THEIA Overview

- Overall Vision
- Some physics motivation(s)
- Overview of detector
- Progress on many fronts

Josh Klein, Penn
THEIA Workshop, UC Davis 4/2018

Vision Statement (2017)

THEIA Collaboration Vision Statement

The goal of the THEIA collaboration is to perform a broad program of world-leading neutrino research including unprecedented sensitivity to neutrinoless double decay, a precision measurement of neutrino CP violation, and a high statistics measurement of the individual components of the solar neutrino flux. In addition, THEIA will measure the flux of diffuse supernova neutrinos, search for nucleon decay in relatively unexplored modes, make a precise measurement of the geoneutrino flux, and be able to discern the flux of individual neutrino flavors from a galactic supernova well beyond the sensitivity of current detectors.

The concept for the THEIA program includes use of the high-intensity neutrino beam generated at Fermilab's Long Baseline Neutrino Facility (LBNF) plus the design and construction of a 50-kiloton scale detector deep underground in the LBNF far site at the Sanford Underground Research Facility in South Dakota. Realization of this ambitious program will require significant extension of present-day liquid scintillator and water Cherenkov optical detector technology using novel target media, ultra-fast photosensors, and new concepts in machine learning, advanced image analysis, and large scale data handling. These key THEIA technologies have wide application in many other areas including medicine, engineering, chemistry, and commerce. Thus, the collaboration is strongly committed to educating a new generation of scientists and engineers in these key areas so important to society by emphasizing inclusion of students and young researchers in all stages of the THEIA research, development, design, and construction process.

Vision Statement (2017)

Broad Program of world-leading research:

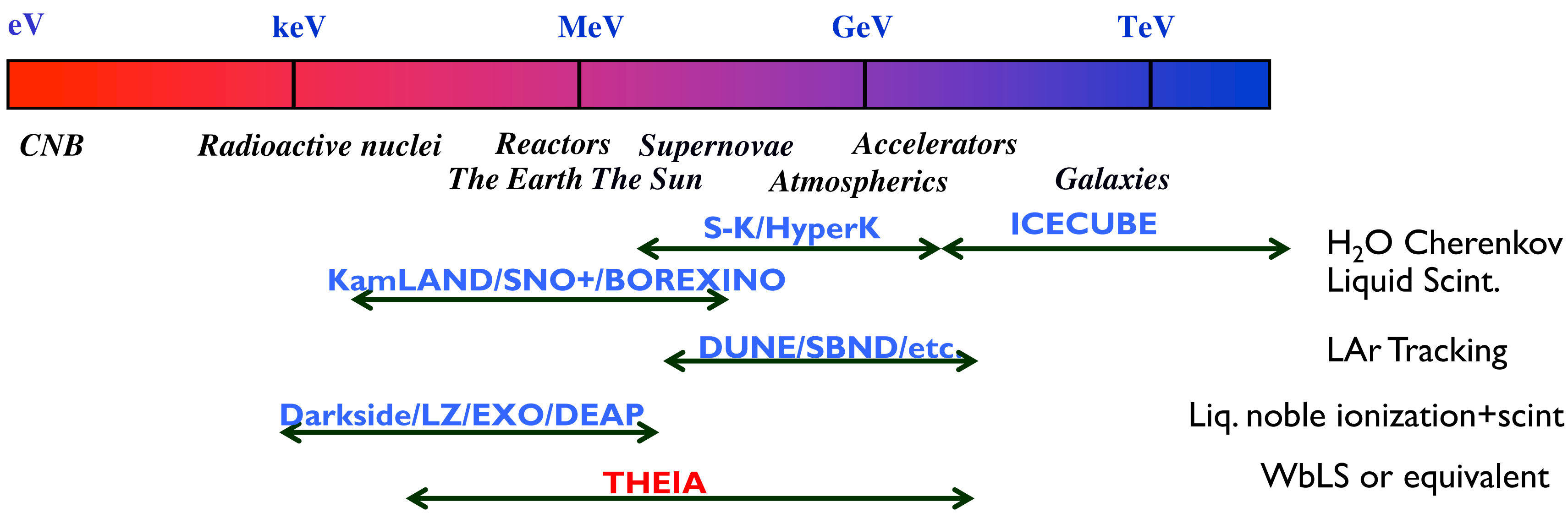
- Unprecedented sensitivity to $0\nu\beta\beta$ [beyond tonne-scale]
- Precision measurement of leptonic CP violation
- High-statistics measurements of solar neutrino flux components

And also:

- Diffuse supernova neutrinos
- Nucleon decay into relatively unexplored modes
- Supernova burst sensitivity with flavor separation

Most-favored location at LBNF: Depth and beam available

Physics Breadth Motivates Detector



New Technologies---

- Scintillator cocktails (including water-based)
- Fast photon detector timing
- High-efficiency photon detection
- Advanced reconstruction methods

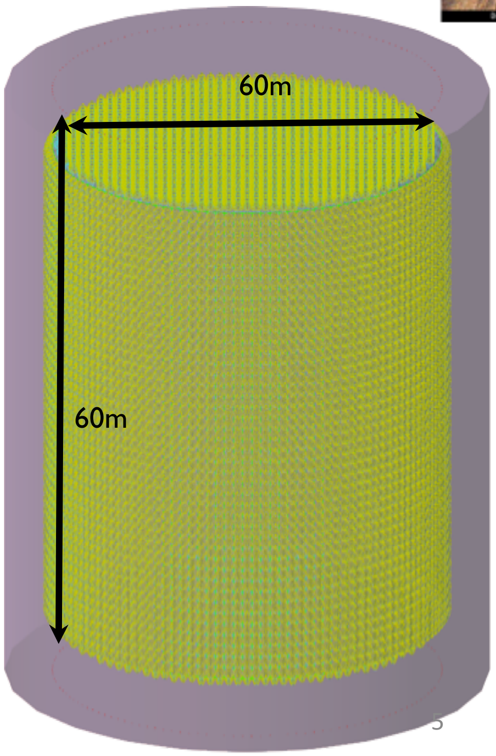
Allow a rich low-energy program of neutrino physics
(+ complement the high-energy program)

Theia Reference Design

Reference Design:

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

"Forward-looking infrastructure" would allow long-term, phased program to accomplish full physics range.



Gets around the "one number problem" for neutrino experiments---THEIA is a facility for many critical neutrino measurements

0νββ

Are matter and antimatter fundamentally different?

If neutrinos are not Majorana, we have four neutrino states:

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

How are these different? ($\bar{\nu}_R$ ↔ ν_R)

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

They have:

- Same charge (0)
- Same mass
- Same chirality

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

$0\nu\beta\beta$

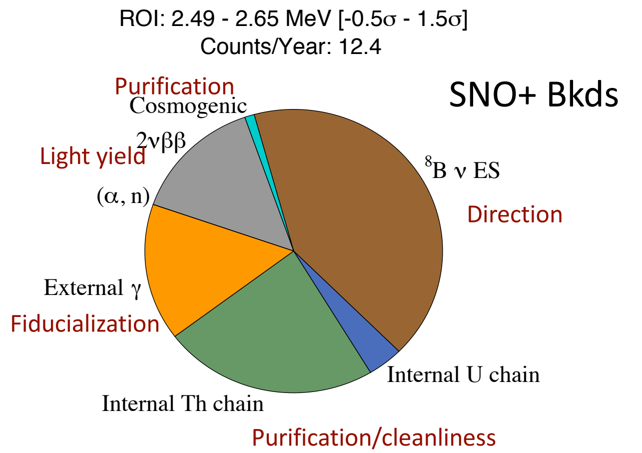
Are matter and antimatter fundamentally different?

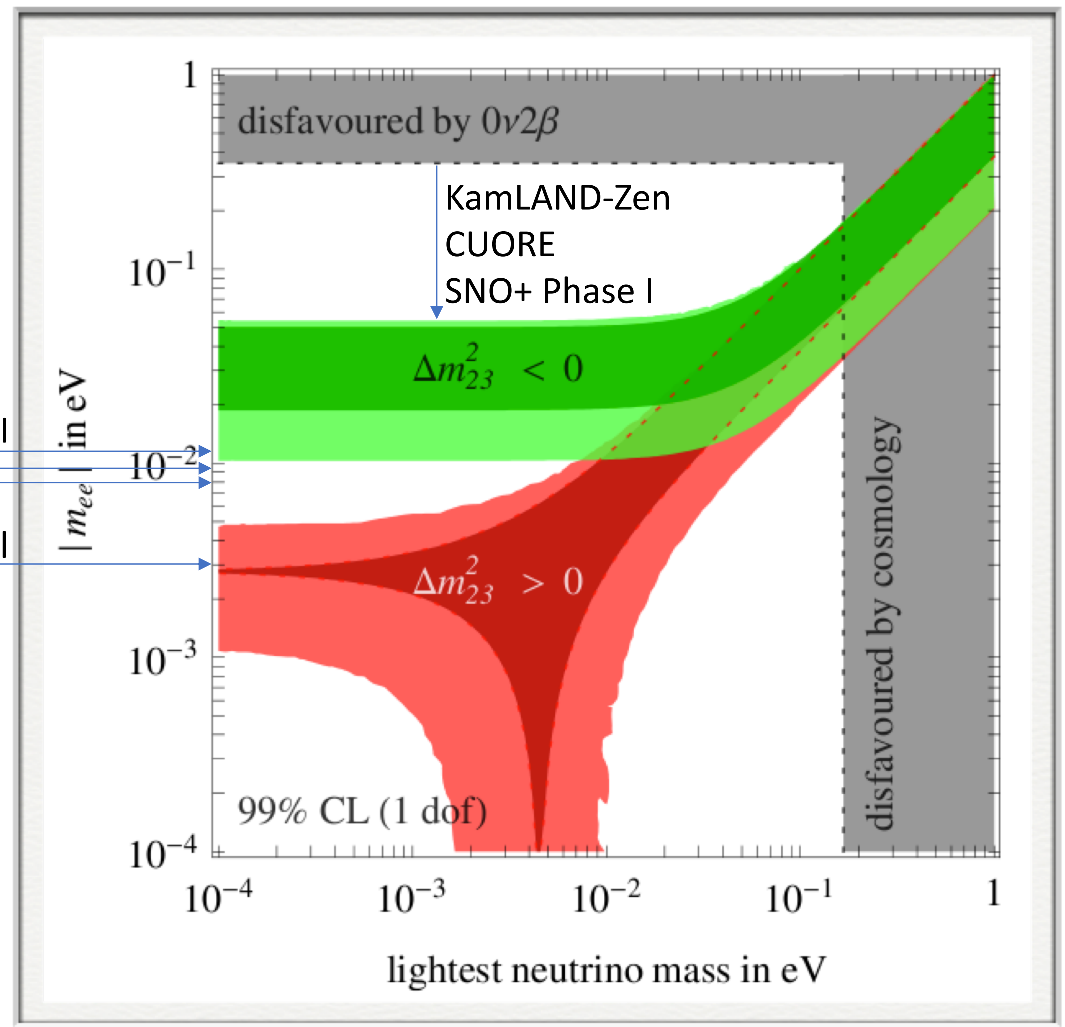
So Dirac neutrinos promote a global symmetry to a fundamental symmetry.

Meanwhile, Majorana neutrinos have a dimension-5 mass term---
Not even renormalizable (need a new mass-generating mechanism).

There is no "Standard" Model until this is settled.

0νββ





Getting below 5 meV will require > 10 tonnes of isotope, a small fiducial volume, and reduction of backgrounds though good resolution (2ν) and direction (^{8}B)

Solar Neutrinos

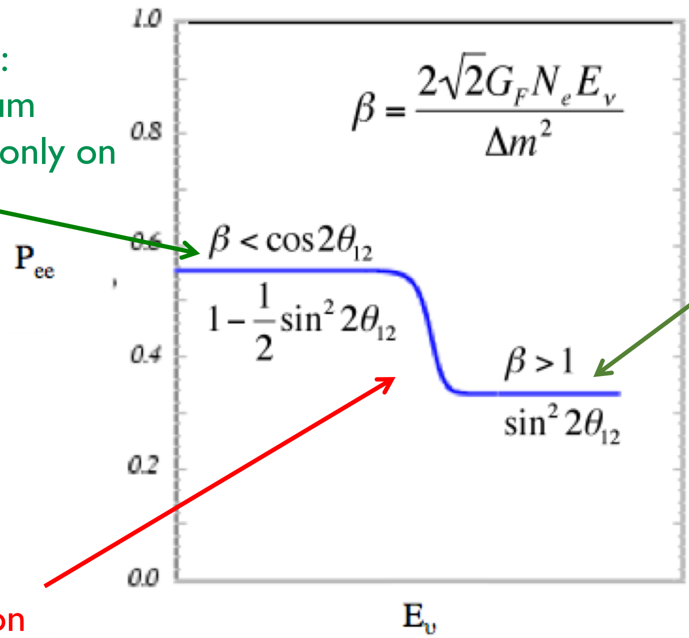
Important measurements still to make:

