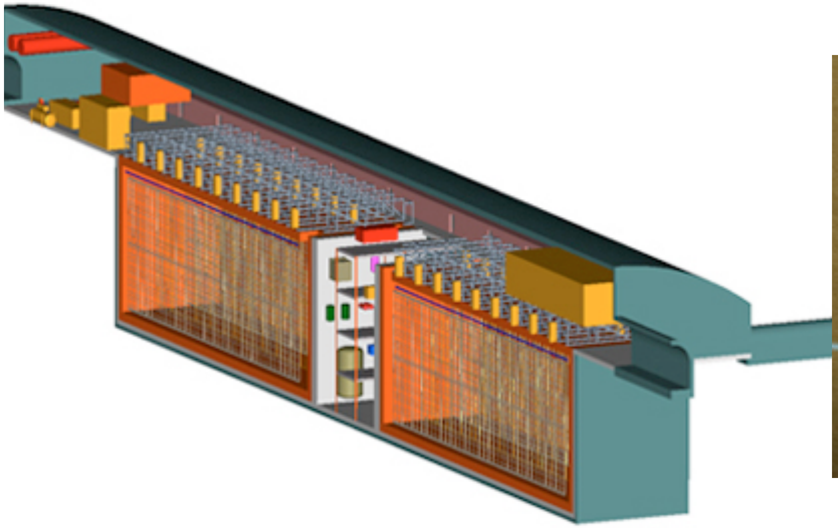
Physics Program of a
Water-based Liquid Scintillator Detector

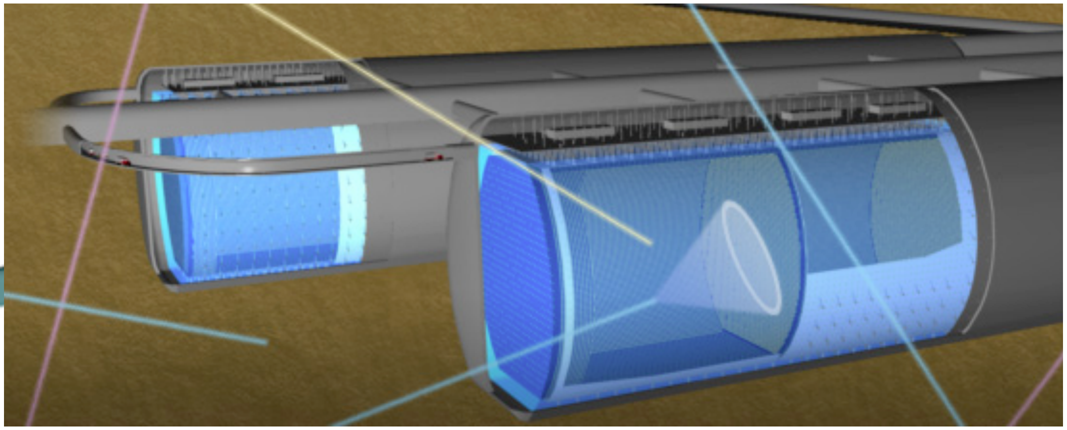
Motivation

Long-baseline physics goals have gotten a lot of attention:

- 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.





Motivation

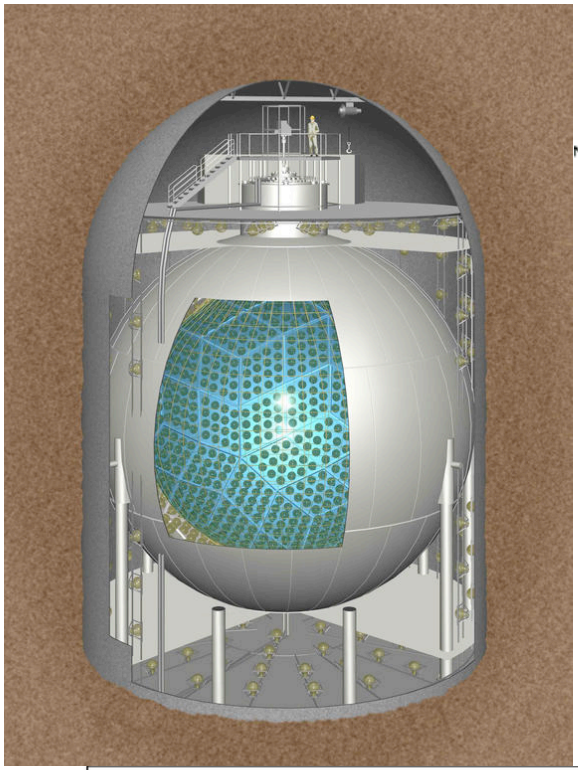
Critical physics to do outside of LBL program:

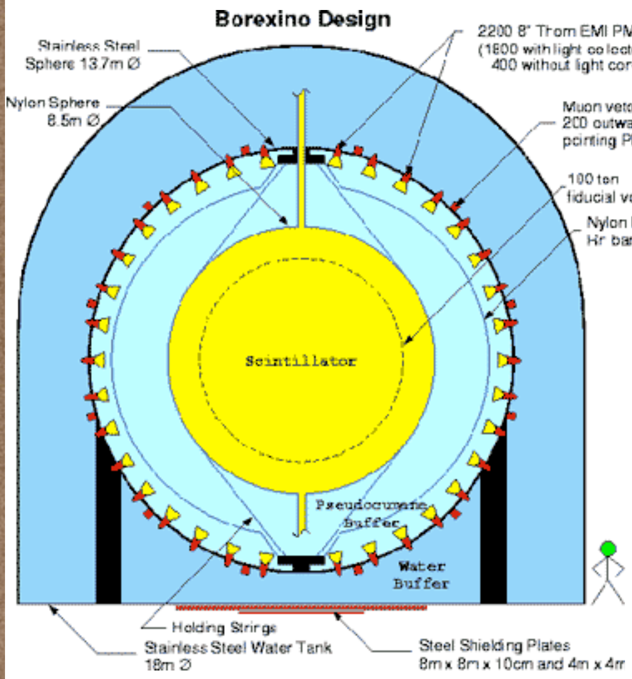
- Majorana vs. Dirac
- Solar neutrinos
- Mixing angles and mass differences in (1,2) sector
- Geoneutrinos
- Diffuse supernova (anti)neutrino background

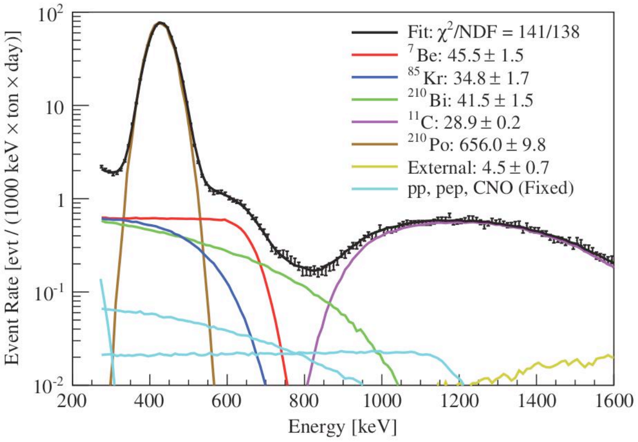
(Clearly this list is not exhaustive either)

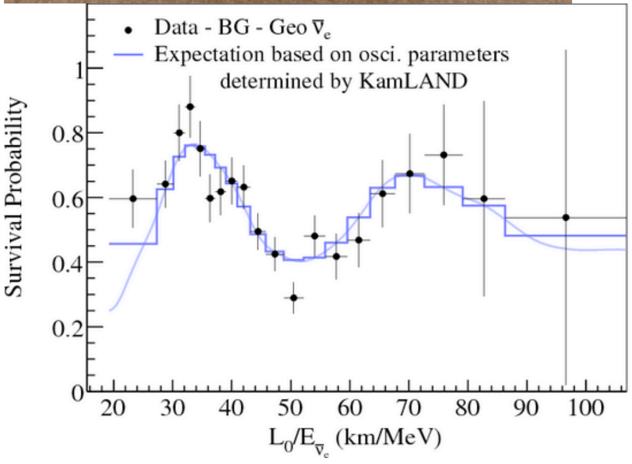
Broadening the Program

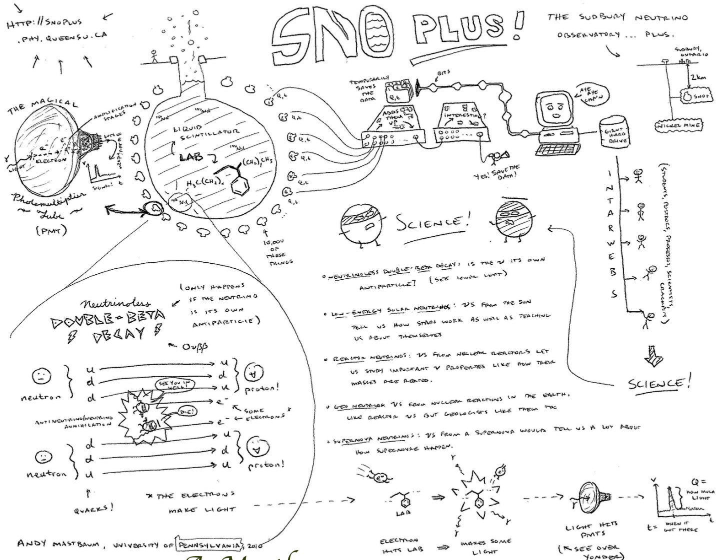
A large-scale scintillation detector clearly has access to low-E physics:







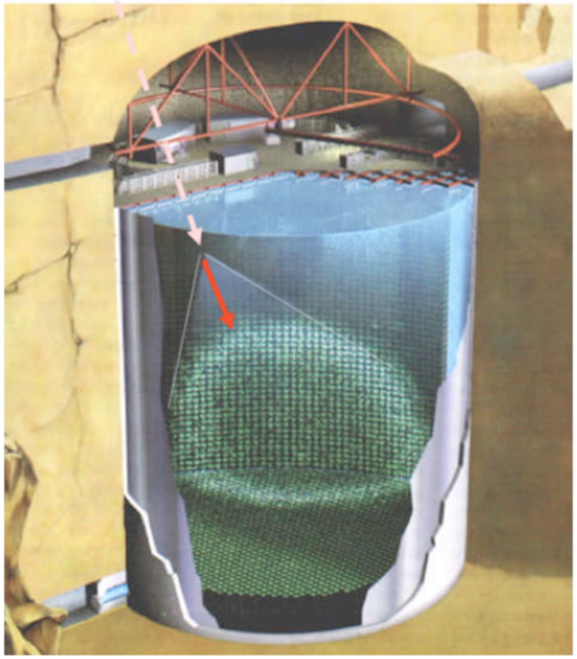


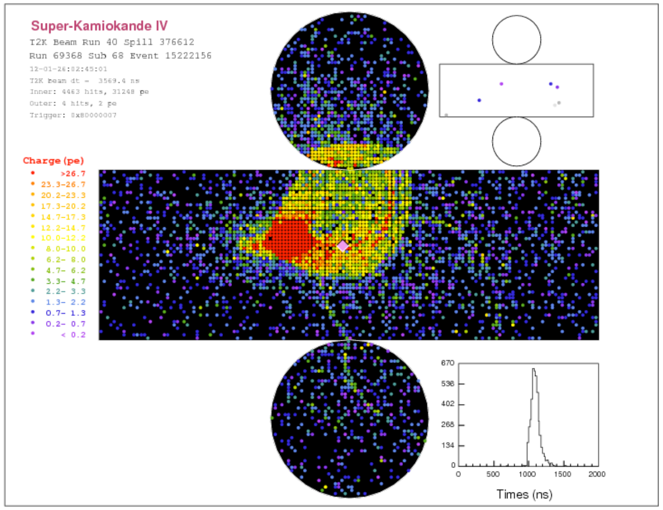


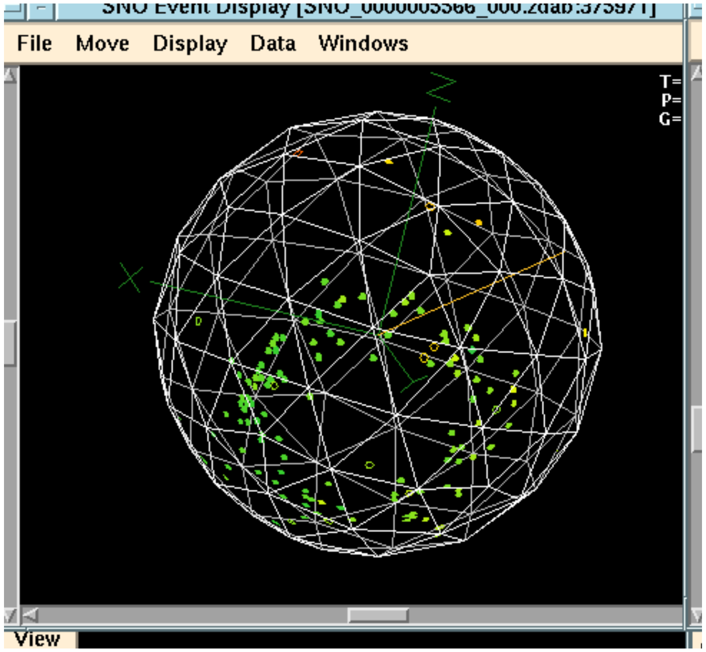
A. Mastbaum

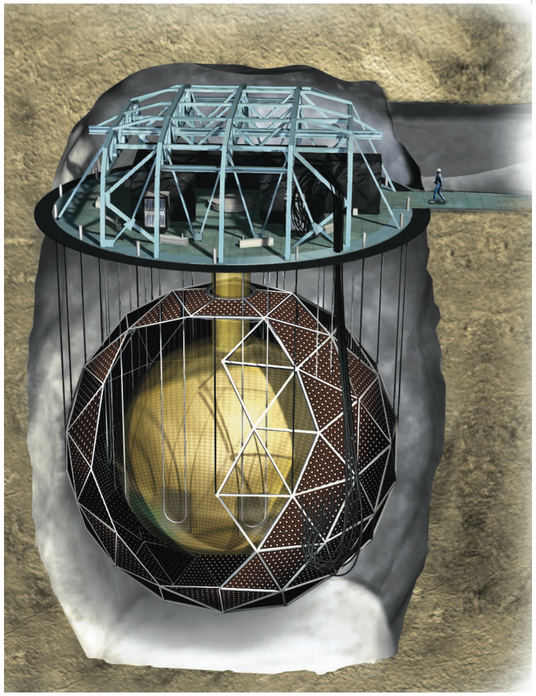
Broadening the Program

And big Cherenkov detectors to high-energy physics:




Super-Kamiokande IV
T2K Beam Run 40 Spill 376612
Run 69368 Sub 68 Event 15222156
12-01-26:02:45:01
T2K beam dt = 3569.4 ns
Inner: 4463 hits, 31248 pe
Outer: 4 hits, 2 pe
Trigger: 0x80000007





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:

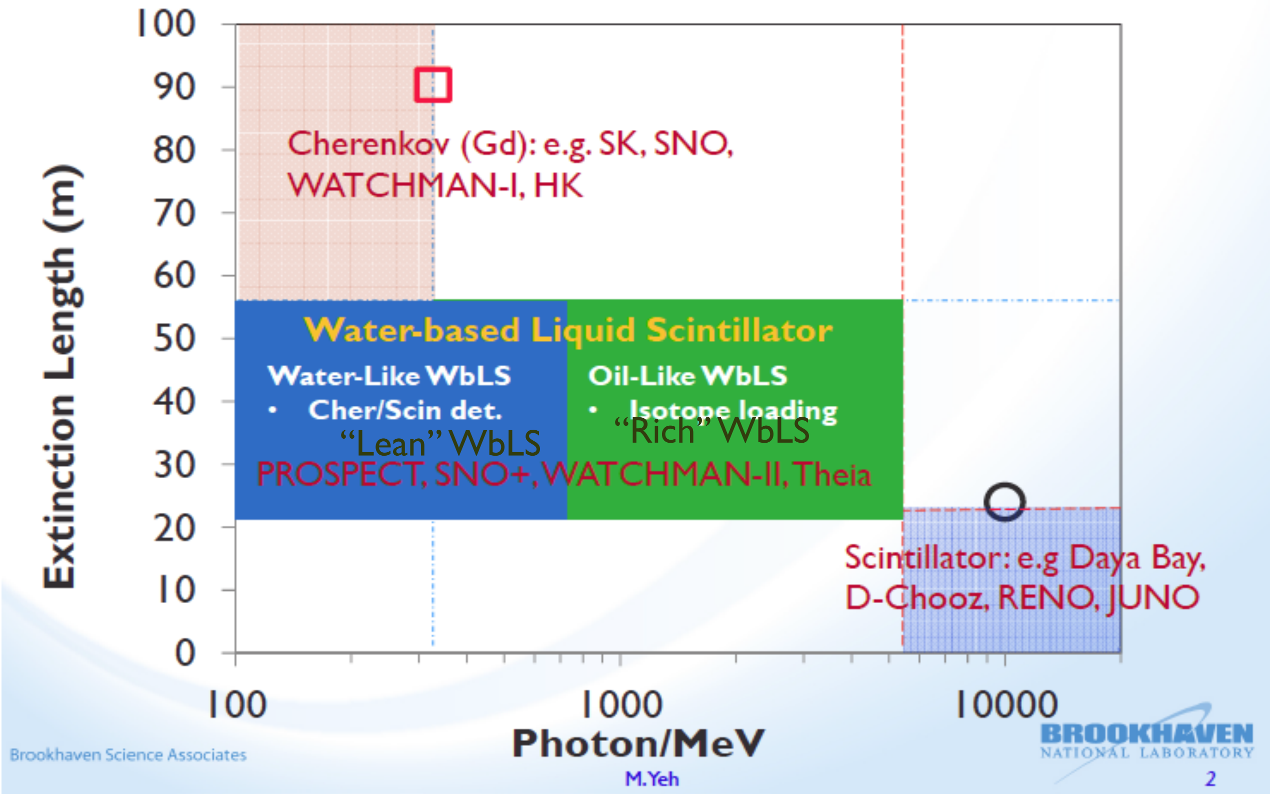
- Limited in size because scintillator absorbs light
- Have high scattering making direction reconstruction difficult
- Are expensive even if they could be made large

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

Water-based Liquid Scintillator

Developed at Brookhaven National Lab



- Long attenuation length compared to scintillator=bigger detector
- Higher light yield=low threshold, good energy resolution
- High Cherlight/scintlight ratio makes directionality and background rejection possible

Water-based Liquid Scintillator Detector

- New materials (water-based liquid scintillator)

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

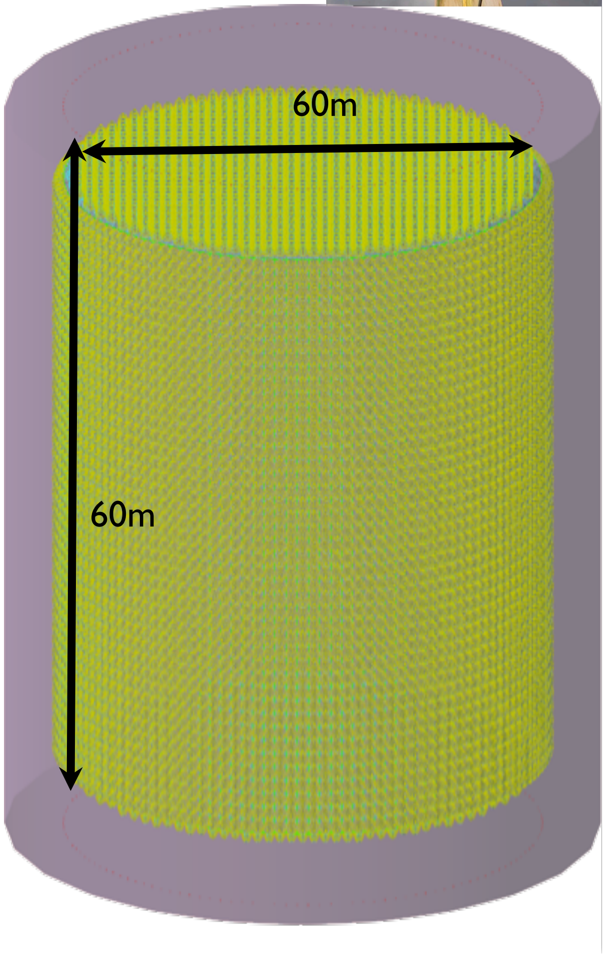
\+ Flexible design

May satisfy conflicting requirements.

THEIA

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"



High coverage with sensitive photodetectors makes up for lower light yield than scintillator

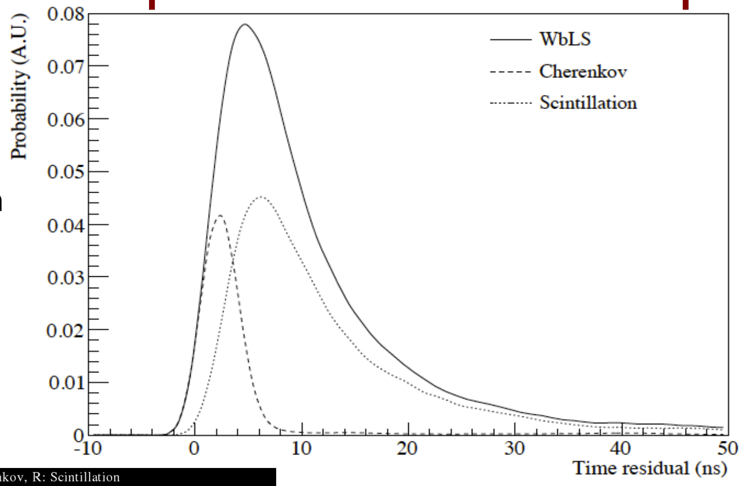
Fast timing (or other tricks) distinguishes cherlight from scintlight for direction reconstruction

Water-based Liquid Scintillator

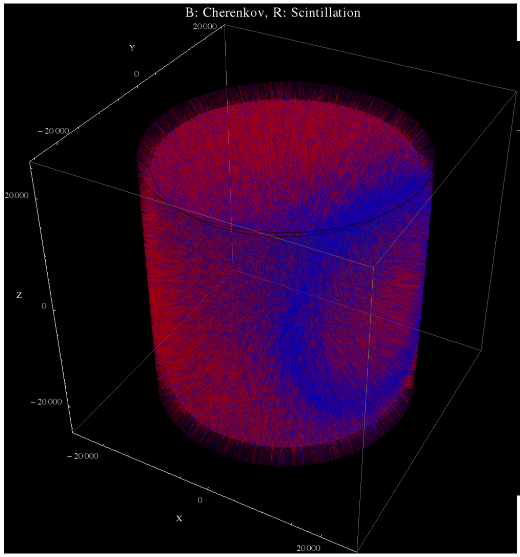
Cherenkov/Scintillation Separation

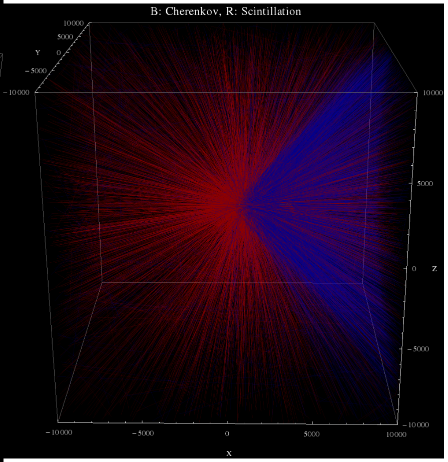
- Long extinction length means detector can be large
- About ½ of Cherenkov light absorbed or scattered
- But separation of two components still possible

A. Mastbaum (Penn)



THEIA





B. Land (Berkeley)

Cherenkov ID scales like

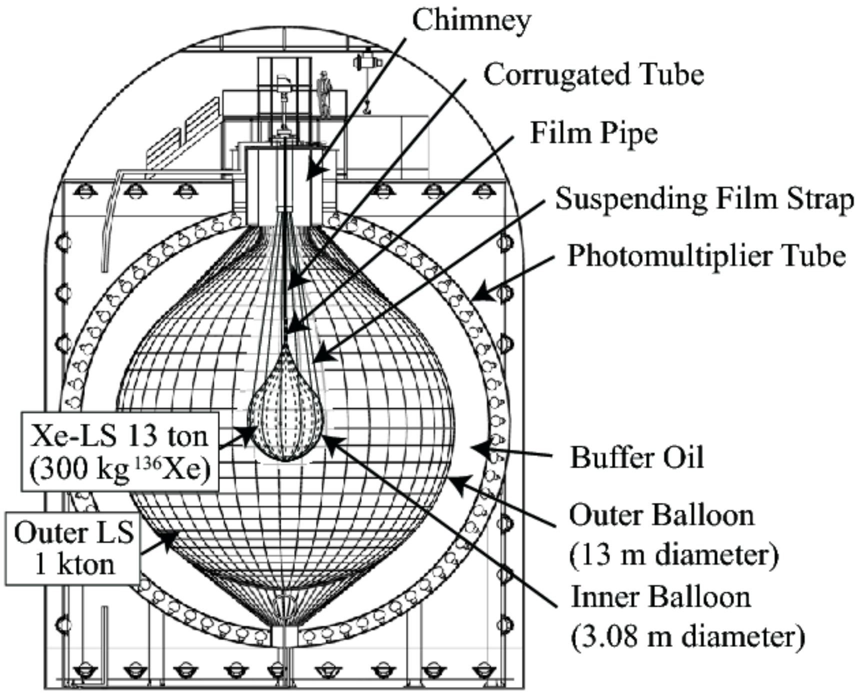
$$R_{s/c} \sim \frac{\gamma_C}{\gamma_S} \frac{t_{jitt}}{\tau_{scint}} \rho(\cos\alpha_C) R(\lambda)$$

