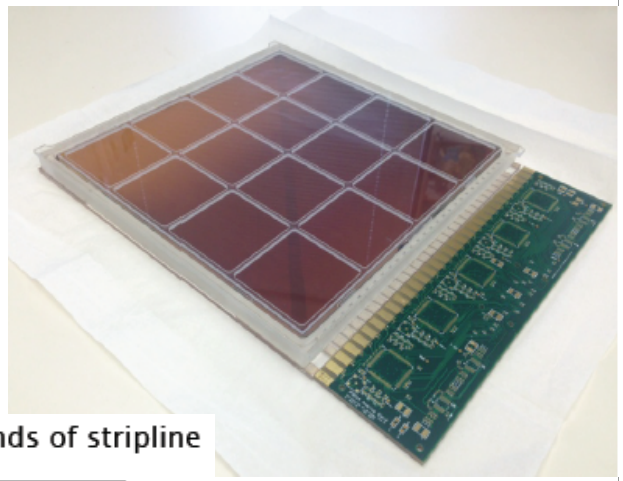
0.1 ns time resolution e.g. LAPPD

C. Aberle et al, JINST 9 P06012 (2014)

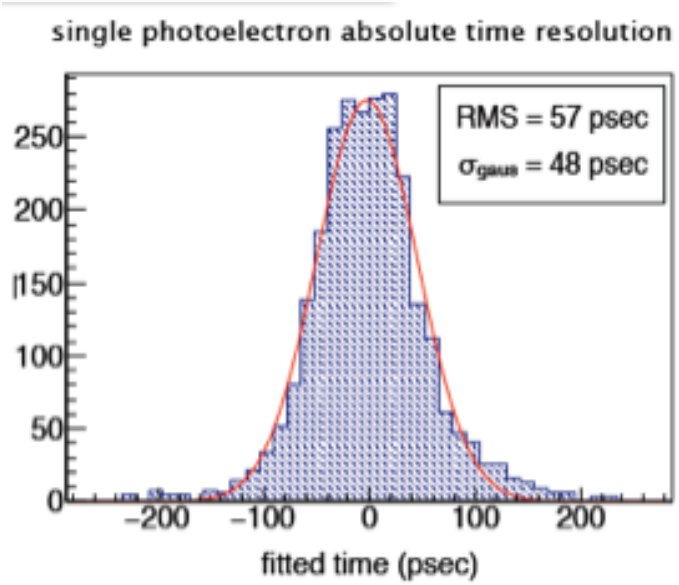
Cherenkov/Scintillation Separation

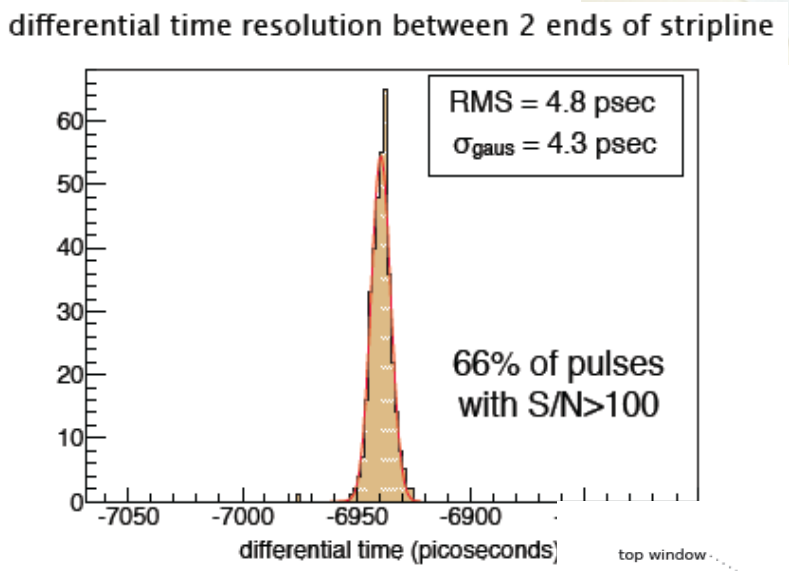
Separation via Timing

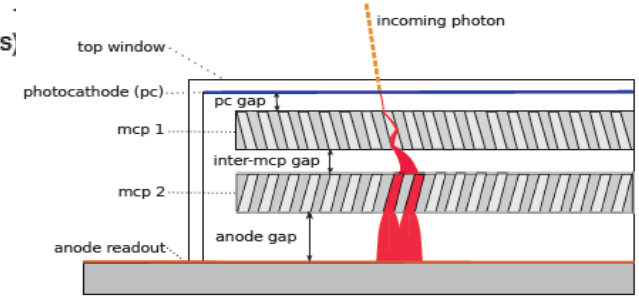
Large Area Picosecond Photodetectors (LAPPDs)



- Large, flat-panel MCP-based photosensors
- 50-100 ps time resolution (<1cm spatial)
- working readout system





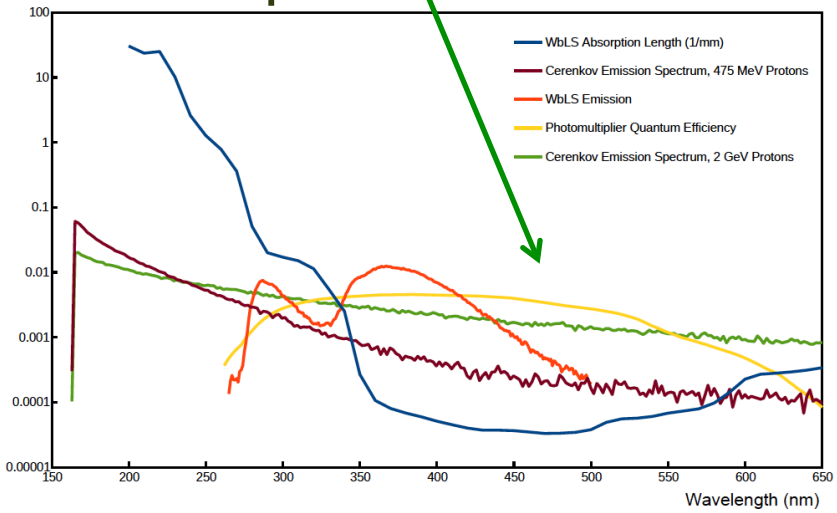


M. Wetstein

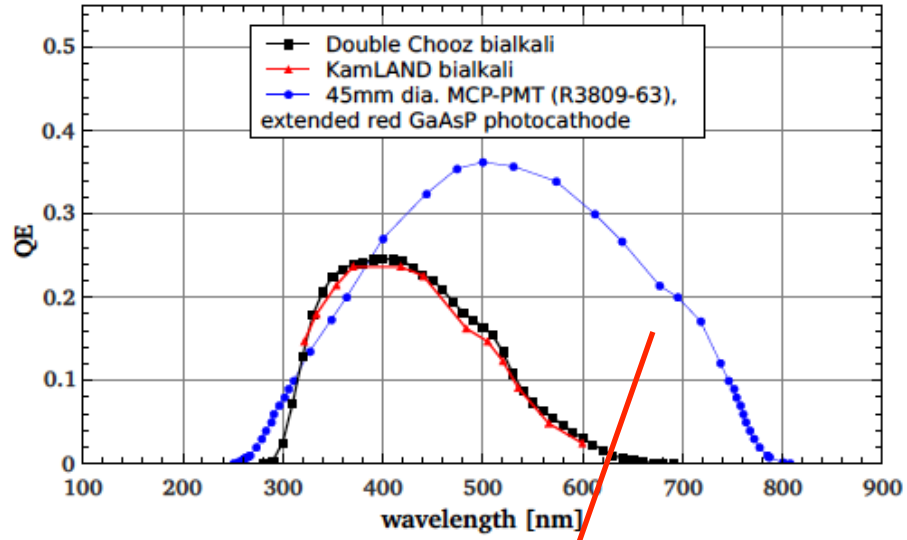
Cherenkov/Scintillation Separation

Separation via Wavelength (+timing)

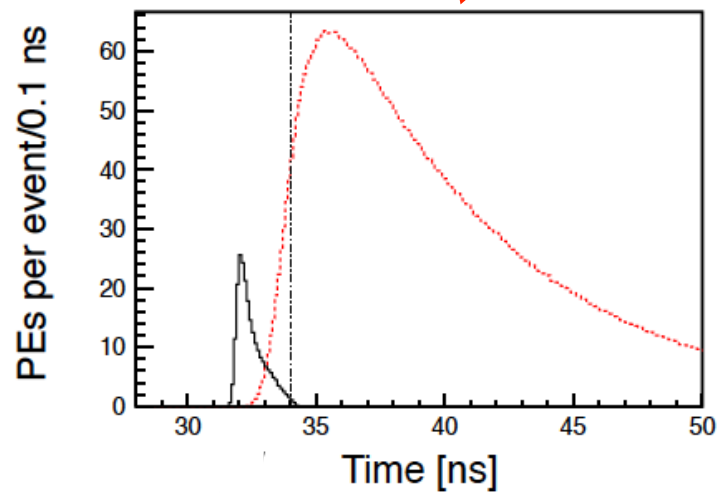
Cherenkov light extends beyond scintillation emission and absorption