- 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

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

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



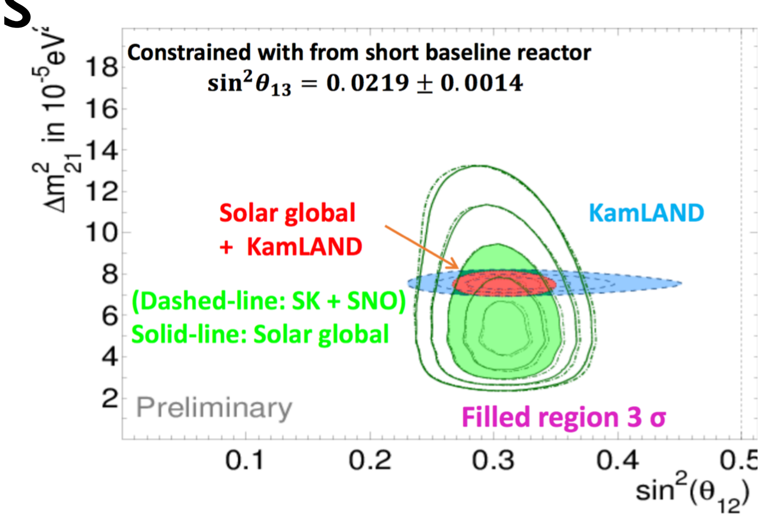
Transition region

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

Solar Neutrinos

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	⋯



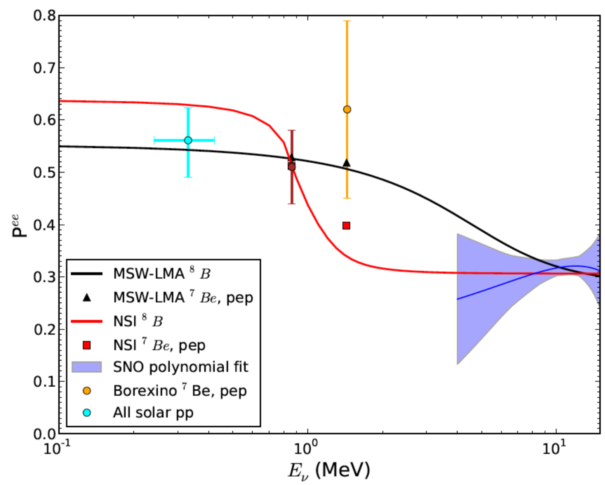
Super-K, TAUP 2017

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



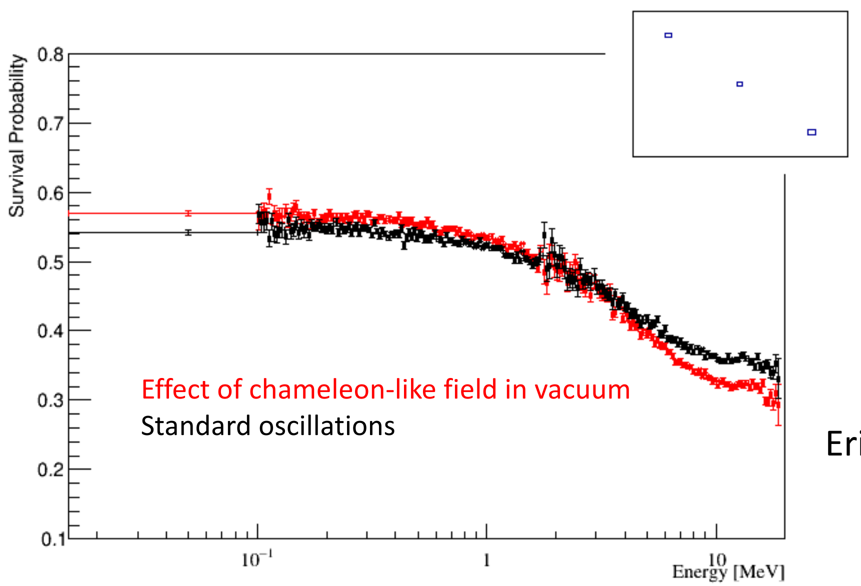
Sensitivity non-standard effects entirely driven by lack of precision ^{8}B data in transition region

Solar Neutrinos

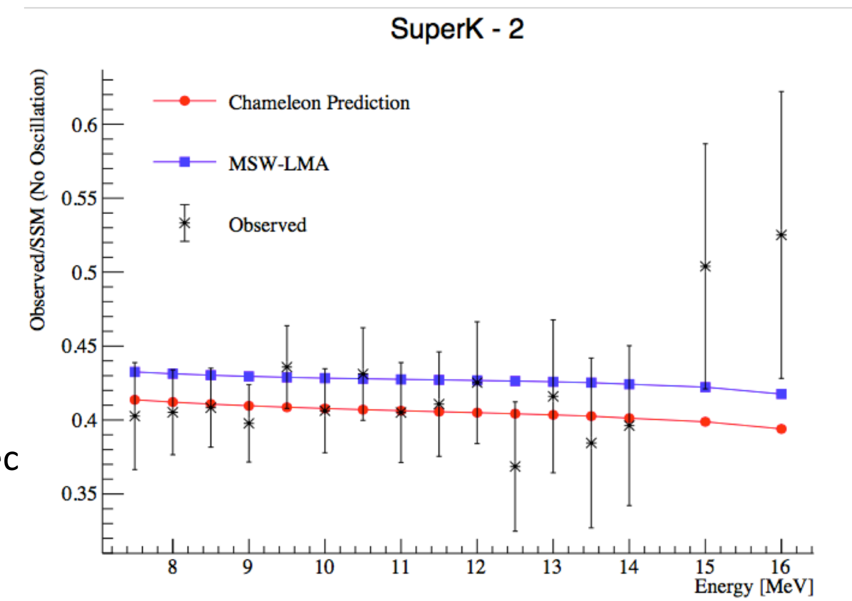
Or even…

"Chameleon"-like fields are screened in matter (including atmosphere)

Only solar neutrinos probe these potentials while traveling in *vacuum*



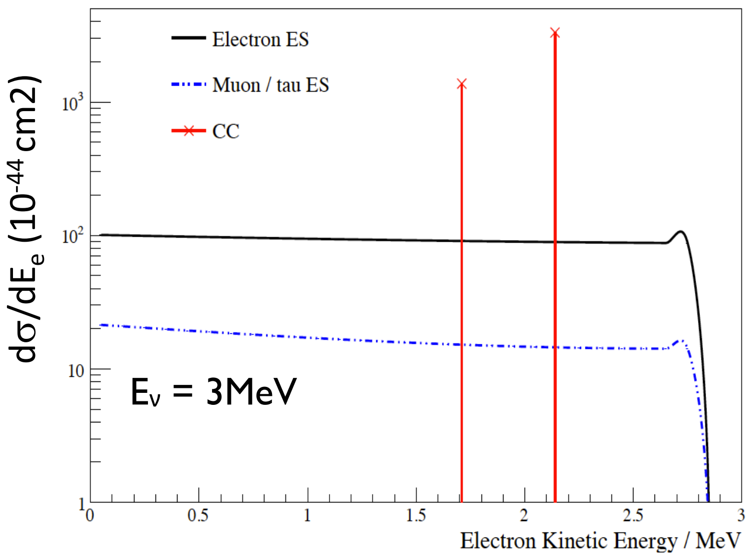
Eric Marzec



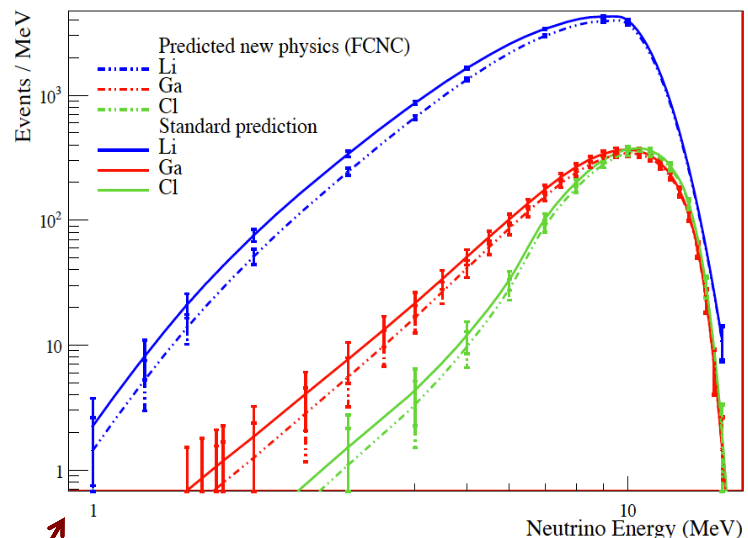
Solar Neutrinos

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

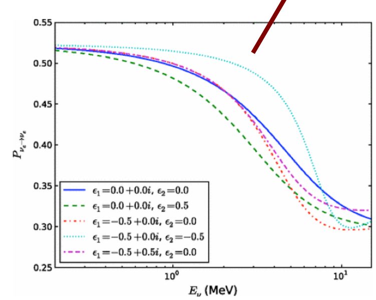
Loading with (e.g.) ^{7}Li provides CC cross section with narrow dσ/dE.



Makes models easy to distinguish

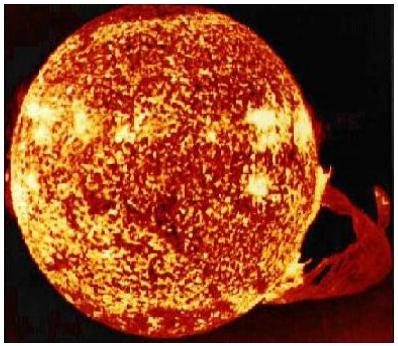


G. D. Orebi Gann (Berkeley)



Solar Neutrinos

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

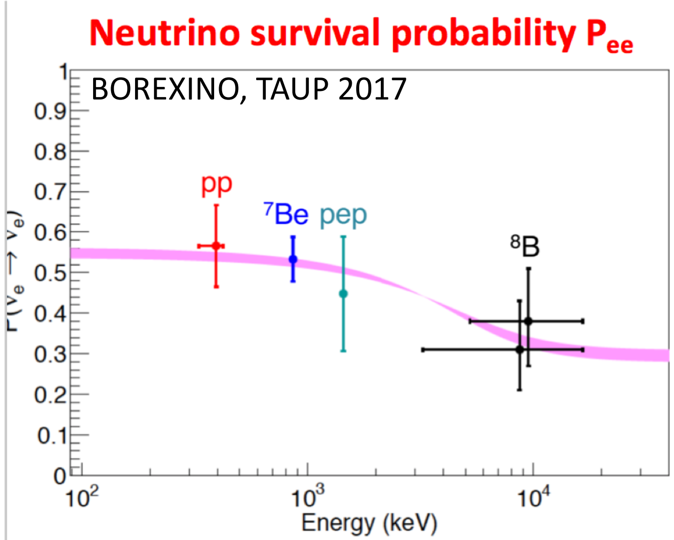
But! CNO neutrinos tell us metallicity of solar core

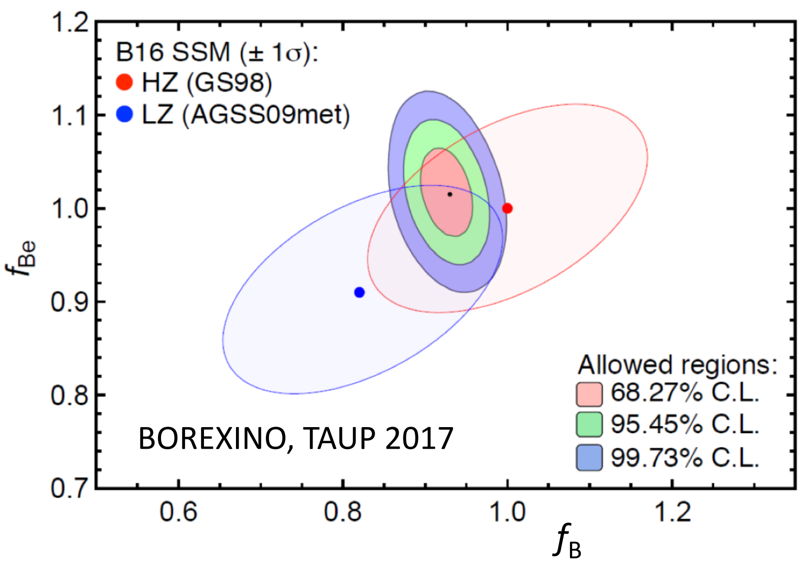
⟶ Flux may differ by factor of 2 between old/new metallicity

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

Solar Neutrinos

CNO





CNO Neutrino Grand Prix: The race to solve the solar metallicity problem

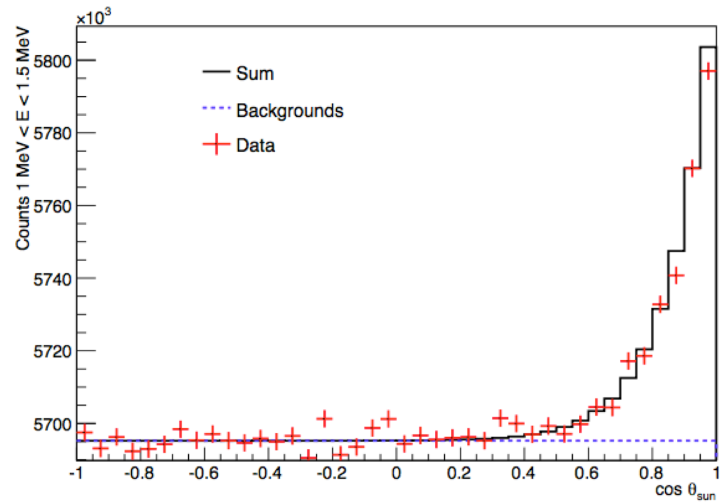
or 2018

David G. Cerdeño,[a] Jonathan H. Davis,[b] Malcolm Fairbairn[b] and Aaron C. Vincent[c,d]

As a final point, we note that it is possible that new technologies may allow the CNO flux to be measured by electron-recoil experiments sooner, in particular the development of experiments which can detect both scintillation and Cherenkov light, such as THEIA [52–54]. This would mean that the direction of the recoiling electrons could be measured in addition to their energies, which would break the degeneracy between solar neutrinos and background such as ^{210}Bi.

Sensitivity of a low threshold directional detector to CNO-cycle solar neutrinos

R. Bonventre[a,2], G.D. Orebi Gann[1,2]



Solar Neutrinos

Are all energy generation/loss mechanisms accounted for?