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

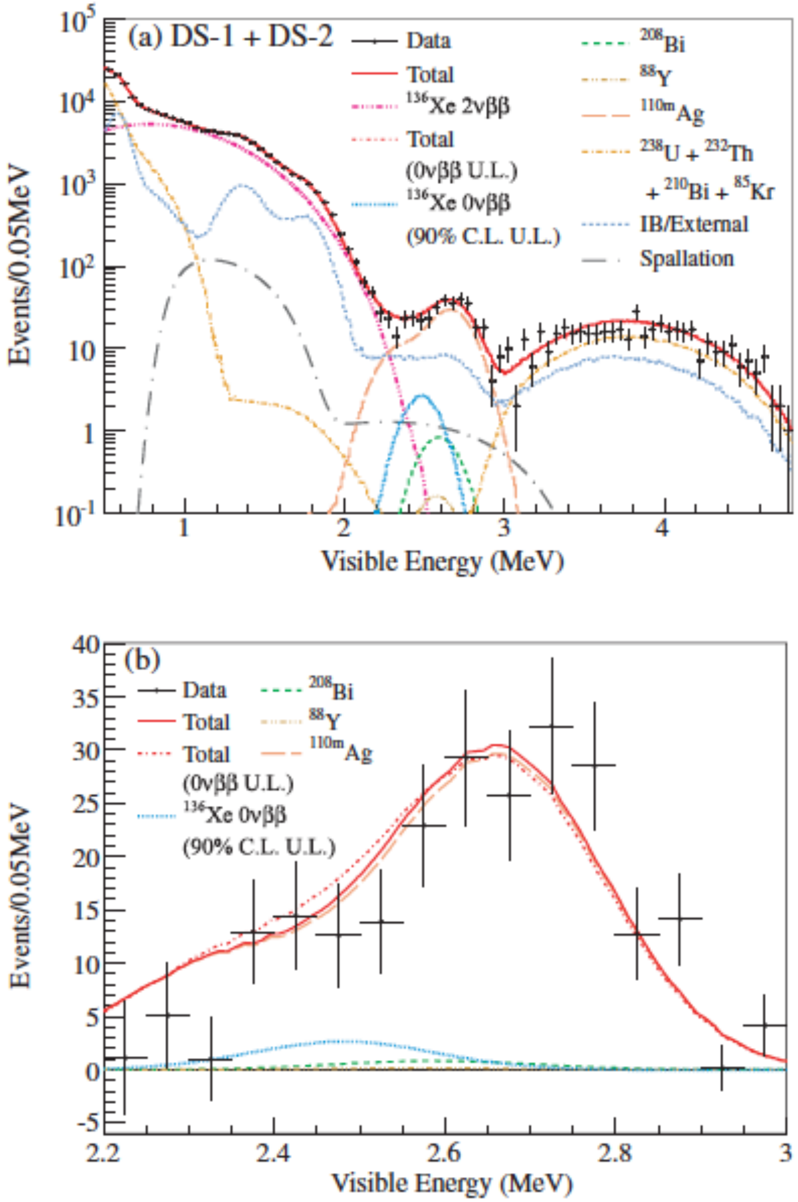
So for a 4% scintillation fraction, standard PMTs, no use of angular information, and equal spectral response for C and S, $R_{s/c}$~ 0.25

0νββ with WbLS

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



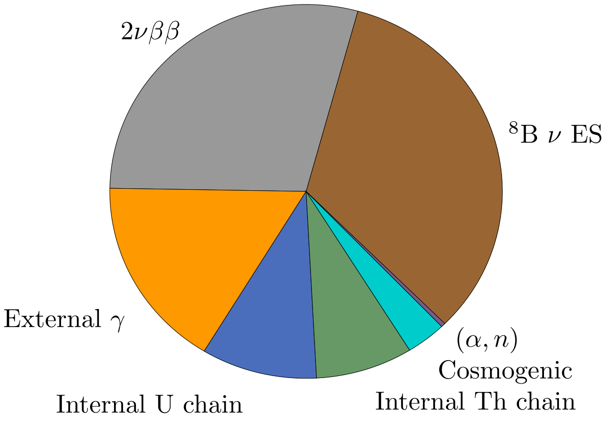
And yet KamLAND-Zen has best ββ limit

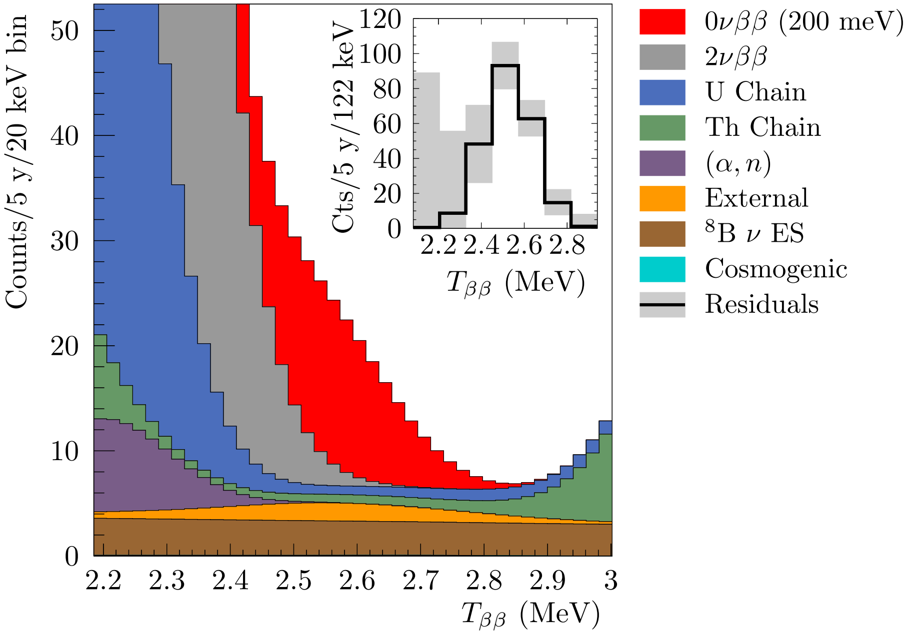


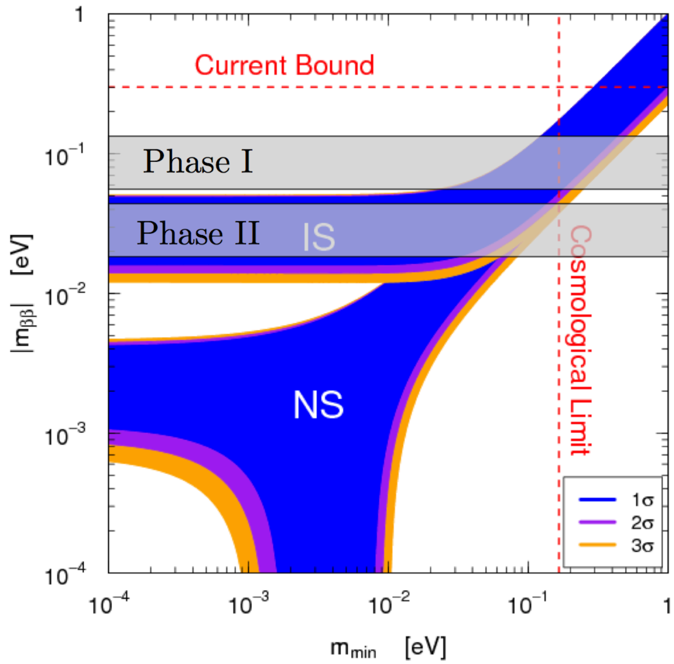
Phys. Rev. Lett. 110, 062502

$0\nu\beta\beta$ with WbLS

SNO+ Approach







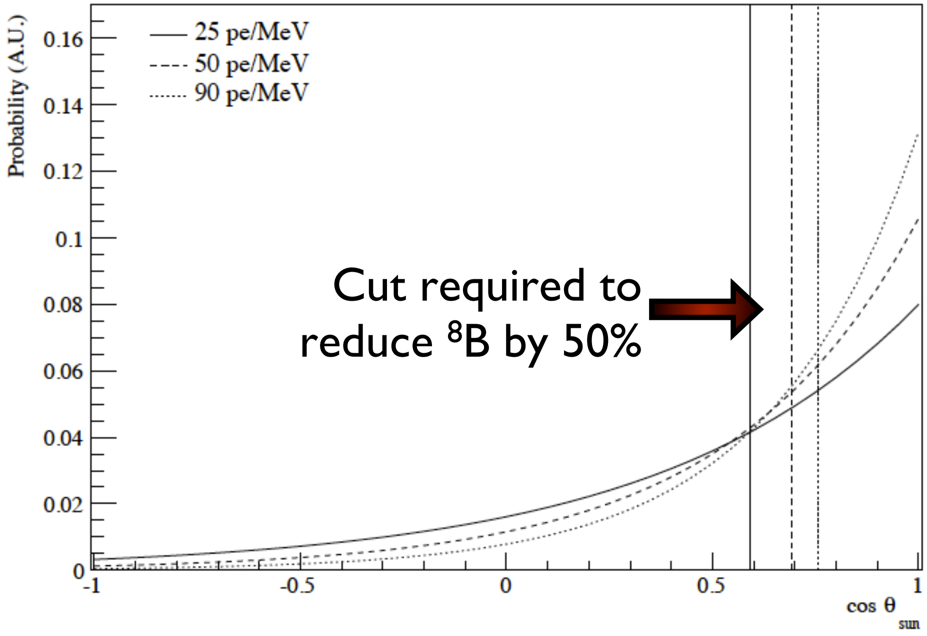
adapted from Bilenky & Giunti

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" (NSAC criterion)