Red-sensitive PMTs exist



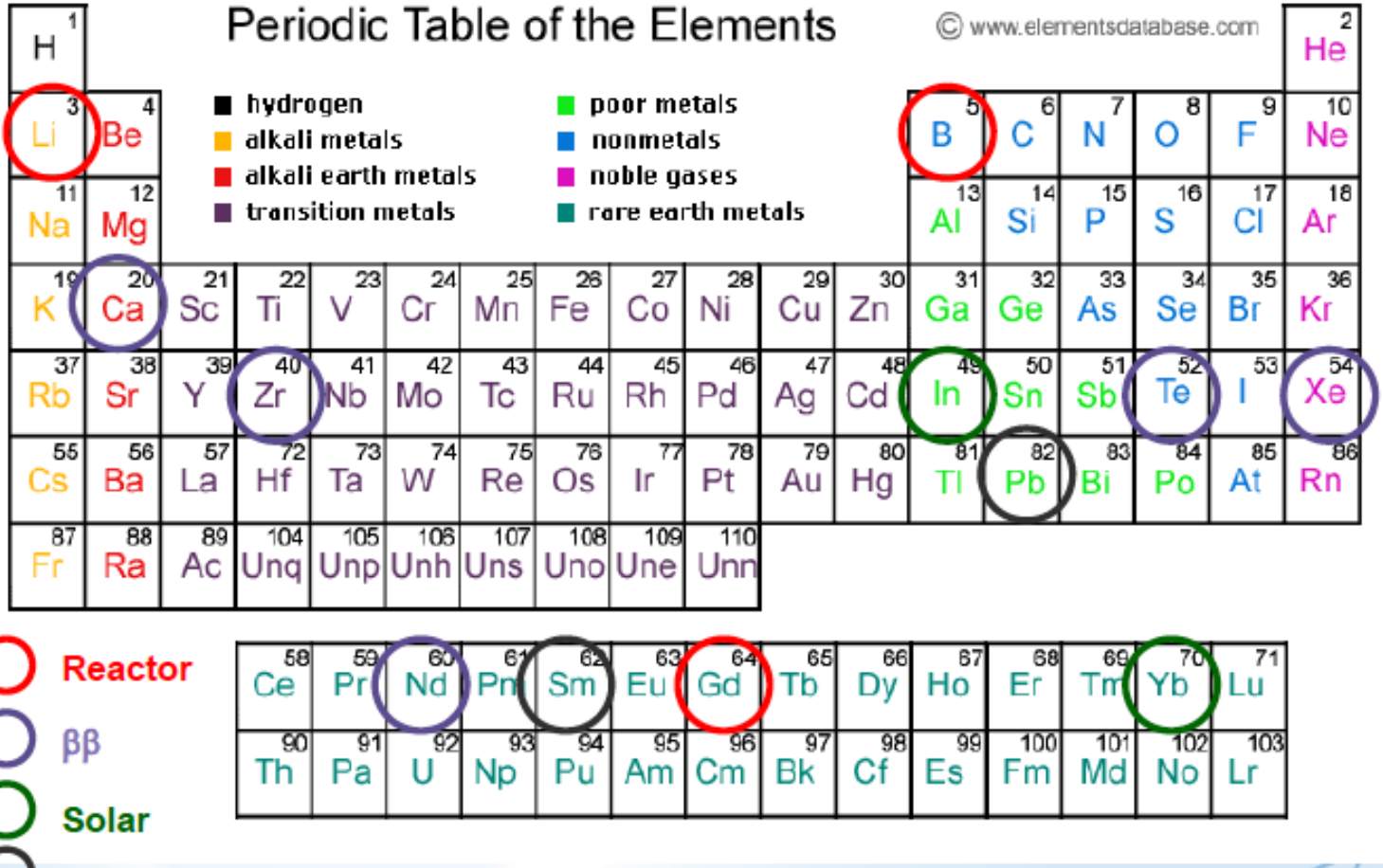
L. Winslow



And red travels faster than blue…

Isotopic Loading

Many possible elements can be loaded into LS

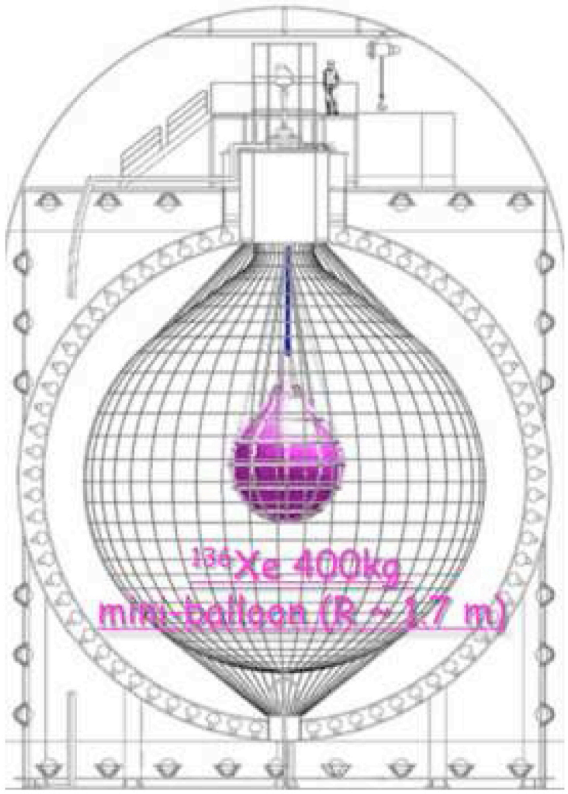


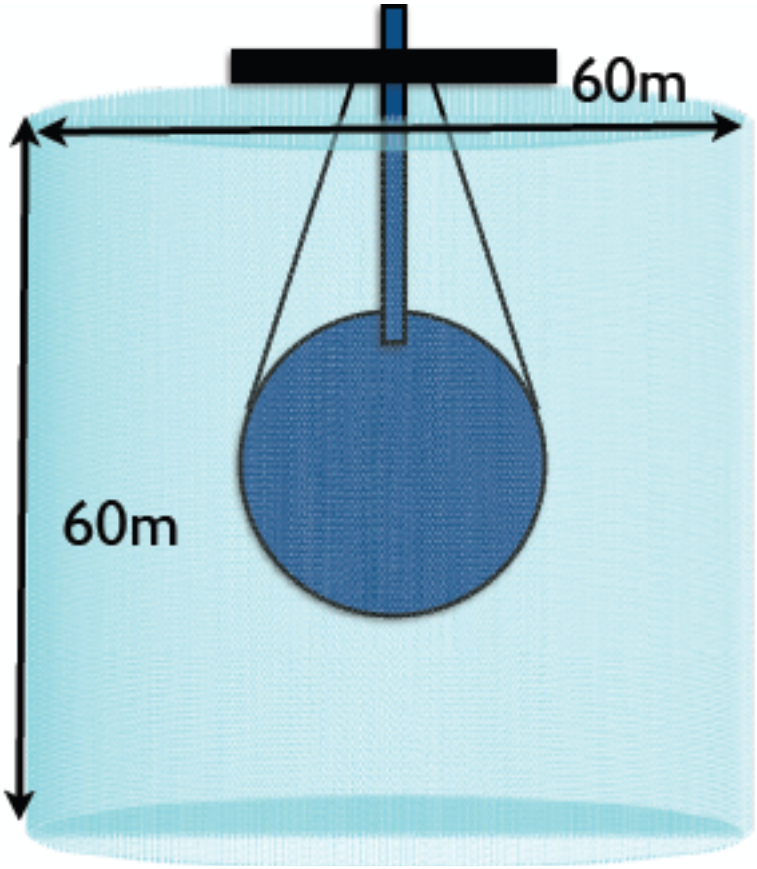
Flexibility

Containment "bag" would allow:

- Richer scintillator mixture
- Loaded scintillator distinct from rest of volume
- Simultaneous all water/all scintillator detector
- Deployment depending on physics needs

KamLAND-Zen





Flexibility

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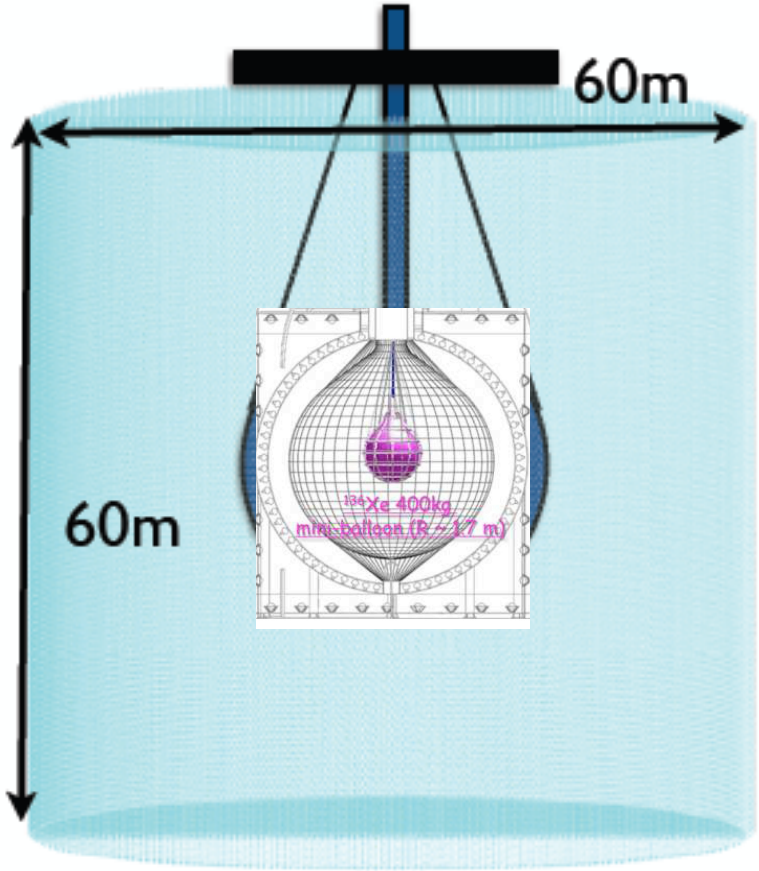
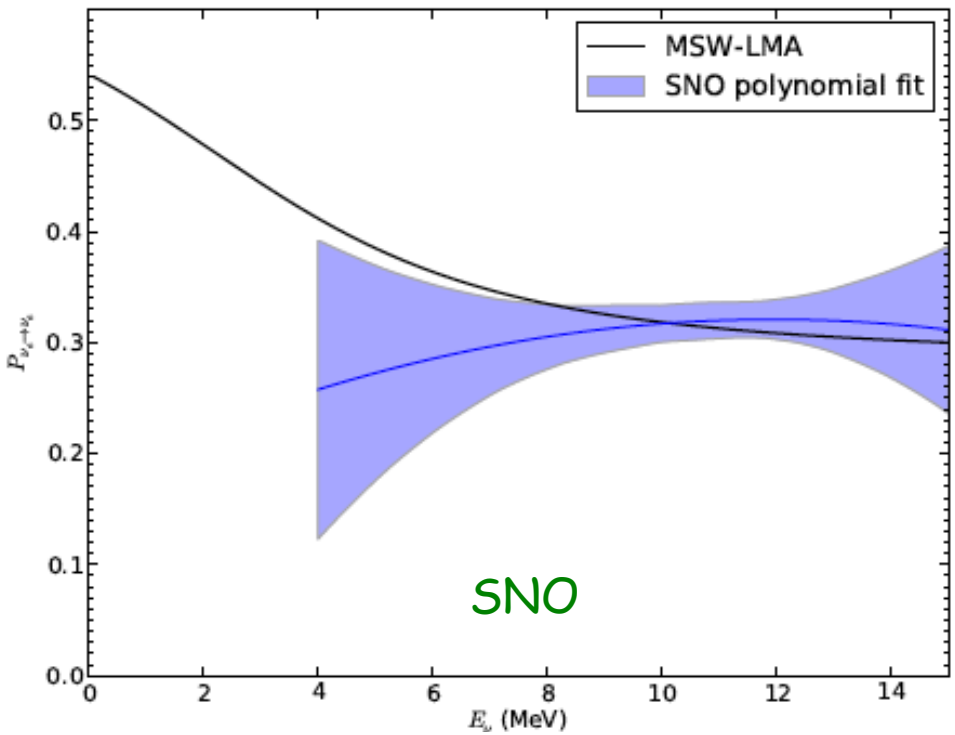
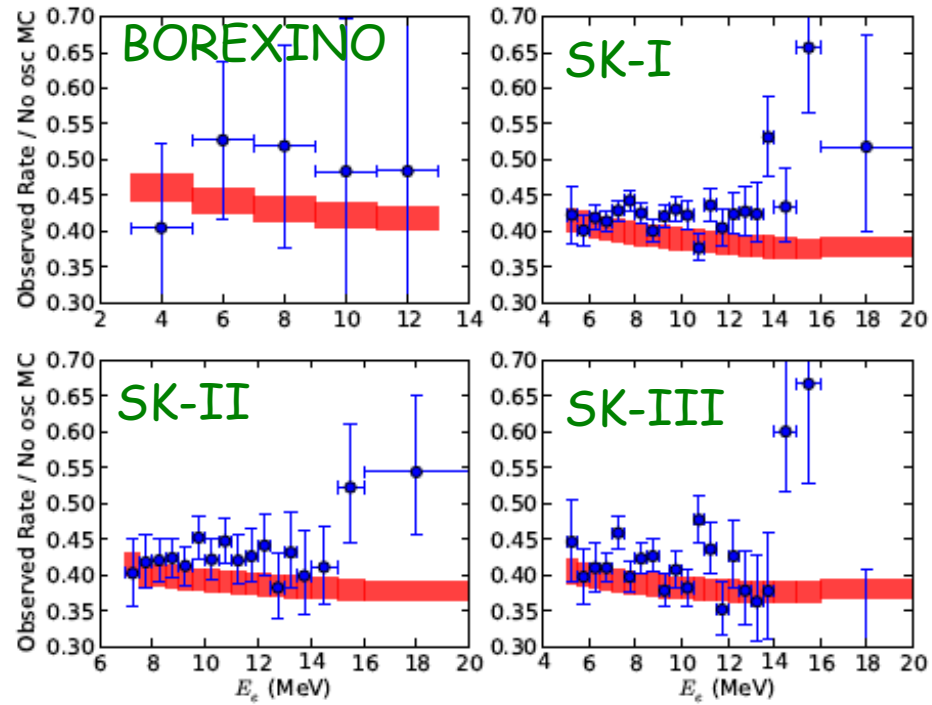


Solar νs at THEIA

Searching for new physics in MSW transition region

"The statistics of Super-K with the light yield of BOREXINO."





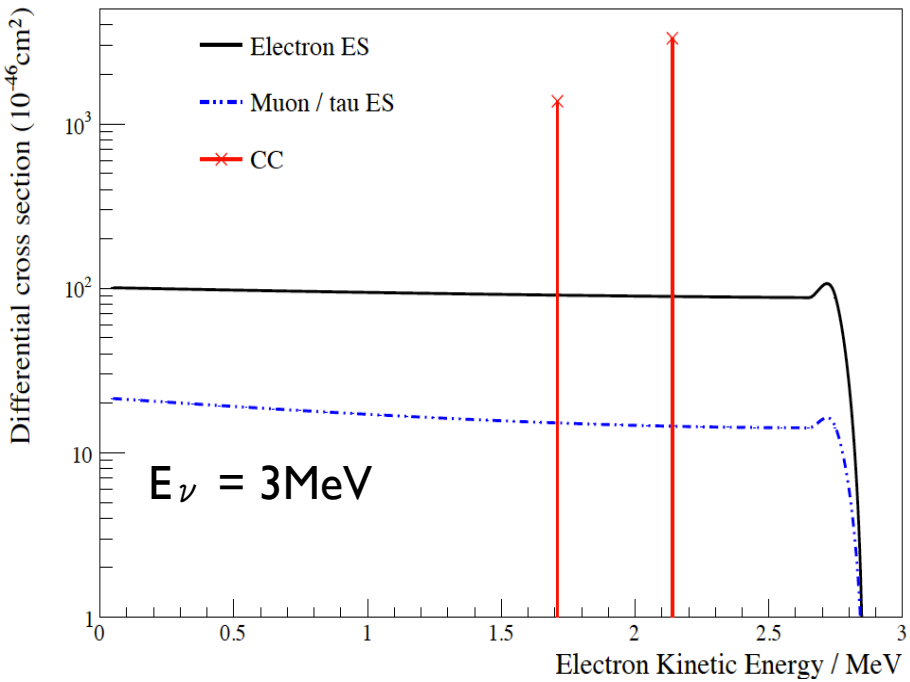
"Non-Standard Models, Solar Neutrinos, and Large θ_{13},"
Bonventre, LaTorre, et al.

Transition between matter and vacuum oscillations ~1-4 MeV.
Need low threshold, and high statistics!