With luminosity constraint:

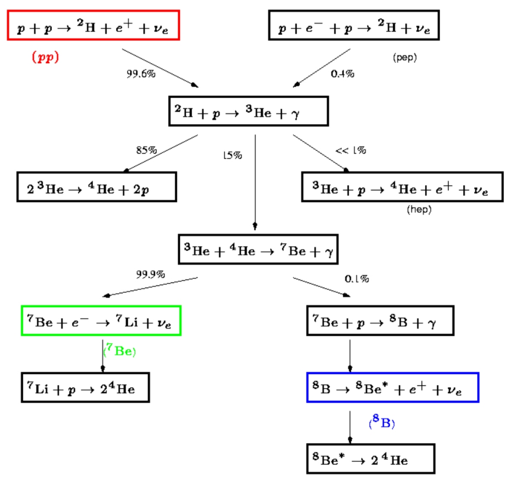
Exp. Uncs. Theory Uncs.

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

Bahcall and Pinsonneault

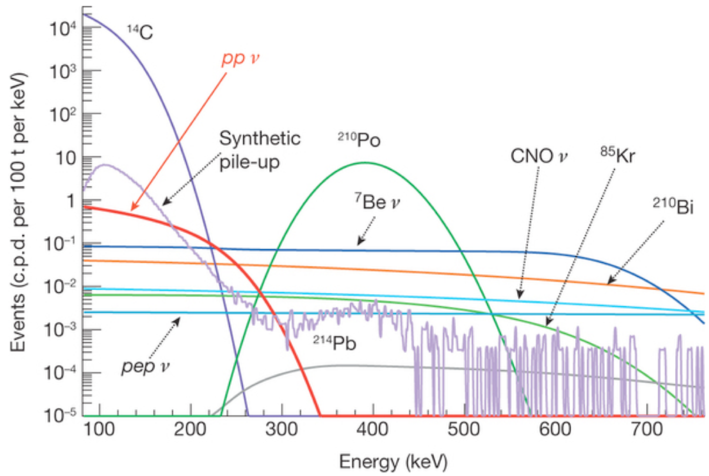
But without constraint: $L_\nu/L_\odot$ known only to 20-40%

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



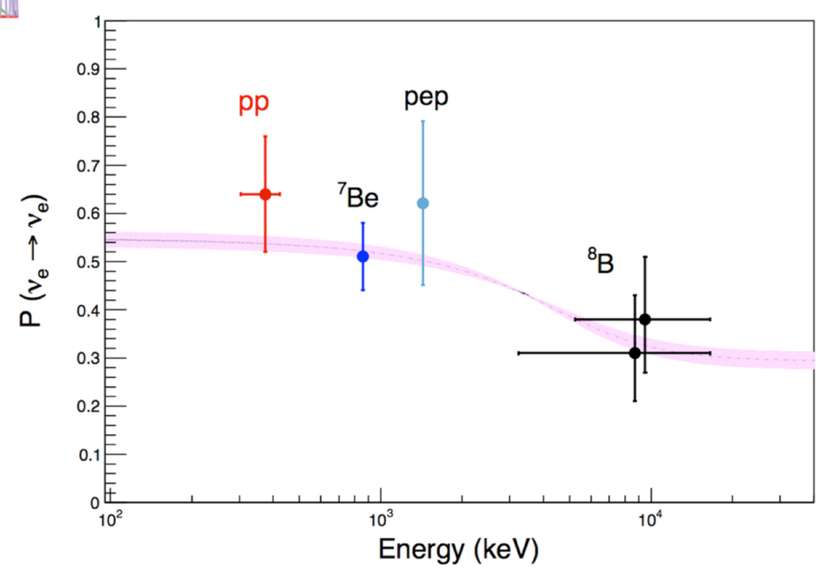
Solar Neutrinos

BOREXINO spectacularly clean…first *exclusive* pp measurement!



Precision comparable to inclusive Ga experiments

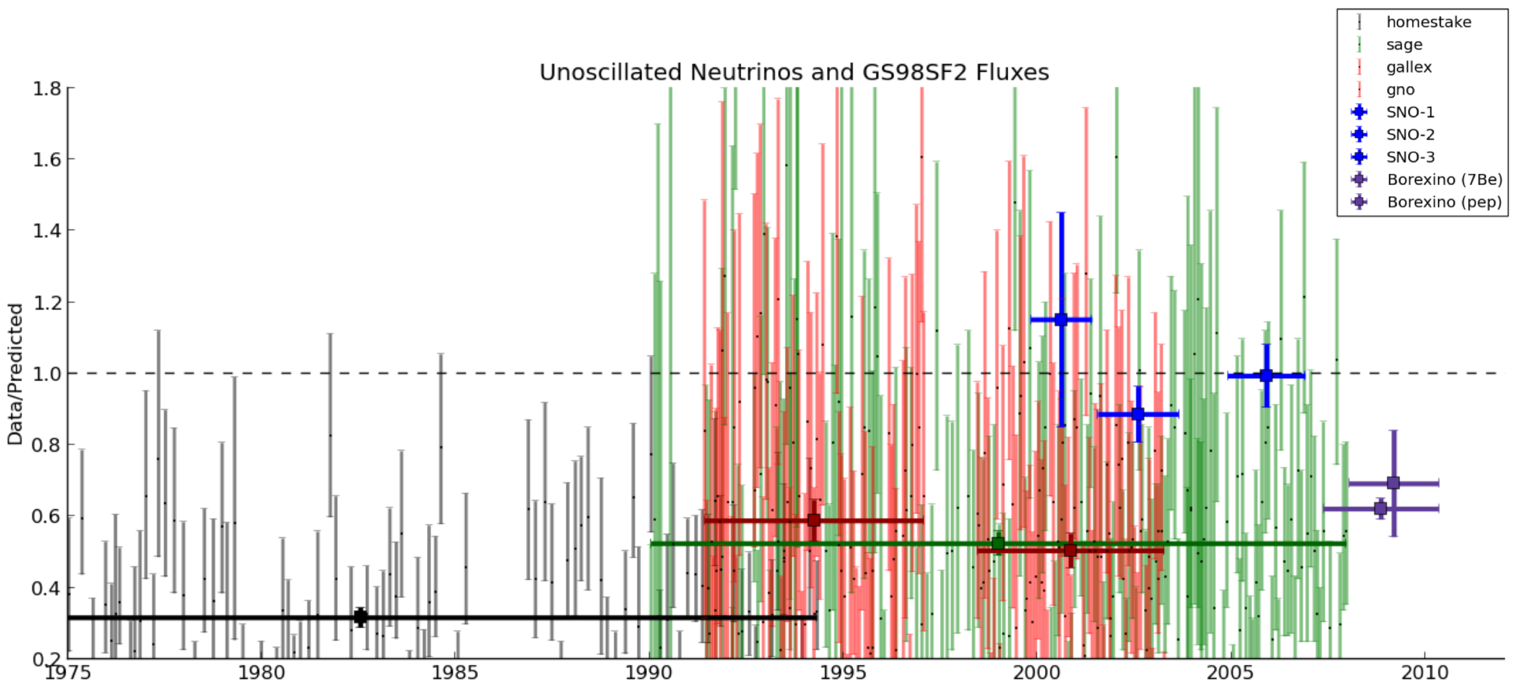
But far from what is needed for precision luminosity test.



Solar Neutrinos

The (Very) Recent History of the Solar Core

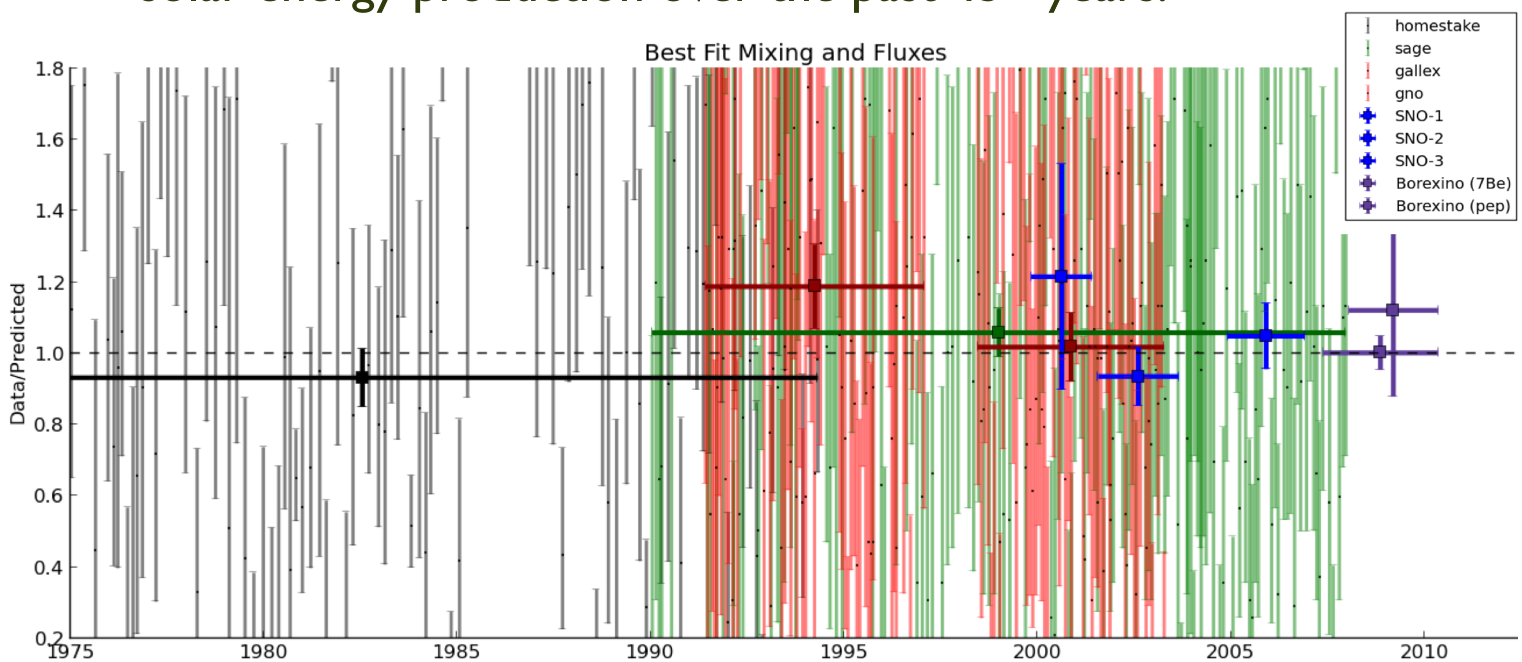
Without mixing correction, this is a history of the Solar Neutrino Problem



A. LaTorre

Solar Neutrinos

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



A. LaTorre

Long Baseline Oscillations

Phenomenology is very rich:

$$P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

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

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

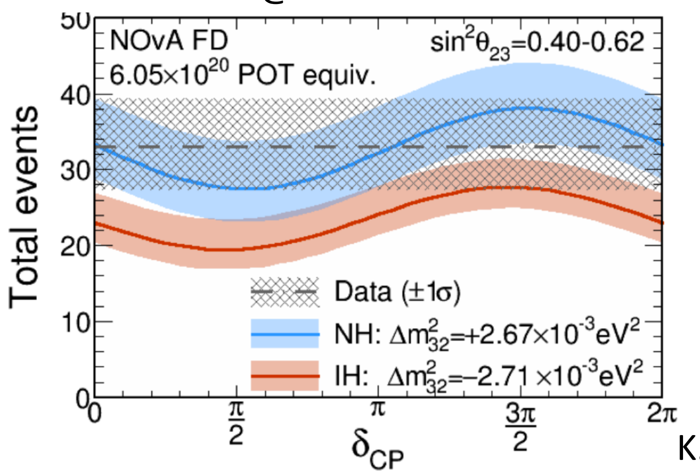
Matter term → $-8C_{13}^2 S_{13}^2 S_{23}^2 \left(1 - 2S_{13}^2\right) \frac{aL}{4E_\nu} \cos\Phi_{32} \sin\Phi_{31}.$

$$\Phi_{ij} \equiv \Delta m_{ij}^2 L/4E_\nu \quad c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij}$$

"All the neutrinos, all the time"

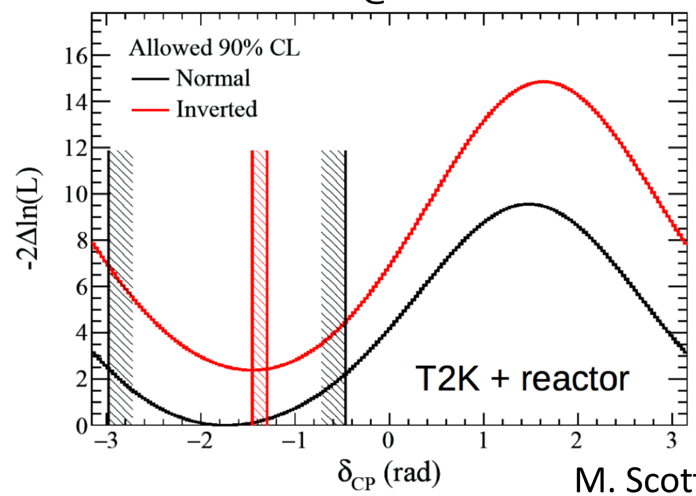
Long Baseline Oscillations

NOvA @NuFact 2017



K. Bays

T2K @TAUP 2017



M. Scott

An “observation” of CP violation by neutrinos is perhaps not far away.

If $\delta=90^\circ$, it is probably very interesting!

If $\delta=78^\circ$, it is probably not so interesting!