0νββ with WbLS



Cut required to reduce ^{8}B by 50%

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

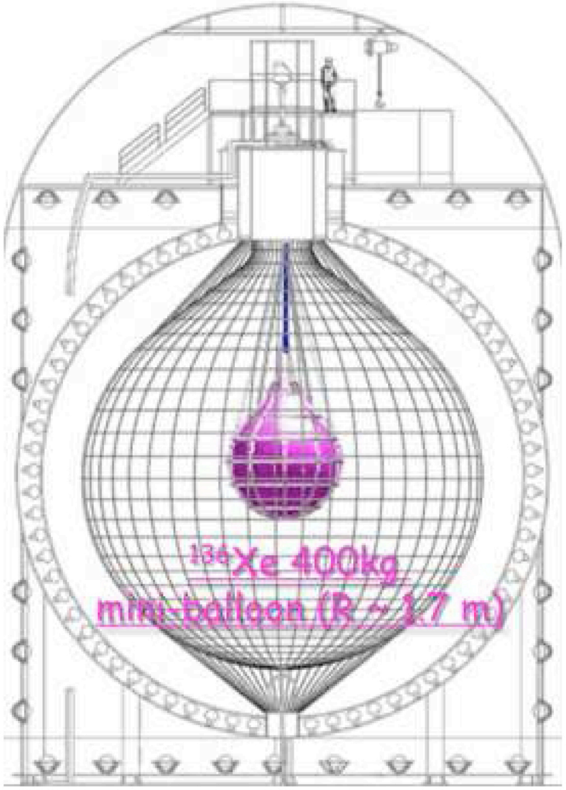
$t = 10$ y

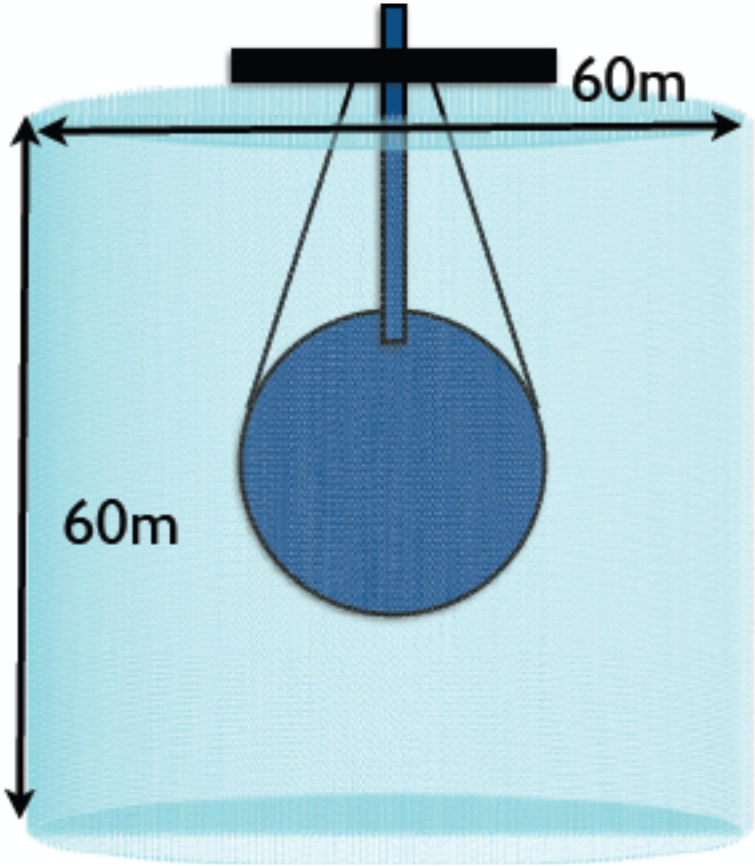
Flexibility

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

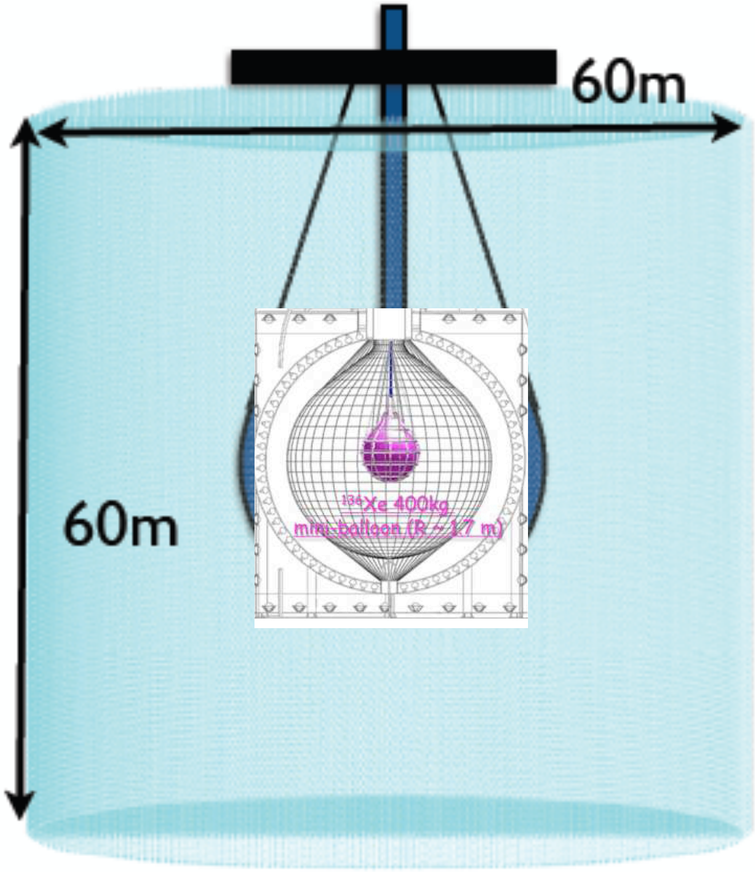




Flexibility

Containment "bag" would allow:

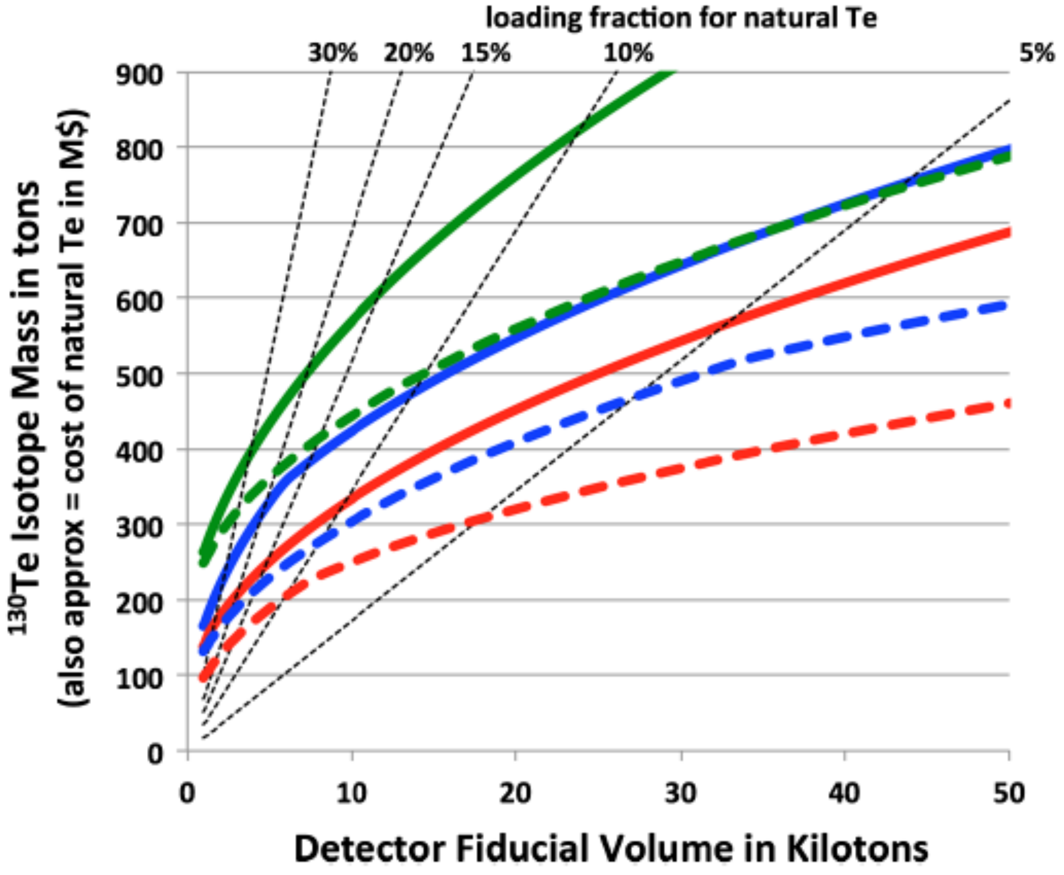
- Richer scintillator mixture
- Loaded scintillator distinct from rest of volume
- Simultaneous all water/all scintillator detector
- Deployment depending on physics needs



0νββ at THEIA

Going further….

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

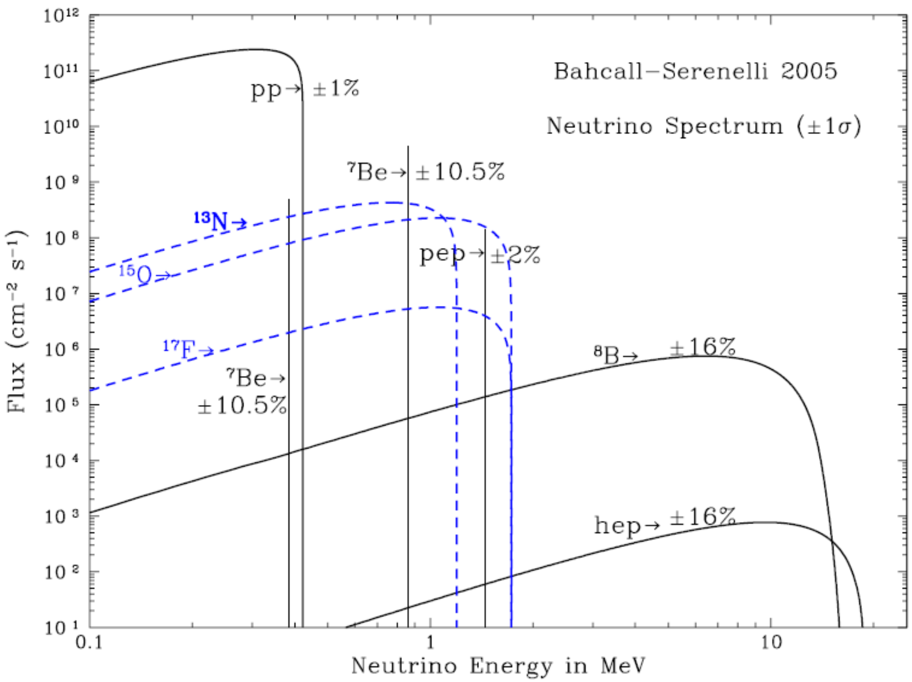


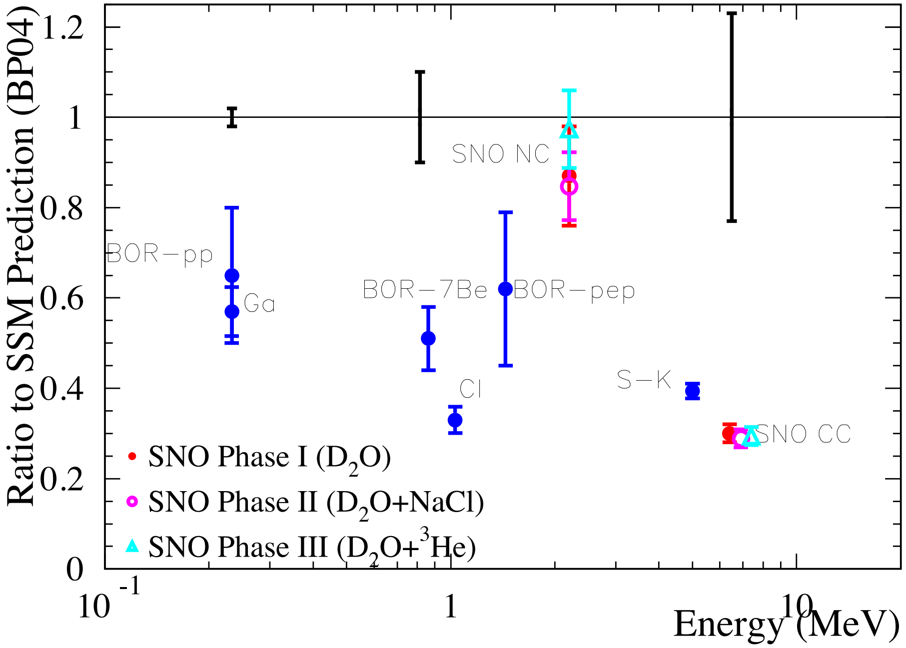
Likely would require a balloon inside THEIA to maximize useful isotope and light yield.

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

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





Aren’t we done here?

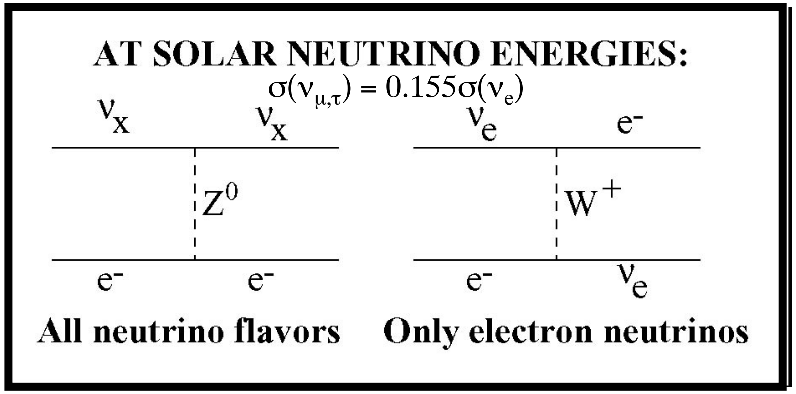
Solar Neutrinos
Physics

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

Observing MSW Phenomenology

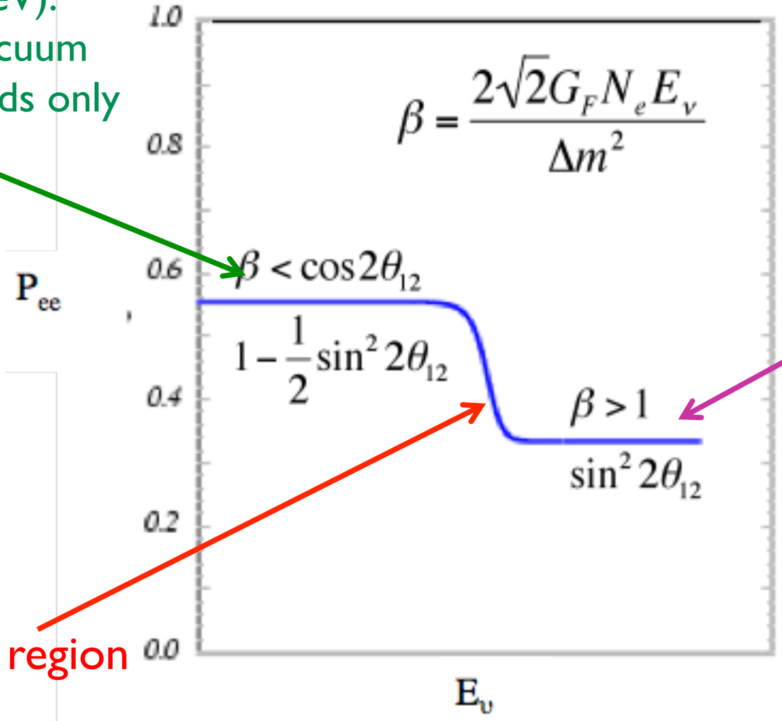

AT SOLAR NEUTRINO ENERGIES:

$\sigma(\nu_{\mu,\tau}) = 0.155\sigma(\nu_e)$

All neutrino flavors **Only electron neutrinos**

Day/Night ν_e Asymmetry

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



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

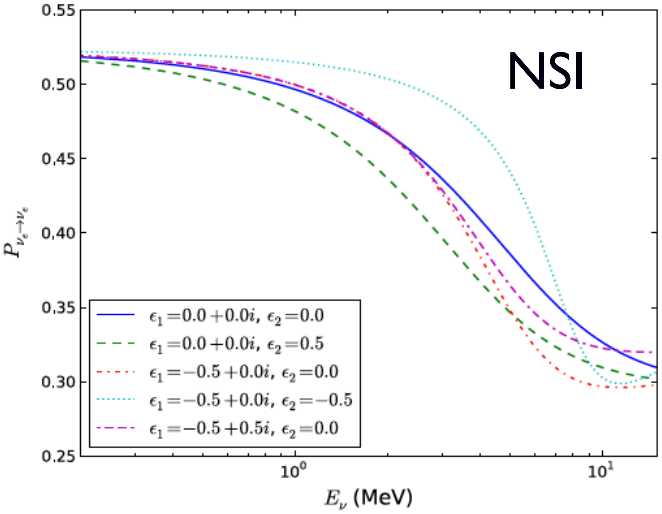
Transition region

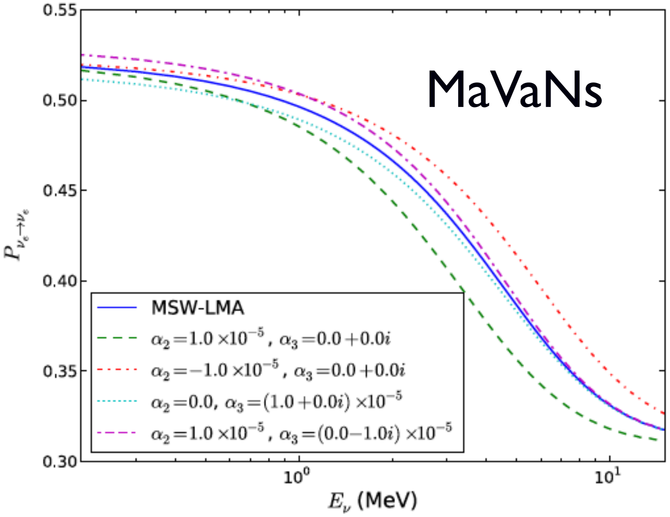
Interferometry on top of interferometry…

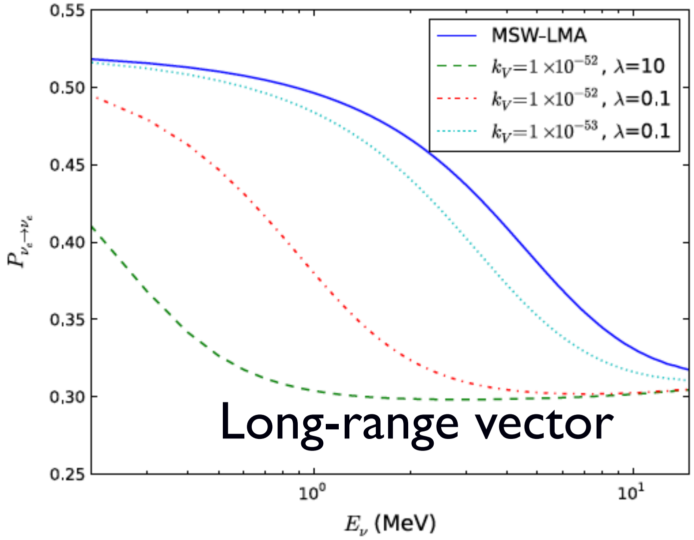
Anything that distinguishes flavor or mass states changes position and width of transition region

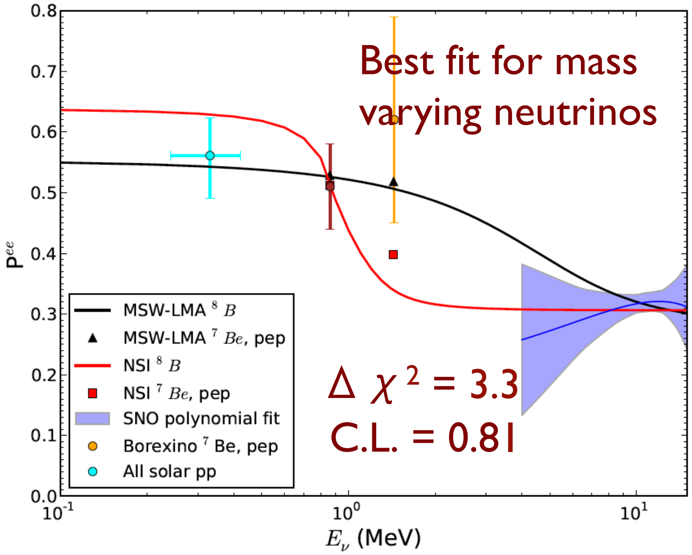
Observing MSW Phenomenology

Vacuum/matter transition region









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

Need "statistics of Super-K with light yield of BOREXINO"

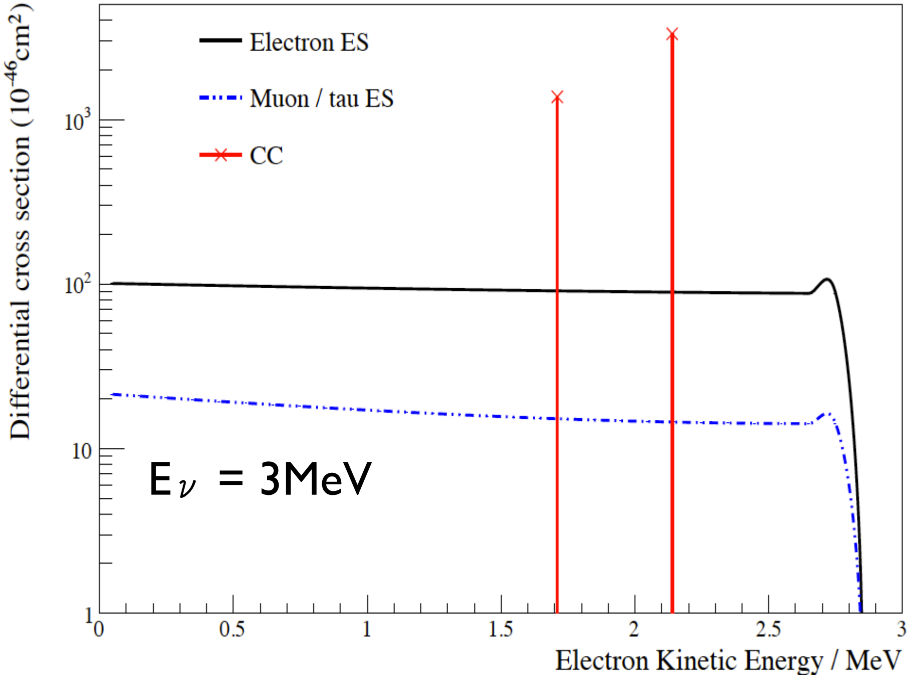
Bonventre, LaTorre, et al.

PHYSICAL REVIEW D **88,** 053010 (2013)

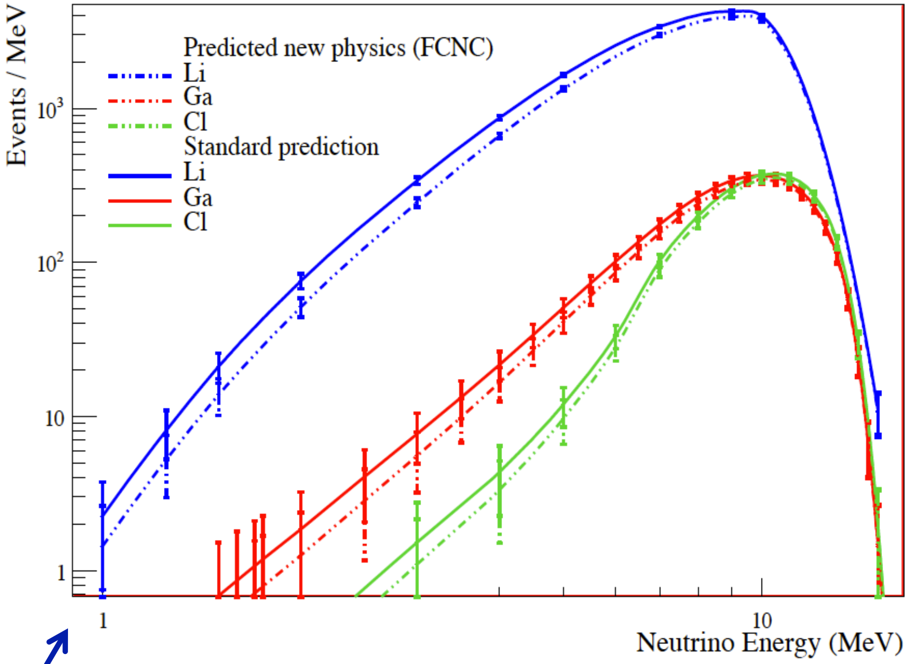
Solar νs with WbLS

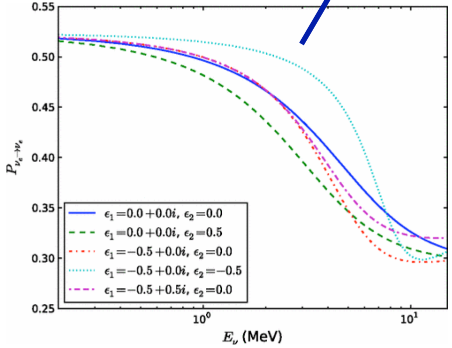
Even better: “Salty water Cherenkov detectors” W.C. Haxton PRL 76 (1996) 10

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



Makes models easy to distinguish

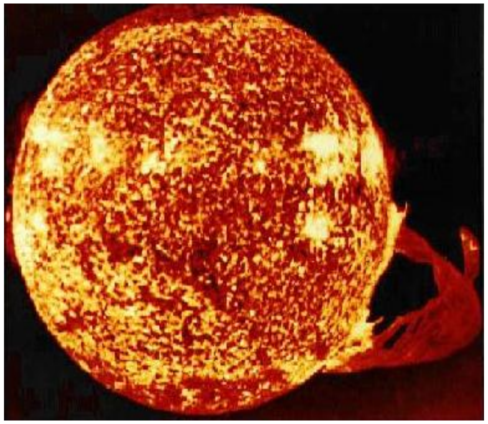


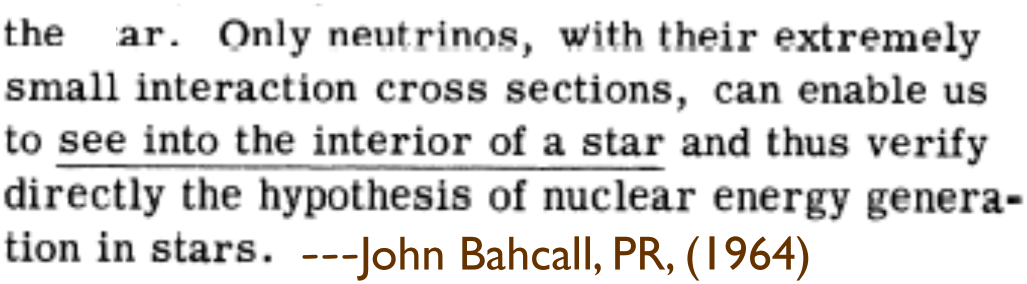


G. D. Orebi Gann (Berkeley)

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

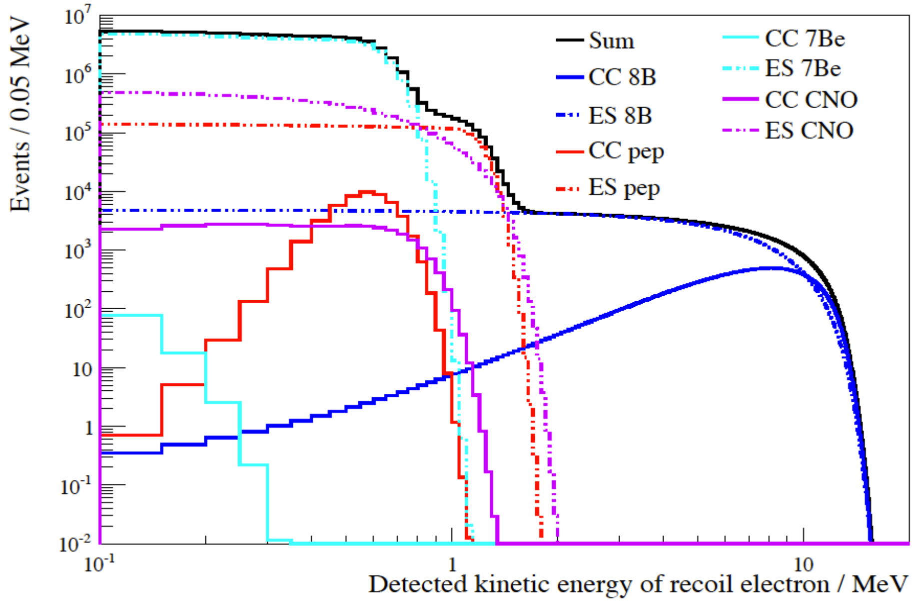
→ Flux may differ by factor of 2 between old/new metallicity

(Maybe Jupiter and Saturn `stole’ metals from solar photosphere?