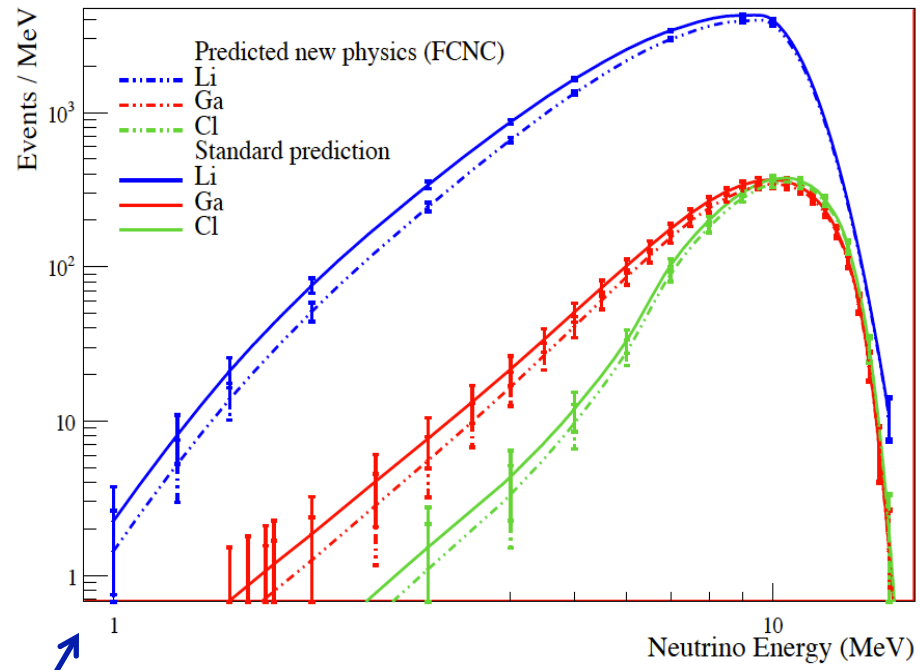
Solar νs at THEIA

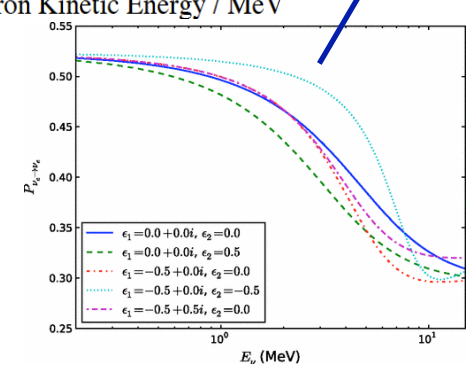
Even better: "Salty water Cherenkov detectors" W.C. Haxton PRL 76 (1996) 10

Loading with (e.g.) ^{7}Li provides CC cross section with narrow dσ/dE.



Makes models easy to distinguish

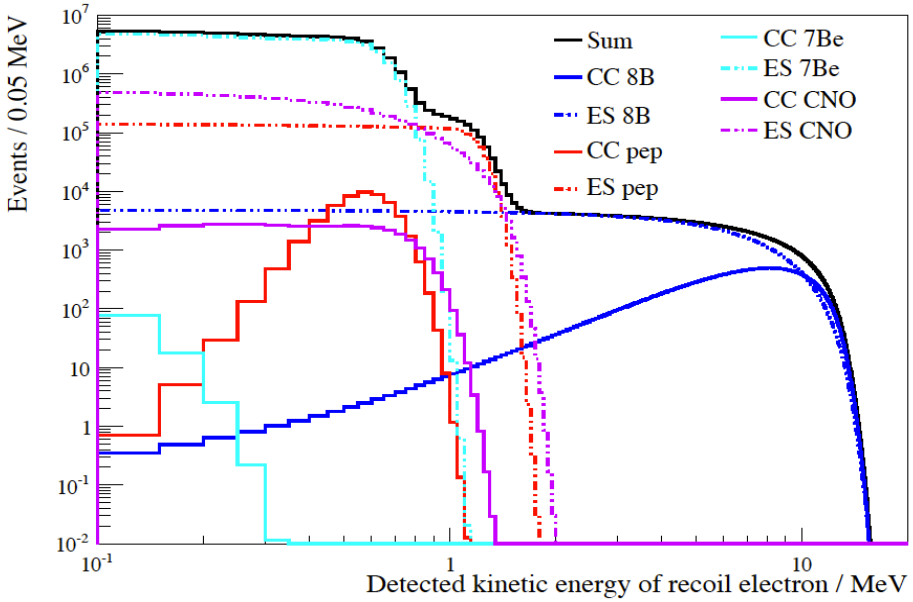




G. D. Orebi Gann (Berkeley)

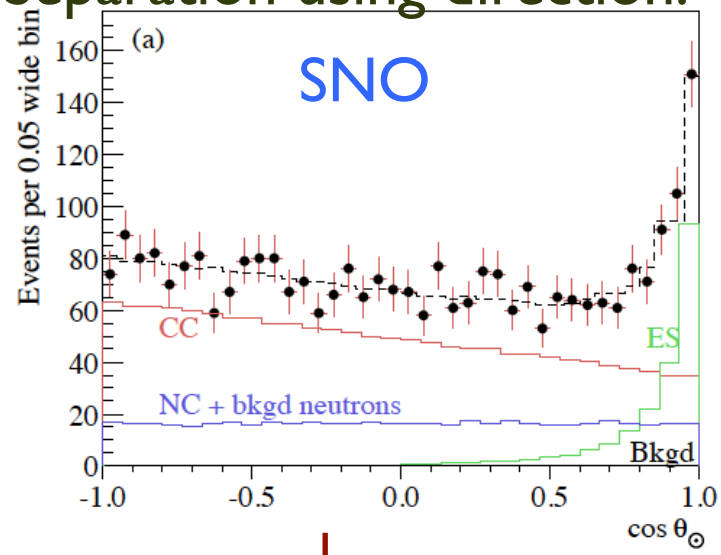
Solar νs at THEIA

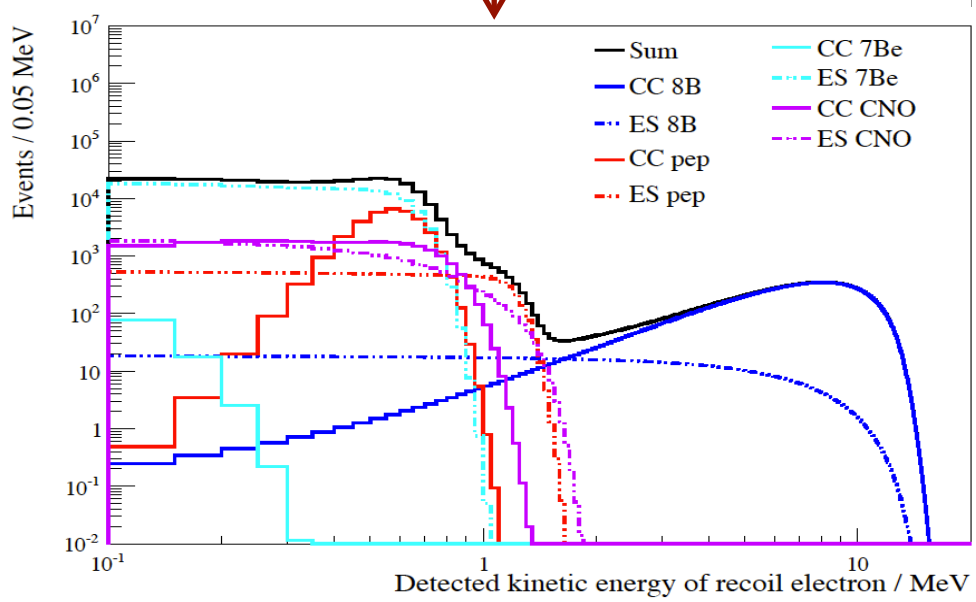
Low-energy solar νs also now possible via CC and ES:



G.D. Orebi Gann

Separation using direction:

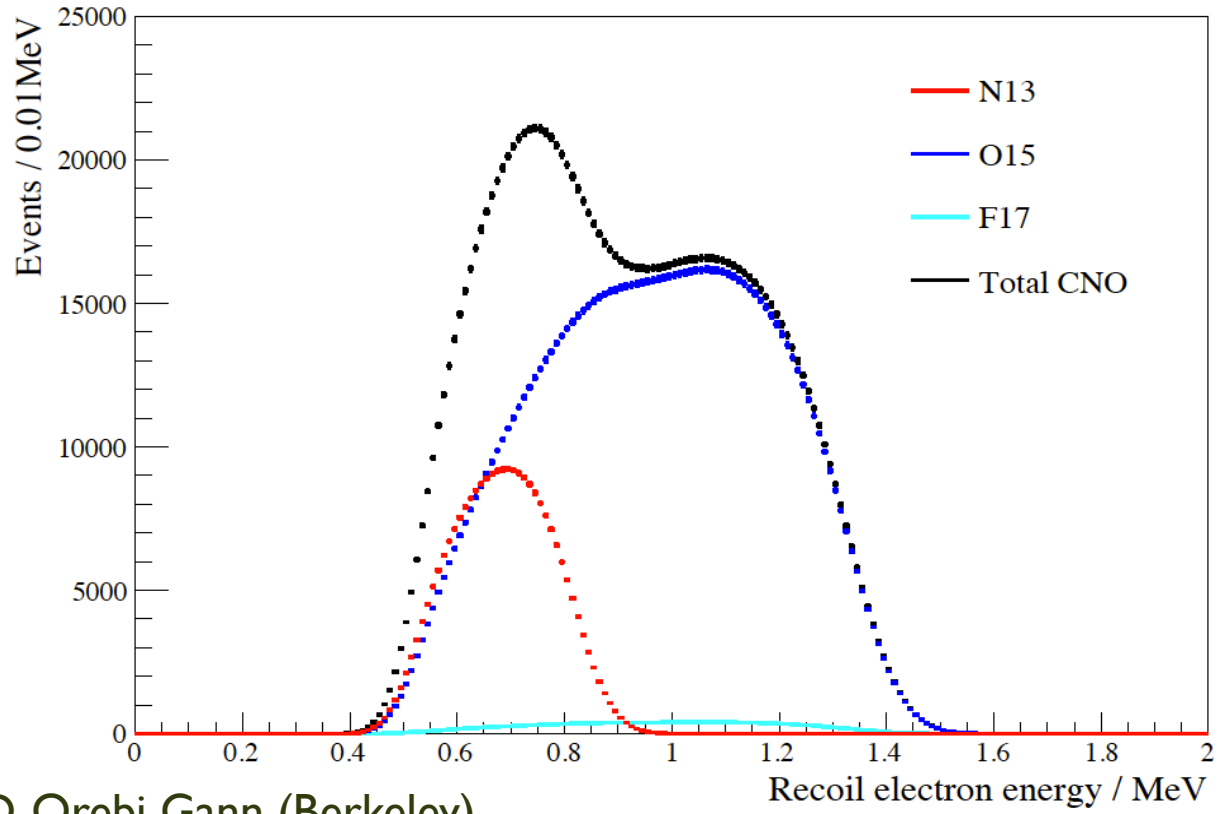




CC+ES also yields total flux via NC component of ES

Solar νs at THEIA

CC spectral sensitivity might also allow shape separation of CNO components

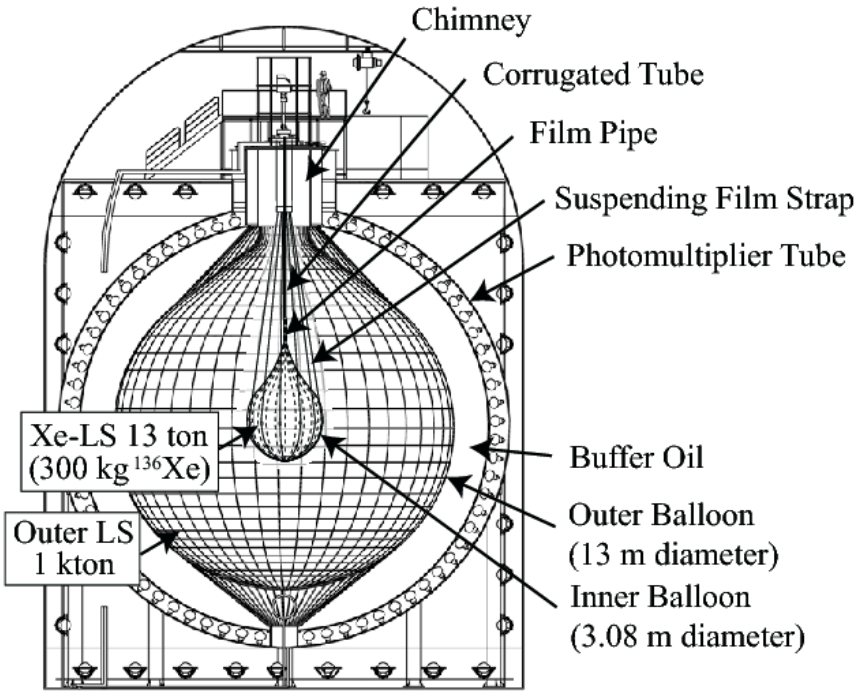


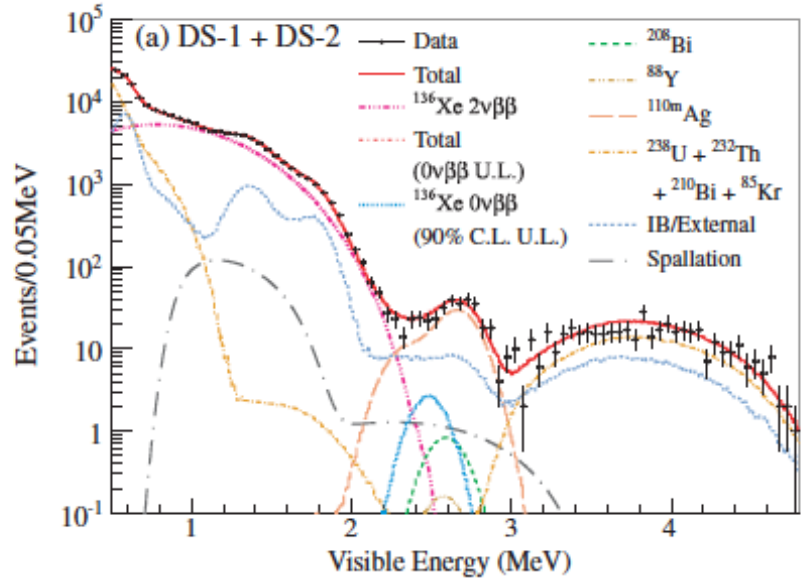
G.D. Orebi Gann (Berkeley)

