New Technologies for Neutrino Astrophysics

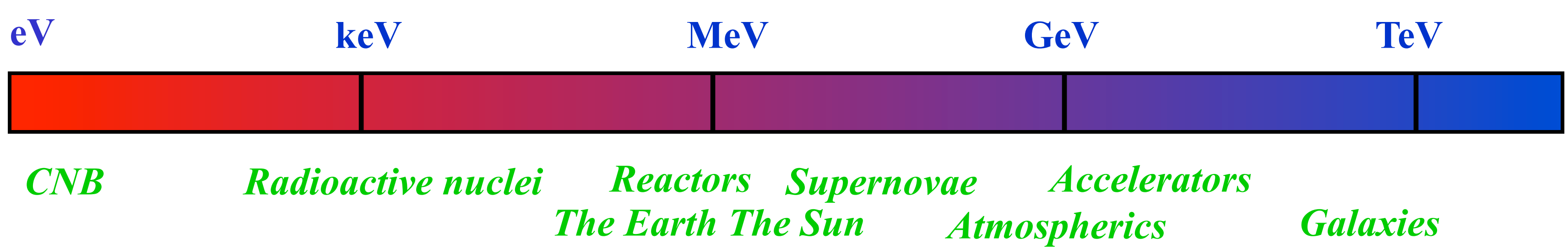
- Physics Drivers
- New Instrumentation for Detectors Based On:
  - Water Cherenkov
  - Liquid Scintillator
  - Water-based Liquid Scintillator
  - Noble Liquid Scintillation
  - Liquid Argon TPCs

Josh Klein, Penn

“Astrophysical” νs

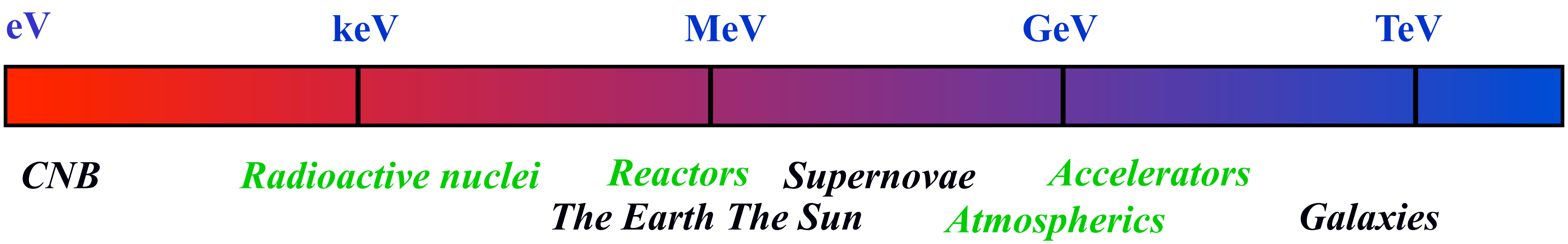
- Solar
- Geoneutrinos [according to The Aliens]
- Supernova burst
- Diffuse supernova neutrinos
- High-energy (extragalactic) neutrinos
- Exotic sources (neutron star collisions?)
- Cosmic Background Neutrinos

These all have in common the fact that neutrinos can be used to understand the source (as well as neutrino properties).



On the other hand, they span about 12 orders of magnitude in energy.

“Astrophysical” νs



Technical challenges very different from other sources:

- Can’t get any closer
- Can’t change beam energy or flavor/antiflavor content
- Most sources are low energy
- Fluxes typically inversely proportional to energy
- Can’t turn off the beam
- Can’t turn ON the beam (e.g., supernovae)

“Breakthrough” Technologies

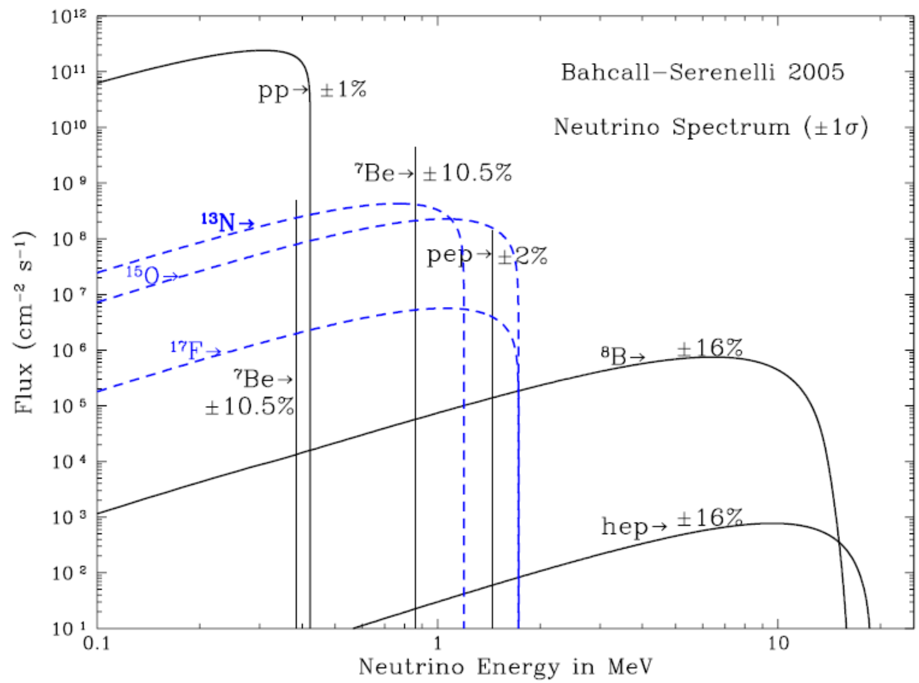
Spoiler

For most topics, biggest improvements will come from:

- More efficient photon detection
- Better photon detection timing
- Higher photon yields of materials (WLS, scintillator, etc.)
- Ability to load metals into liquids
- Front-end intelligence

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



On the other hand, we're stuck with disappearance or inclusive appearance, which limits some of the accessible phenomenology (e.g., CP violation)

Six Things We Should Measure

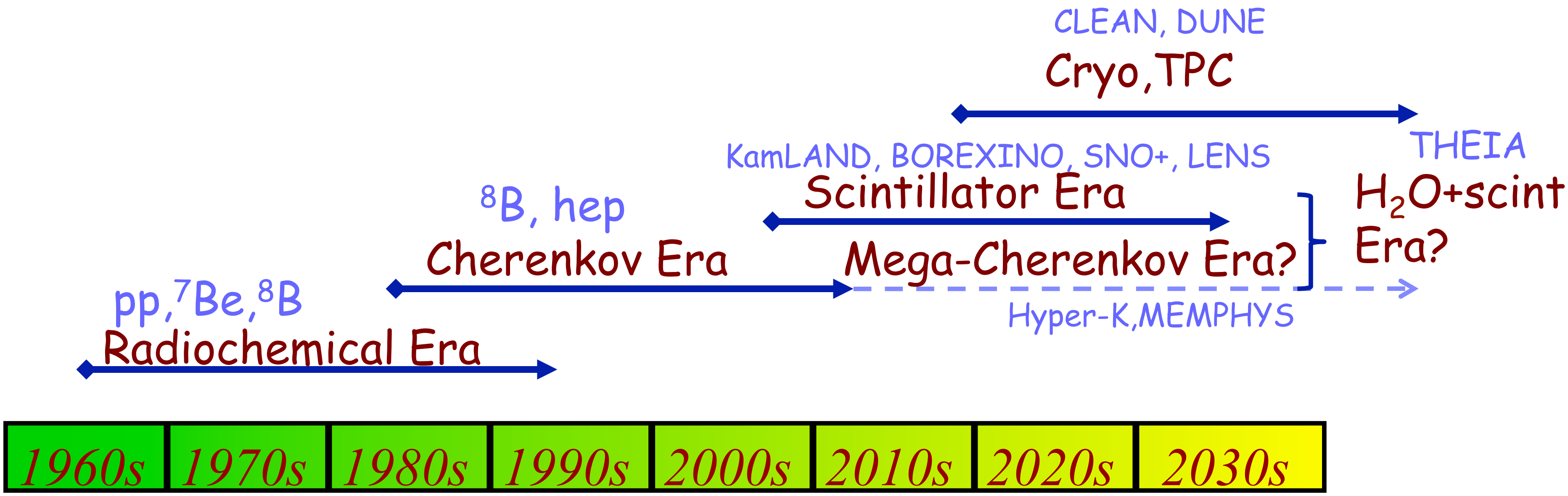
(in no particular order)

1. Precision ^8B Day/Night asymmetry
2. Vacuum/matter transition region
3. Exclusive, precision measurement of pep flux
4. Exclusive, precision measurement of CNO flux
5. Exclusive, precision measurement of pp flux
6. Observation of solar hep neutrinos

Physics Drivers:

- Exploit the discovery of neutrino mass
- Search for the unknown

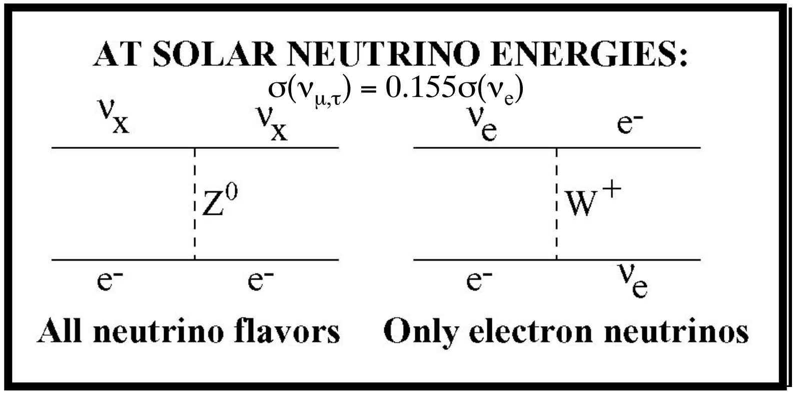
Next Generations



→ Nearly all future experiments are multi-purpose:

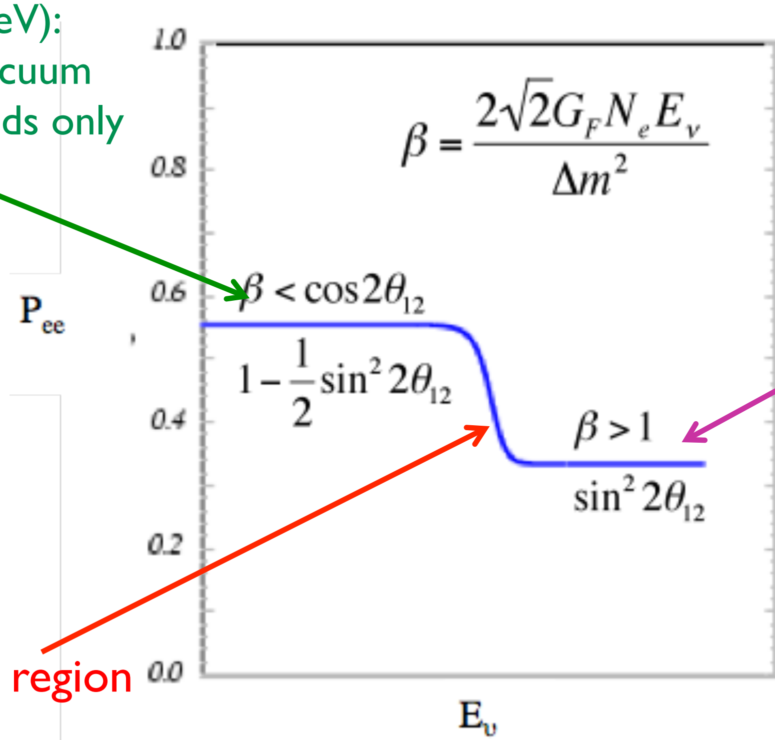
- Dark matter
- $0\nu\beta\beta$
- Reactor anti-νs
- Long baseline/proton decay
- neutrino magnetic moment