---Haxton and Serenelli, Astrophys.J. 687 (2008)

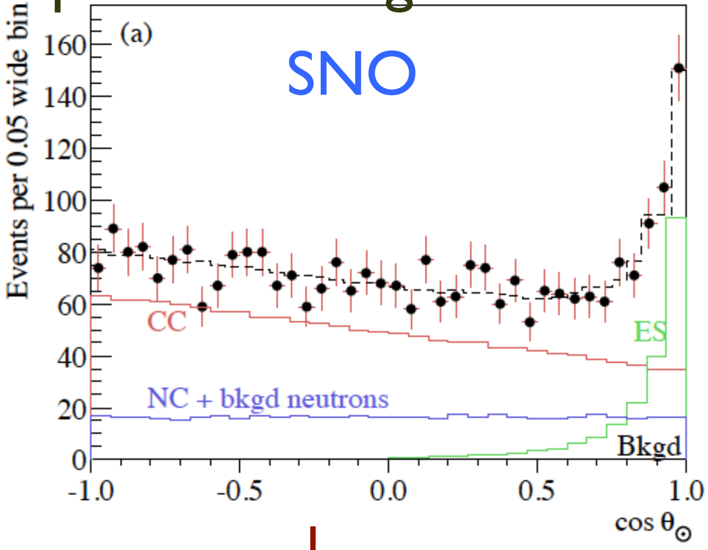
Solar νs with WbLS

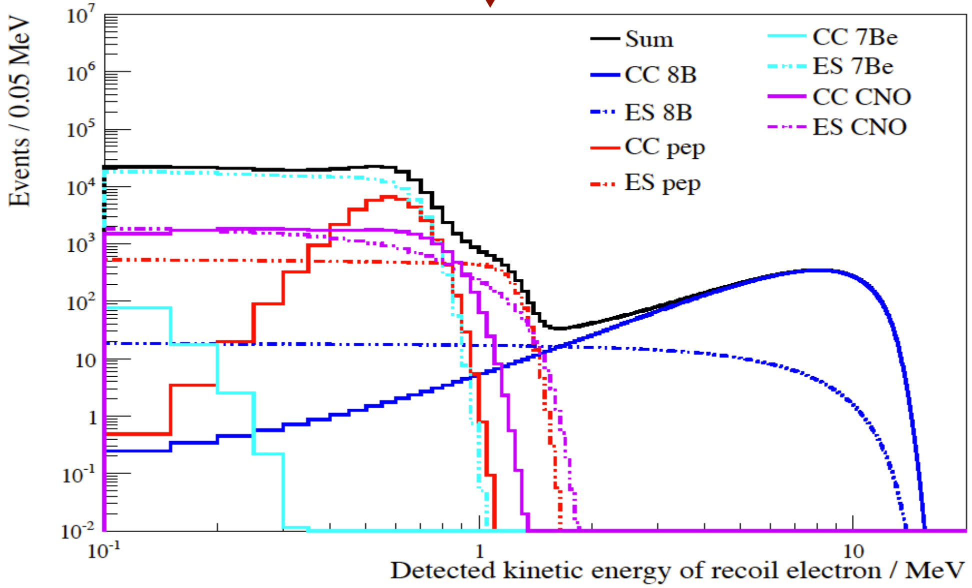
Low-energy solar νs also possible via CC and ES via Li loading:



G.D. Orebi Gann

Separation using direction:





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

pp/pep and the Sun

Are all energy generation/loss mechanisms accounted for?

With luminosity constraint:

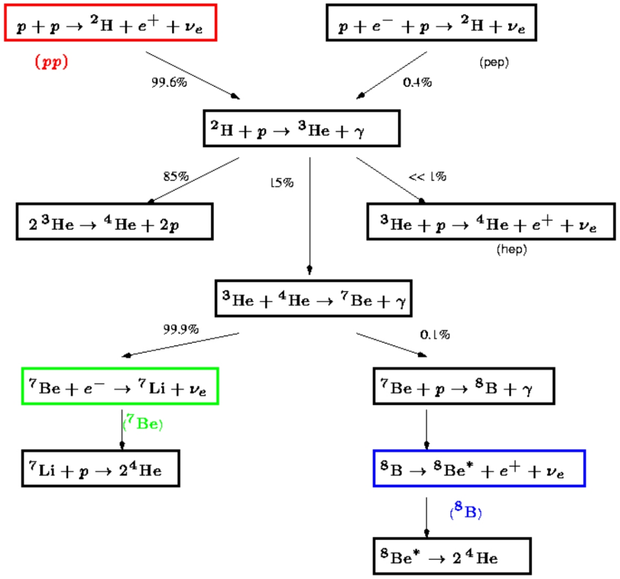
Exp. Uncs. Theory Uncs.

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

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



$p+p \rightarrow {}^2\mathrm{H} + e^+ + \nu_e$

(pp)

$p + e^- + p \rightarrow {}^2\mathrm{H} + \nu_e$

(pep)

99.6%

0.4%

${}^2\mathrm{H} + p \rightarrow {}^3\mathrm{He} + \gamma$

85%

15%

<< 1%

$2\,{}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2p$

${}^3\mathrm{He} + p \rightarrow {}^4\mathrm{He} + e^+ + \nu_e$

(hep)

${}^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$

99.9%

0.1%

${}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e$

$({}^7\mathrm{Be})$

${}^7\mathrm{Li} + p \rightarrow 2\,{}^4\mathrm{He}$

${}^7\mathrm{Be} + p \rightarrow {}^8\mathrm{B} + \gamma$

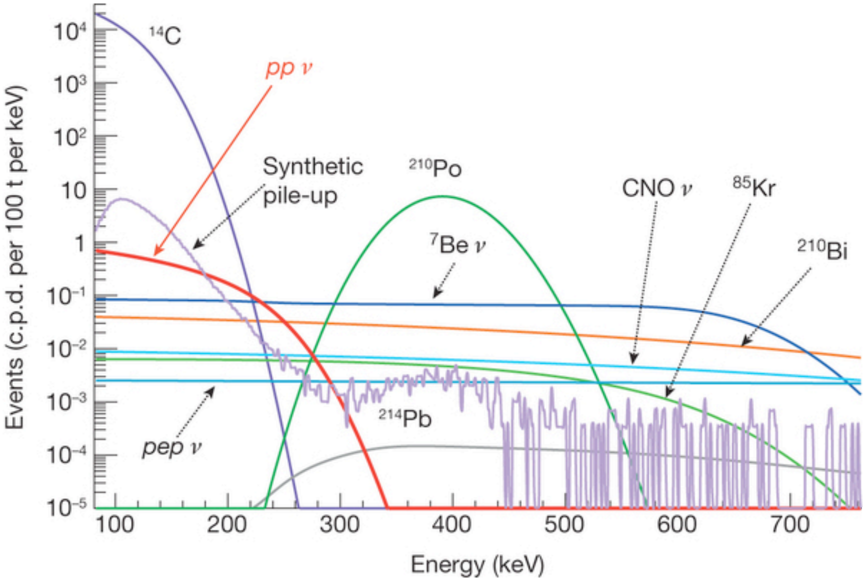
${}^8\mathrm{B} \rightarrow {}^8\mathrm{Be}^* + e^+ + \nu_e$

$({}^8\mathrm{B})$

${}^8\mathrm{Be}^* \rightarrow 2\,{}^4\mathrm{He}$

pp Measurements

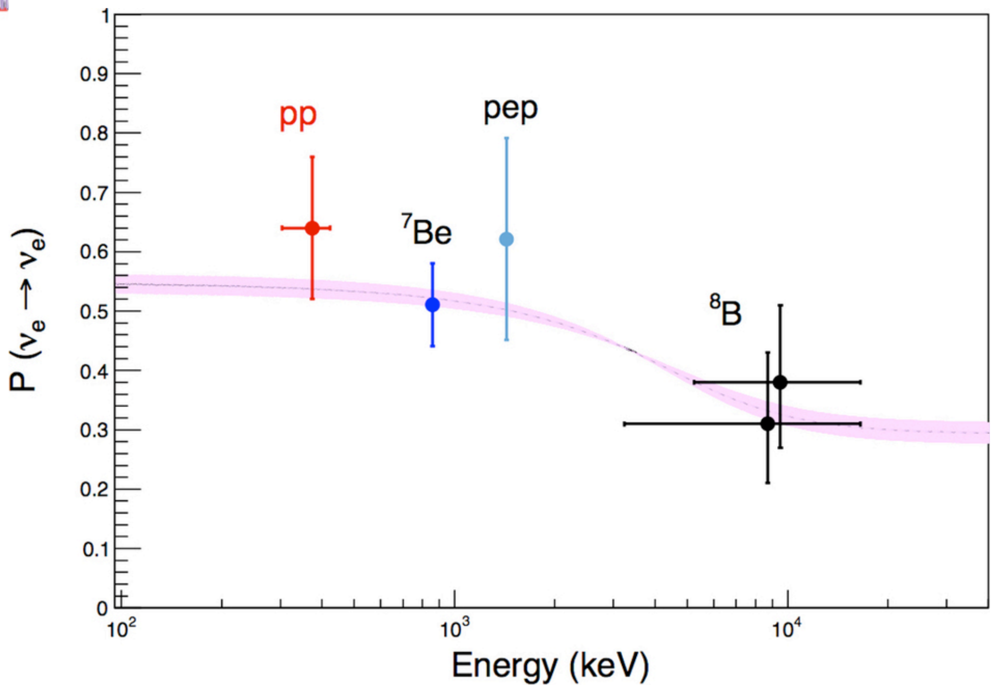
BOREXINO spectacularly clean…first *exclusive* pp measurement!



Precision comparable to inclusive Ga experiments

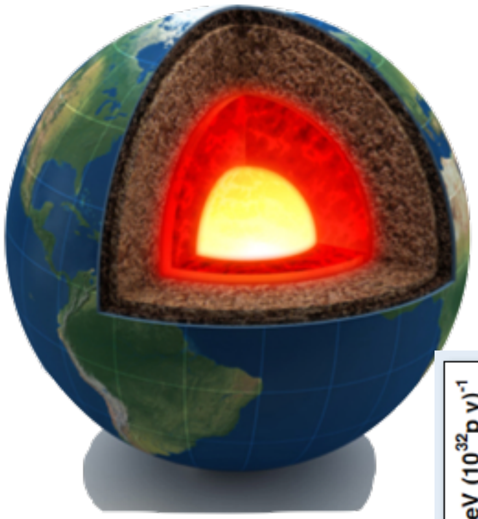
But far from what is needed for precision luminosity test.

About $5\text{x}10^6$ events/year in 50 ktonne WbLS detector!