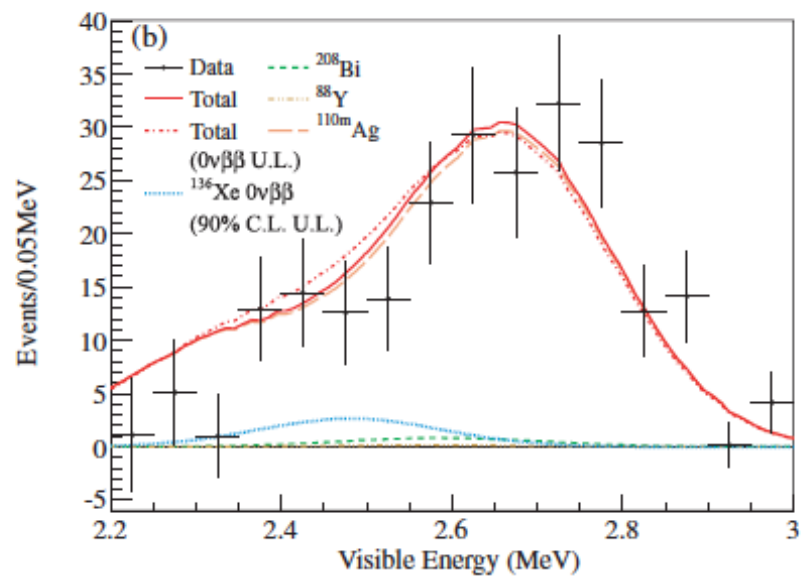
What about *pp*?
About 5×10^6 events/year in 50 ktonne!

0νββ at THEIA

"Loaded scintillator" 0νββ searches violate conventional wisdom that energy resolution is the entire game.





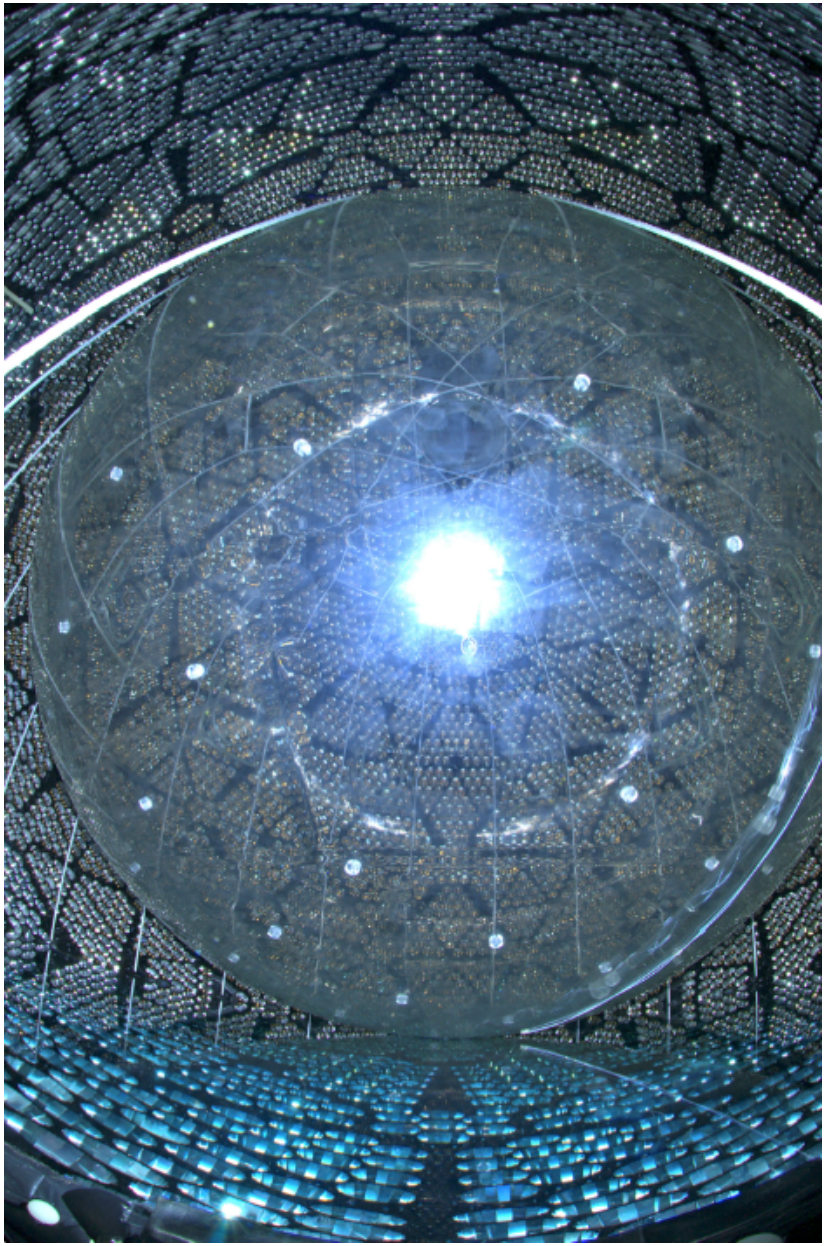


And yet KamLAND-Zen has best ββ limit, without >decade of R&D and many millions of dollars

Phys. Rev. Lett. 110. 062502

$0\nu\beta\beta$ at THEIA

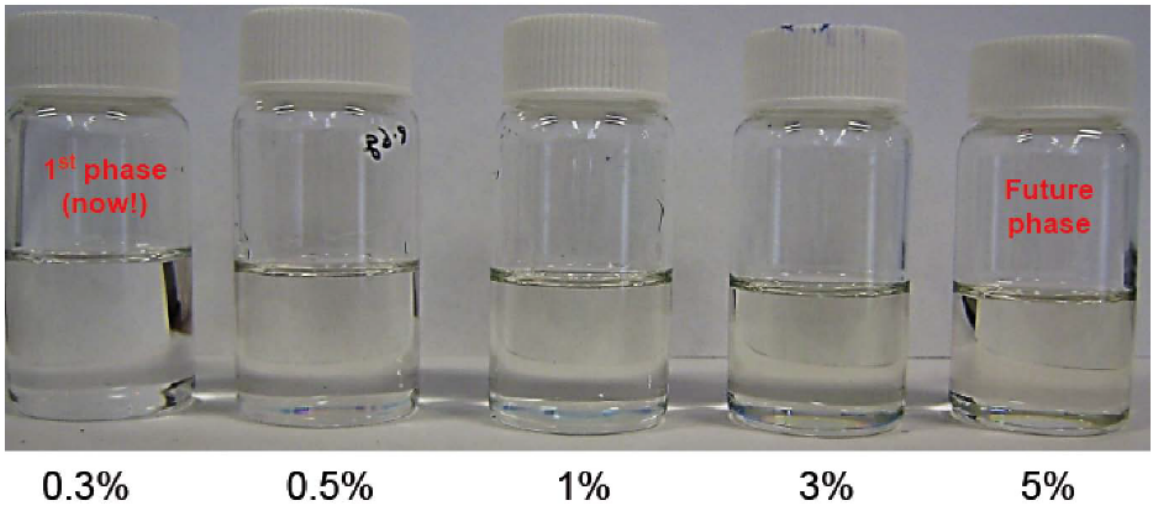
SNO+ Approach



- Re-use SNO detector
  - 12-m diameter acrylic vessel
  - ~9500 PMTs
- Replace D_2O with liquid scintillator (LAB)
- New hold-down rope net
- 7kT H_2O buffer
- Load LAB with 0.3% ^{nat}Te

0νββ at THEIA

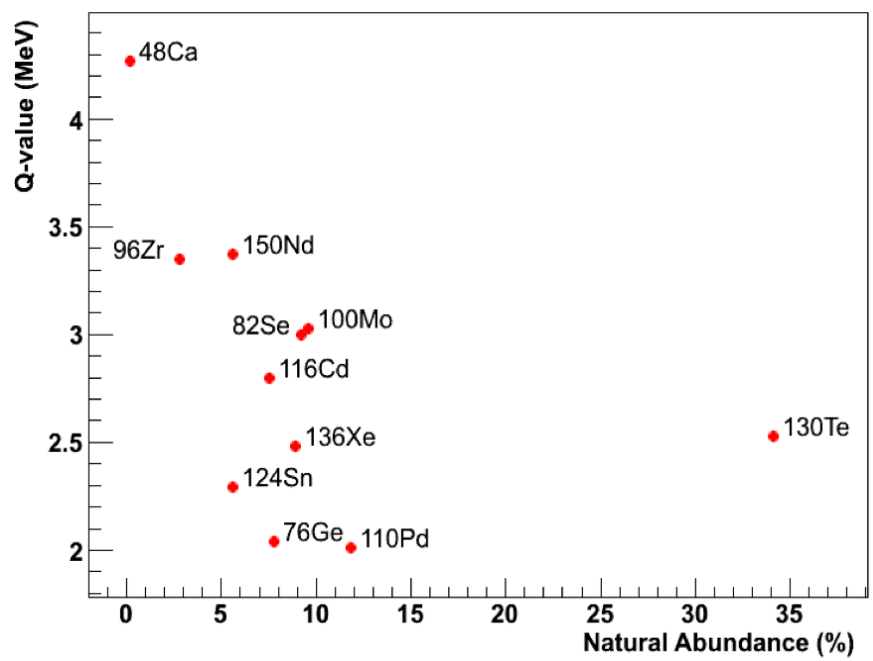
SNO+ Approach



Te can be loaded up to very high fractions.

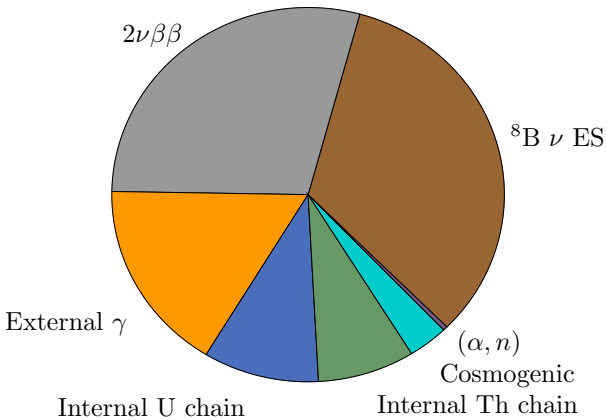
^{130}Te has highest natural abundance of ββ isotopes.

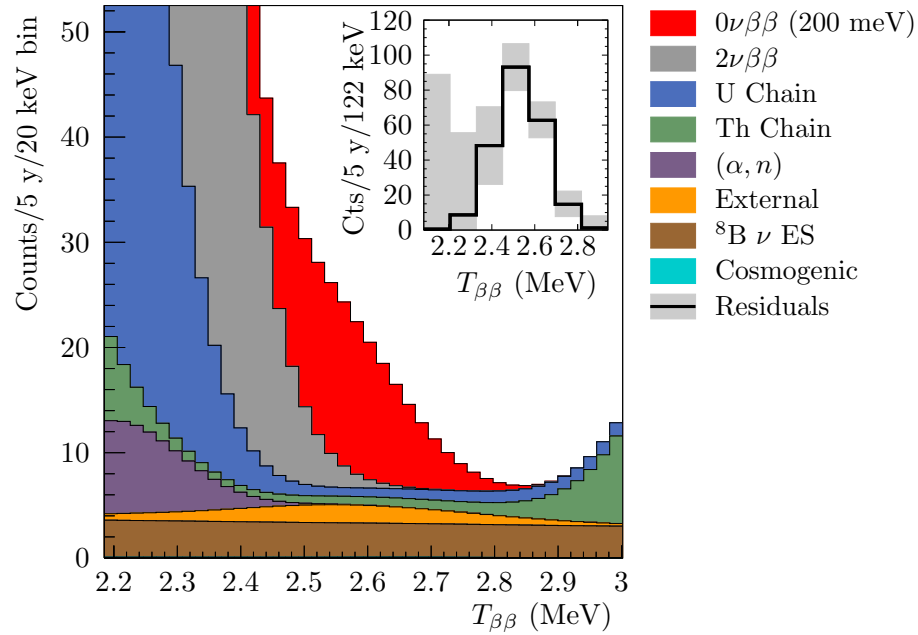
And long 2ν lifetime (low 2ν rate).