Long Baseline Oscillations

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:

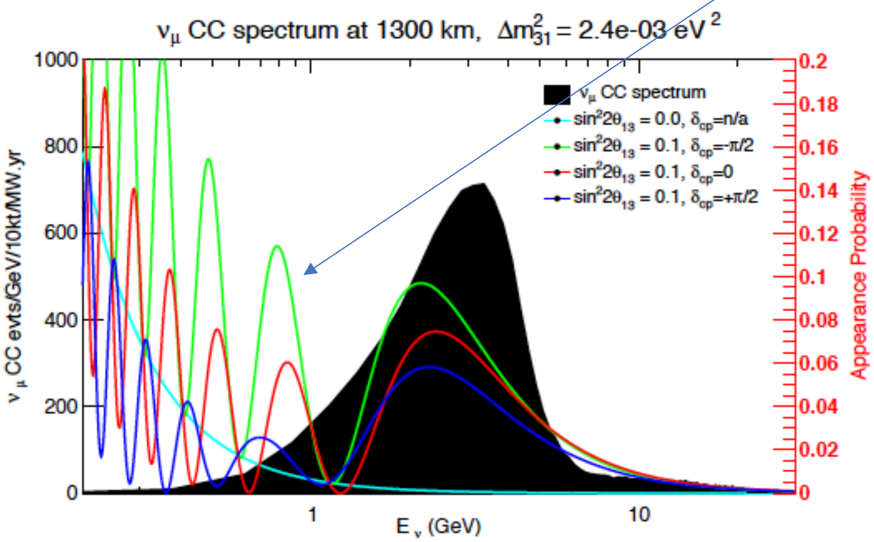
$$\frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \stackrel{?}{\simeq} \frac{\Delta m^2_{12} L}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \cdot \sin\delta$$

Long Baseline Oscillations

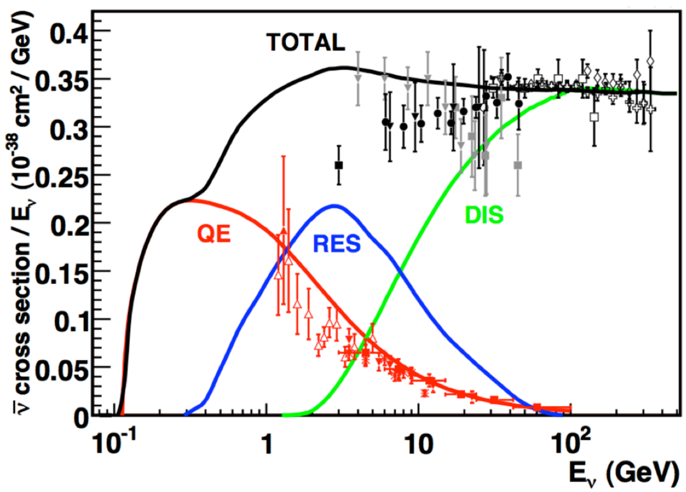
- Neutrinos don't just transform, they *oscillate*
- Coherent interactions with matter alter oscillation pattern
- Mixing parameters are universal
  - Neutrinos and antineutrinos have the same mixing parameters
  - And it doesn't matter how you measure them
- $\Delta m_{12}^2 + \Delta m_{23}^2 + \Delta m_{13}^2 = 0$
- For 3 light flavors, mixing matrix is unitary (but we should not suffer from unitarity envy)

Long Baseline Oscillations

"Smoking gun" of oscillations is second maximum



2nd Max sits where QE dominates---fewer uncertainties

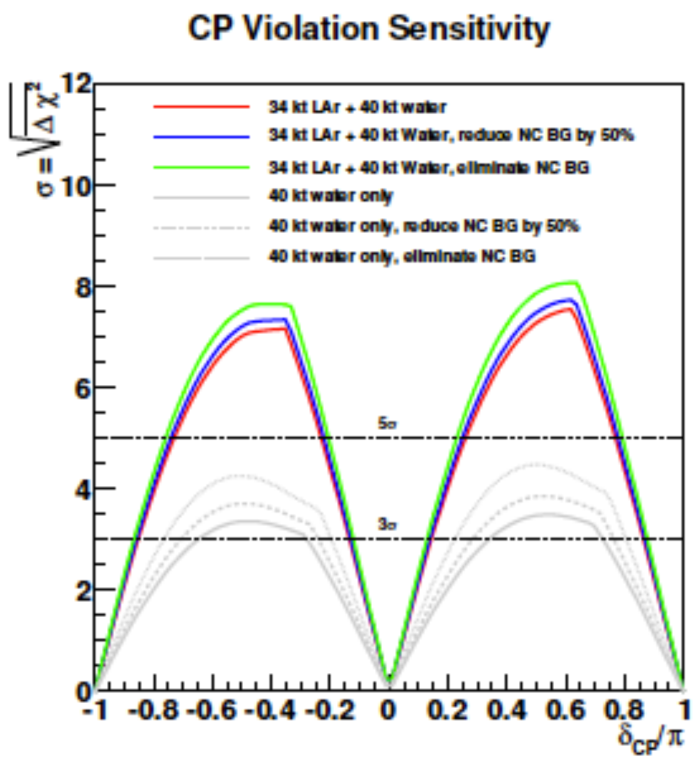


Even in "new" LNBF beam flux is low here, so detector needs to be big.

But also: resolution of LArTPC in this regime is ~20% (!)

Neutron tagging in Theia will help to constrain missing energy

Long Baseline Oscillations

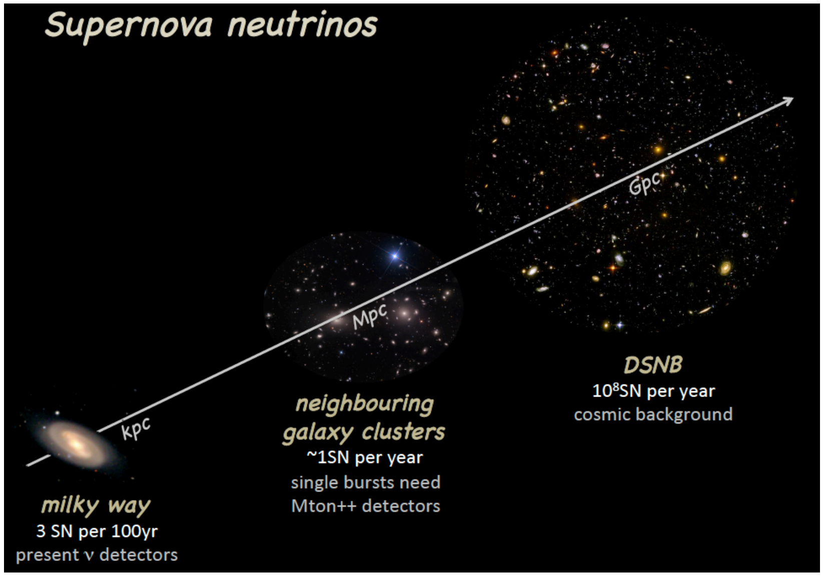


100 ktonne THEIA=40 ktonne LAr

IF scintillation light "doesn't hurt"

E. Worcester

Diffuse Supernova (Anti)Neutrino Background

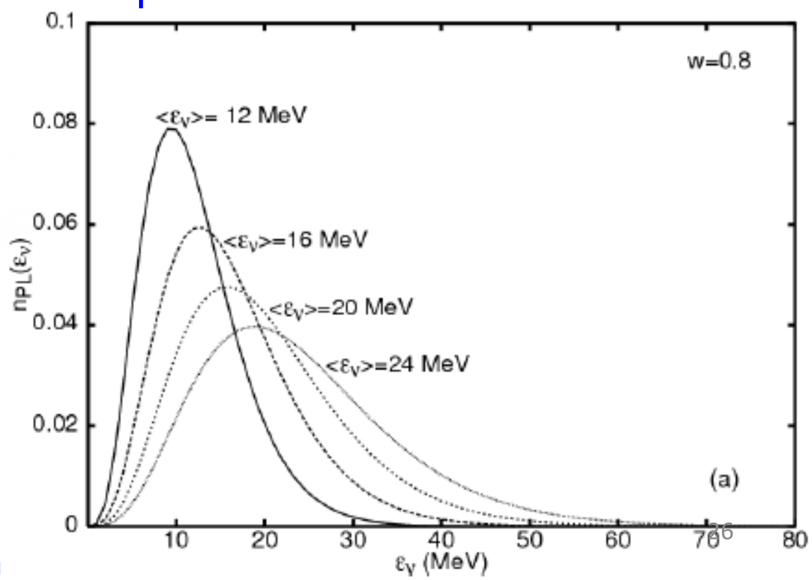


Why wait for a supernova burst?

"Relics" from all supernovas since Big Bang are detectable.

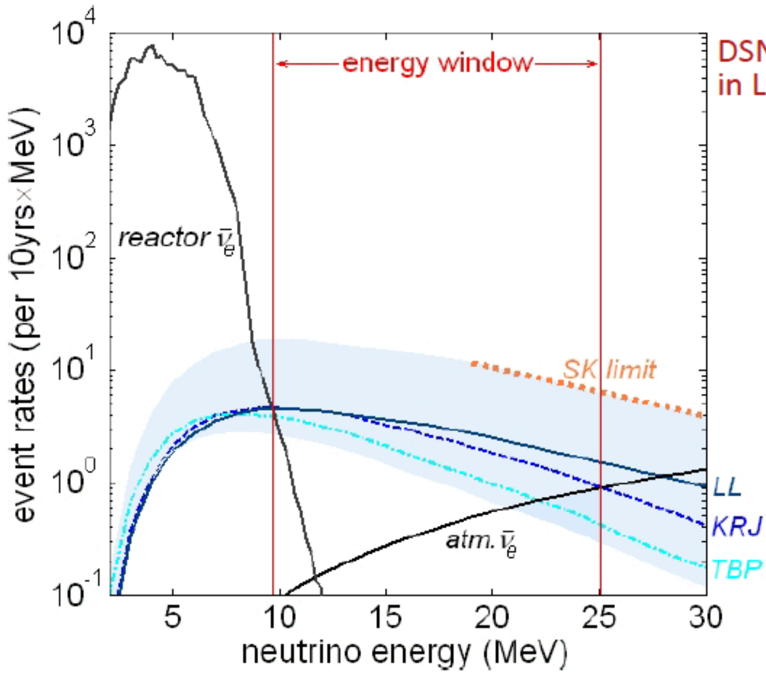
About 1 event/10kt/year.

Observed spectrum depends on supernova mechanism



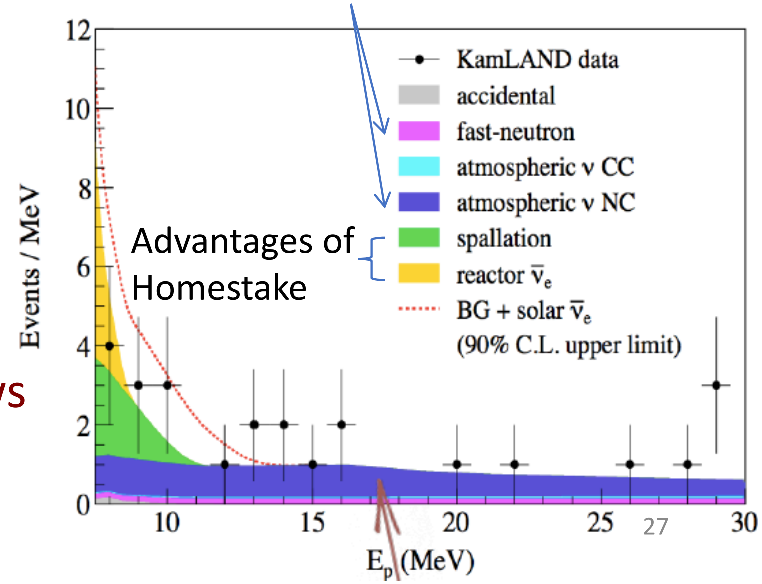
M. Wurm

Diffuse Supernova (Anti)Neutrino Background



DSNB detection in LENA (2006)

Big advantage of LS is "free" neutron tags and low threshold---
Provides background rejection

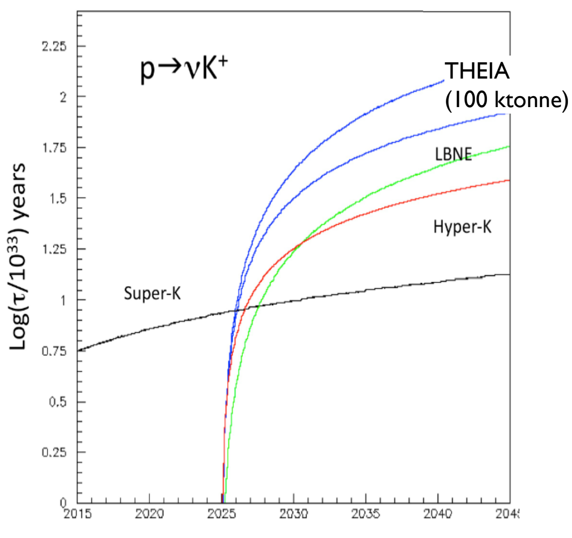


Pulse-shape discrimination also allows rejection of non-electron events.