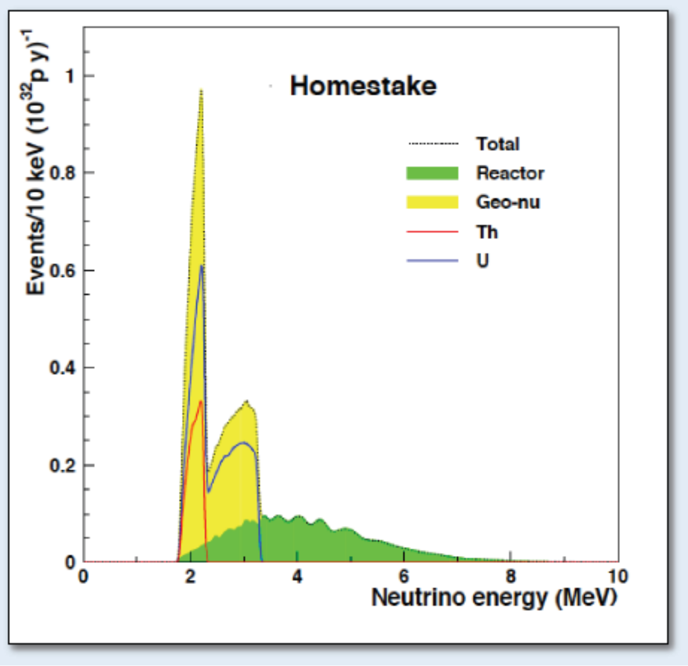


Geoneutrinos

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



Assay the Earth by looking at the "antineutrino glow"



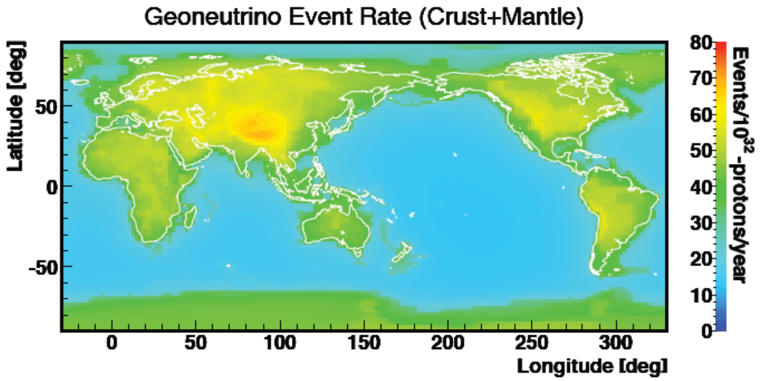


Image: S. Enomoto

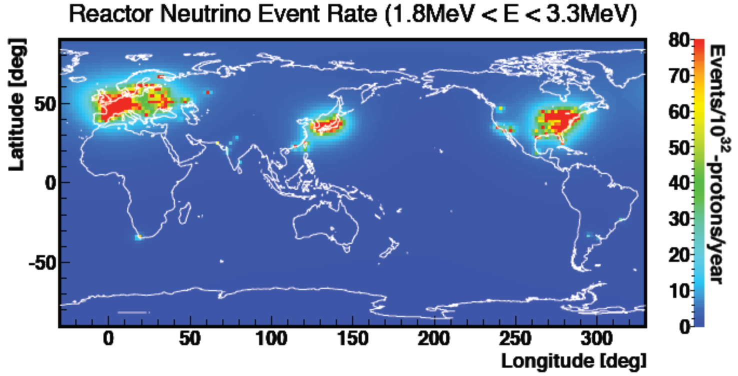


Image: S. Enomoto

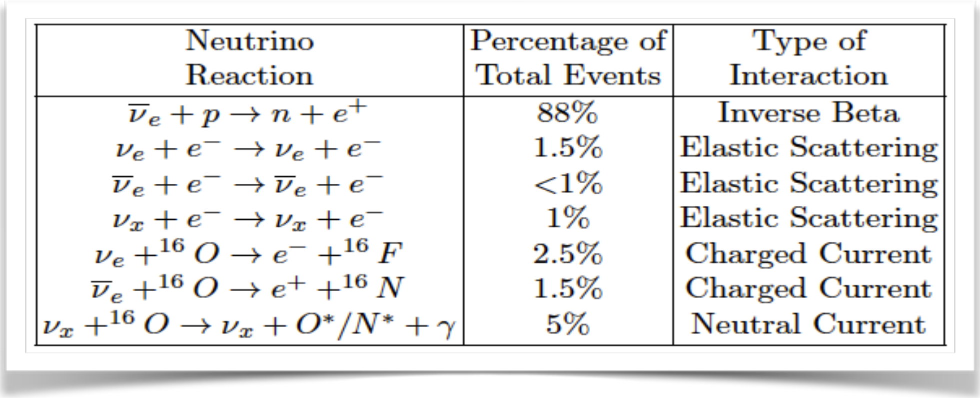
arXiv:1409.5864

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

Lot of work on this
already done by LENA

Supernova Bursts

- ~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

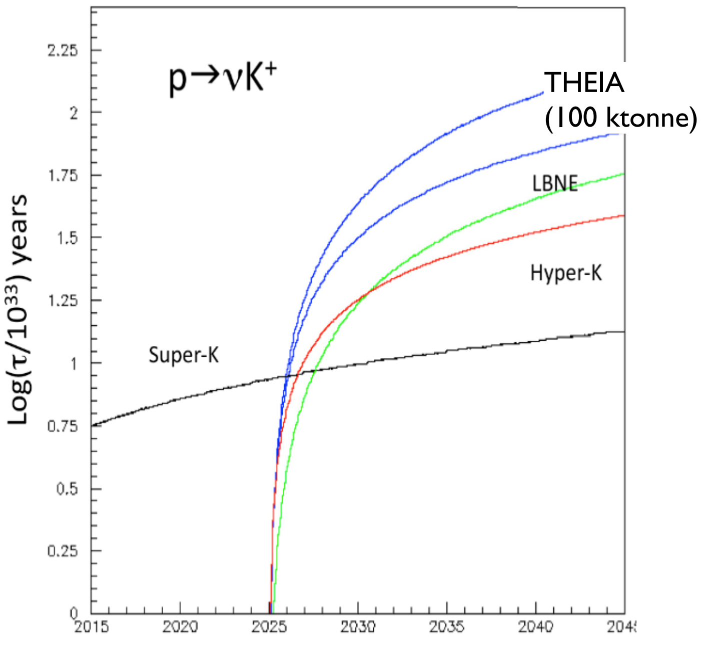
- Detect via IBD+neutron tag---very low background
- Scintillation light has higher efficiency than Gd+H_2O
- Low NC background
    - Atmospheric ν+C → n + fragments
    - WbLS allow rejection of recoils via Cher/Scint
    - “Isotropy” of Cherlight also helps discrimination

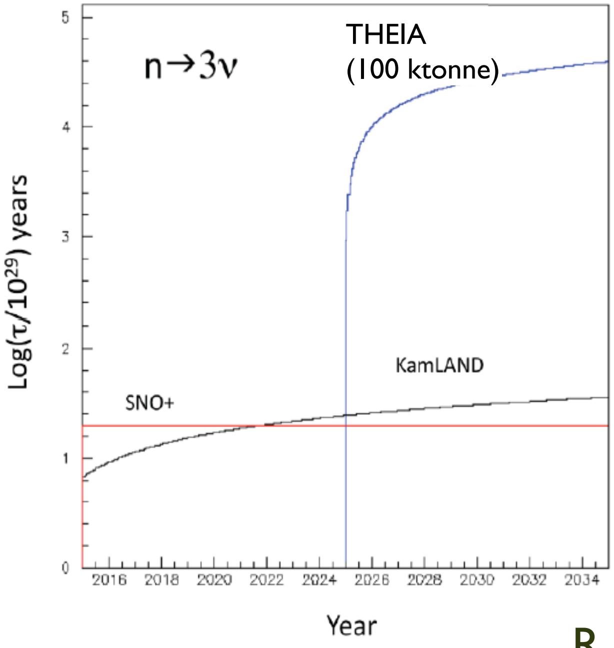
Loading with Cl or Li would allow ν_e detection in same detector.

- 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.





R. Svoboda (Davis)

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

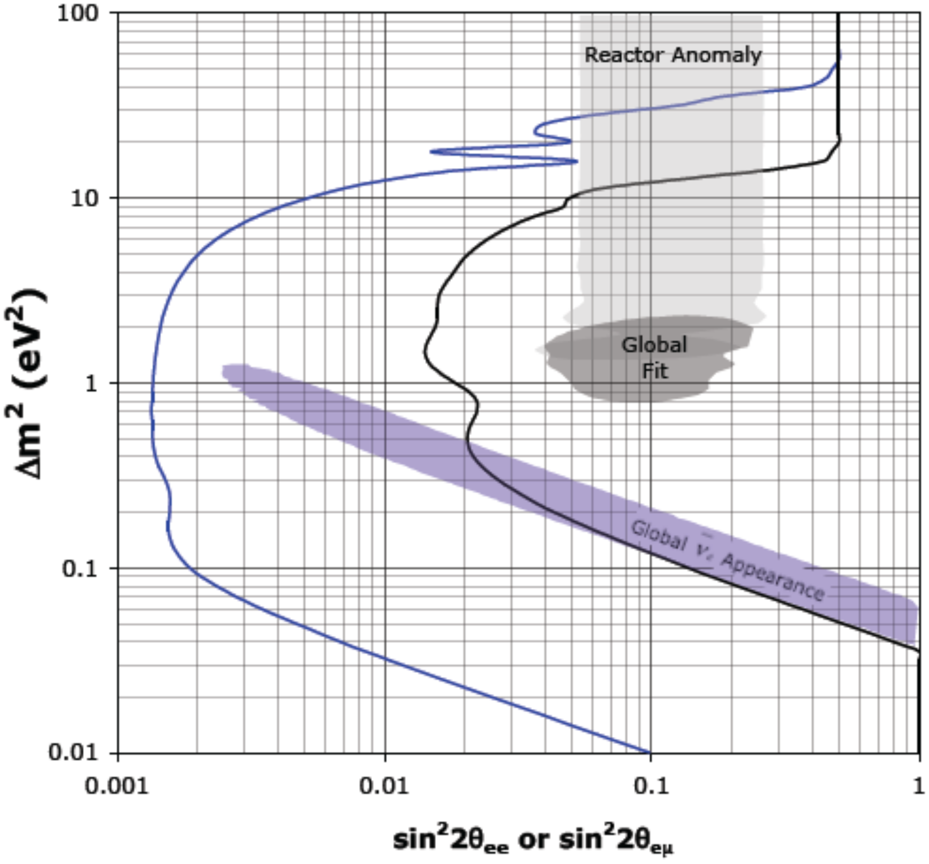
Deep, low threshold
De-excitation γs observaiable via Cher or Scint

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 WbLS

If "reactor anomaly" persists….

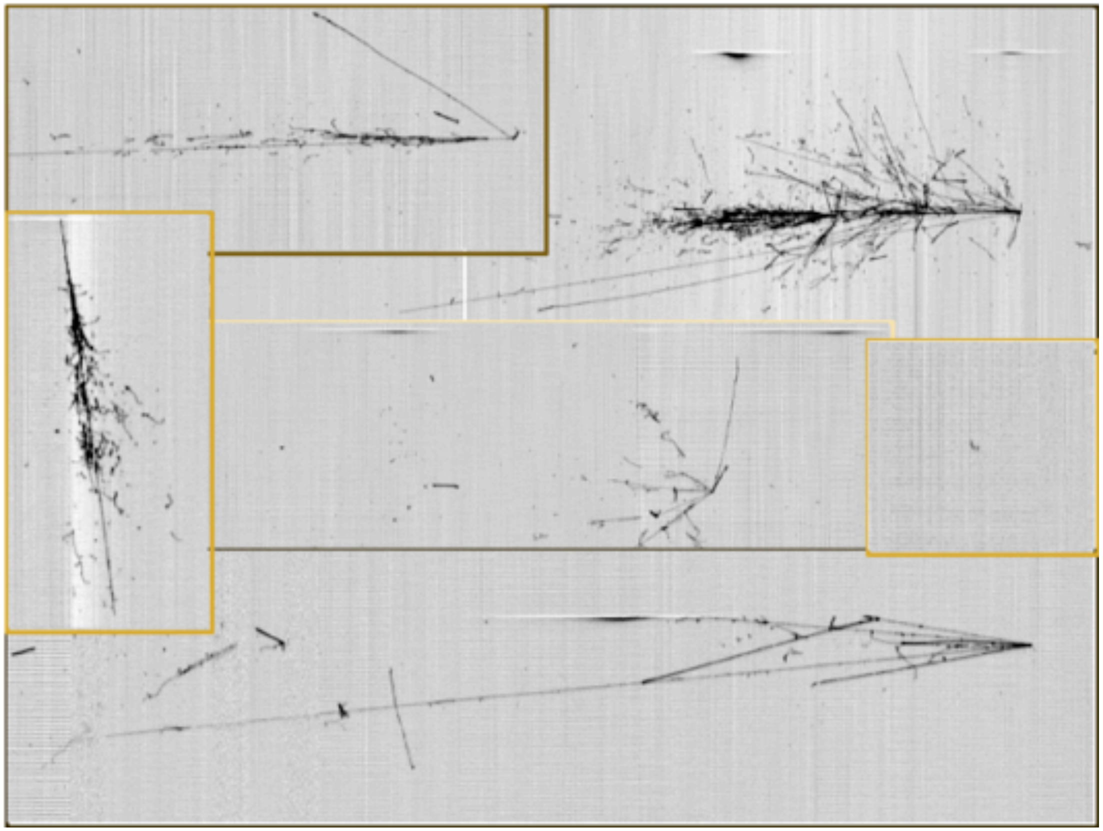
- ISODAR uses ^{8}Li with 13 MeV endpoint
- Could potentially resolve oscillation pattern within single detector
- Need 15% σ_E and 50 cm σ_R



Long Baseline Program with WbLS

"…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?