Observing MSW Phenomenology



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}

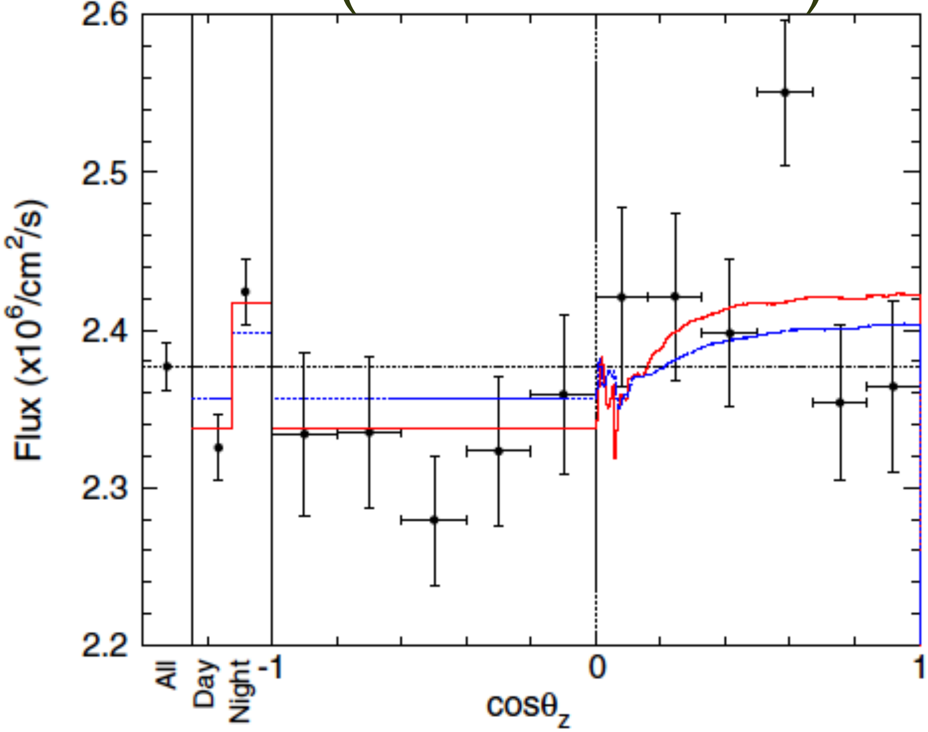
Transition region

Interferometry on top of interferometry…

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

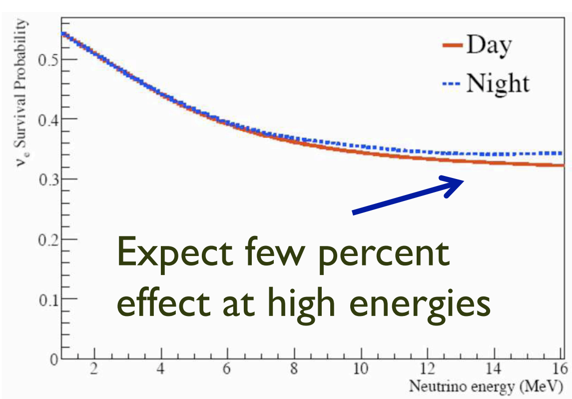
Observing MSW Phenomenlogy

2.7 σ (from unbinned fit)

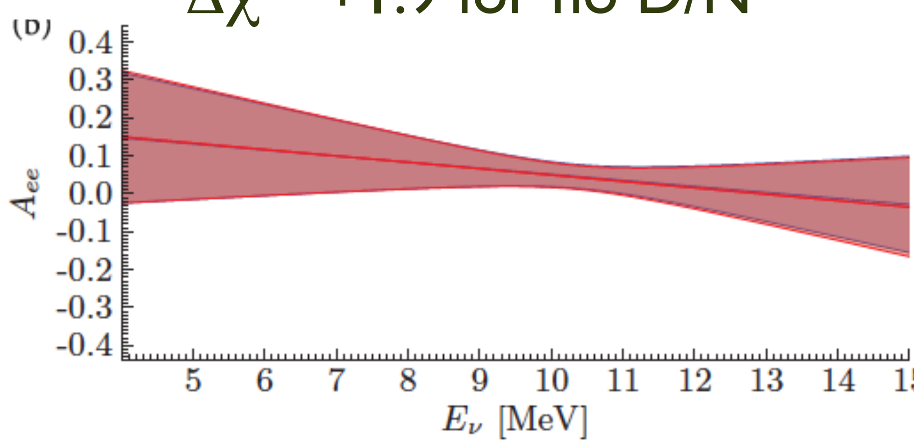


Super-Kamiokande, PRL **112** 091805

Hint of Day/Night Effect from Super-Kamiokande, but statistics make this very hard.



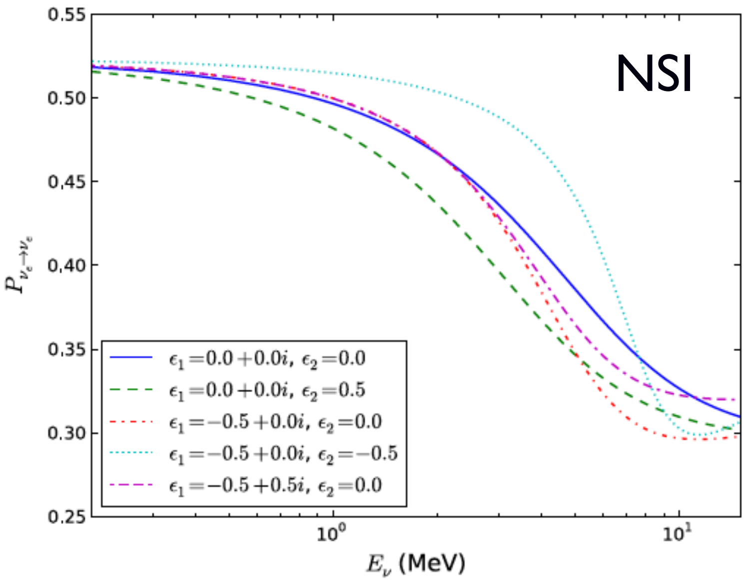
$\Delta\chi^{2}$= +1.9 for no D/N

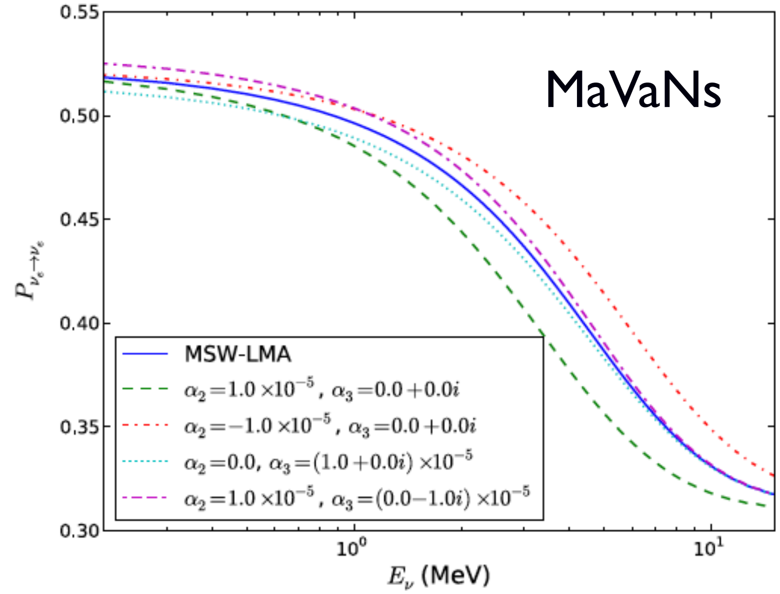


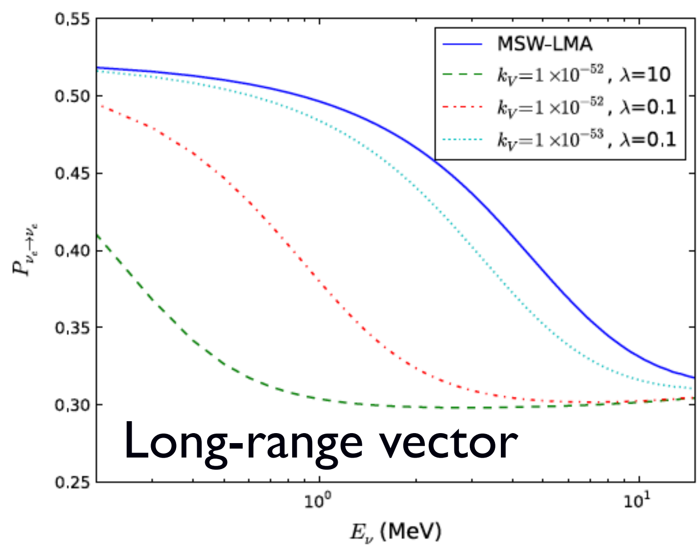
SNO, PRC **88** 025501

Observing MSW Phenomenology

Vacuum/matter transition region





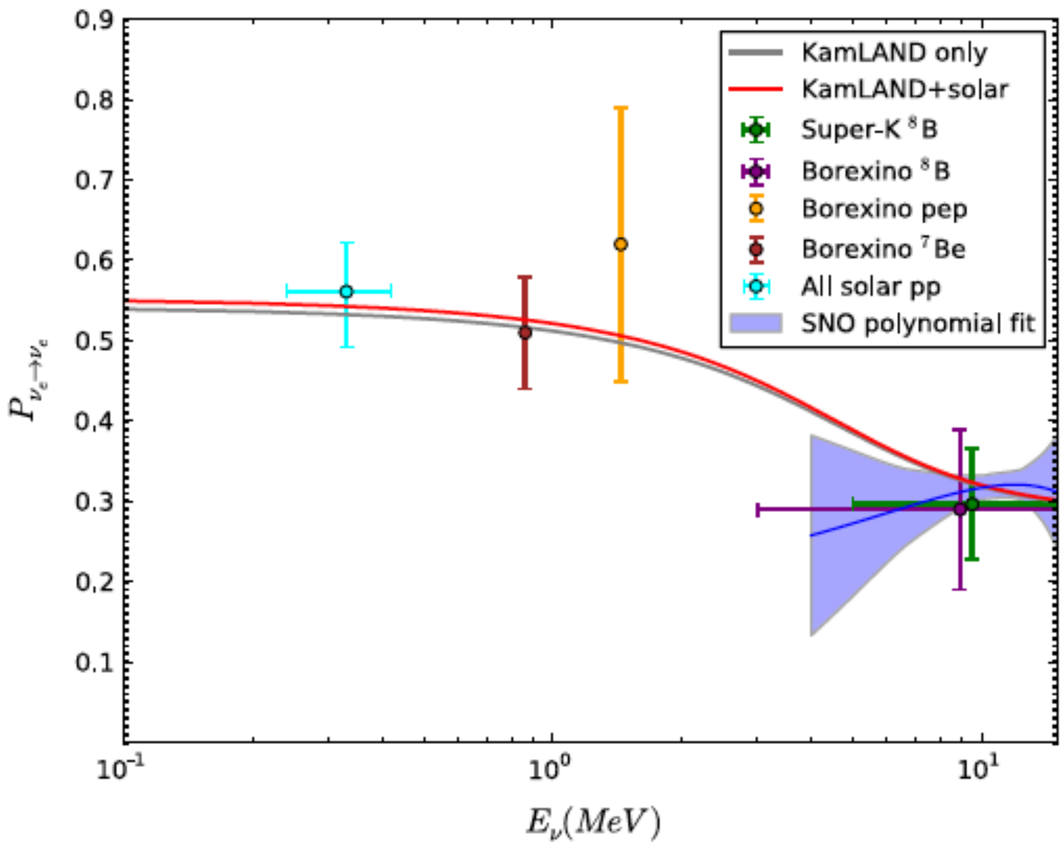


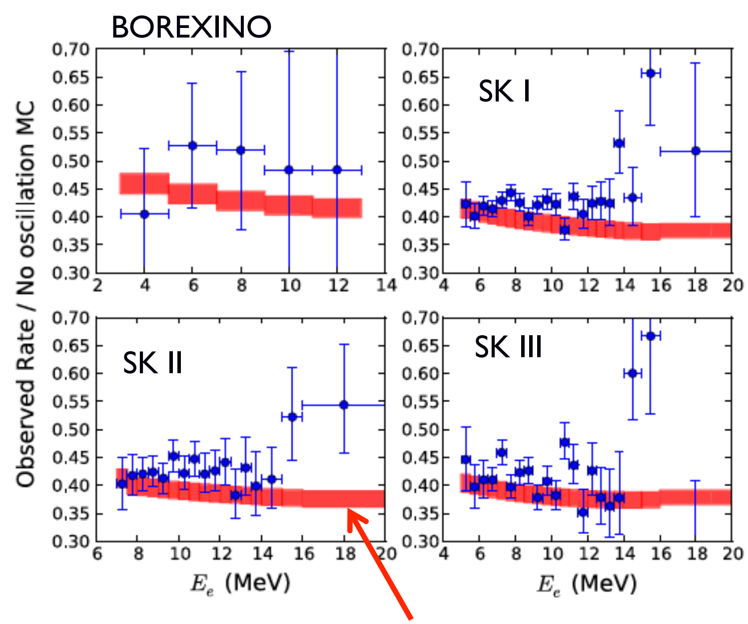
Bonventre, LaTorre, et al.