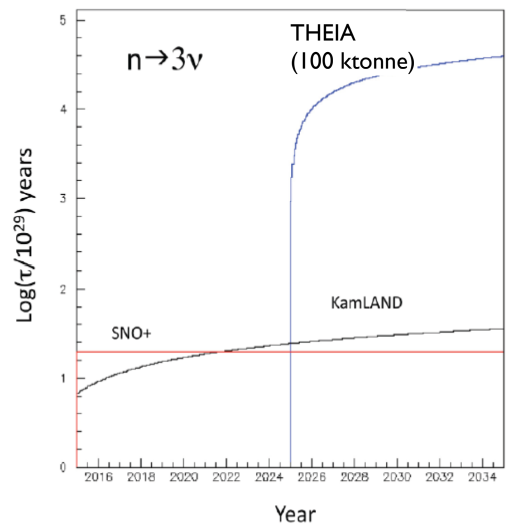
M. Wurm

Nucleon Decay

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

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

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 (and high E physics) difficult
- Are expensive even if they could be made large

Water Detectors:
- No access to physics below Cherenkov threshold
- Low light yield makes resolution poor even at ~10 MeV, making low E physics impossible
- Are hard to make ultra-clean

We'd really like the best of both worlds.

Physics Requirements

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/tracking/particle ID

Theia

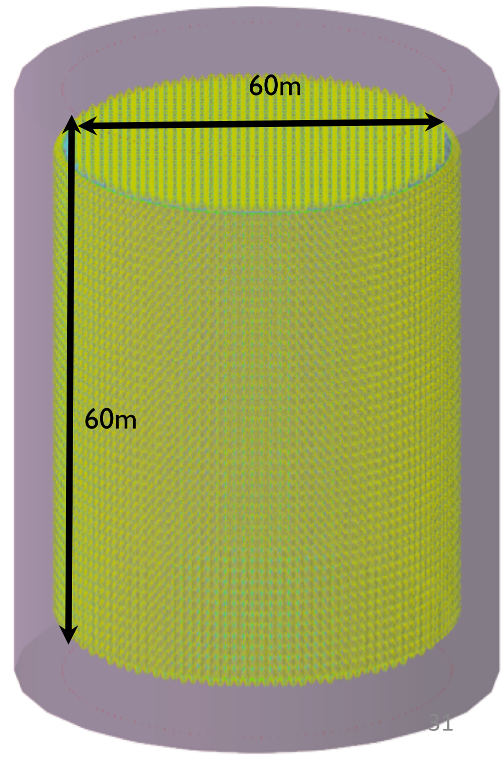
Most critical ingredient is distinguishing Chertons from Scintons

Cherenkov light gives us:

- Electron vs. muon PID (like T2K)
- Multi-ring rejection of NC π^0s (like T2K)
- Rejection of ^{8}B ES background to $0\nu\beta\beta$ (or even $\beta\beta$ topology?)
- Discrimination of CNO from ^{210}Bi (Bonventre/Orebi Gann)
- Discrimination of CC solar (Li) from ES (Bonventre/Orebi Gann)

Scintillation light gives us:

- Energy resolution for $0\nu\beta\beta$ search (KamLAND, SNO+)
- Sensitivity to K^+ in nucleon decay (Svoboda)
- $\beta/\gamma/\alpha$ separation for $0\nu\beta\beta$ (Borexino,SNO+)
- Energy resolution for seeing MSW rise in ^{8}B solar (Borexino)
- Neutron sensitivity for geoneutrinos and DSNB (K, Borexino, LENA)

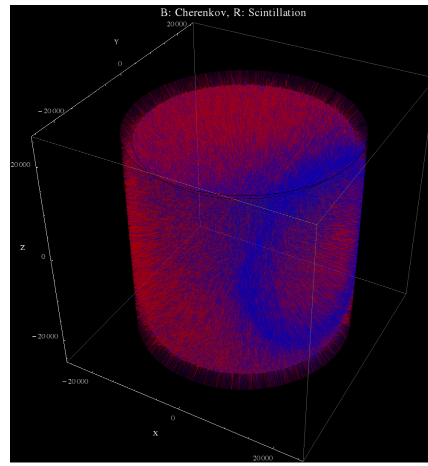


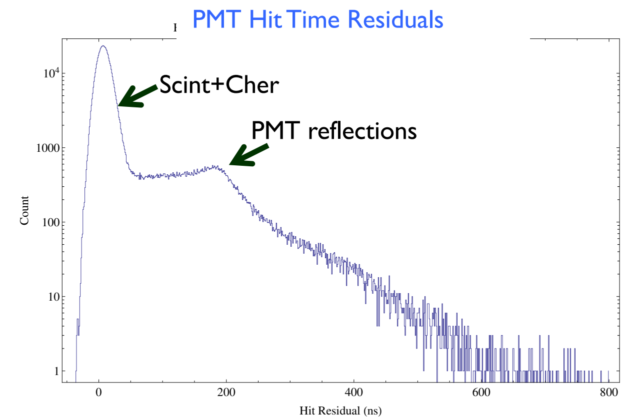
Theia

Chertons from Scintons

Fortunately, many ways to do this!

- "Lean" scintillator cocktails (WbLS)
- Timing of photon sensors
- Scintillator time profile
- Angular distribution of Cherenkov light
- Photon spectral separation
- Polarization (?)

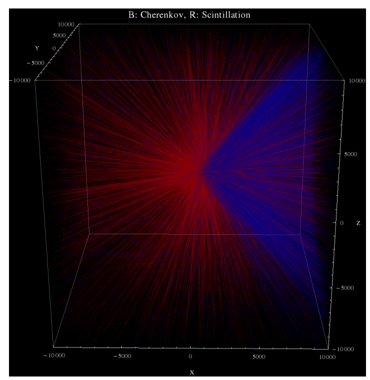


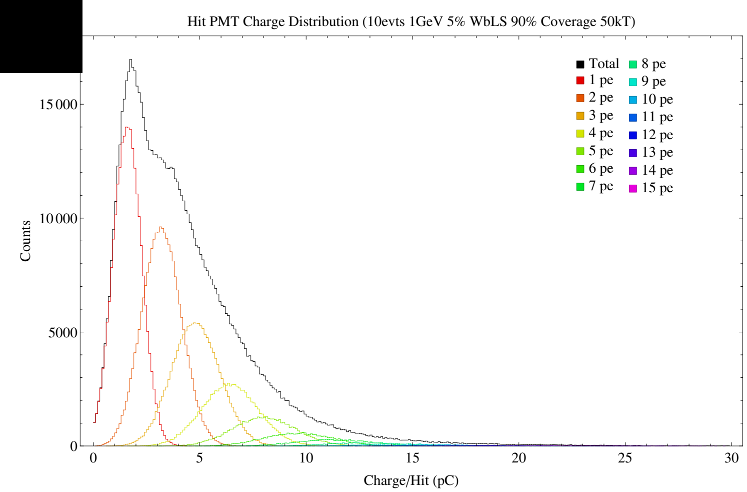


Cherenkov ID scales like

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

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

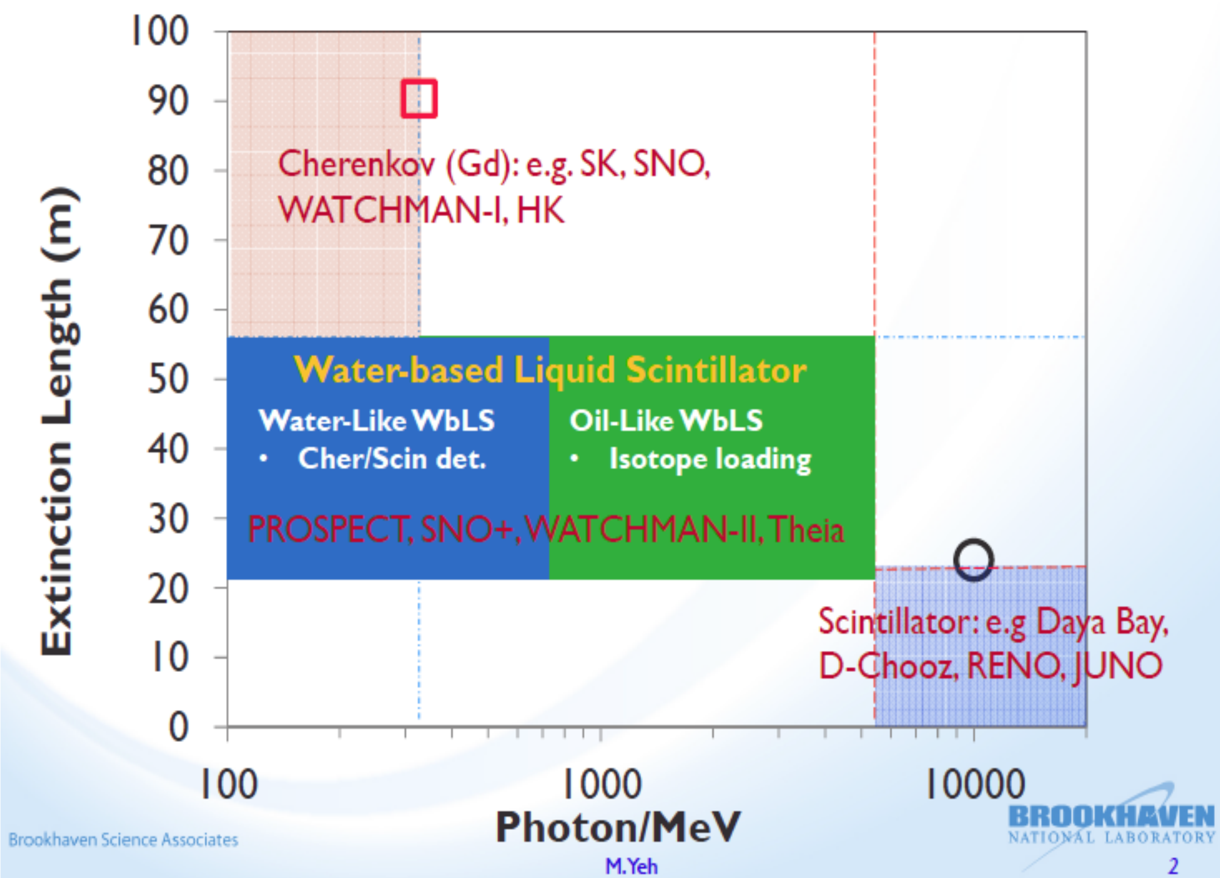




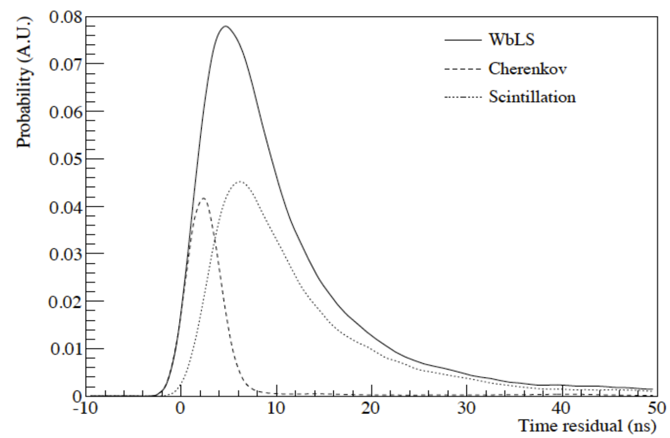
B. Land (Berkeley)

Theia

"Lean" Scintillator Cocktails - γ_c/γ_s

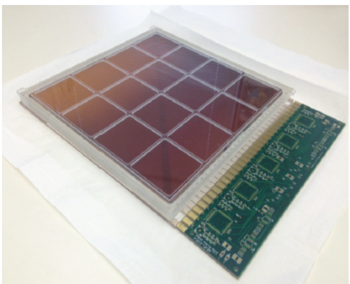


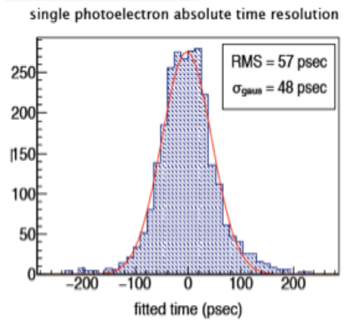
A. Mastbaum



Theia
Photon Sensor Timing -- t_{jitt}

LAPPDs now exist in the wild…will be deployed in ANNIE





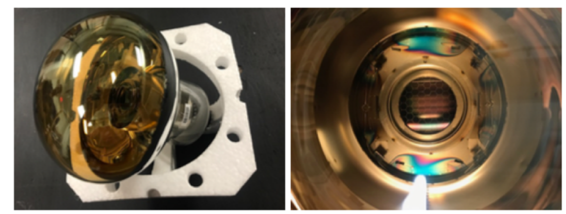


Figure 2: An image of the full R5912-MOD PMT (left) and a photo of the inside of the PMT (right).

But even standard large-area PMTs are looking good

Characterization of the Hamamatsu 8" R5912-MOD Photomultiplier Tube

Tanner Kaptanoglu[a] [1]

[a] *University of Pennsylvania, Philadelphia PA 19104, USA*

NIMA 889 (2018)

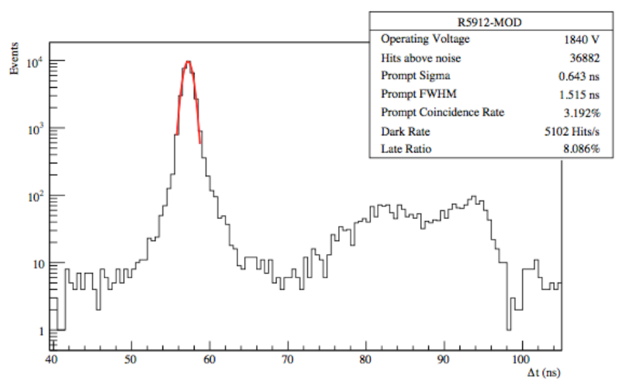
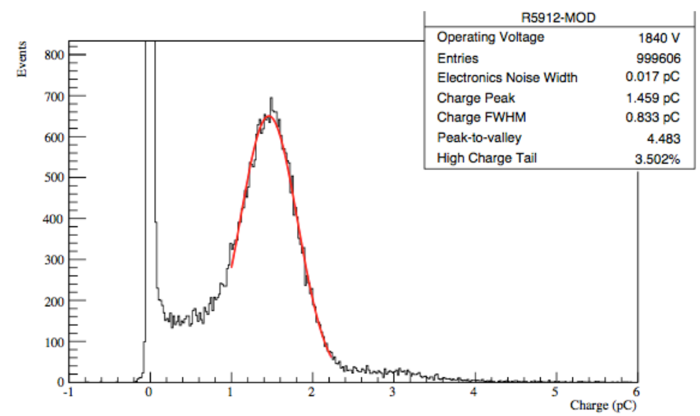


Figure 8: The transit time profile of the R5912-MOD. Shown in the statistics box is some important characteristic of the SPE time response. The Gaussian fit to the prompt light peak is shown in red.