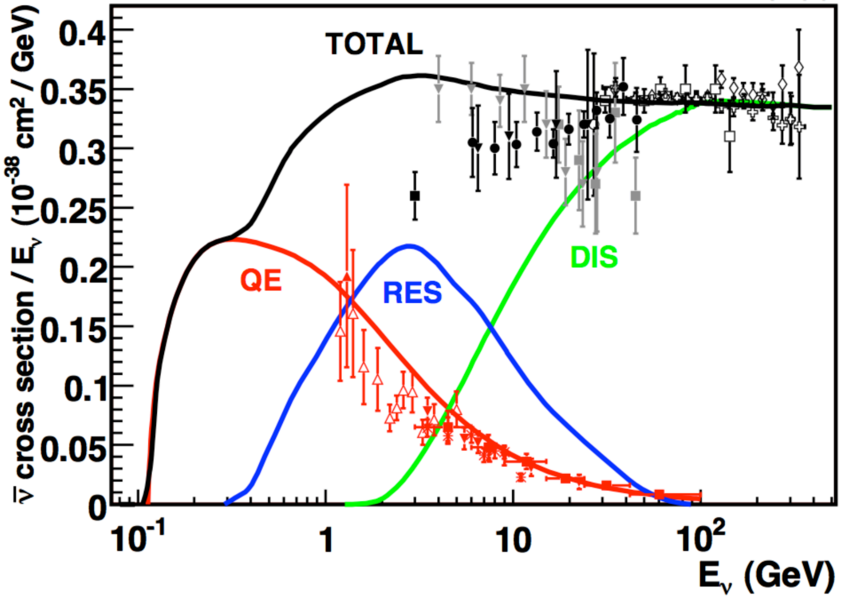
Long Baseline Program with WbLS

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

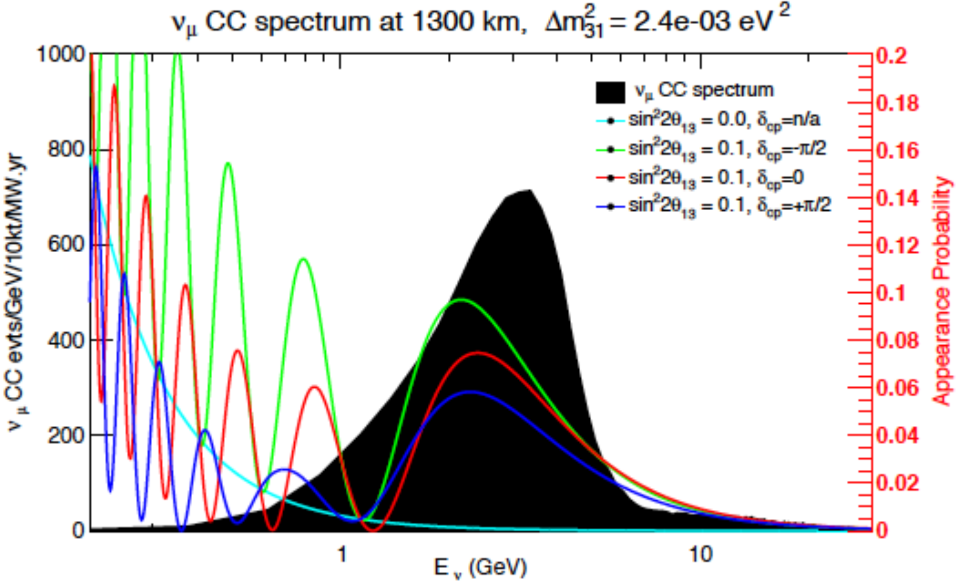
- Low-energy secondaries may be invisible (Cherenkov)
- No real tracking (scintillation in particular)
- Precision of vertex reconstruction limited

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

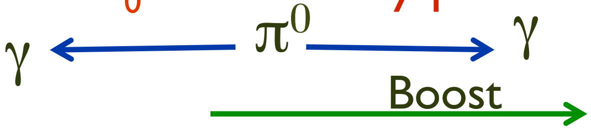
…and Cherenkov detectors using primarily quasi-elastic events…



…which for L=1300 km is non-optimal.



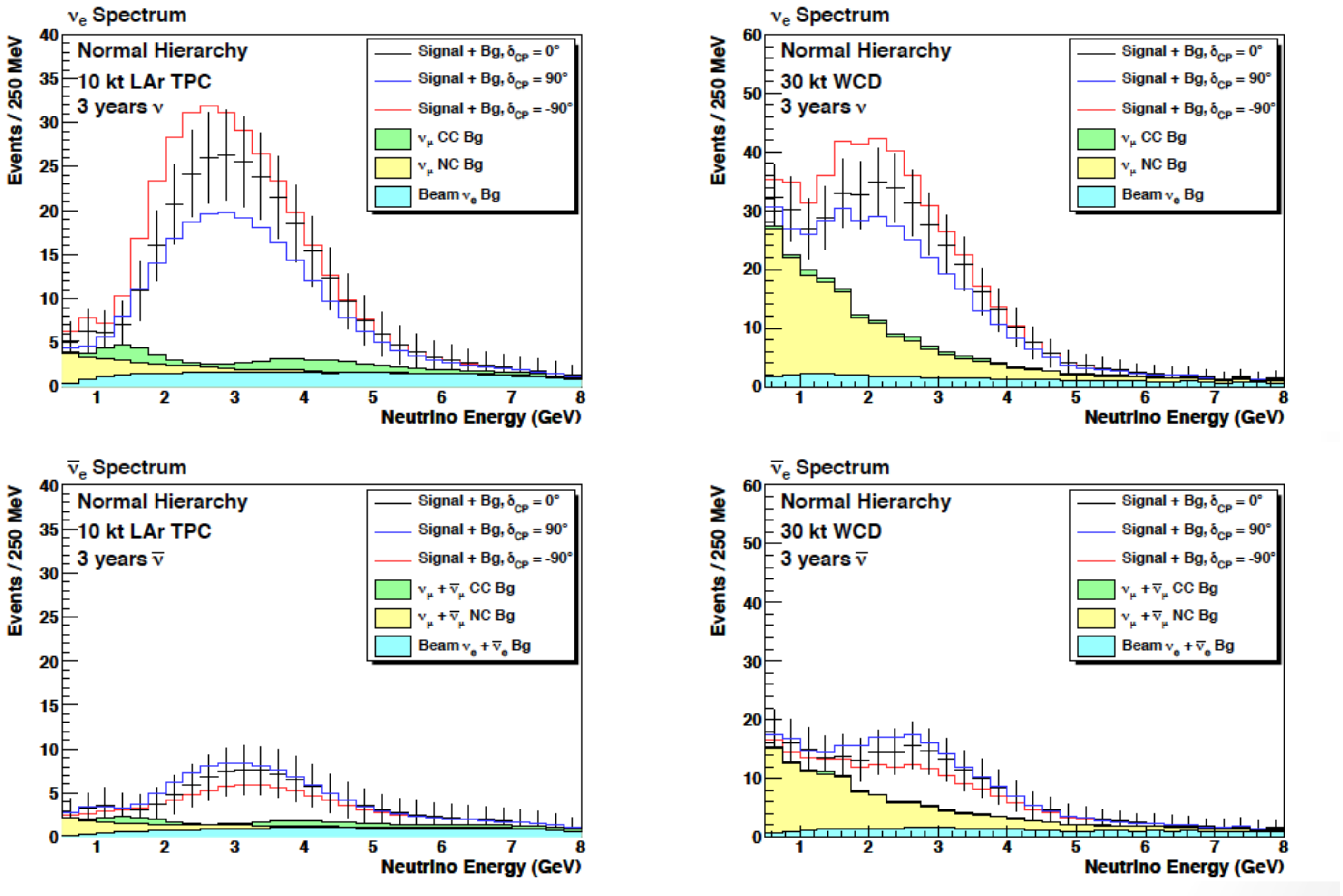
And rejection of asymmetric π_0s is relatively poor---low acceptance even for QE



Long Baseline Program with WbLS

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

30 kt$_{\mathrm{H2O}}$ vs. 10 kt$_{\mathrm{LAr}}$

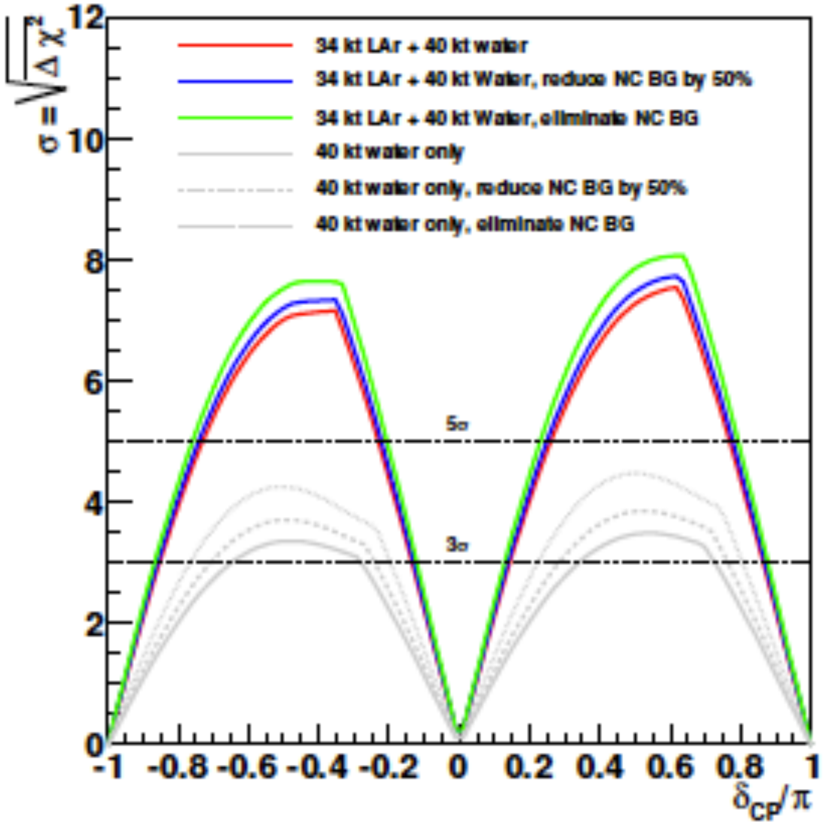


E. Worcester (BNL)

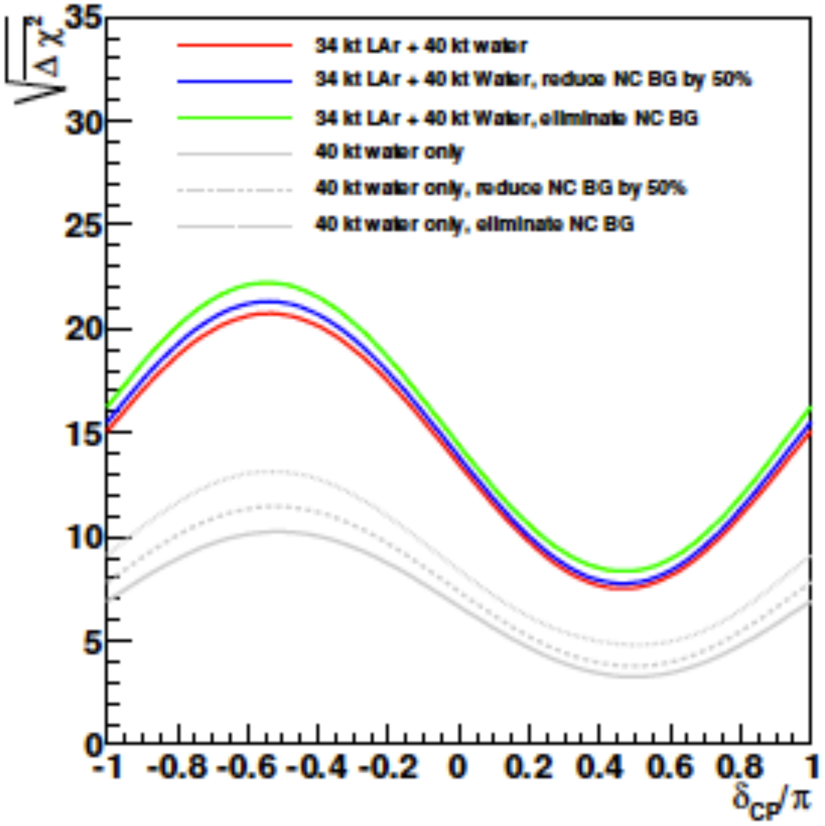
Long Baseline Program with WbLS

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

CP Violation Sensitivity



Mass Hierarchy Sensitivity



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 with WbLS

Yet several ways in which WbLS detetcor 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 beam is off-axis then second oscillation maximum will have more flux

Summary

- Broad program of physics possible with WbLS detector
- But a lot remains to do to optimize program
- Critical issue in US is whether WbLS can perform well $ for $ with LAr
- If so, makes sense to enhance LBL program with a detector capable of a broad program
- Plenty of R&D, simulation, analysis left to do!