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

Observing MSW Phenomenology

Vacuum/matter transition region





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

Bonventre, LaTorre, et al.
PHYSICAL REVIEW D **88**, 053010 (2013)

pp/pep and the Sun

Are all energy generation/loss mechanisms accounted for?

With luminosity constraint:

Exp. Uncs. Theory Uncs.

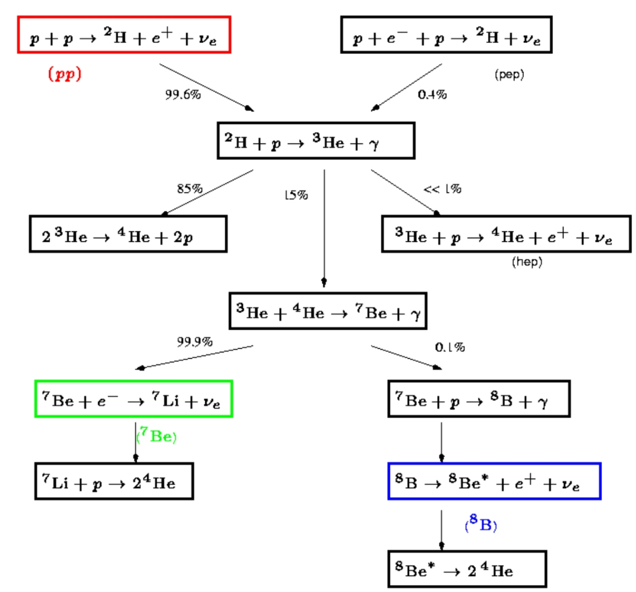
$$\begin{aligned}
\phi(\mathrm{pp})_{\mathrm{measured}} &= (1.02 \pm 0.02 \pm 0.01)\phi(\mathrm{pp})_{\mathrm{theory}} \\
\phi(^8\mathrm{B})_{\mathrm{measured}} &= (0.88 \pm 0.04 \pm 0.23)\phi(^8\mathrm{B})_{\mathrm{theory}} \\
\phi(^7\mathrm{Be})_{\mathrm{measured}} &= (0.91^{+0.24}_{-0.62} \pm 0.11)\phi(^7\mathrm{Be})_{\mathrm{theory}}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

Bahcall and Pinsonneault

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

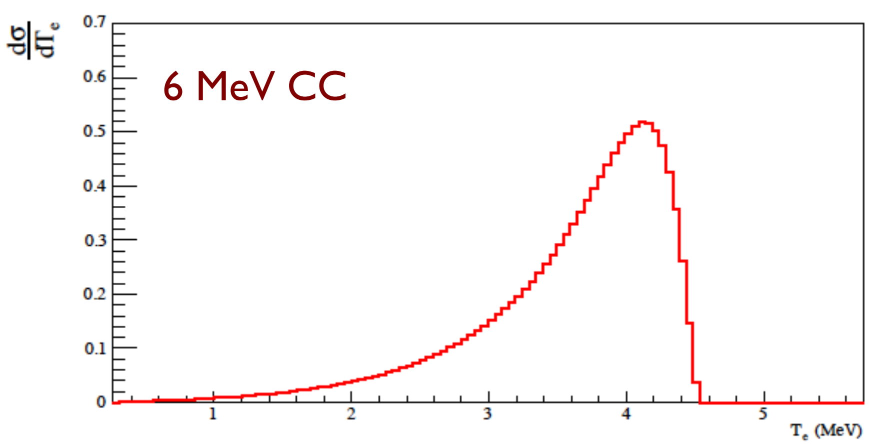
→ \`Unitarity' test that integrates over a lot of new physics

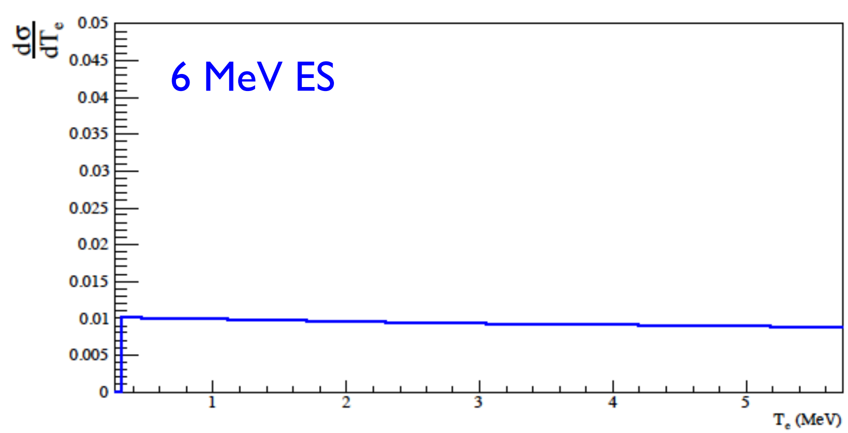
most sensitive to pp flux, but also pep



Solar ν Technological Challenges

Physics	Threshold	Size	Resolution	CC/ES	Cleanliness
pp/luminosity constraint	100 keV	>10 tonnes	Moderate	Either	Extremely high
CNO νs	500 keV	> 1 ktonne	Very good	CC	Extremely high
pep	1 MeV	> 1 ktonne	Good	Either	High
MSW transition	1 MeV	> 50 ktonnes	Excellent	CC	High
Day/Night	10 MeV	> 50 ktonnes	Good	Either	Moderate
hep νs	10 MeV	> 10 ktonnes	Excellent	CC	Moderate





Geoneutrinos

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

Assay the Earth by looking at the "antineutrino glow"

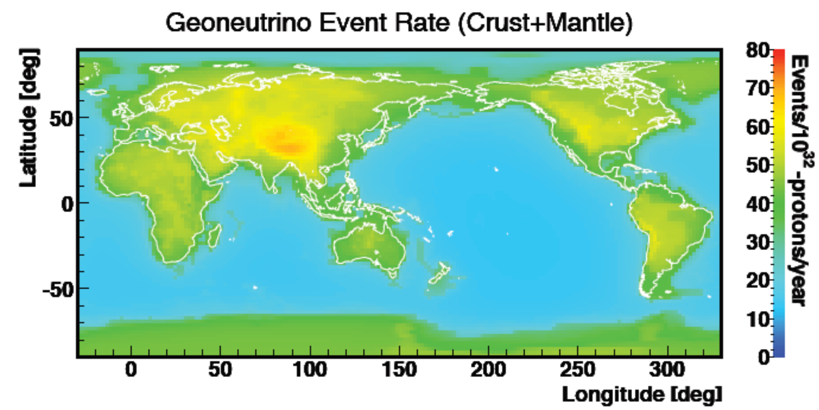


Image: S. Enomoto

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

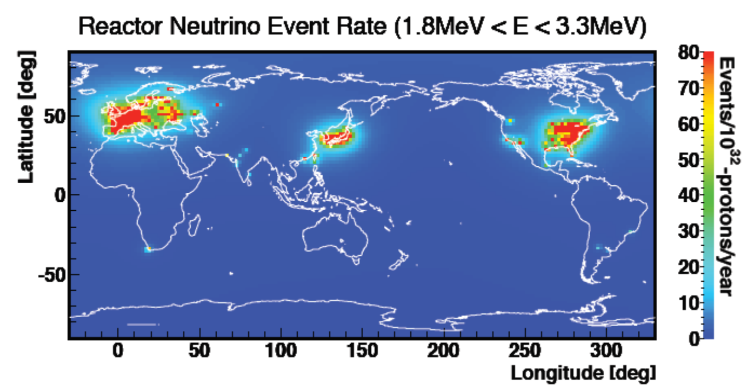


Image: S. Enomoto

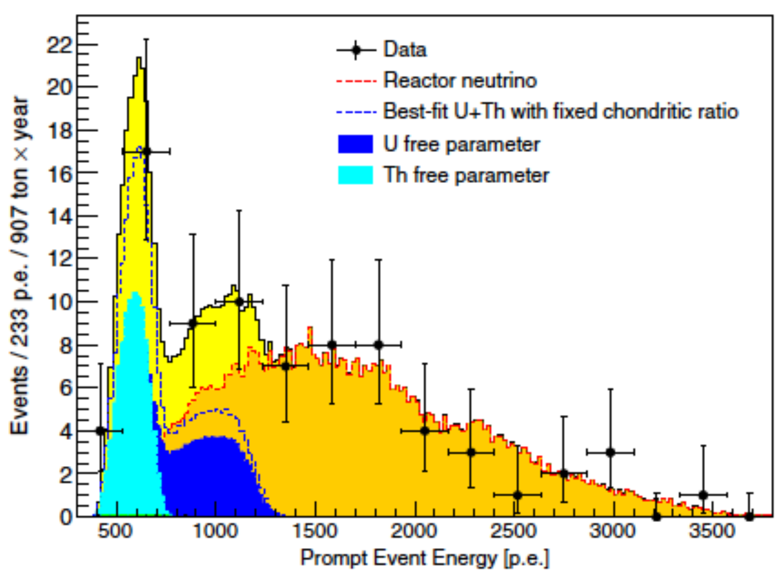
Geo ν Technological Challenges

Biggest difference between this and solar νs is IBD.

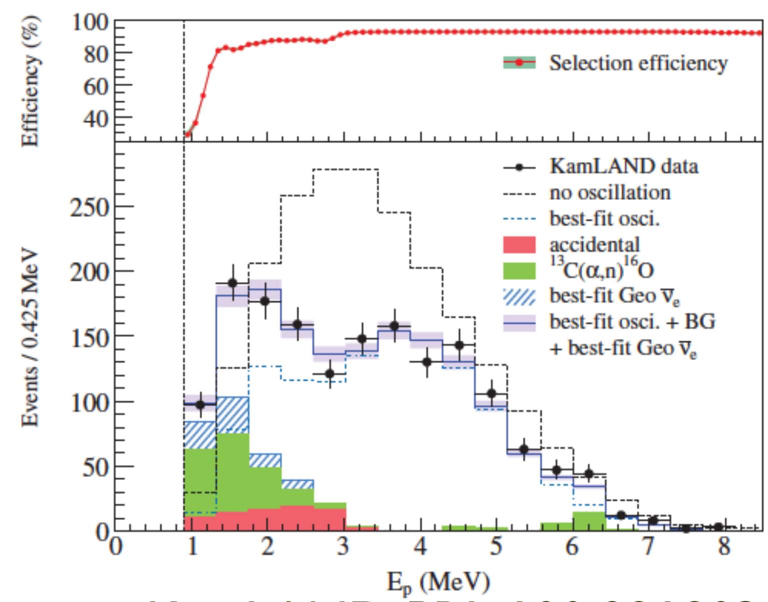
Otherwise want

- Low reactor backgrounds
- Low threshold
- Better resolution
- Better statistics (bigger detector)
- More samples (more detectors)

But cleanliness less of an issue because of IBD neutron tag.