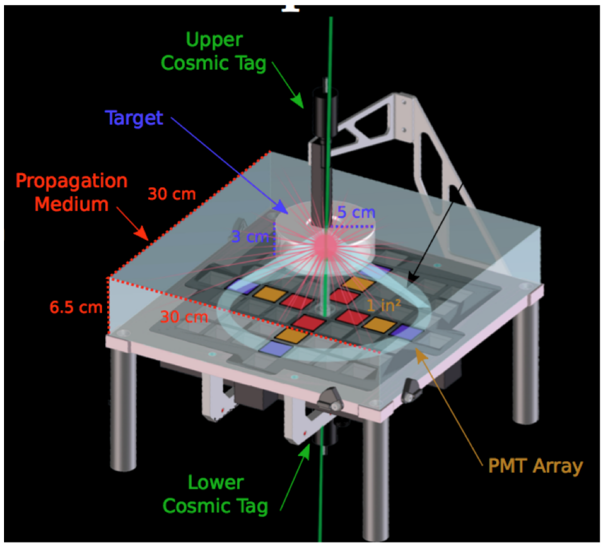


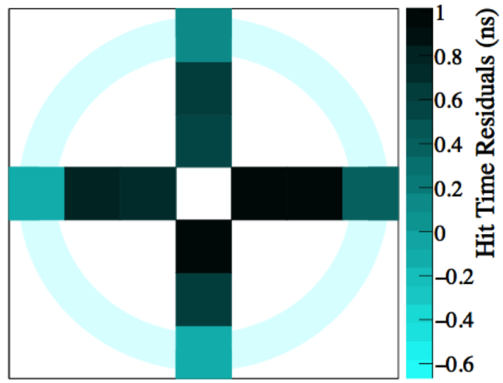
More exotic: Gaseous photon sensors (Sebastian White)

Theia

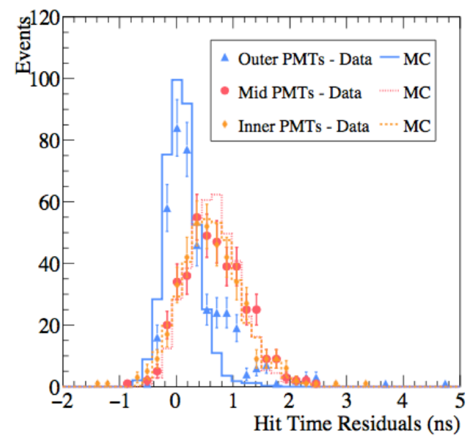
Photon Sensor Timing--t_{jitt}

CHESS at Berkeley demonstrates separation with ~200 ps timing





Typical ring candidate event



Theia

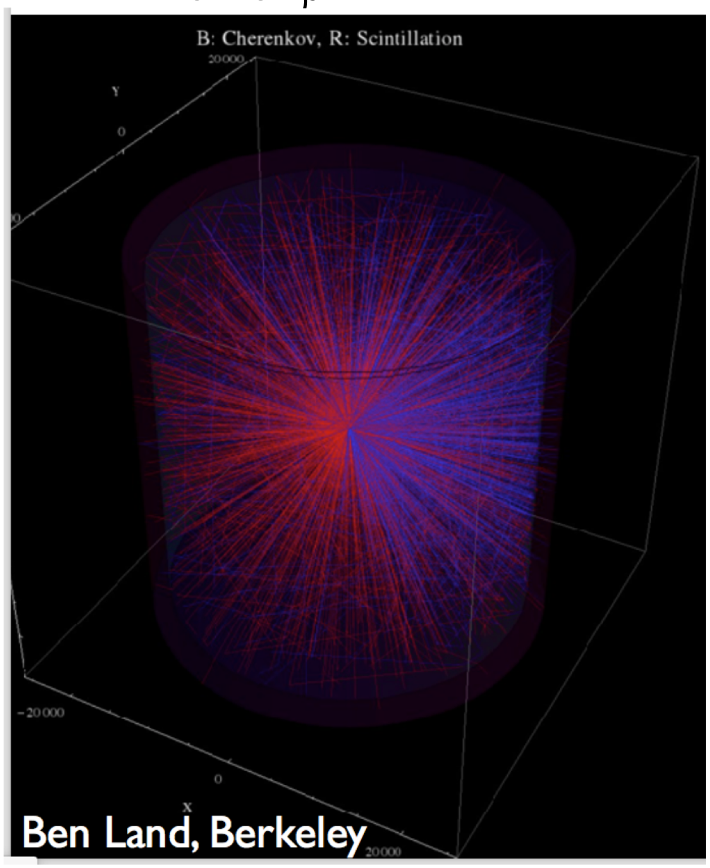
Scintillator Time Profile--τ_{scint}

Some secondary fluors in place of PPO can have risetimes (τ_{scint}) as slow as 15 ns! (Biller, Dunger et al)

Challenge will be to ensure light yield and reconstruction resolution.

Theia
Angular Distribution—$\rho(\cos\alpha,\lambda)_{scint}$

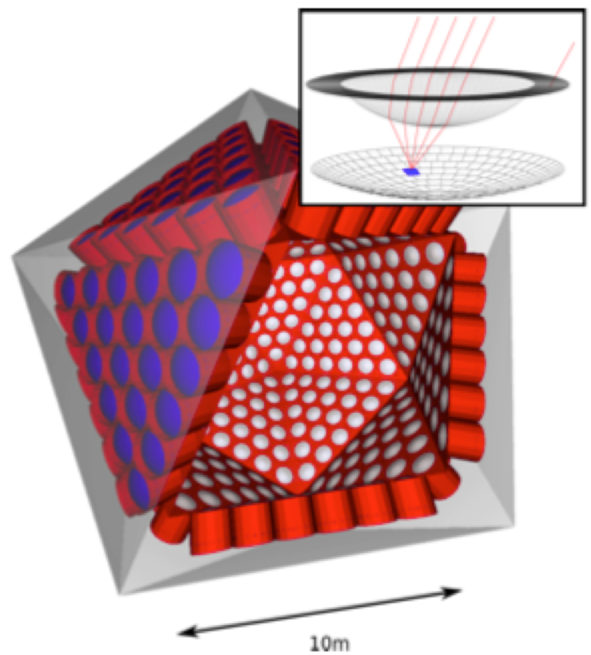
3 MeV β



27 Nov 2017

Distributed Imaging for Liquid Scintillation Detectors

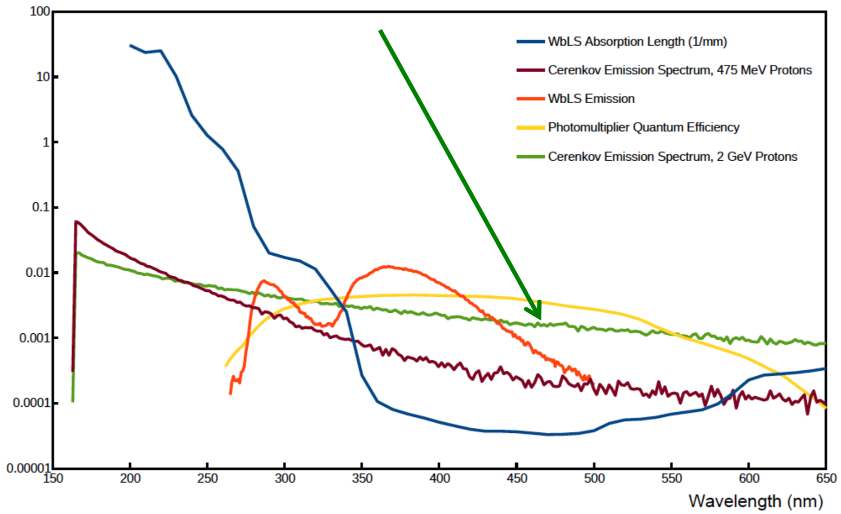
J. Dalmasson,[1] G. Gratta,[1] A. Jamil*,[1,2] S. Kravitz†,[1] M. Malek,[1] K. Wells,[1] J. Bentley,[3] S. Steven,[3] and J. Su[4]



(not really a Cher/scint thing but very cool!)

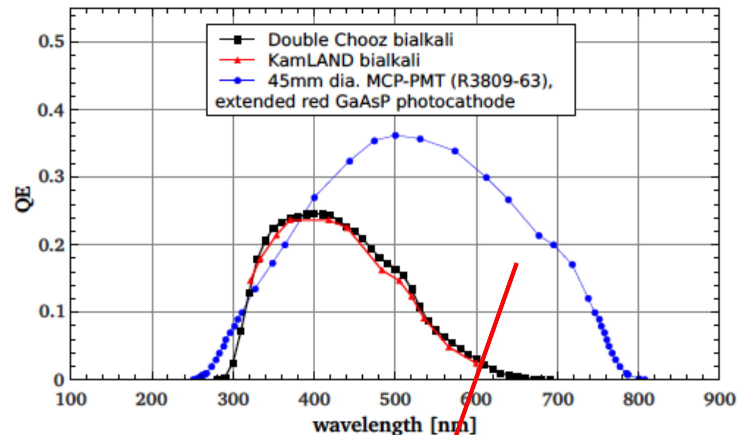
Theia
Spectral Separation—R(λ)

Cherenkov light extends beyond scintillation emission and absorption

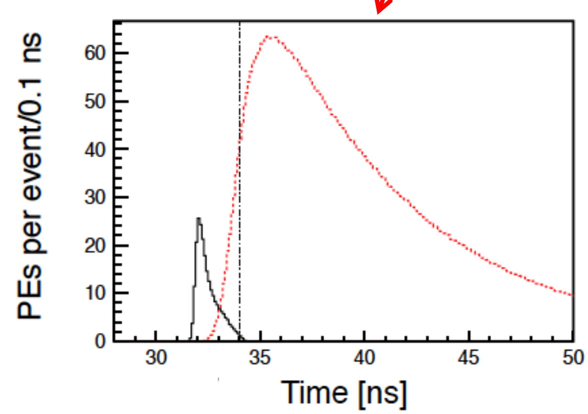


And red travels faster than blue…

Red-sensitive PMTs exist

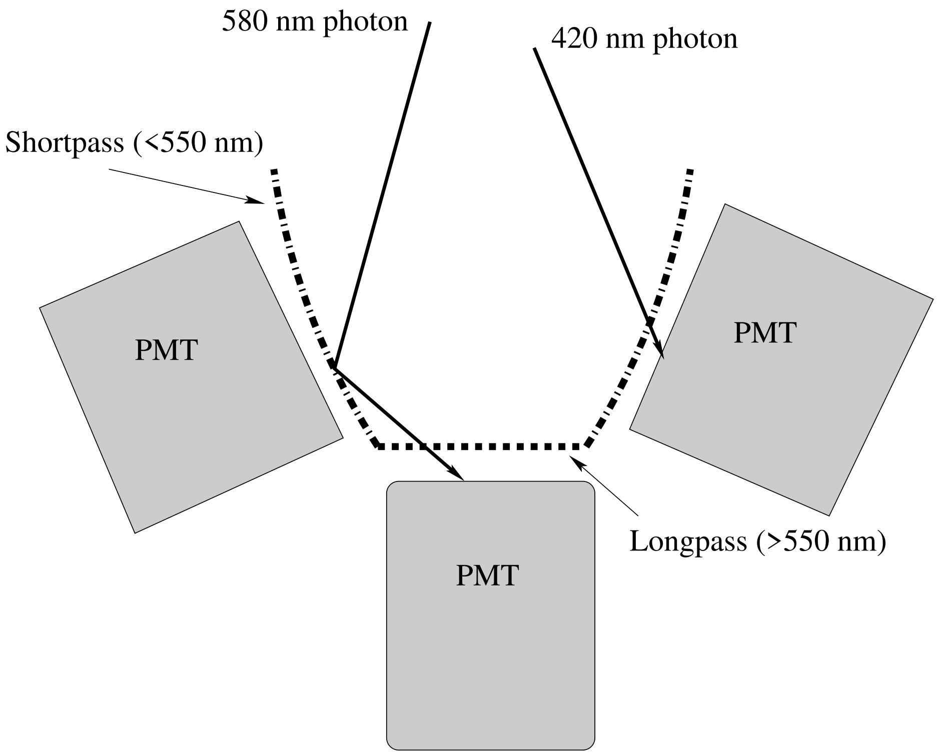


L. Winslow



Theia
Spectral Separation—R(λ)

Photon sorting by dichroic Winston cones (JRK)

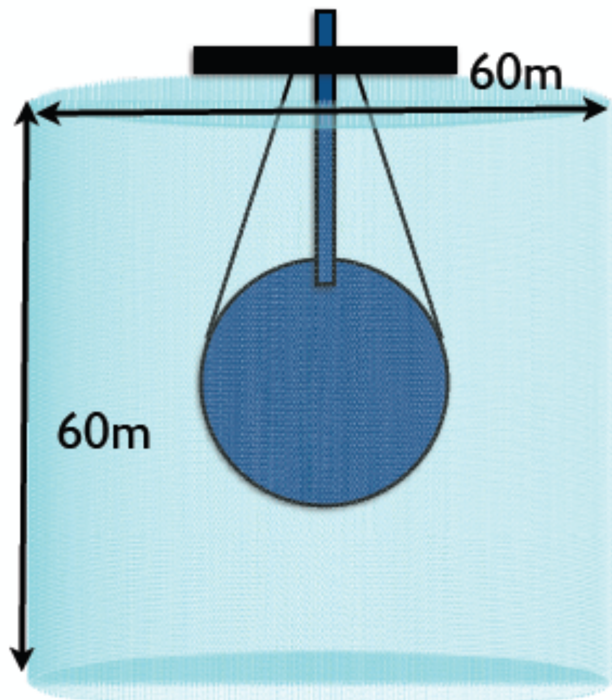


V. Rusu at FNAL: LDRD for graphene-based spectral photon detection

Theia

Beyond Cher/Scint, we also need a "forward-looking infrastructure":

- Detector needs to be built clean from the beginning
- It has to be ready for upgrades to light sensors
- It has to allow for loading (Li, Gd, Te, Xe…)
- It has to allow for extensive calibrations
- It has to be able to include an inner containment vessel.