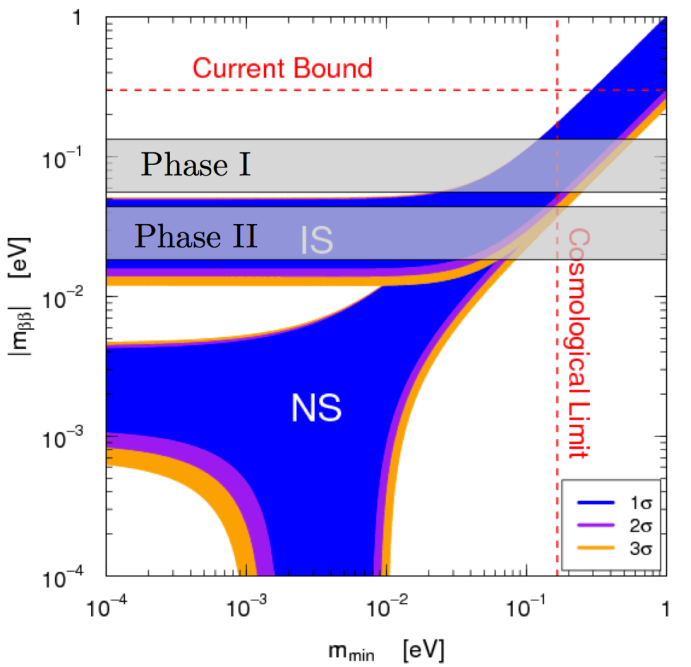


0νββ at THEIA

SNO+ Approach





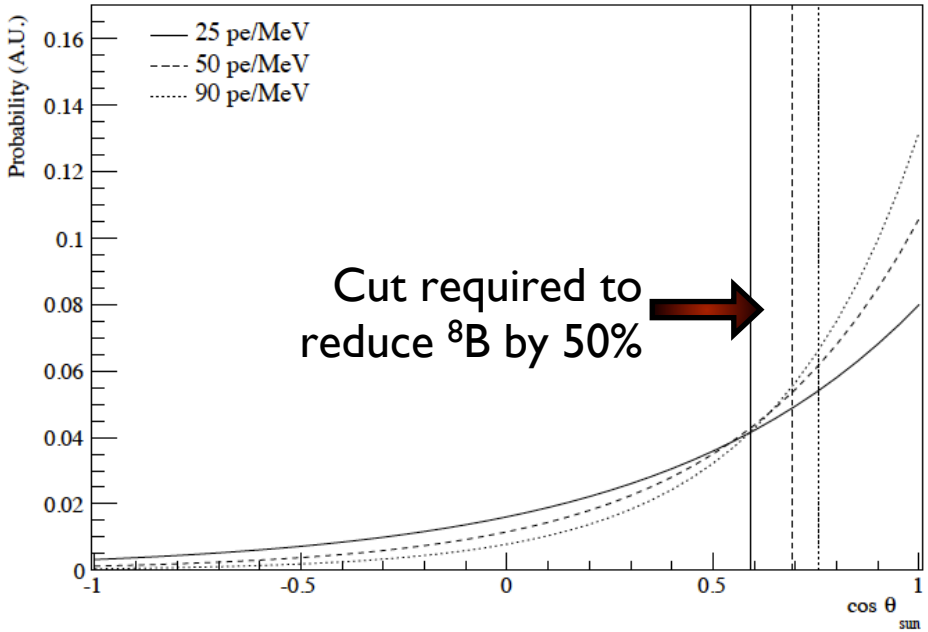


adapted from Bilenky & Giunti

Phase I is 0.3% loading
Phase II is 3% if optics are good enough.

Still does not get to "3σ discovery at $m_{\beta\beta}$> 15 meV"

0νββ at THEIA



A. Mastbaum (Penn)

Directionality will allow reduction of dominant ^{8}B background---size eliminates backgrounds from PMTs and walls.

A 1% loading of ^{nat}Te will achieve 15meV criterion

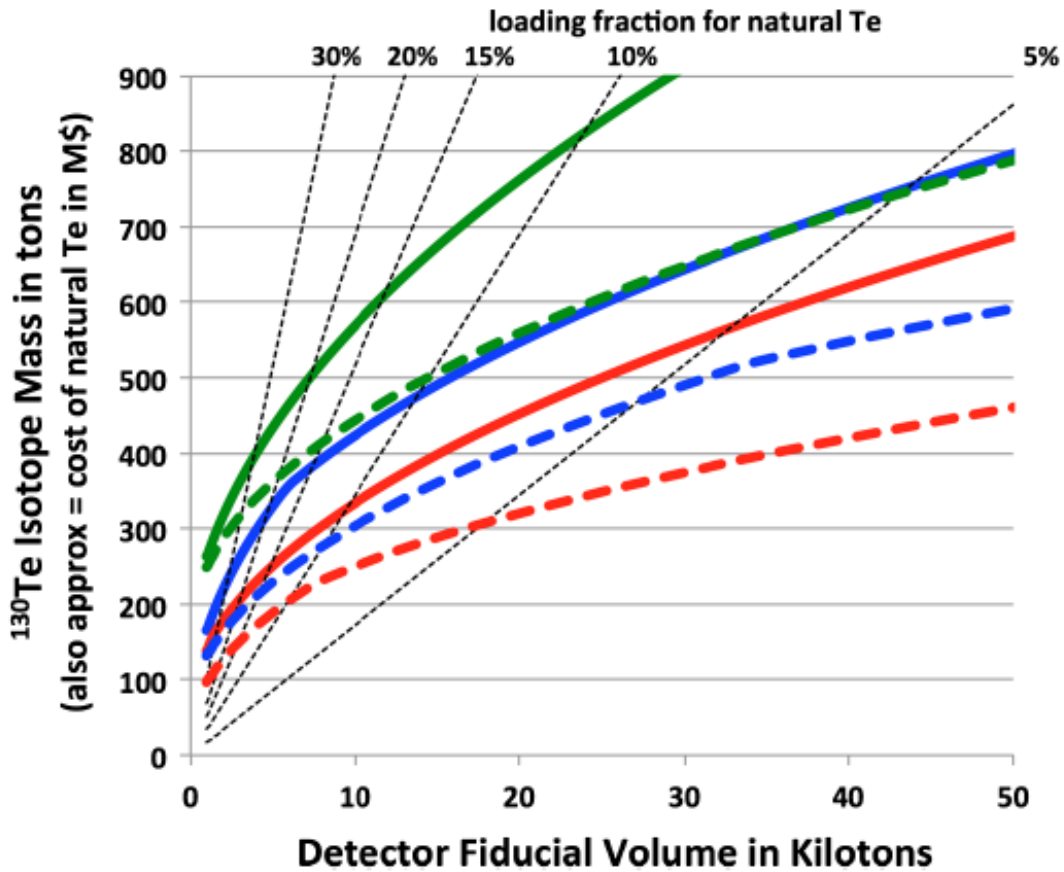
	ΔE (%)	f_{iso} (%)	M_{iso} (tons)	b (cts/MeV·ton·y)	$\widehat{T}^{0\nu}_{1/2}$ (10^{26} y)	$\widehat{m}_{\beta\beta}$ (meV)
SNO+[4]	4.5	0.3	0.16	775	0.85	75
SNO+	3.6	3.0	2.4	260	6.6	27
CUORE[5]	0.2	–	0.74	0.01	0.76	78
CUORE	0.2	–	0.74	0.001	2.4	44
WbLS	5.0	1.0	100	930	19.5	**15**
WbLS	5.0	3.0	300	850	35.5	11

$t = 10$ y

0νββ at THEIA

Going further….

With 1000 pe/MeV (green) or more, can get 90% CL at 2.5 meV!



Likely would require a balloon inside THEIA to maximize useful isotope and light yield.

S.D. Biller, PRD **87,** 071301, (2013)

Supernova Bursts

Lot of work on this already done by LENA

- ~12k events for 10kpc Supernova in 50 ktonne
- Scintillation light makes n tag easy for IBD
- Gd makes n tag even better (200 μs becomes 20μs)

Neutrino Reaction	Percentage of Total Events	Type of Interaction
$\overline{\nu}_e + p \rightarrow n + e^+$	88%	Inverse Beta
$\nu_e + e^- \rightarrow \nu_e + e^-$	1.5%	Elastic Scattering
$\overline{\nu}_e + e^- \rightarrow \overline{\nu}_e + e^-$	<1%	Elastic Scattering
$\nu_x + e^- \rightarrow \nu_x + e^-$	1%	Elastic Scattering
$\nu_e +^{16} O \rightarrow e^- +^{16} F$	2.5%	Charged Current
$\overline{\nu}_e +^{16} O \rightarrow e^+ +^{16} N$	1.5%	Charged Current
$\nu_x +^{16} O \rightarrow \nu_x + O^*/N^* + \gamma$	5%	Neutral Current

NC elastic scattering of p may also be visible by scintillation light.

Literally complementary to LAr (anti-ν_e vs. ν_e)
Better resolution than Super-K, allows some discrimination of signals

Diffuse Supernova Antineutrino Background

Lot of work on this already done by LENA

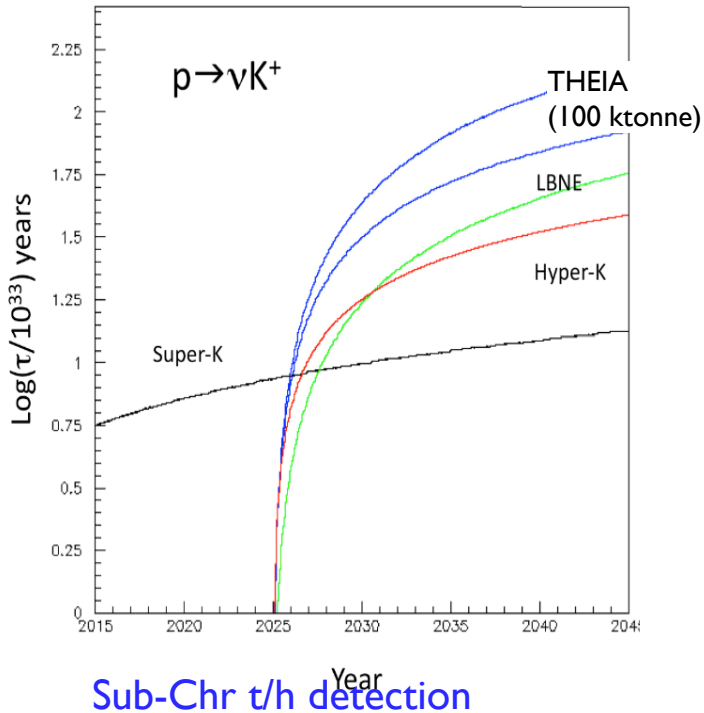
- Detect via IBD+neutron tag---very low background
- Scintillation light has higher efficiency than Gd+H_2O
- Low NC background
  - Atmospheric ν+C → n + fragments
  - WbLS allow rejection of recoils via Cher/Scint
  - "Isotropy" of Cherlight also helps discrimination

Loading with Cl or Li would allow ν_e detection in same detector.

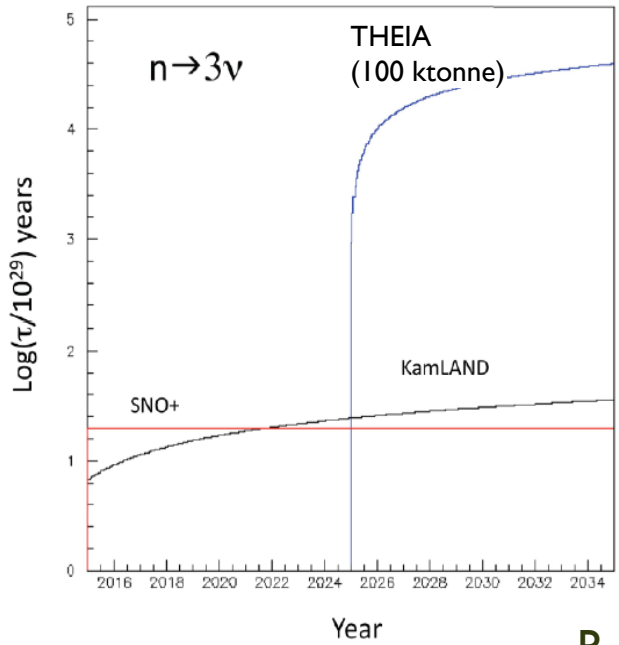
- Unlikely to be as good at ν_e as LAr unless single low-E events are below LAr-TPC threshold.

Nucleon Decay with THEIA

Scintillation light allows observation of K+, as well as de-excitation γs from "invisible"decay modes.