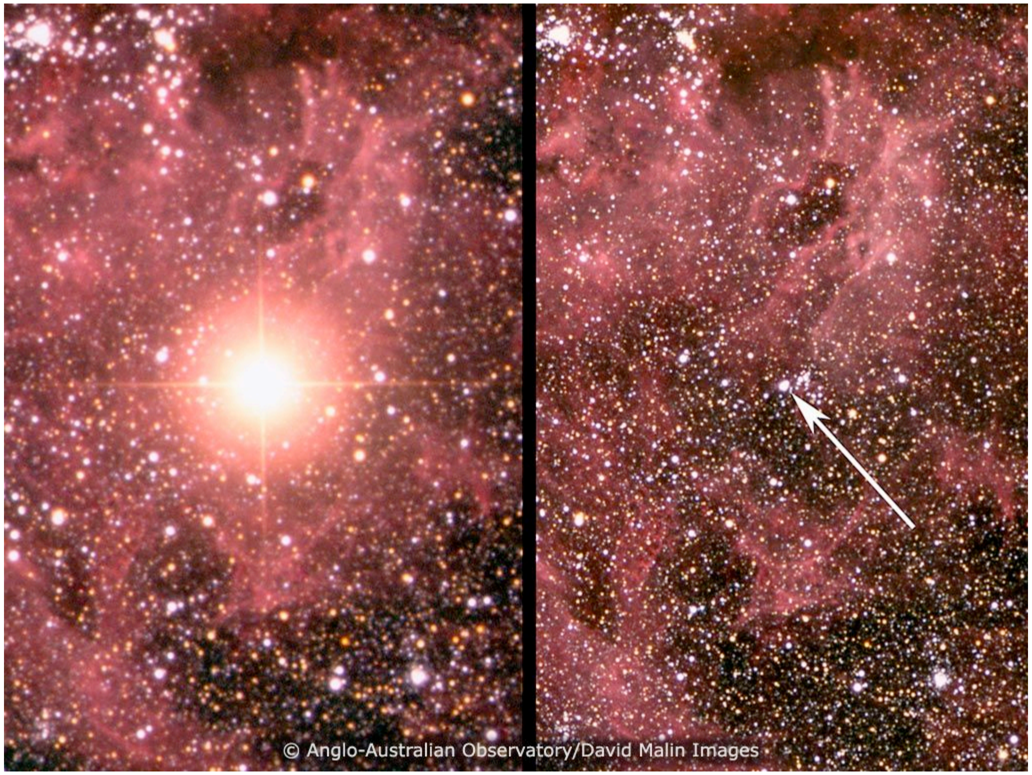


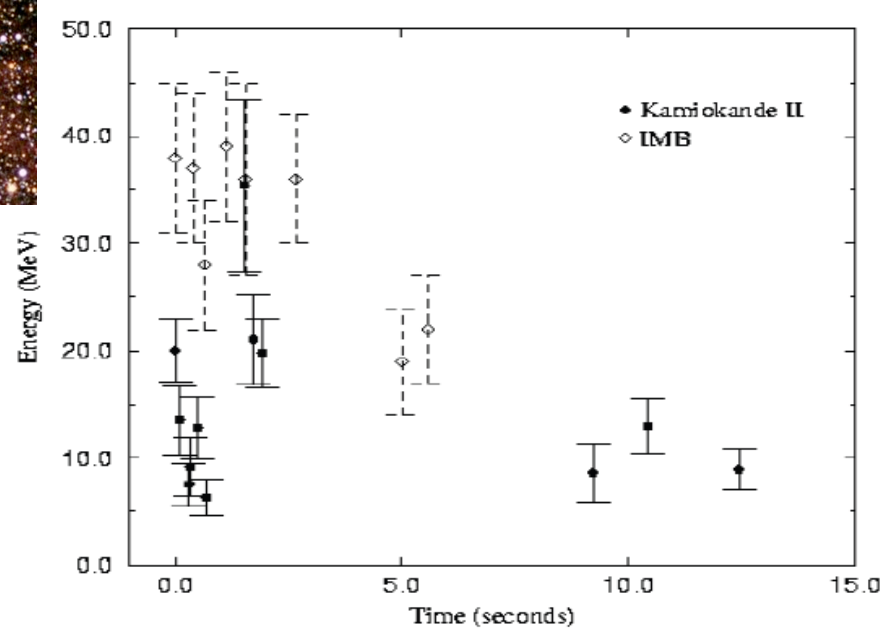
BOREXINO, PRD 92 031101(R)



KamLAND, PRL 100 221803

Supernova νs

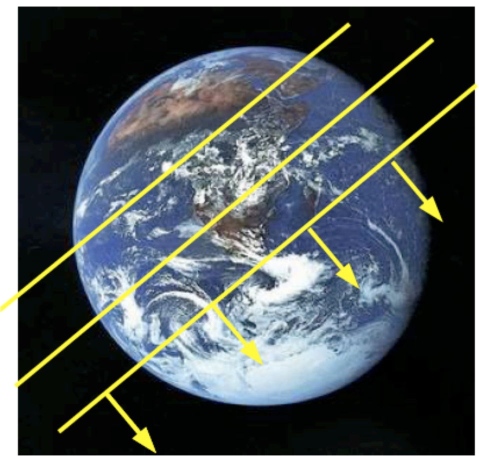




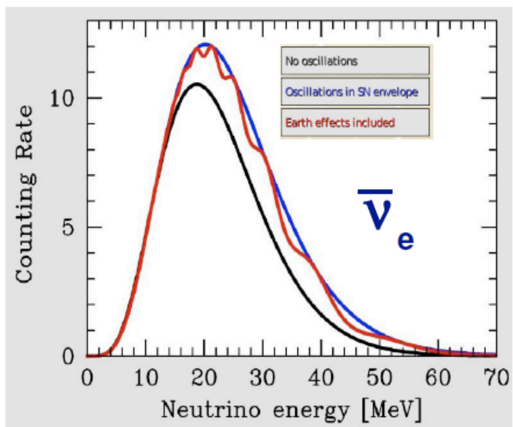
Supernova Burst νs

➢ Physics

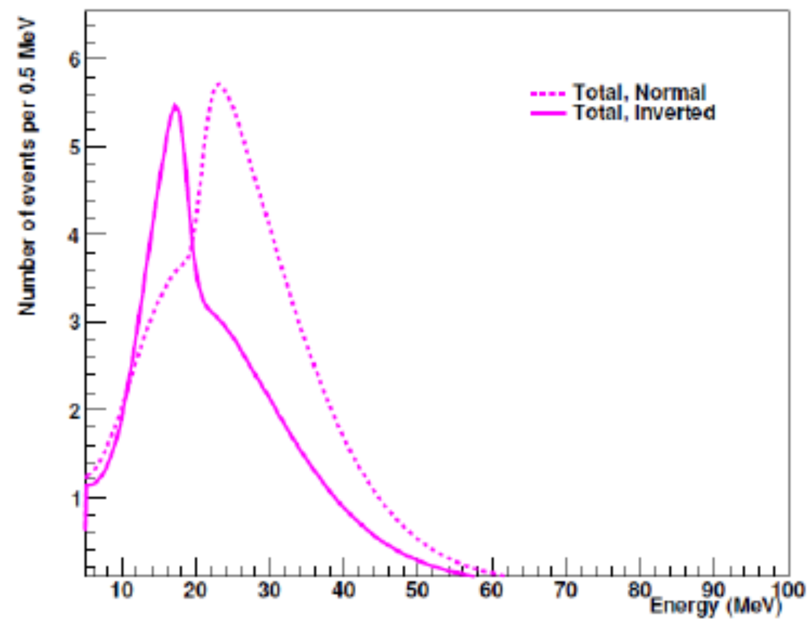
- Supernova core collapse
- Neutrino oscillation: MSW in supernova shock
- ν magnetic moment
- θ_{13}
- Mass Hierarchy



Kachelreiss, Raffelt et al.

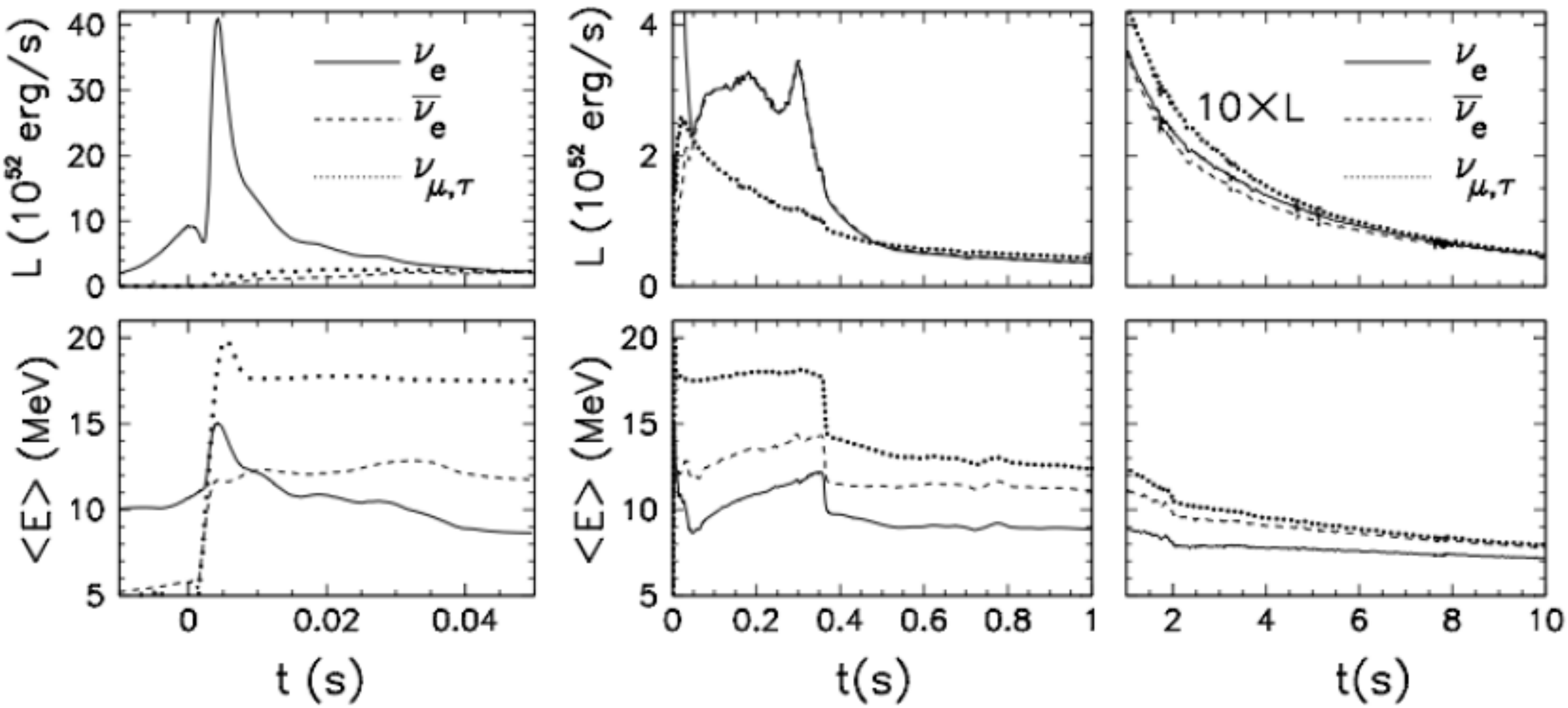


K. Scholberg



LBNE SciOpp

Supernova νs



Models differ in details, but ν_e `breakout burst' and energy region are generically the same
(and they fit SN1987A)

Wurm *et al*, LENA collab. 2011
Fischer *et al*, Astron. Astrophys. 517:A80, 2010

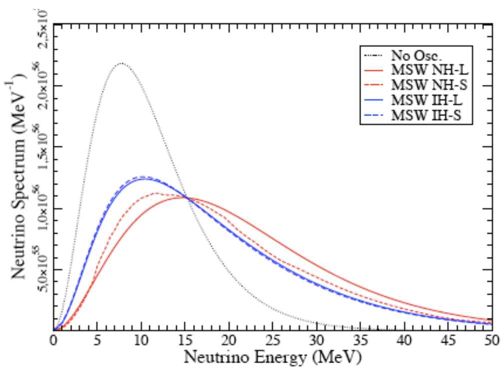
Diffuse Supernova Background νs

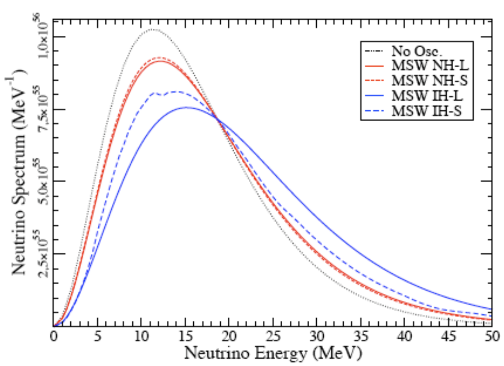
Physics:

- Cosmological star formation rate

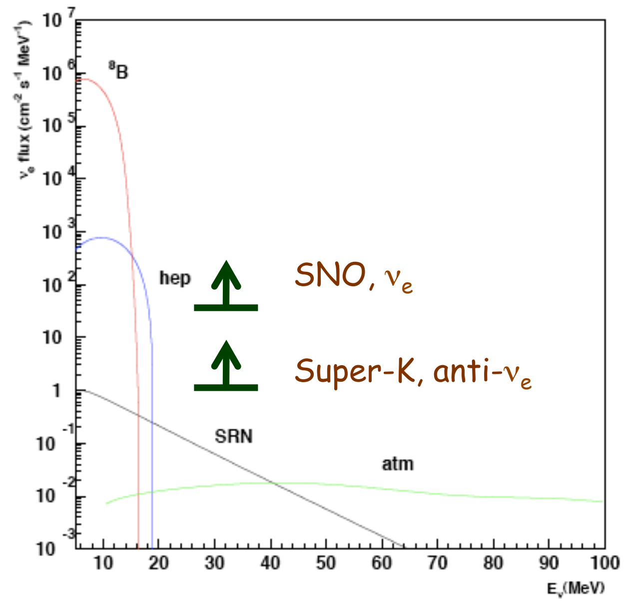
$$\frac{dF}{dE_\nu} = \int_0^{z_{max}} \mathcal{R}_{SN}(z, \Omega_\lambda, \Omega_m) \frac{dn_\nu((1+z)E_\nu)}{dE_\nu}(1+z)\frac{dt}{dz}dz$$