Theia

Beyond Cher/Scint, we also need a "forward-looking infrastructure":

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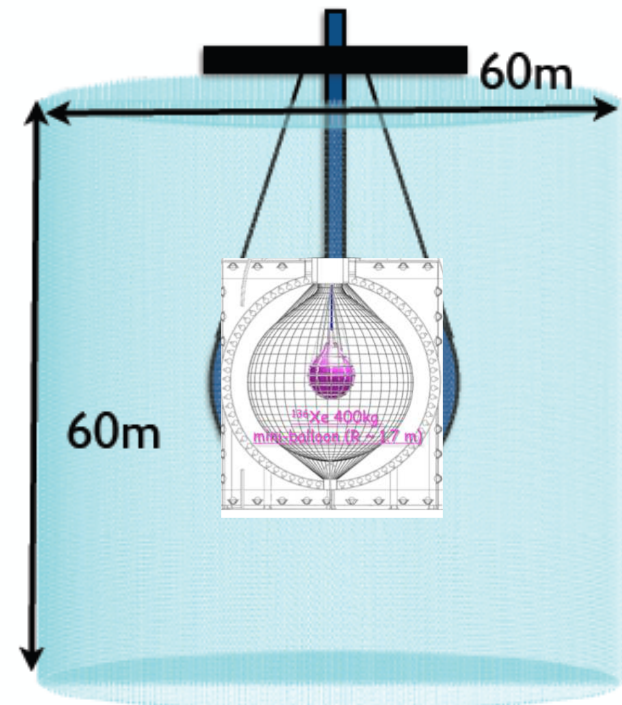


Theia

Physics program covers 5 orders of magnitude in E_ν.

A possible phased program:

I. Water-based LS+20% photon coverage
   - High-E solar, long-baseline νs, supernova burst

II. Richer scintillator mix, 80% fast photon coverage, Li-loaded
   - Low E solar, MSW transition, DSNB, geo-ν

III. Inner balloon, Te or Xe-loaded liquid scintillator
   - $0\nu\beta\beta$ with sensitivity toward normal hierarchy regime

It may actually make sense to skip right to Phase II

Theia
Advanced Reconstruction

Reconstructing with both scintillation and Cherenkov light is not so easy (cf. Tzanov and MiniBooNE)

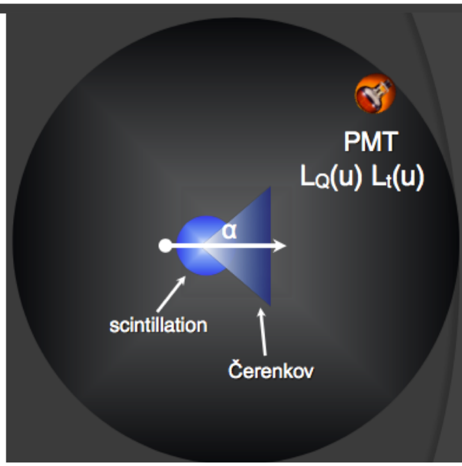
$$\mathcal{L}(\mathbf{x}) = \prod_{i=1}^{N_{unhit}} \mathcal{P}_i(\text{unhit};\mathbf{x}) \prod_{j=1}^{N_{hit}} \mathcal{P}_j(\text{hit};\mathbf{x}) f(q_j;\mathbf{x}) f(t_j;\mathbf{x})$$

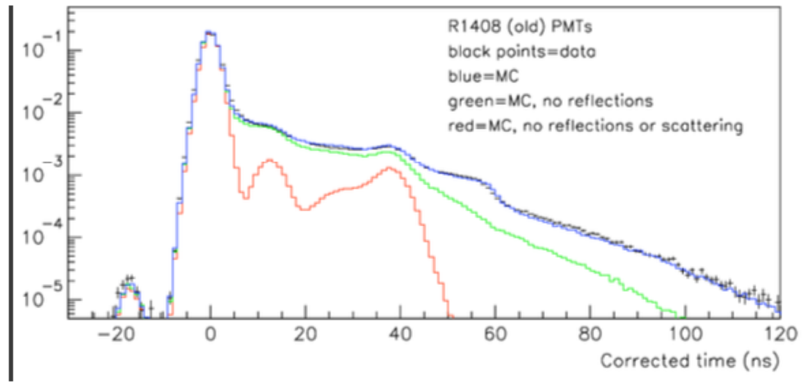
$$-\log(\mathcal{L})(\mathbf{x}) = F_q(\mathbf{x}) + F_t(\mathbf{x})$$

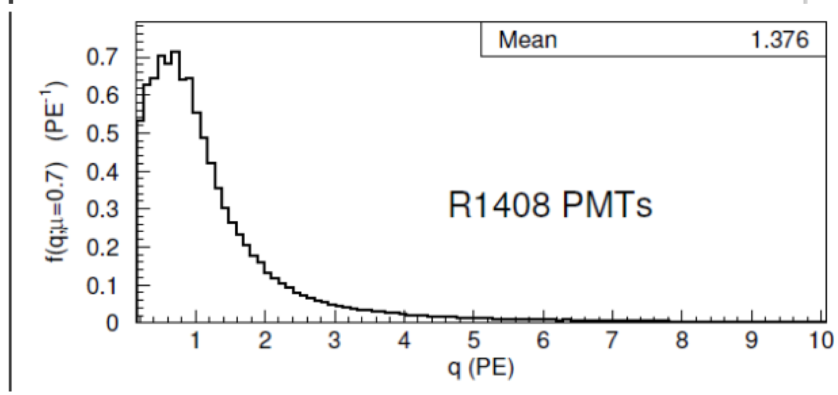
$$F_q(\mathbf{x}) = -\sum_{i=1}^{N_{unhit}} \log(\mathcal{P}_i(\text{unhit};\mathbf{x})) - \sum_{j=1}^{N_{hit}} \log(\mathcal{P}_j(\text{hit};\mathbf{x}) f(q_j;\mathbf{x})),$$

$$F_t(\mathbf{x}) = -\sum_{j=1}^{N_{hit}} \log(f(t_j;\mathbf{x})).$$

$$\mathcal{P}(\text{hit};\mu(\mathbf{x})) = 1 - \mathcal{P}(\text{unhit};\mu(\mathbf{x})) = 1 - e^{-\mu}.$$



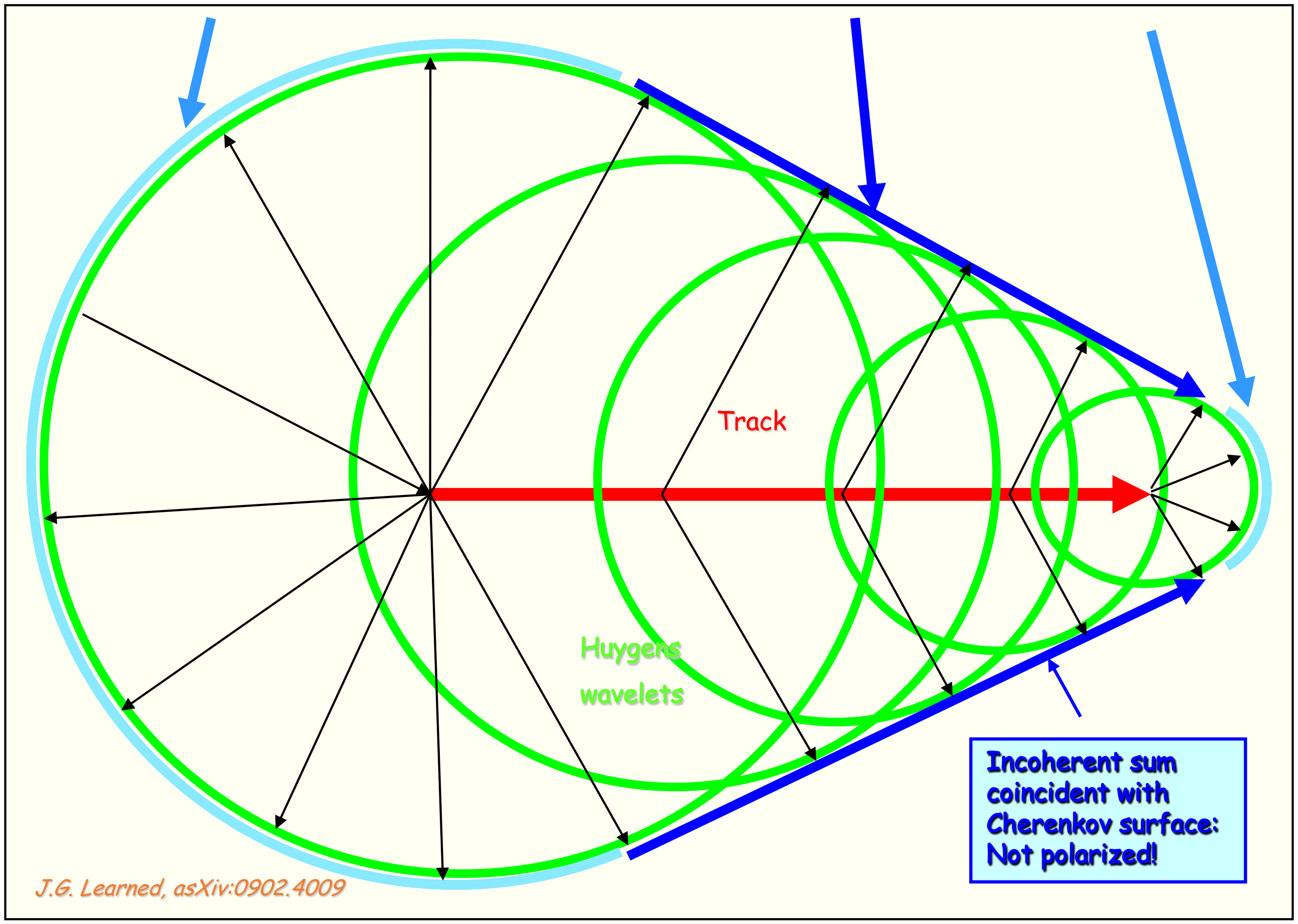




Theia
Advanced Reconstruction

There are more exotic techniques that look good!

Snapshot of the Fermat Surface for a Single Muon-likeTrack



Theia
Advanced Reconstruction

Even at low energies direction is possible:

- **For emitted isotropic light we have:**

$$\langle \vec{D} \rangle = \sum_i \vec{d}_i = \vec{0}$$

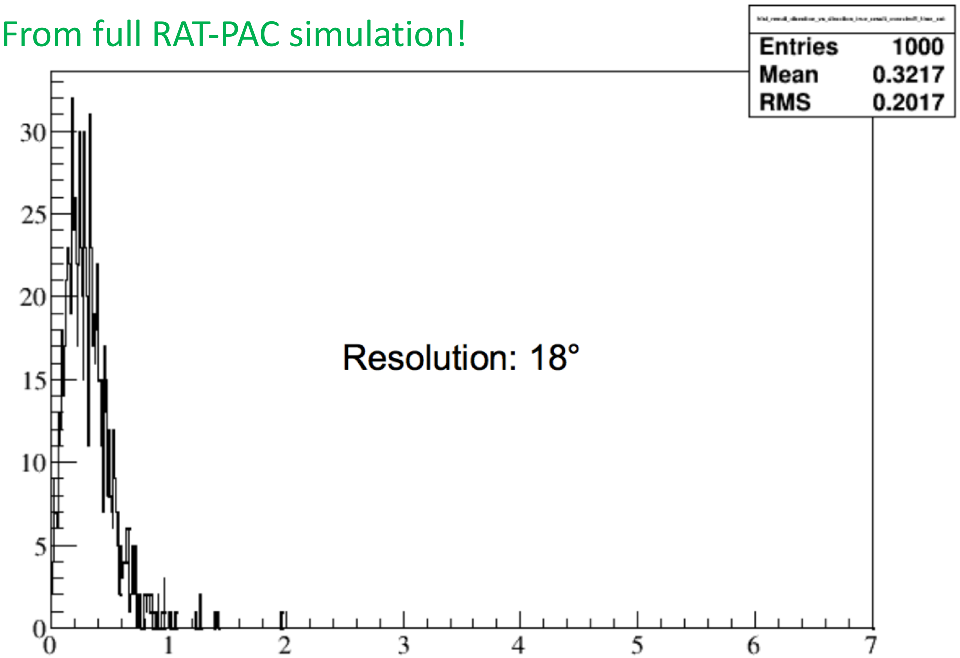
- **For emitted Cherenkov light we have:**

$$\langle \vec{D} \rangle = \sum_i \vec{d}_i = N_{Cher} \cdot \cos(\theta) \cdot \vec{P}$$

with:

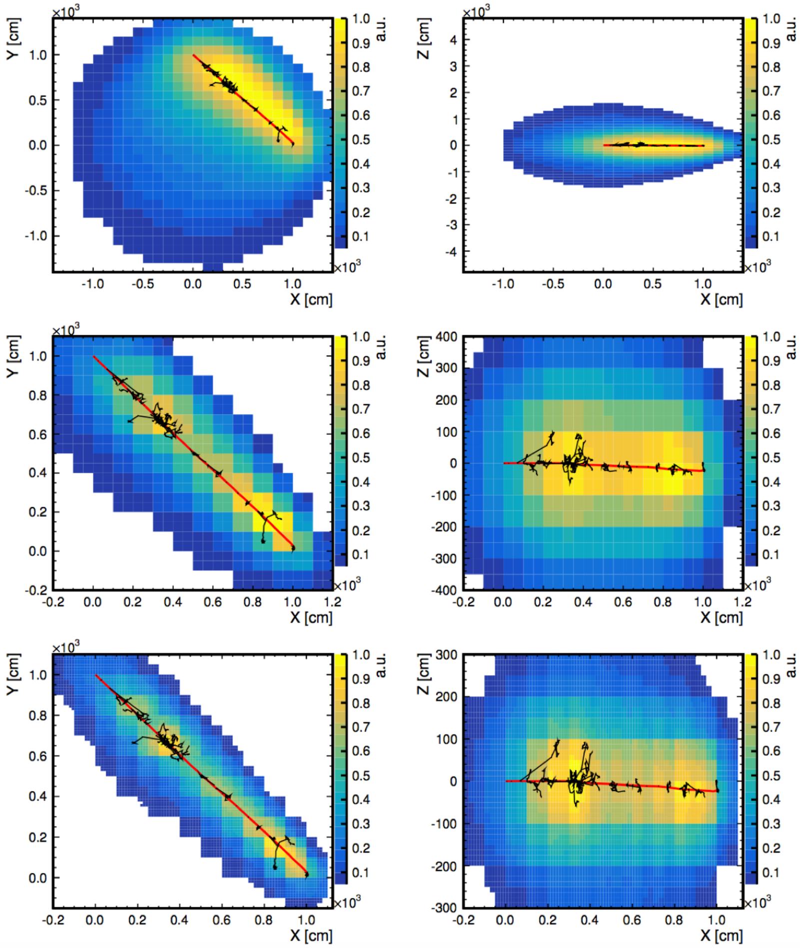
- $\vec{D}$ = total
- $\vec{d}_i$ = single photon direction
- $\vec{P}$ = direction of particle
- N_{Cher} = Number of Cherenkov photons

From full RAT-PAC simulation!

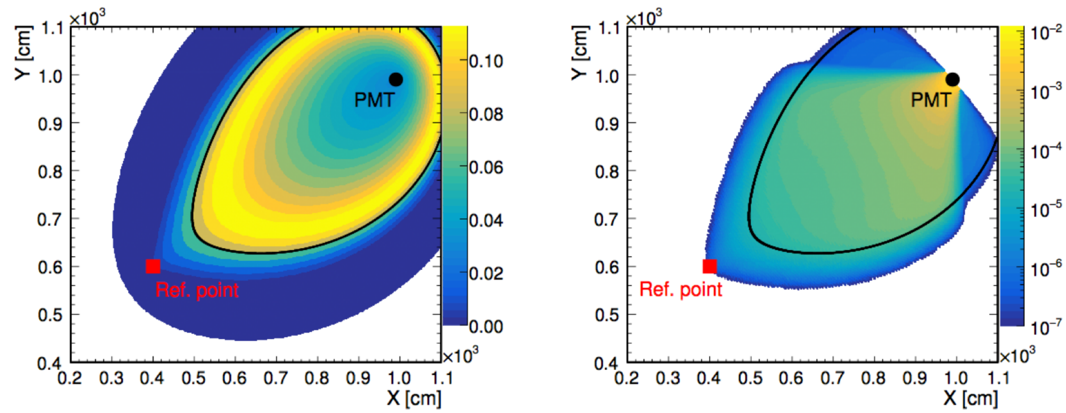


Bjorn Wonsak

Theia
Advanced Reconstruction



Topological approach allows tracking even in all liquid scintillator



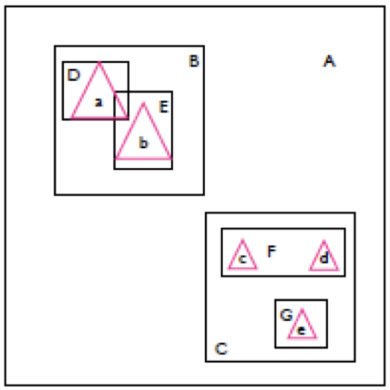
Sebastian Lorenz

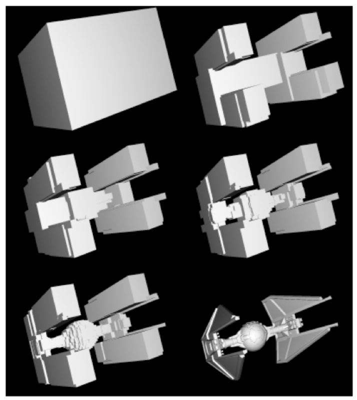
Theia

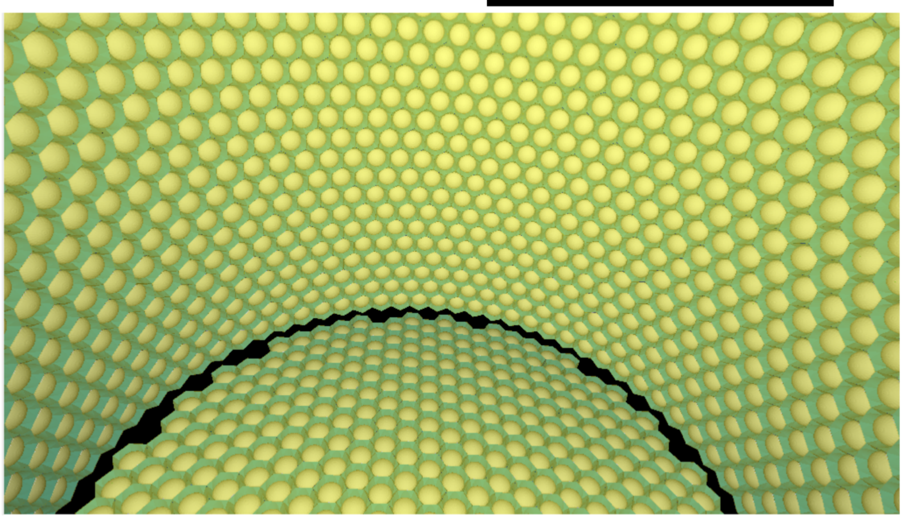
Advanced Reconstruction

Chroma?

Ray tracing x200 faster than GEANT4



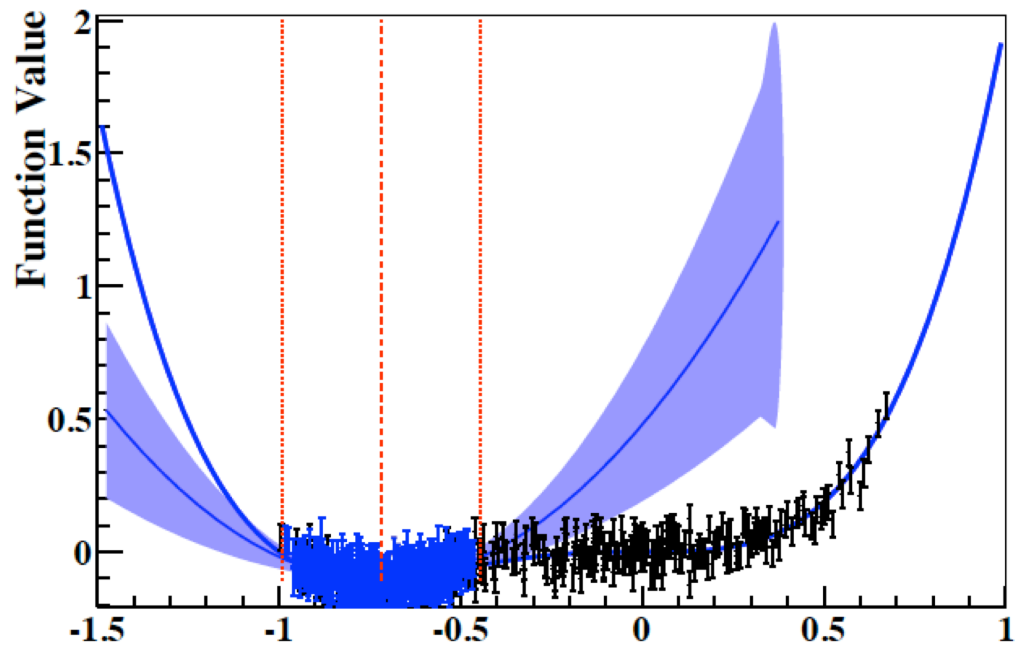


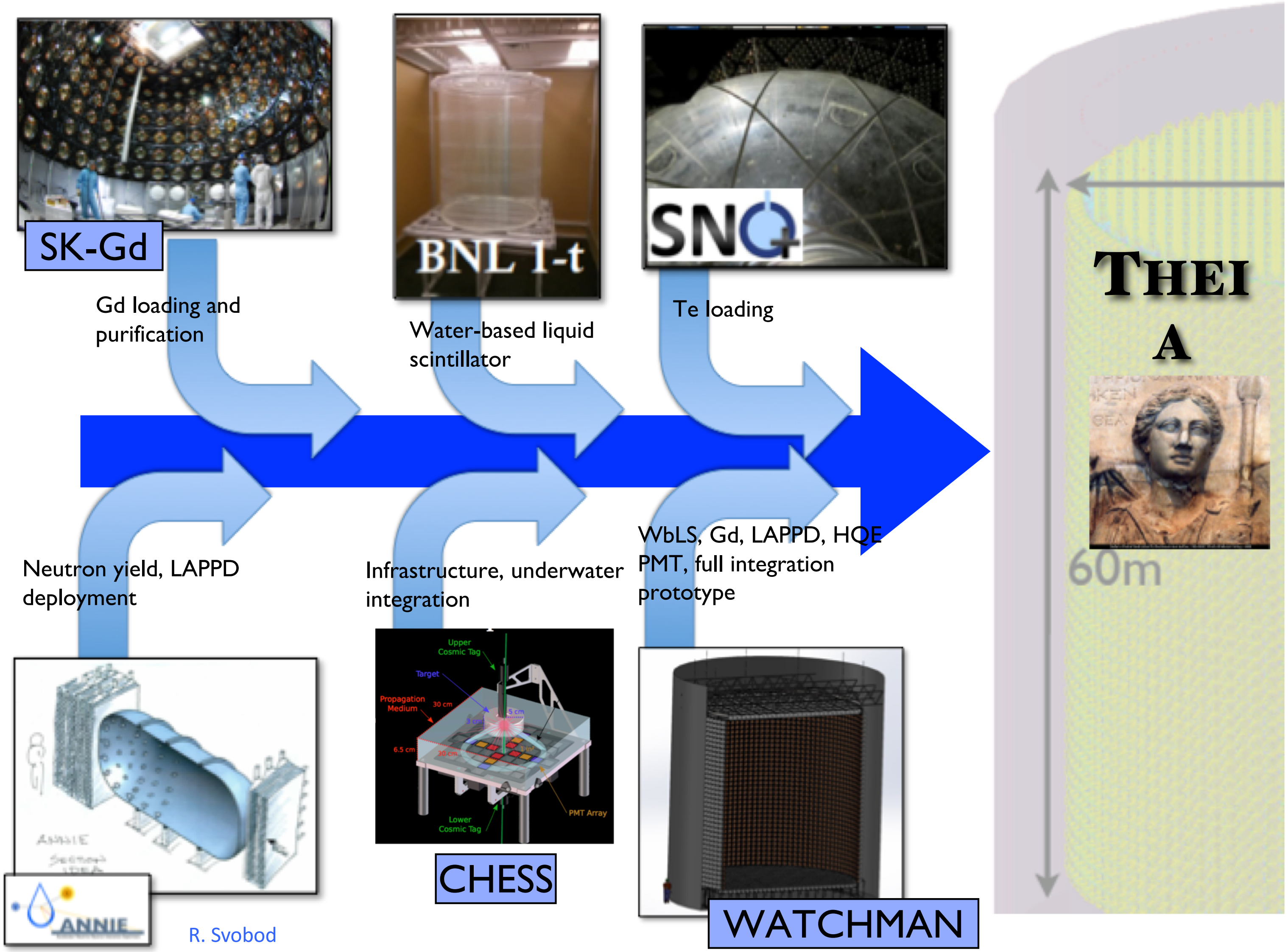


Use GPU-based ray tracer to generate PDFs

$$L(x,y,z,t,\vec{p},ID) \sim \prod_{i=1}^{N_{PMT}} p_i(t_i^{res}, Q_i \mid x,y,z,t,\vec{p},ID)$$

Combined with "fuzzy fitter"





R. Svobod

Great progress!

- SNO+ running
- ANNIE running
- WATCHMAN/ AIT moving ahead
- SK-Gd happening
- CHESS running
- JUNO progressing

Summary

- Theia physics program remains as compelling as ever
- Rapid progress on R&D but plenty yet to do
- Lots of creative ideas still moving ahead
- Great news on the “prototype” front (WM,ANNIE,SNO+, JUNO…)
- Need here to start thinking of firm plans and decisions