Sub-Chr t/h detection
⇒ Directly visible K^+
A 50 ktonne THEIA+DUNE ~ 100 ktonnes



R. Svoboda (Davis)

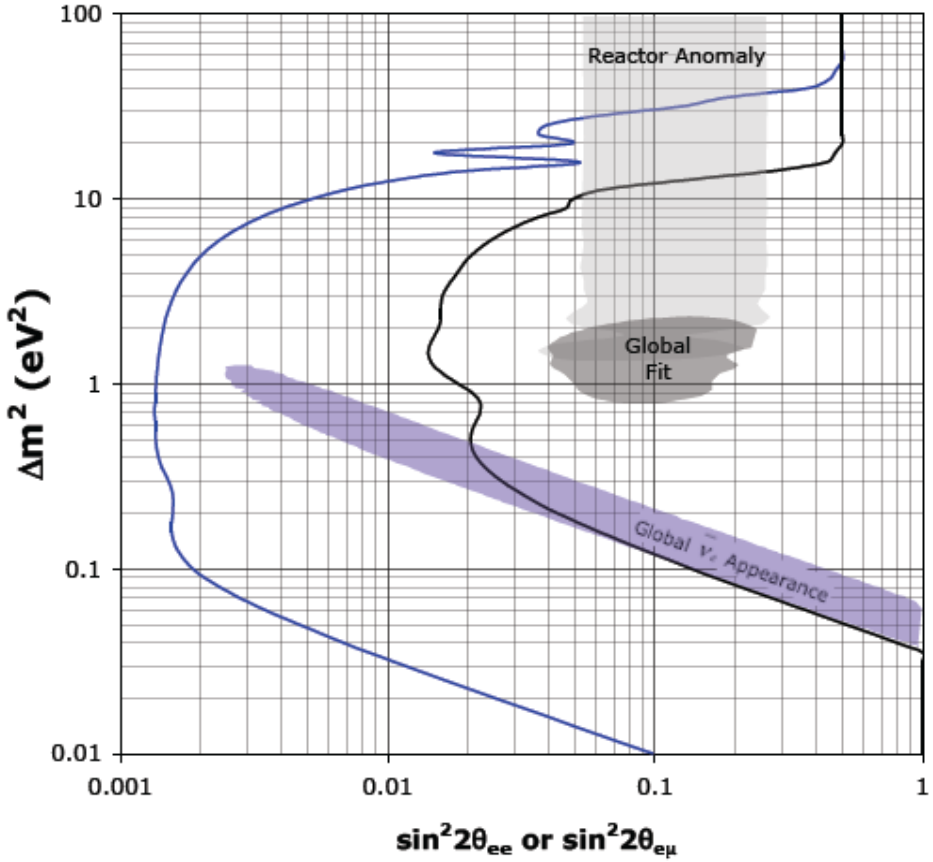
Deep, low threshold
De-excitation γs observaiable via Cher or Scint

For $p \rightarrow e^+\pi^0$ mode, not likely to be competitive with Super-K/Hyper-K unless THEIA can be made > 200 ktonne

Sterile νs with THEIA

If "reactor anomaly" persists….

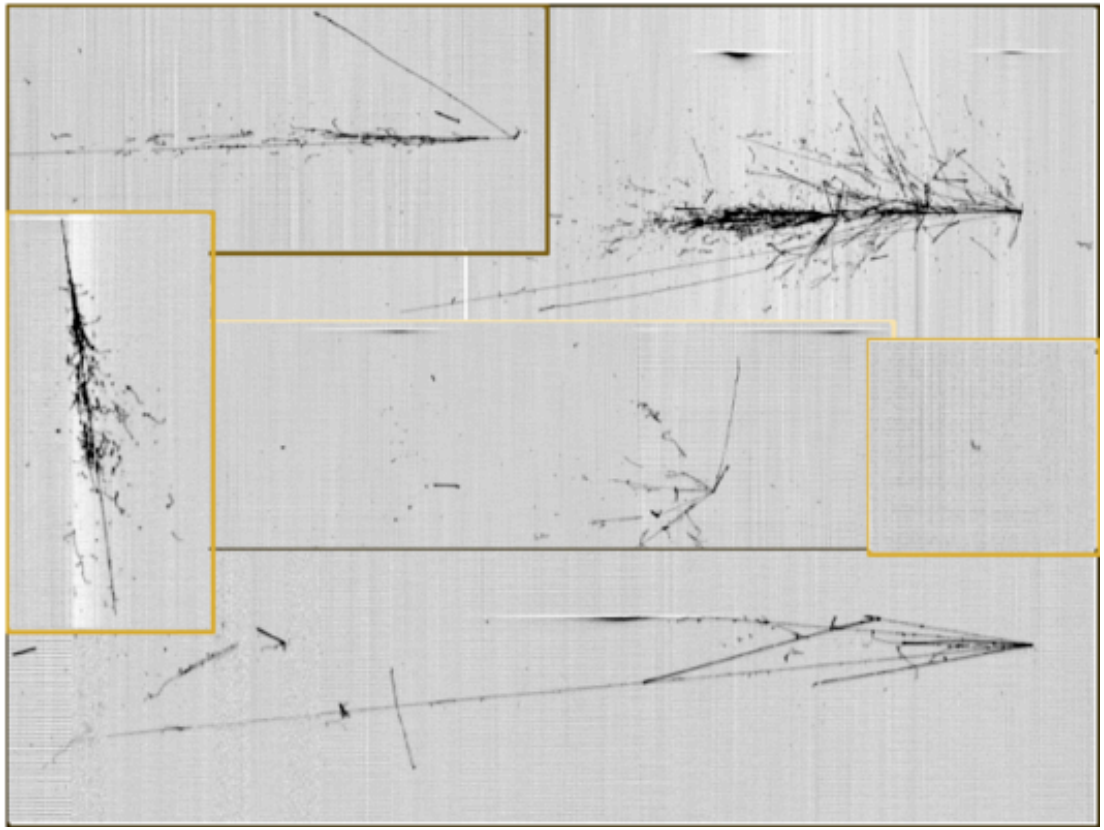
- ISODAR uses ^{8}Li with 13 MeV endpoint
- Could potentially resolve oscillation pattern within single detector
- Need 15% σ_E and 50 cm σ_R



Long Baseline Program with THEIA@LBNF

"…the U.S. to host a large water Cherenkov neutrino detector, as one of three additional high-priority activities, to complement the LBNF liquid argon detector, unifying the global long-baseline neutrino community to take full advantage of the world's highest intensity neutrino beam. The placement of the water and liquid argon detectors would be optimized for complementarity. This approach would be an excellent example of global cooperation and planning" – P5 (Scenario C)

Seriously? What could a water(-based liquid scintillator) detector possibly add to this?



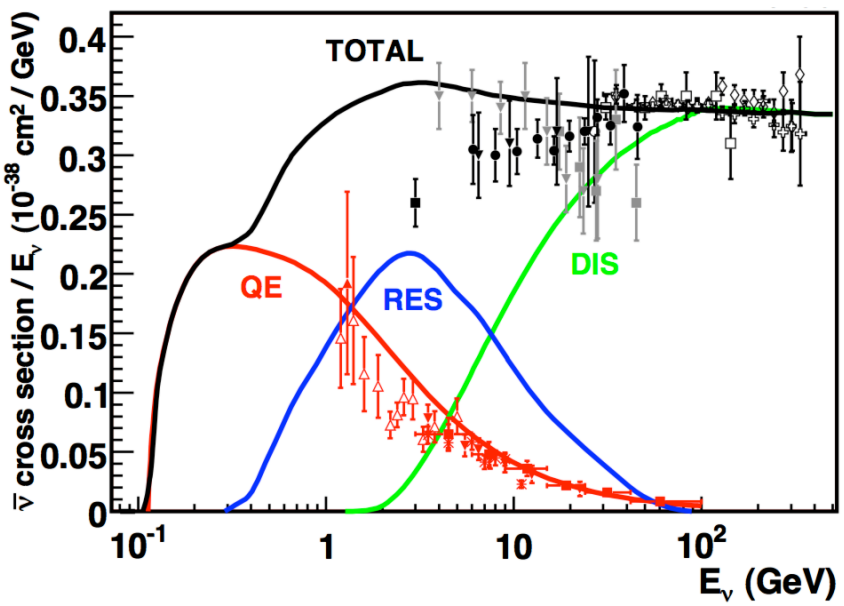
Long Baseline Program at THEIA

Challenges for photon-based detectors for long-baseline νs:

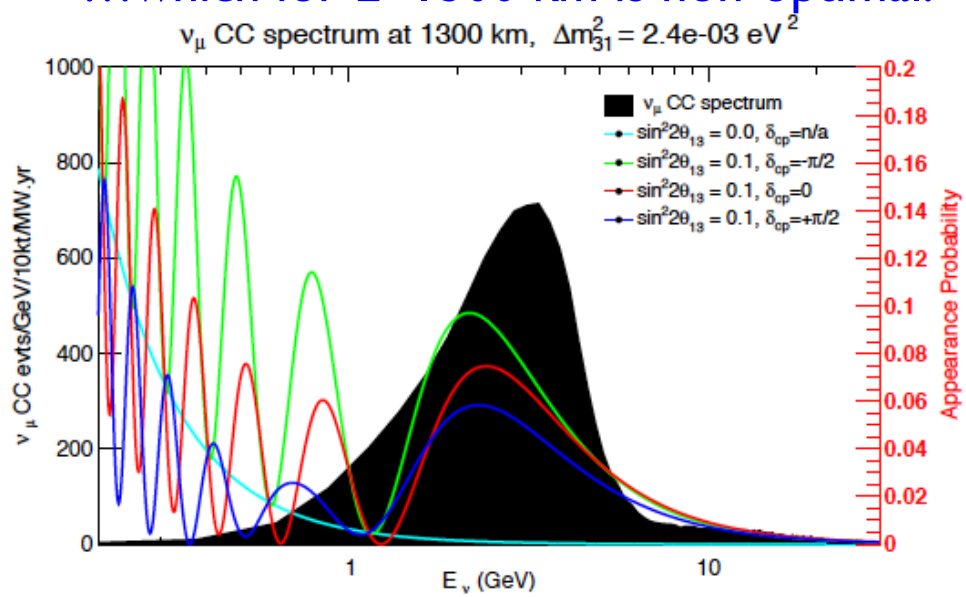
- Low-energy secondaries may be invisible (Cherenkov)
- No real tracking (scintillation in particular)
- Precision of vertex reconstruction limited

This leads to scintillation detectors focused only on low-energy νs…

…and Cherenkov detectors using primarily quasi-elastic events…



…which for L=1300 km is non-optimal.



And rejection of asymmetric π_0s is relatively poor---low acceptance even for QE

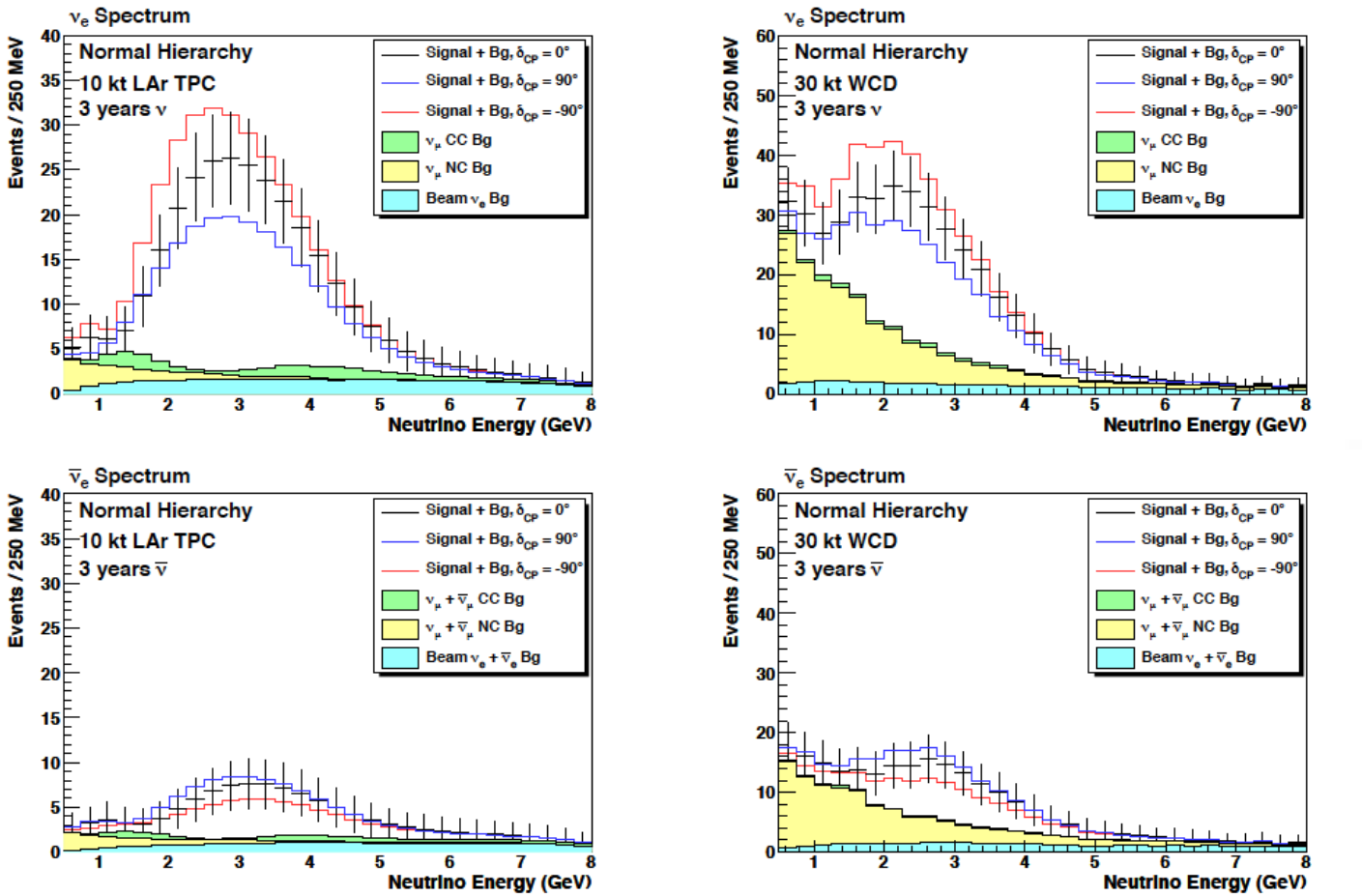
$\gamma \longleftarrow \pi^0 \longrightarrow \gamma$