- Spectrum gives information about supernova details
- Spectrum also influenced by MSW within supernova





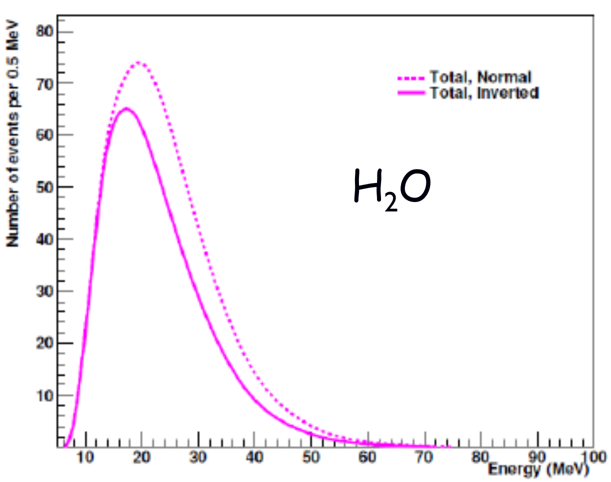
Cocco et al, hep-ph/0408031v2

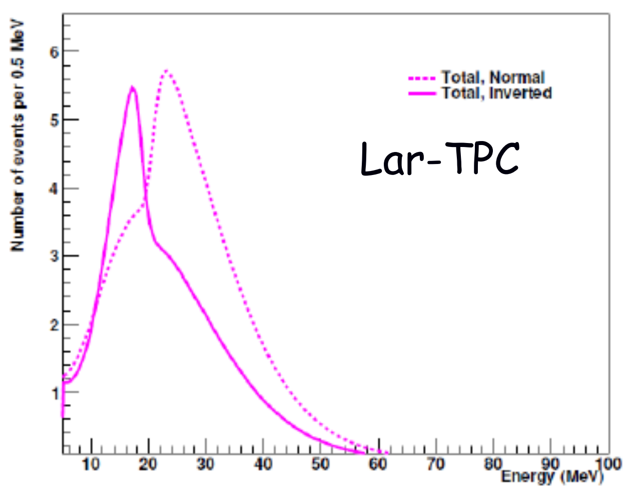


- Potential \`continuum' source of supernova νs to study
- \`guaranteed' to be there

Supernova ν Technological Challenges

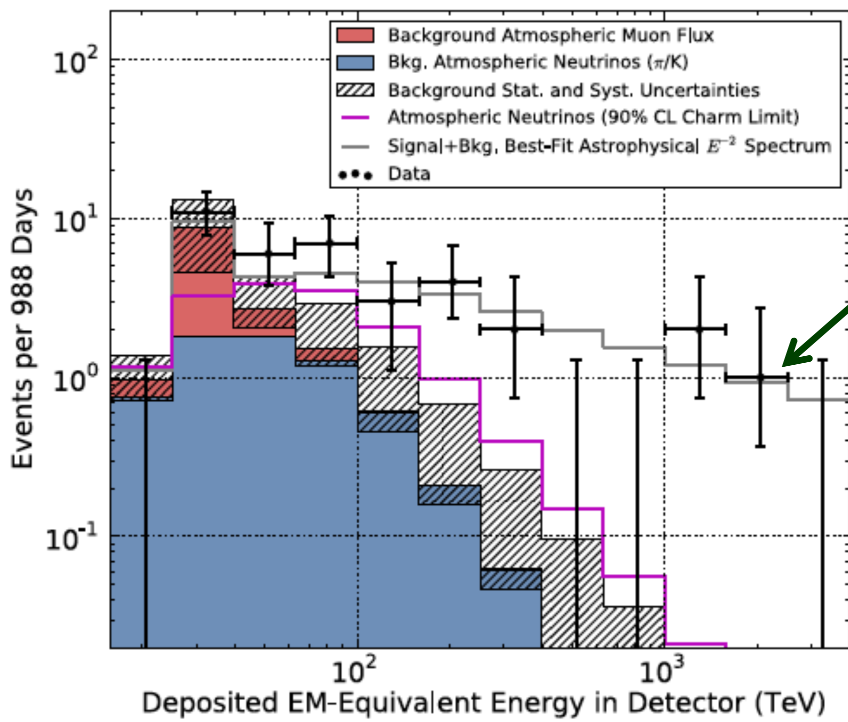
- High statistics (big detector)
- But not too high!?---Want ability for high rates, large storage
- Flavor and antiflavor sensitivity
- High background rejection for DSNB
- Fast trigger decision (minutes or better)
- Reasonably low threshold (E>5-10 MeV)
- Reasonably clean detector
- Reasonably good timing (~few ms for breakout burst)
- Good energy resolution



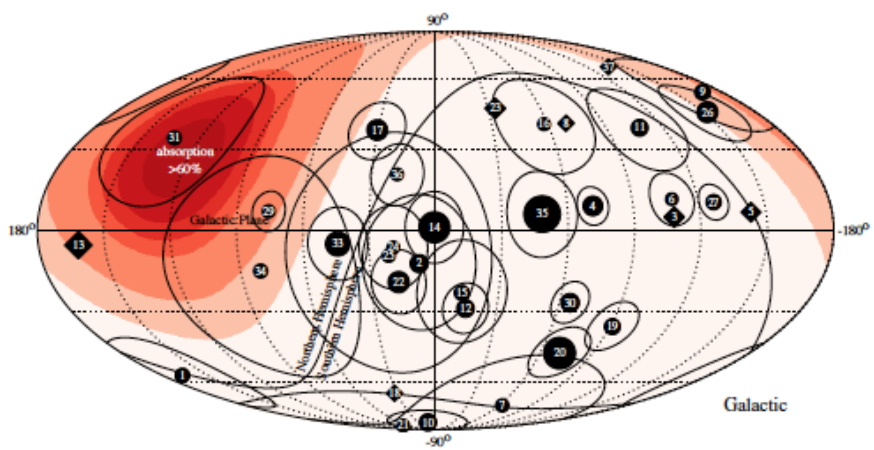


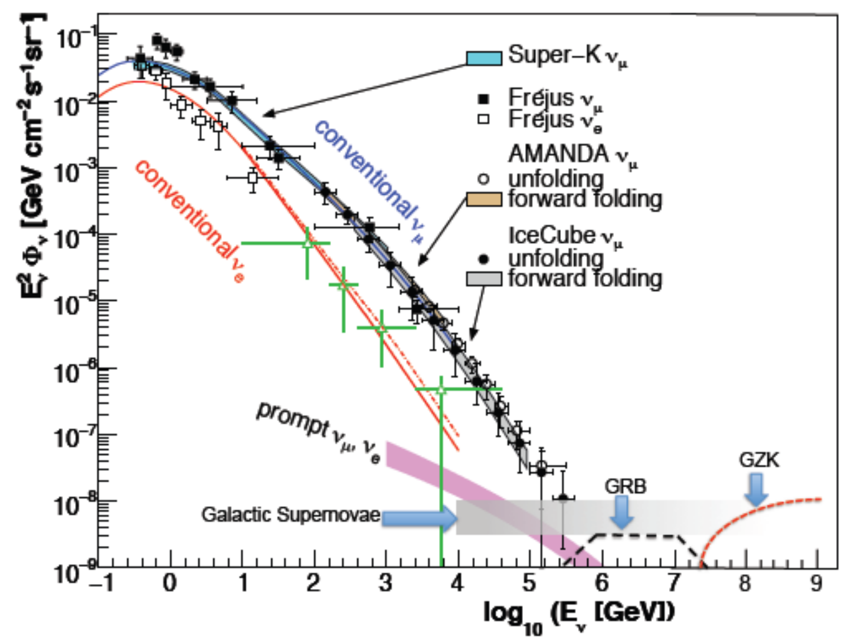
ICECUBE

Astrophysical νs



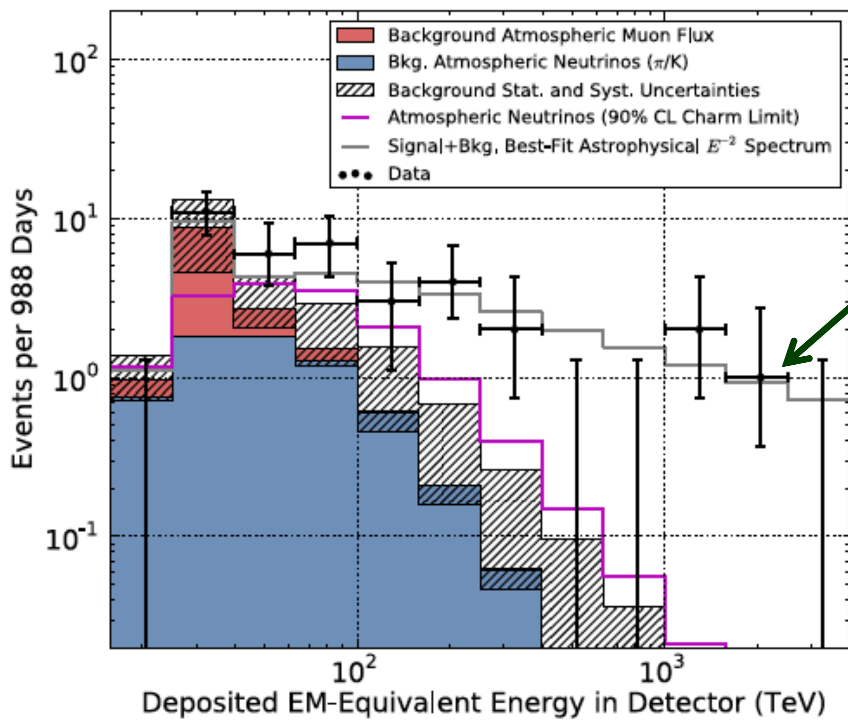
"Highest energy ν ever observed"





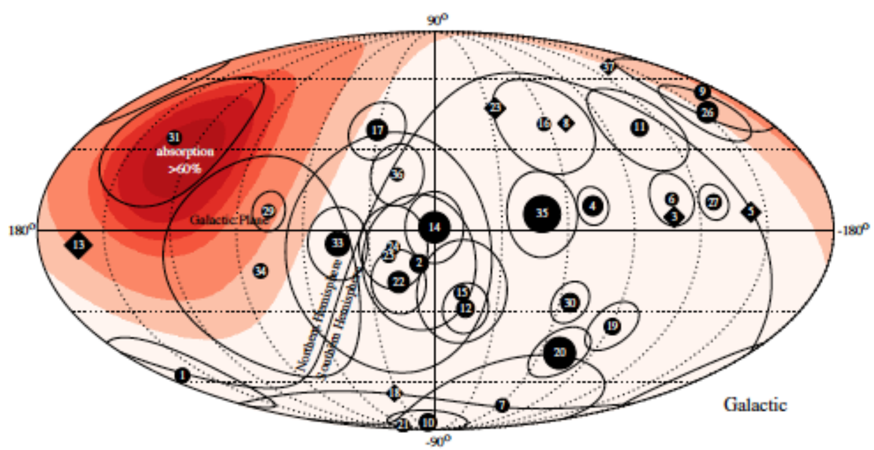
Astrophysical νs

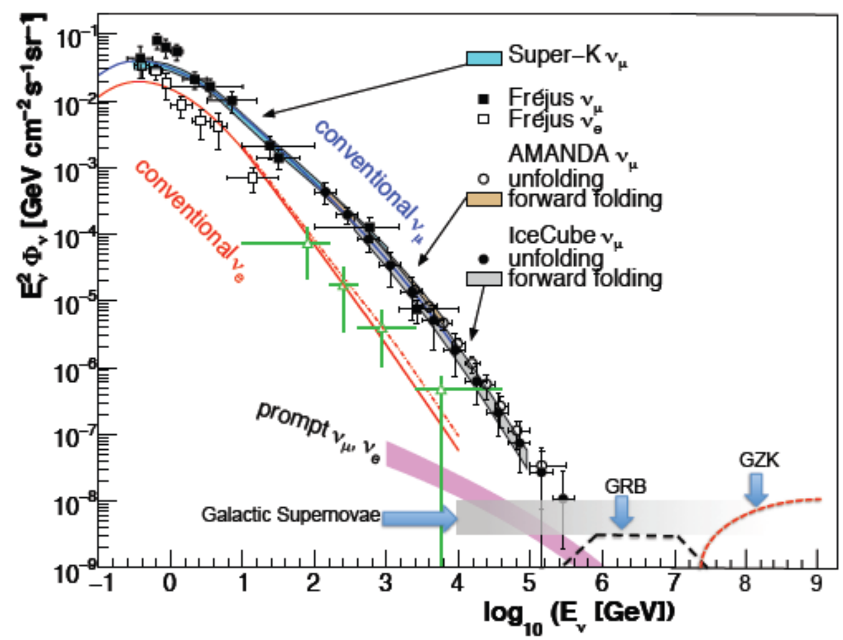
ICECUBE



"Highest energy ν ever observed"

Better:
Fastest massive particle ever observed!
$\gamma > 10^{15}$!!

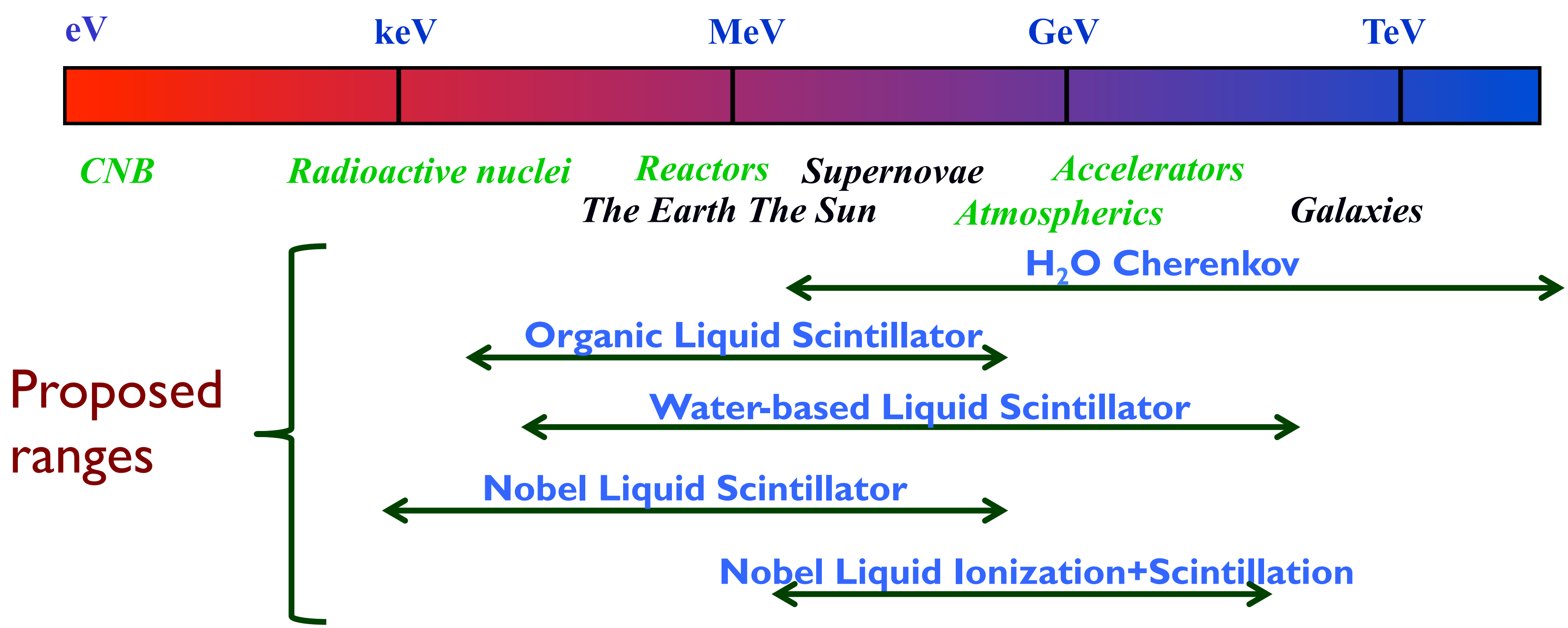




New Technologies

Physics topics are diverse, but given requirements of size and cost, only a small number of viable basic detection technologies:

- Water Cherenkov (solid or liquid)
- Organic liquid scintillation
- Cherenkov+organic scintillation (water-based liquid scintillator)
- Nobel liquid scintillation (Ar, Ne, Xe)
- Nobel liquid ionization+scintillation light (LAr-TPCs,LXe-TPC)



New Technologies

- Water Cherenkov (solid or liquid)
- Organic liquid scintillation
- Cherenkov+organic scintillation (water-based liquid scintillator)
- Nobel liquid scintillation (Ar, Ne, Xe)
- Nobel liquid ionization+scintillation light (LAr-TPCs, LXe-TPC)

Most of these have been around for a long time…
What is new, and what new instrumentation is needed?

- Loading of water and scintillator detectors
- Better photon production and detection:
  - more light
  - broader spectrum of sensitivity
  - better timing
  - lower backgrounds
  - lower cost
- Robust front-end intelligence

Water Cherenkov

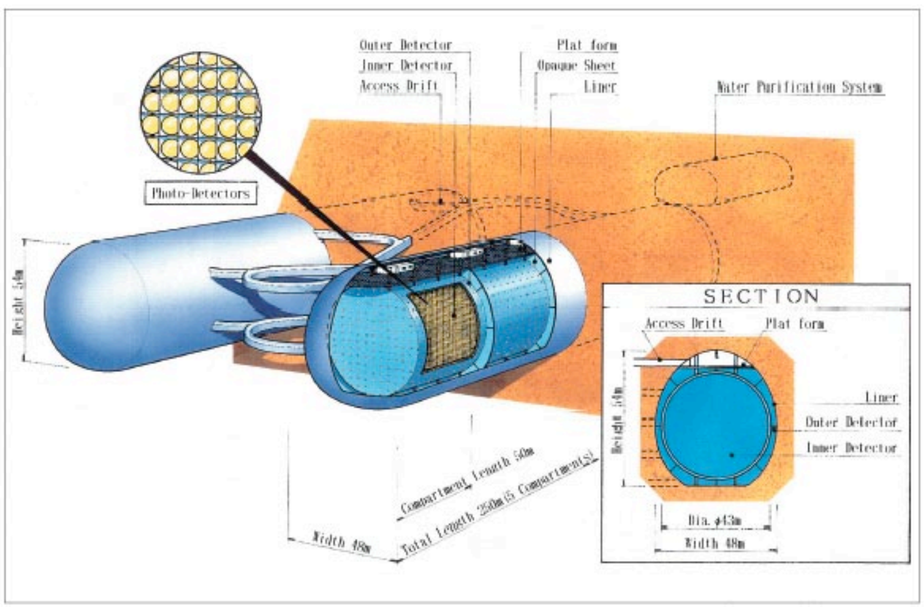
Still the King of the BIG Detector

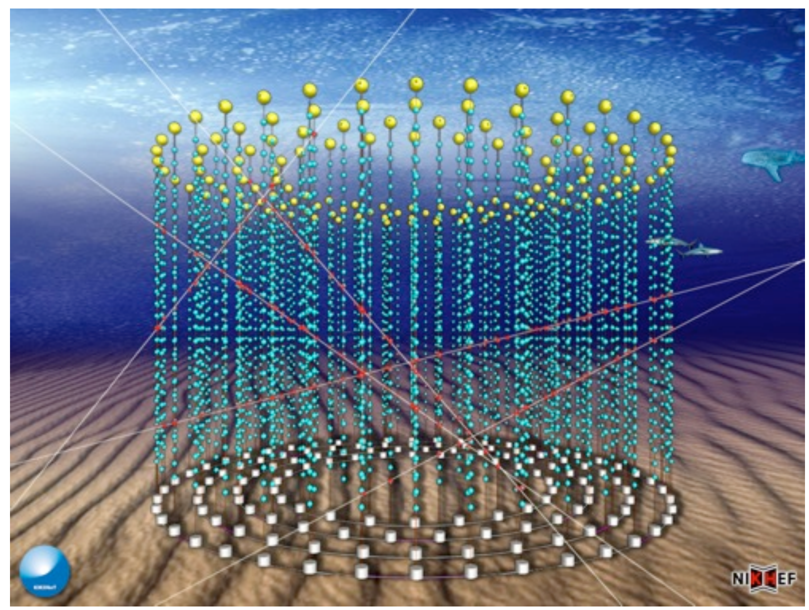
Physics topics:

1. "High energy" solar ν (^{8}B, hep)
2. Diffuse supernova background
3. Supernova bursts
4. Astrophysical νs

External photon detectors
(Super-K, Hyper-K)

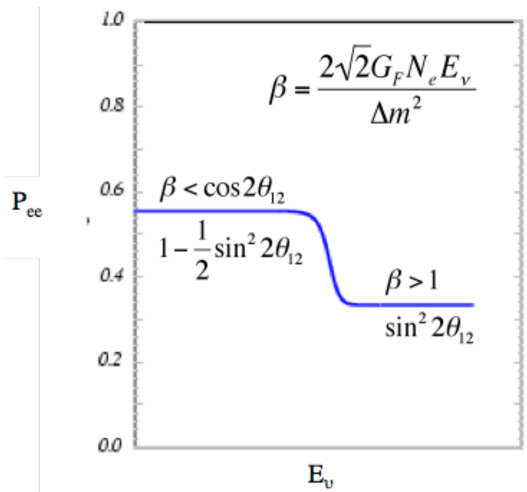
Internal photon detectors
(ICECUBE, KM3Net)





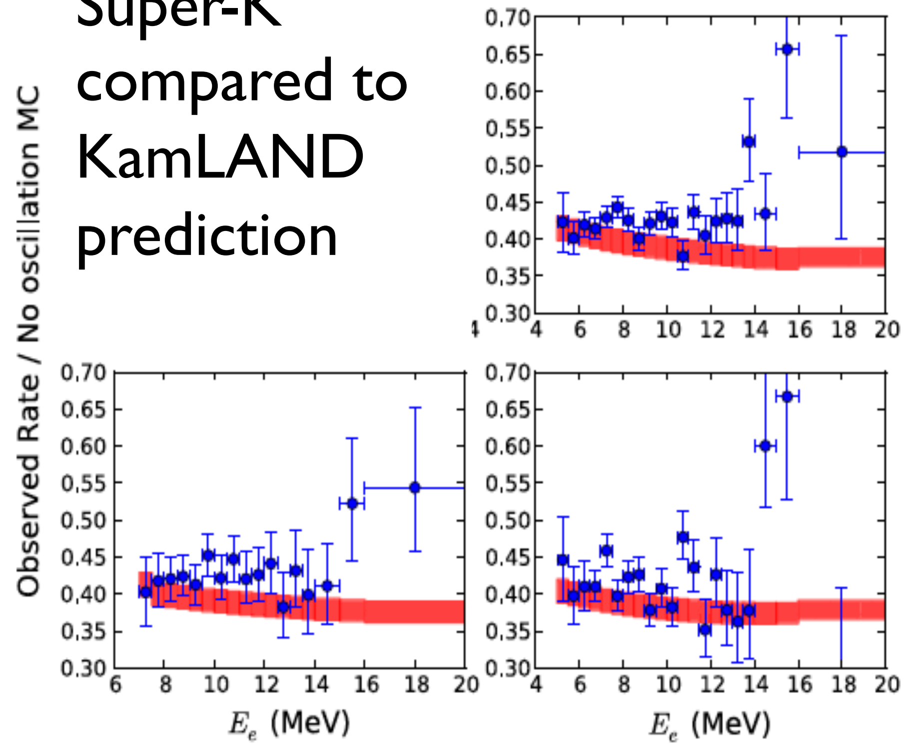
Water Cherenkov

Solar νs



Seeing the transition region requires low thresholds, and for ES νs, very high statistics

Super-K compared to KamLAND prediction



Low threshold=

- Ultra-clean water (hard!)
- Low-background photon sensors
- More photons

  $\sigma(E) \sim 1/\mathrm{sqrt}(N_\gamma)$
- Better photon timing

  $\sigma(r) \sim 1/\Delta t$

[I will say more about photon detection in a few more slides]