Boost $\longrightarrow$

Long Baseline Program at THEIA

Nevertheless…treating scintillation light as just a "nuisance" that effectively degrades the coverage to SK II levels:

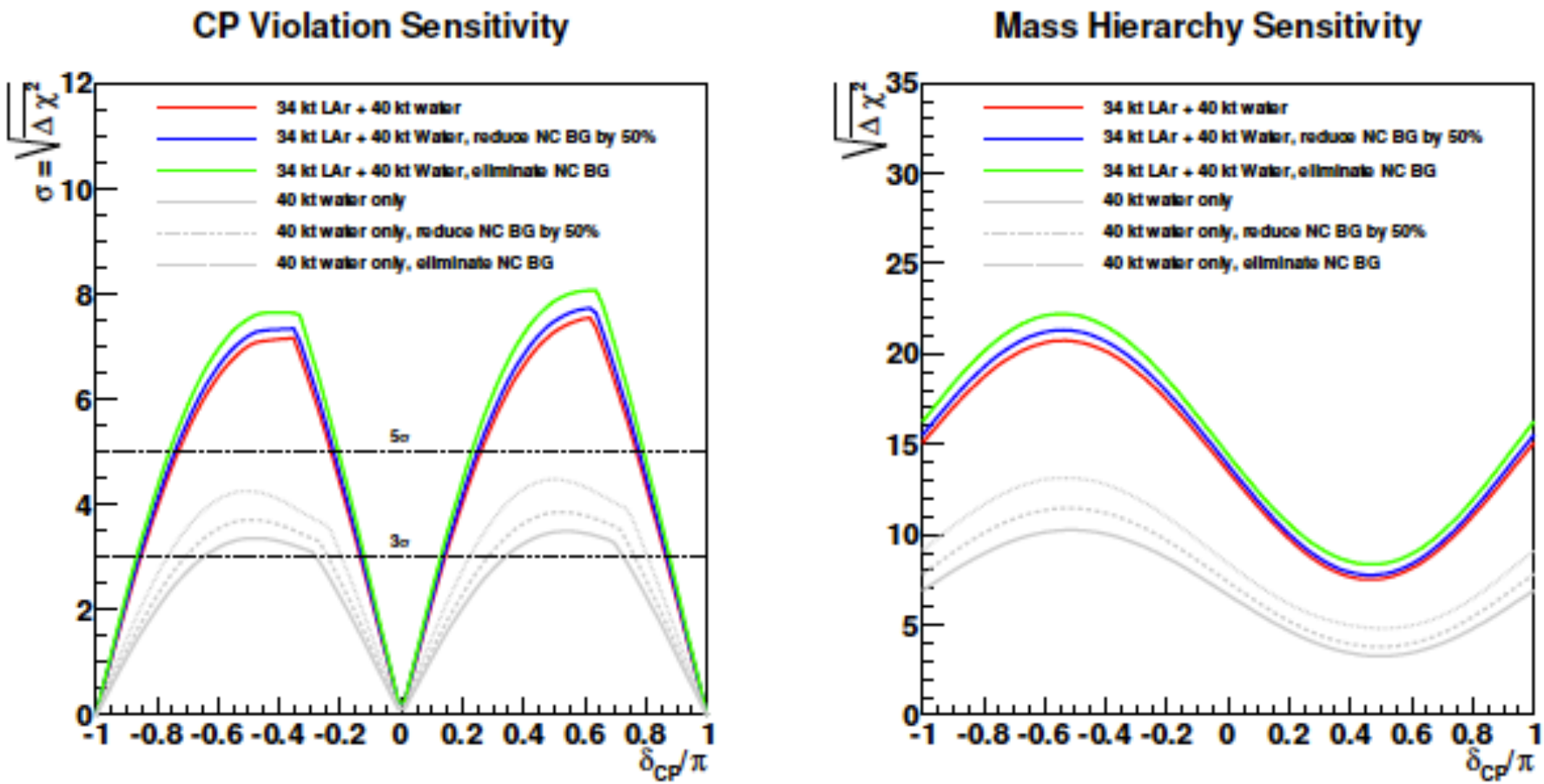
30 kt_{H2O} vs. 10 kt_{LAr}



E. Worcester (BNL)

Long Baseline Program at THEIA

Nevertheless…treating scintillation light as just a "nuisance" that effectively degrades the coverage to SK II levels:



By itself, such a detector would be an interesting experiment, though clearly not as powerful kt-per-kt with LAr-TPC.

E. Worcester (BNL)

Long Baseline Program at THEIA

Yet several ways in which THEIA could make a big difference:

- Measurement dominated by quasi-elastics on O and H
  - Cross sections relatively easy to model
  - Already well-studied
- Mass could be increased if optics more water-like than scint-like
  - 150 ktonne roughly equivalent to 40 ktonne LAr
- Fast timing may make higher multiplicity events reconstructable
  - "Photon TPC" (Wetstein)
  - Makes WbLS and LAr-TPC more comparable kt-for-kt
- Scintillation light may provide additional particle ID
  - Asymmetric π_0 decays have more "scintlight" than expected from "Cherlight"
  - Hadrons also have "anomalous" Cher/Scint ratio
  - Neutrons captures allow counting from low E gammas
- If LBNF beam is steerable (under discussion) then second oscillation maximum will have more flux

Path Forward Toward THEIA

THEIA "Interest Group" formed with concept paper:

Advanced Scintillator Detector Concept (ASDC):
A Concept Paper on the Physics Potential of Water-Based Liquid Scintillator

arXiv:1409.5864

J. R. Alonso,[1] N. Barros,[2] M. Bergevin,[3] A. Bernstein,[4] L. Bignell,[5] E. Blucher,[6] F. Calaprice,[7] J. M. Conrad,[1] F. B. Descamps,[8] M. V. Diwan,[5] D. A. Dwyer,[8] S. T. Dye,[9] A. Elagin,[6] P. Feng,[10] C. Grant,[3] S. Grullon,[2] S. Hans,[5] D. E. Jaffe,[5] S. H. Kettell,[5] J. R. Klein,[2] K. Lande,[2] J. G. Learned,[11] K. B. Luk,[8,12] J. Maricic,[11] P. Marleau,[10] A. Mastbaum,[2] W. F. McDonough,[13] L. Oberauer,[14] G. D. Orebi Gann*,[8,12,†] R. Rosero,[5] S. D. Rountree,[15] M. C. Sanchez,[16] M. H. Shaevitz,[17] T. M. Shokair,[18] M. B. Smy,[19] A. Stahl,[20] M. Strait,[6] R. Svoboda,[3] N. Tolich,[21] M. R. Vagins,[19] K. A. van Bibber,[18] B. Viren,[5] R. B. Vogelaar,[15] M. J. Wetstein,[6] L. Winslow,[1] B. Wonsak,[22] E. T. Worcester,[5] M. Wurm,[23] M. Yeh,[5] and C. Zhang[5]

50 authors, 23 institutions, lots of experience: Borexino, DUNE, KamLAND, SNO, Double CHOOZ, SNO+, Daya Bay, LENA, KamLAND-Zen, MiniBOONE, Super-Kamiokande, WATCHMAN, ANNIE, T2K....

Brookhaven National Laboratory
University of California, Berkeley
University of California, Davis
University of California, Irvine
University of Chicago
Columbia University
University of Hawaii at Manoa
Hawaii Pacific University
Iowa State University
Lawrence Berkeley National Laboratory
Los Alamos National Laboratory
University of Maryland
MIT
University of Pennsylvania
Princeton University
Sandia National Laboratories
Virginia Polytechnic Inst. & State University
University of Washington
RWTH Aachen University
TUM, Physik-Department
University of Hamburg
Johannes Gutenberg-University Mainz

New participation welcome
Contact
G.D. Orebi Gann, R. Svoboda, E. Blucher, JRK

Path Forward Toward THEIA

Critical Near-term Questions:

- What are relevant properties of WbLS?
- How is physics program optimized by WbLS cocktail?
- What is the biggest detector that can reasonably be built?
- How good is reconstruction?
- Are there new particle ID methods made possible by Cher+Scint?
- How good does timing need to be to do Cher/Scint separation?
- Are there technologies that can push this method further?

This is a great R&D program which is accessible to everyone from undergrads to senior scientists.

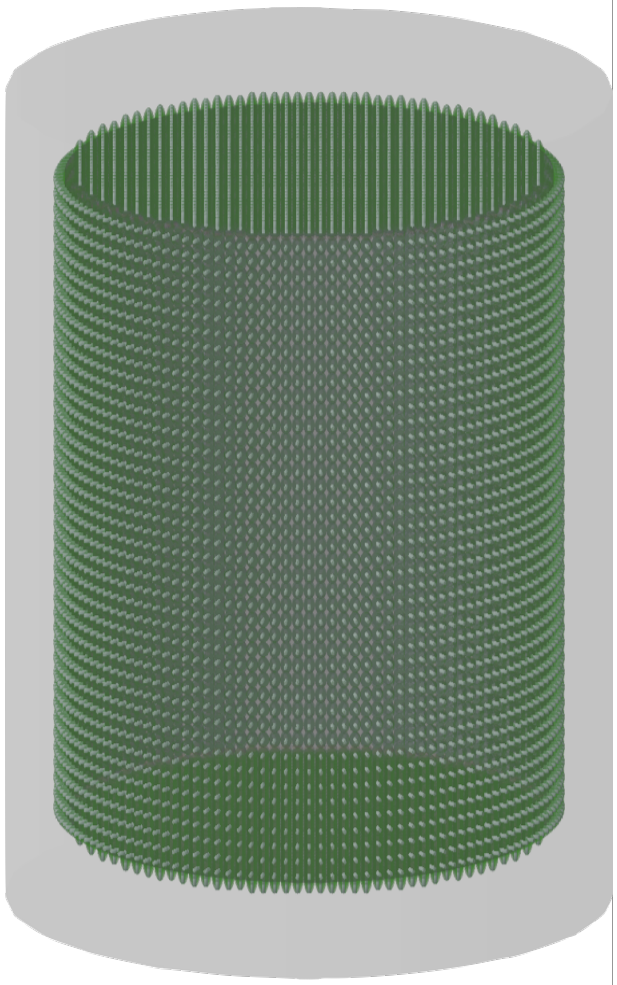
Path Forward Toward THEIA

Simulation and Analysis Development

- Started with "RAT" simulation/analysis package
- Plus Additional Code from L-Z development

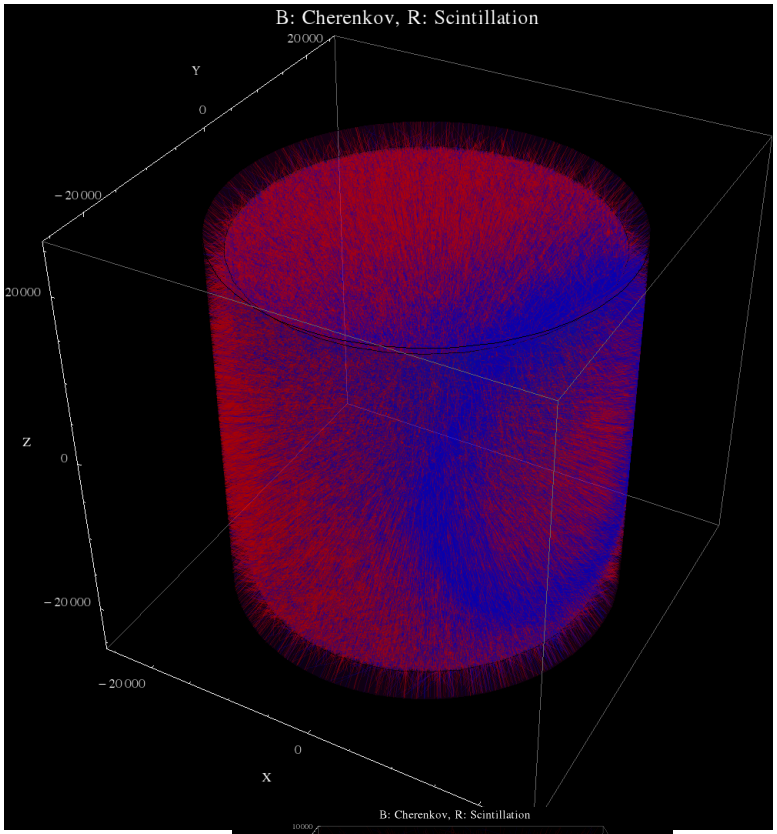
= RAT-PAC

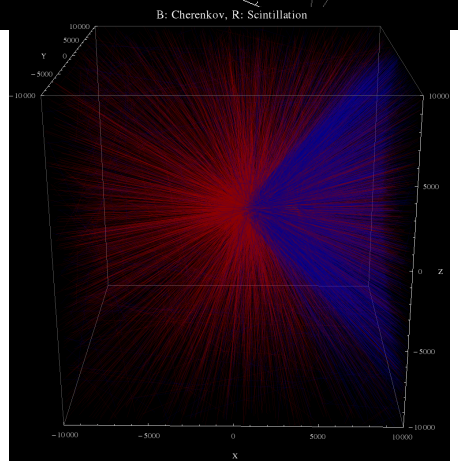
- Fully Open Source
- Includes complete THEIA geometry
  - 12" HQE PMTs
  - Simple WbLS properties
- Ported reconstruction algorithms from SNO and Super-K
- Adopted also by WATCHMAN
- Easily adaptable to test-stands
- Lots of development happening!