Water Cherenkov

Supernova Burst and DSNB νs

H_2O

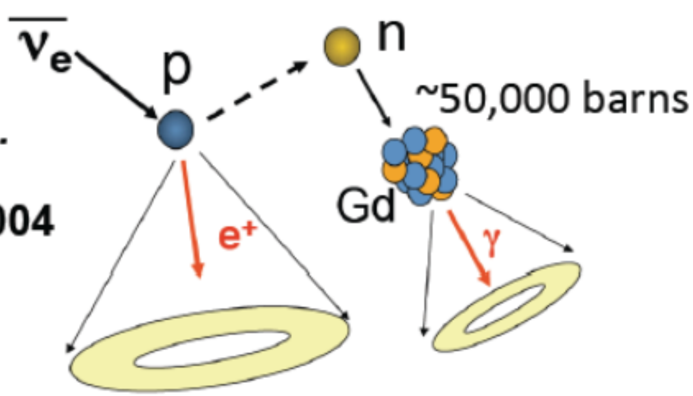
$$\overline{\nu}_e + p \rightarrow n + e^+ \quad (88\%/89\%)\,,$$
$$\nu_e + e^- \rightarrow \nu_e + e^- \quad (1.5\%/1.5\%)\,,$$
$$\overline{\nu}_e + e^- \rightarrow \overline{\nu}_e + e^- \quad (<1\%/<1\%)$$
$$\nu_x + e^- \rightarrow \nu_x + e^- \quad (1\%/1\%)\,,$$
$$\nu_e + {}^{16}O \rightarrow e^- + {}^{16}F \quad (2.5\%/<1\%)$$
$$\overline{\nu}_e + {}^{16}O \rightarrow e^+ + {}^{16}N \quad (1.5\%/1\%)\,, an$$
$$\nu_x + {}^{16}O \rightarrow \nu_x + O^*/N^* + \gamma \quad (5\%/6\%)\,,$$

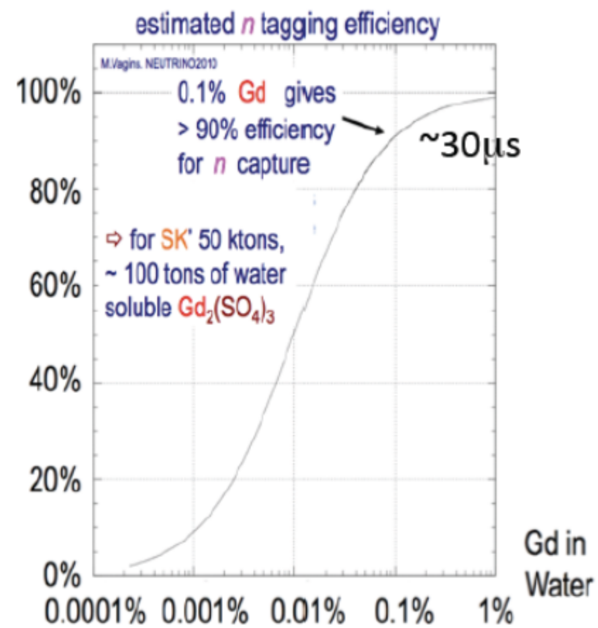
Dominant reaction is IBD, but pointing for bursts comes from ES

For DSNB want to ID e^+ from IBD

Gd loading helps identify neutrons, and makes identification of IBD events much more efficient:

Based on : Beacom and Vagins, *Phys. Rev. Lett.*, 93:171101, 2004



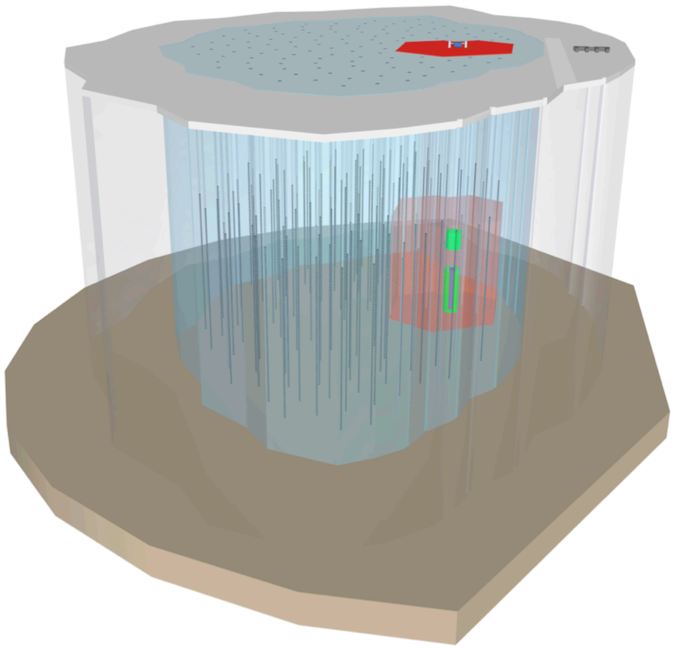


~90% efficiency > 0.1 % Gd

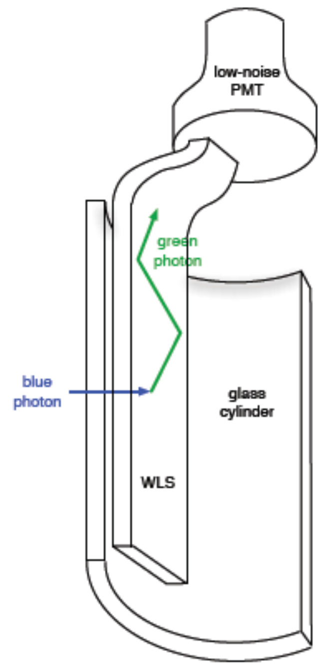
M.Vagins

Water Cherenkov

Supernova Burst and Astrophysical νs



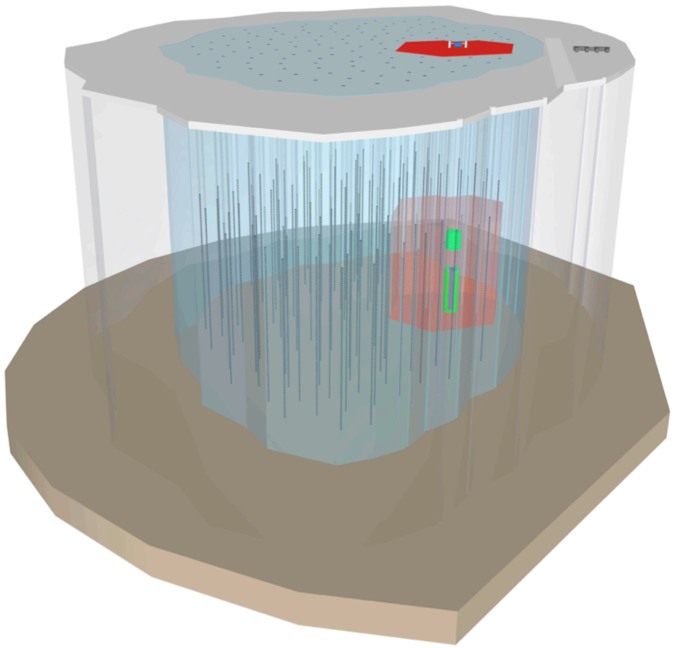
Detection efficiency for supernova burst νs by km-scale detectors with internal photon sensors limited in part by PMT noise rate---



One solution is to use wavelength-shifting lightguides and smaller PMTs: ~50% more light, noise rates ~ 10 Hz

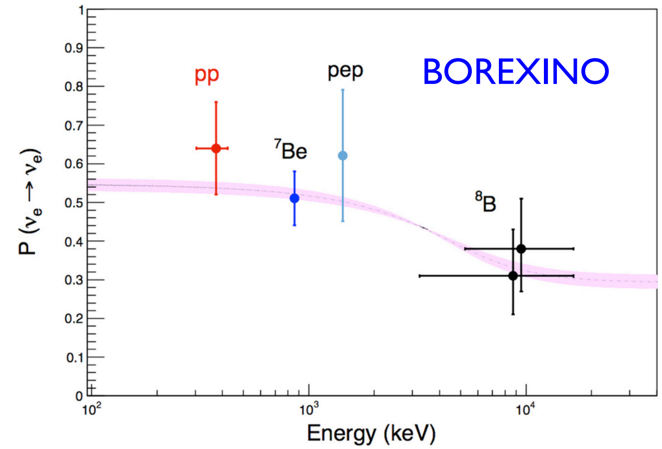
Water Cherenkov

Supernova Burst and Astrophysical νs



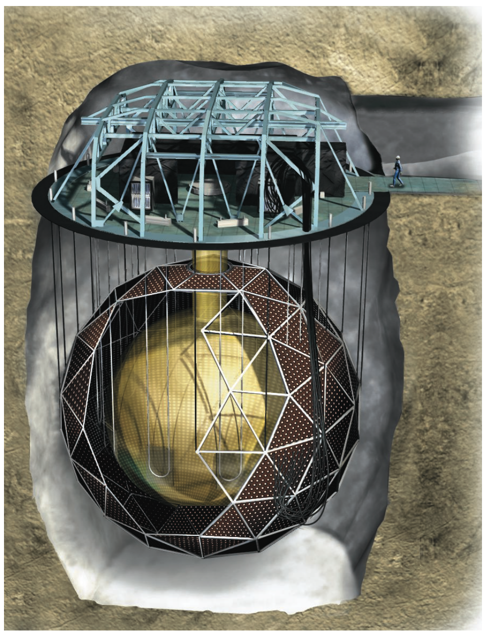
Better light detection means a bigger detector (because sensors are internal)
KM3net-style "multi-PMT" small PMT array helps with timing and direction (and cost):

Liquid Scintillator

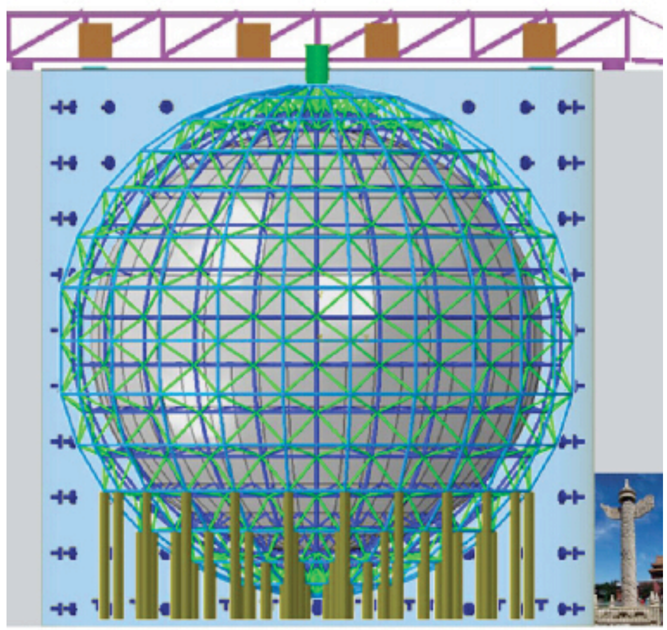


Physics topics:

1. Solar neutrinos from *pp* to hep
2. Diffuse supernova background
3. Supernova bursts



SNO+



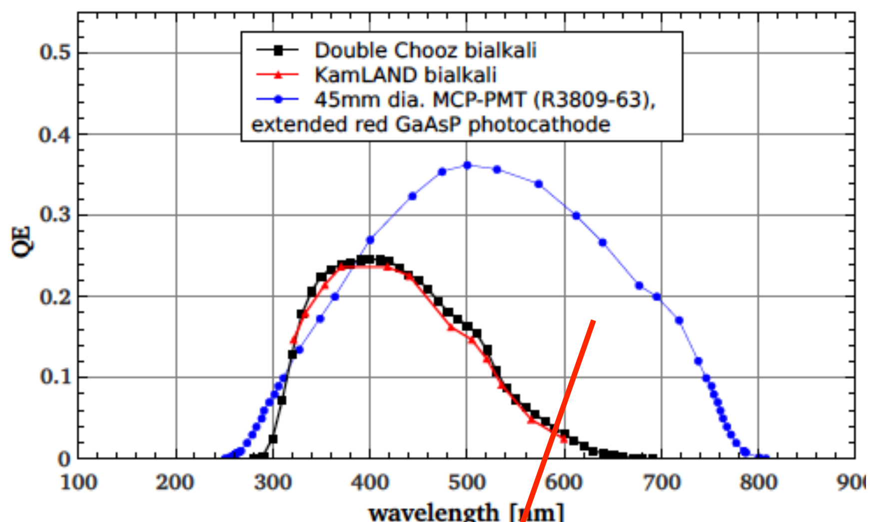
JUNO

LENA

Liquid Scintillator

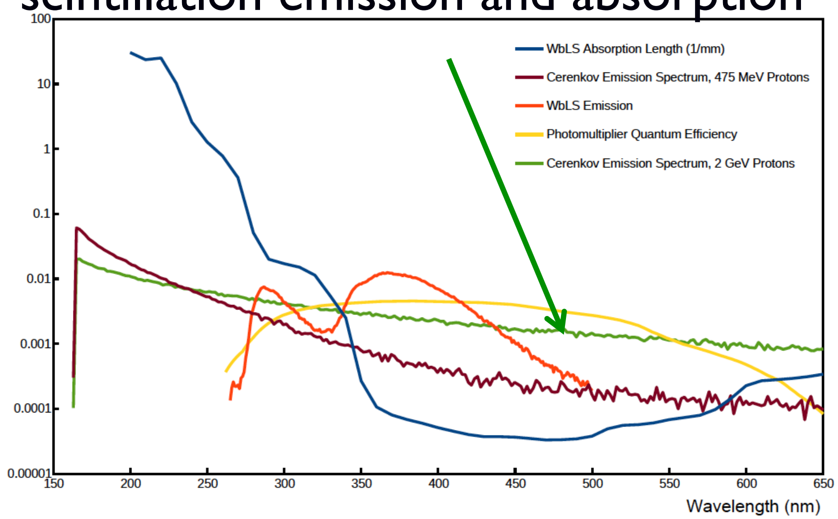
- Size is limited because of transparency (and cost)
- Solar ν reactions are all elastic scattering
  - Poor spectral information
  - And no direction information to separate from backgrounds…