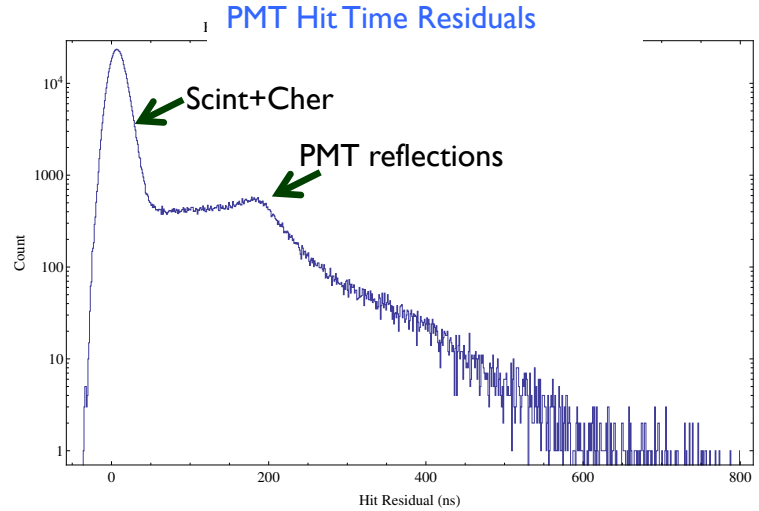


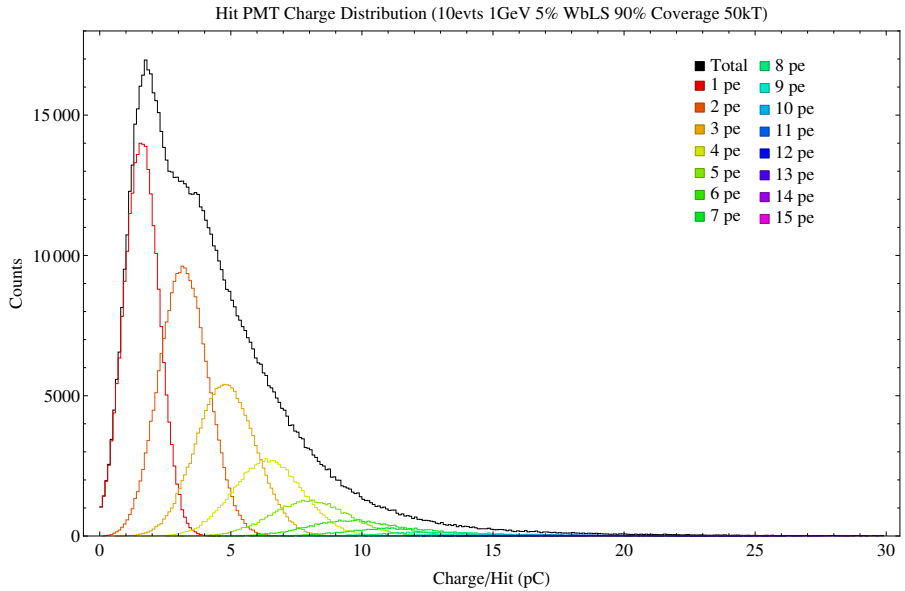
Path Forward Toward THEIA

Simulation and Analysis Development





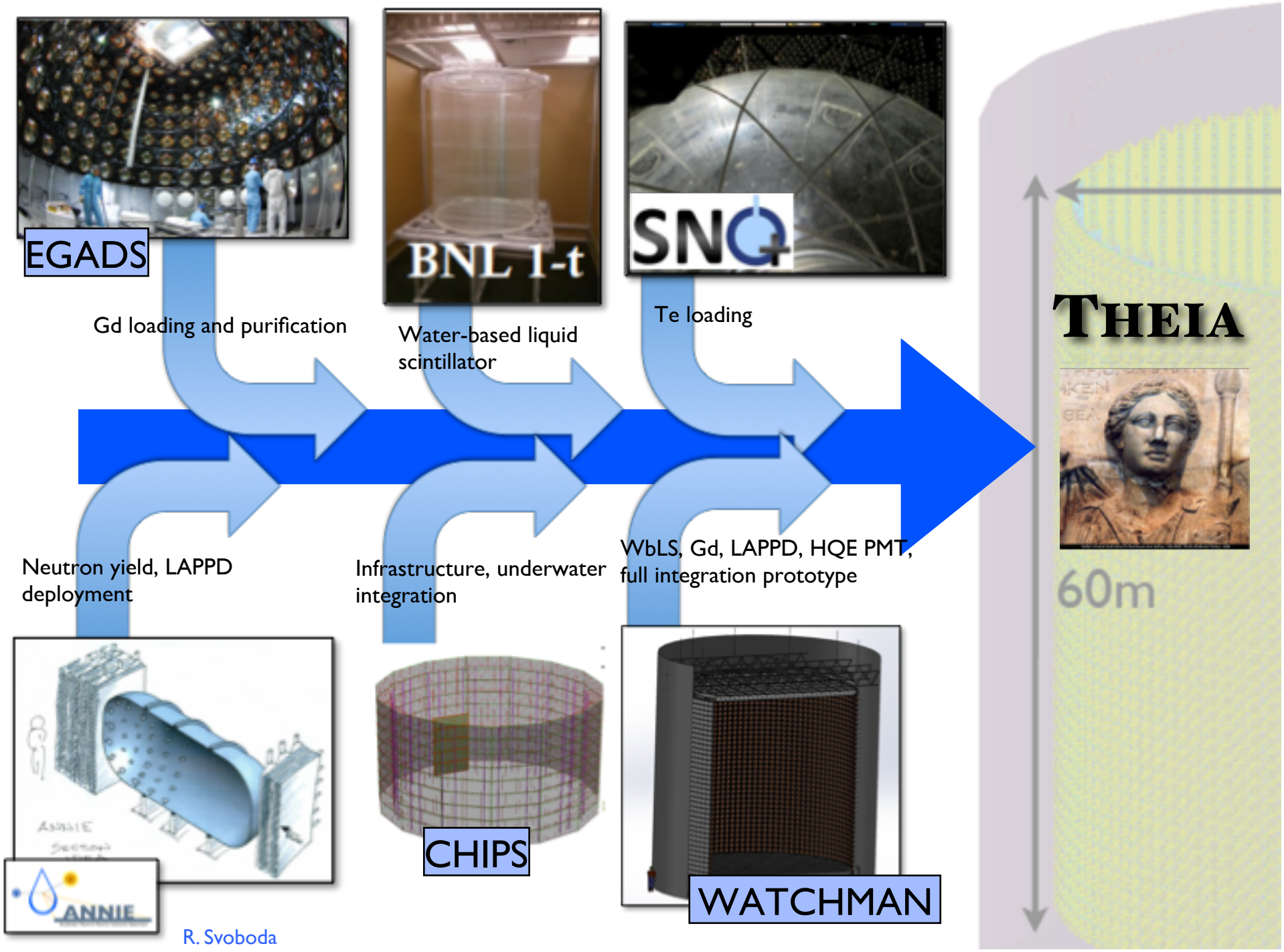




B. Land (Berkeley)

Planned Demonstrations

Site	Scale	Target	Measurements	Timescale
UChicago	bench top	H2O	fast photodetectors	Exists
CHIPS	10 kton		electronics, readout, mechanical infrastructure	2019
EGADS	200 ton	H2O+Gd	isotope loading, fast photodetectors	Exists
ANNIE	30 ton			2016
WATCHMAN	1 kton			2019
UCLA/MIT	1 ton	LS	fast photodetectors	2015
Penn	30 L	(Wb)LS	light yield, timing, loading	Exists
SNO+	780 ton			2016
LBNL	bench top	WbLS	light yield, timing, cocktail optimization, loading, attenuation, reconstruction	Early 2015
BNL	1 ton			Summer 2015
WATCHMAN-II	1 kton			2020

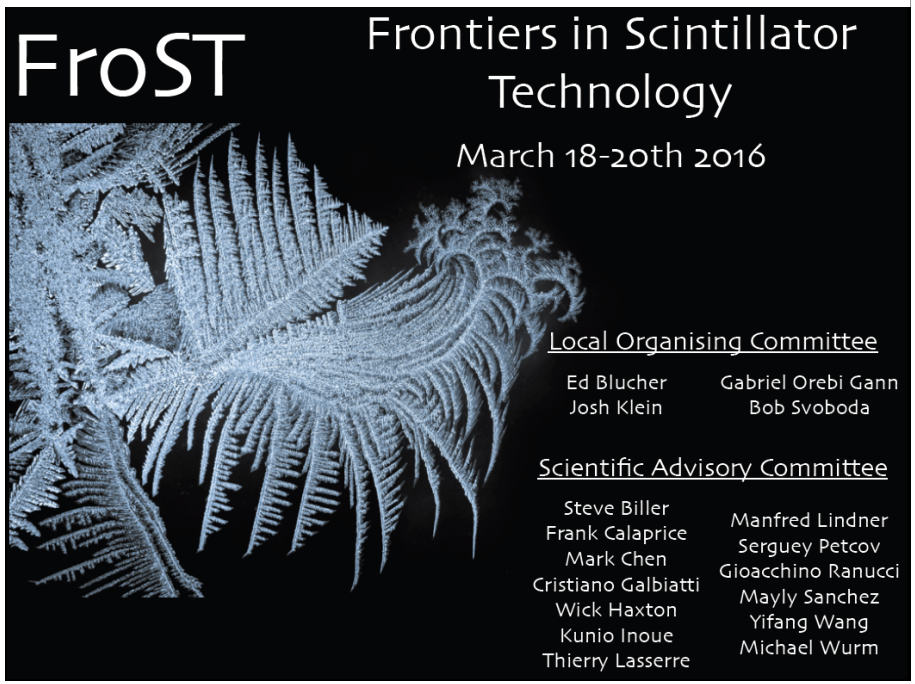

EGADS
BNL 1-t
SNO+
Gd loading and purification
Water-based liquid scintillator
Te loading
THEIA
60m
Neutron yield, LAPPD deployment
Infrastructure, underwater integration
WbLS, Gd, LAPPD, HQE PMT, full integration prototype
ANNIE
CHIPS
WATCHMAN

R. Svoboda

Summary

- Great opportunity with LBNF
- Can exploit this with a broad physics program that overlaps with DUNE
- New technologies (WbLS, LAPPDs, isotope loading) make a very broad program possible
- Work on THEIA is proceeding surprisingly rapidly

Workshop here next year!



Long Baseline Physics

Extremely rich phenomenology,:

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = {} & 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31} \\
& + 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos \Delta_{32} \cdot \sin \Delta_{31} \cdot \sin \Delta_{21} \\
& - 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin \Delta_{32} \cdot \sin \Delta_{31} \cdot \sin \Delta_{21} \\
& + 4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2 \Delta_{21} \\
& - 8C_{13}^2 S_{13}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos \Delta_{32} \cdot \sin \Delta_{31} \\
& + 8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{31}^2} (1 - 2S_{13}^2) \cdot \sin^2 \Delta_{31},
\end{aligned}
$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E_\nu}$$

$$a = 2\sqrt{2} G_F n_e E$$

$$\mathcal{A}_{cp}(E_\nu) \approx \frac{\cos\theta_{23} \sin 2\theta_{12} \sin\delta}{\sin\theta_{23} \sin\theta_{13}} \left(\frac{\Delta m_{21}^2 L}{4E_\nu} \right) + \text{matter effects.}$$

Long Baseline Physics

Should we bother measuring δ?

- "Models can be built…" and "arguments can be made" that connect δ to Majorana CP violation and leptogenesis.

$|\sin\theta_{13}\sin\delta| \gtrsim 0.11$ (Pascoli, Petcov, Riotto, Nuc. Phys. B 774, (2007))

- But we should remember that this

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \simeq \frac{\Delta m^2_{12} L}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \cdot \sin\delta$$

is a *prediction* of the 3-flavor model. δ can (in principle) be measured independently of A_{CP} using just the oscillation patterns. With such a measurement, we predict the oscillation probabilities for anti-ν_μs into anti-ν_es and ask:

$$\frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \stackrel{?}{\simeq} \frac{\Delta m^2_{12} L}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \cdot \sin\delta$$