Red-sensitive PMTs

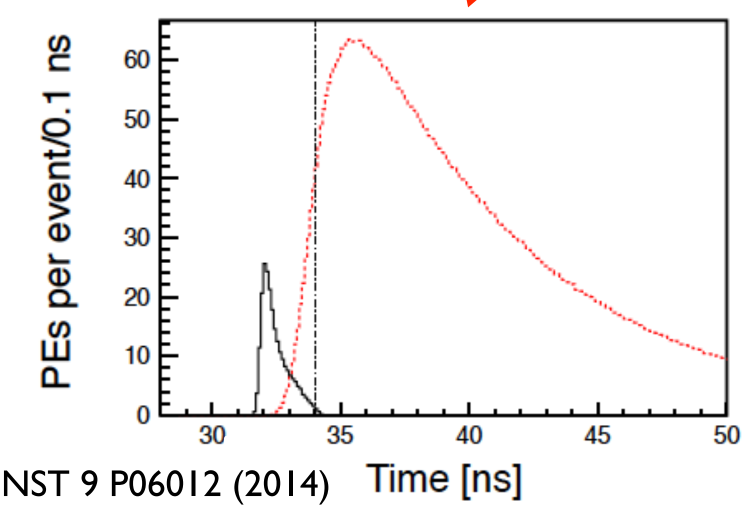


Cherenkov light could provide direction

Cherenkov light extends beyond scintillation emission and absorption



L.Winslow



And red travels faster than blue…

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

Liquid Scintillator

Loading scintillator with ^{115}In allows low-treshold CC!

LENS

$$\nu_e + {}^{115}In \rightarrow e^- + (\tau = 4.76\mu s)2\gamma + {}^{115}Sn$$

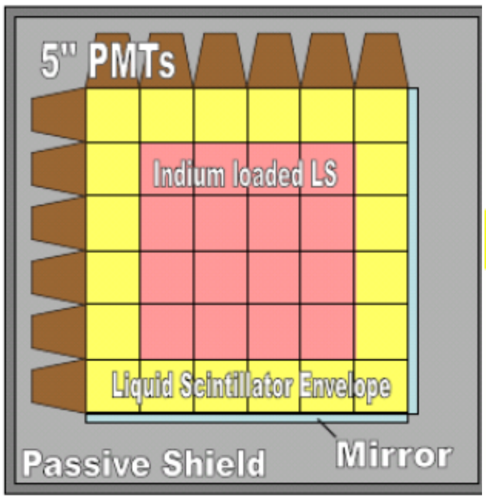
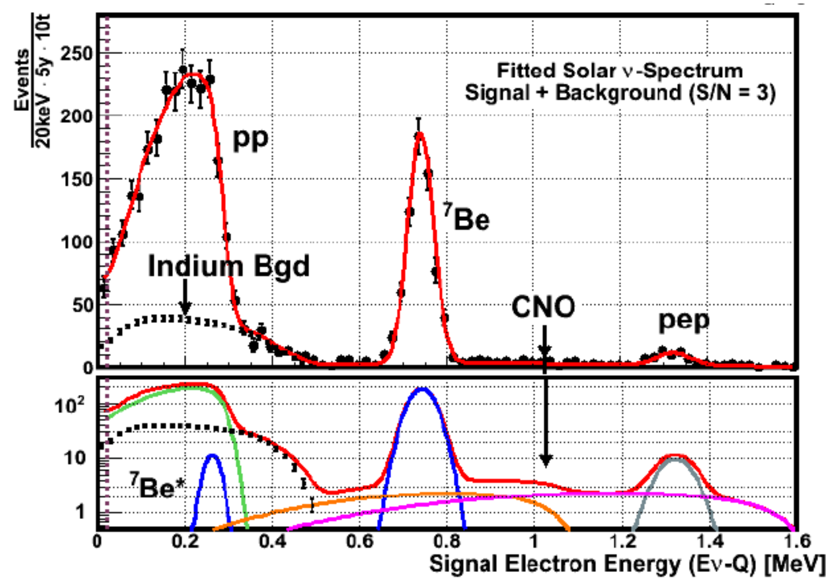


Fig. 12 Schematic design of MINILENS



CC reaction with Q=114 keV

But need segmentation to beat down intrinsic backgrounds…
Can lightguides be made clean and transparent enough to scale?

Water-based Liquid Scintillator

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:

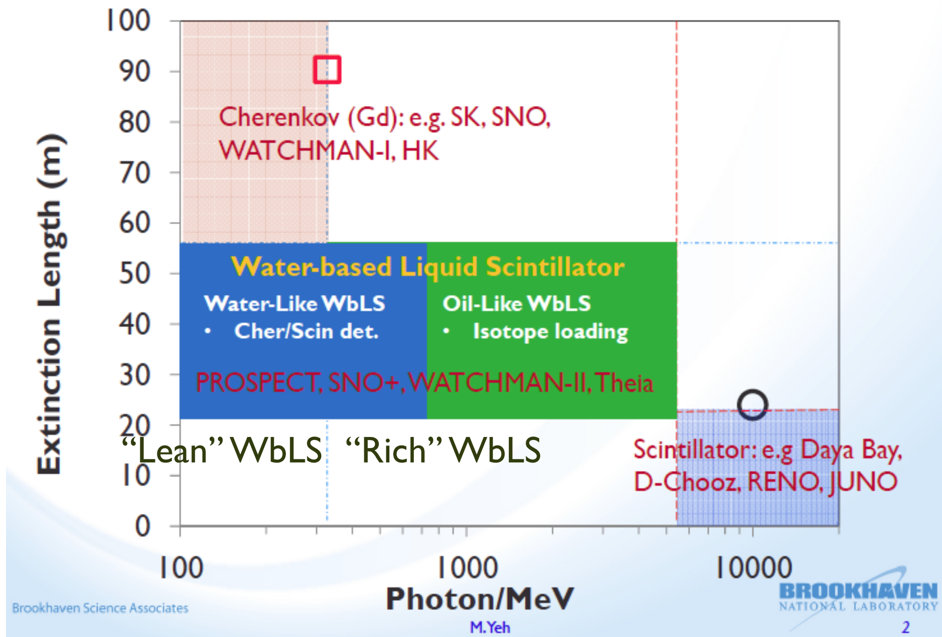
- No access to physics below Cherenkov threshold
- Low light yield makes E & vtx resolution poor even at ~10 MeV
- Are hard to make ultra-clean

New water-based liquid scintillator has advantages of both
(and perhaps some disadvantages of both)

THEIA

Water-based Liquid Scintillator

Developed at Brookhaven National Lab



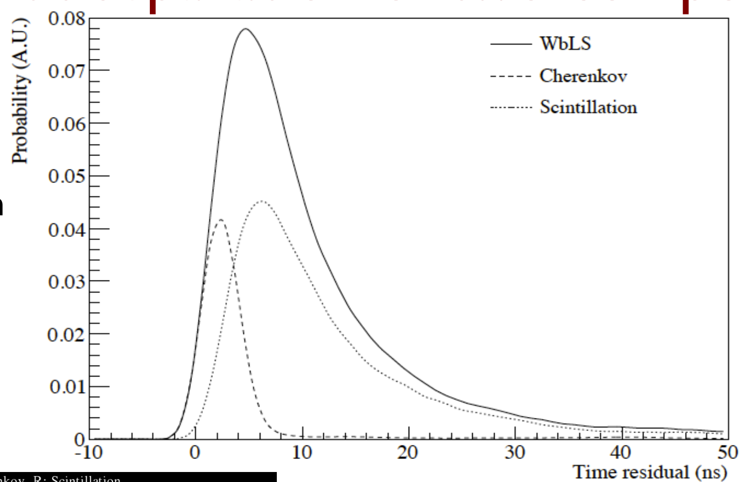
- Long attenuation length compared to scintillator=bigger detector
- Higher light yield=low threshold, good energy resolution
- High Cherlight/scintlight ratio makes directionality and background rejection possible

Water-based Liquid Scintillator

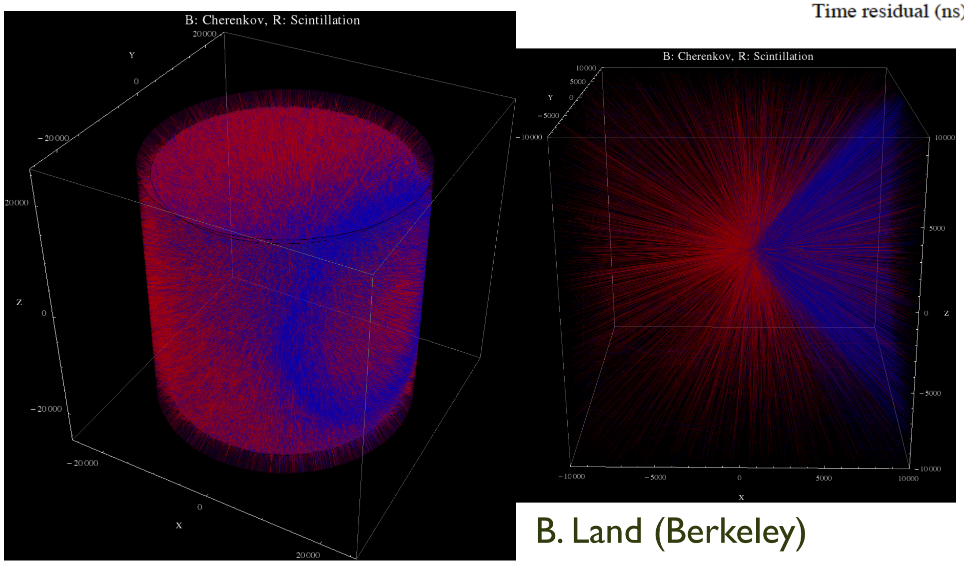
Cherenkov/Scintillation Separation

- 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

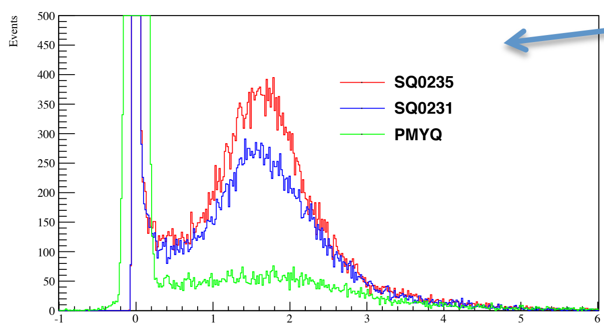
So for a 4% scintillation fraction, standard PMTs, no use of angular information, and equal spectral response for C and S, $R_{s/c}\sim 0.25$

Water-based Liquid Scintillator

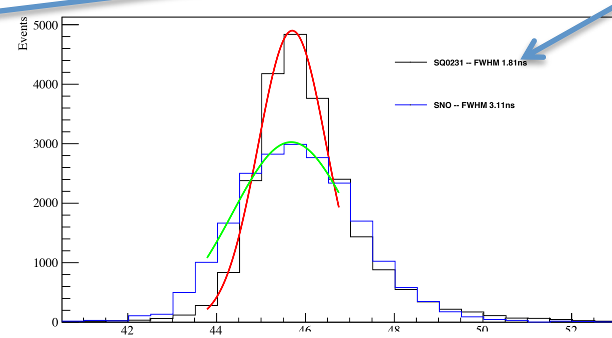
Improved Photon Sensors

Good for scintillation and water Cherenkov detectors also.

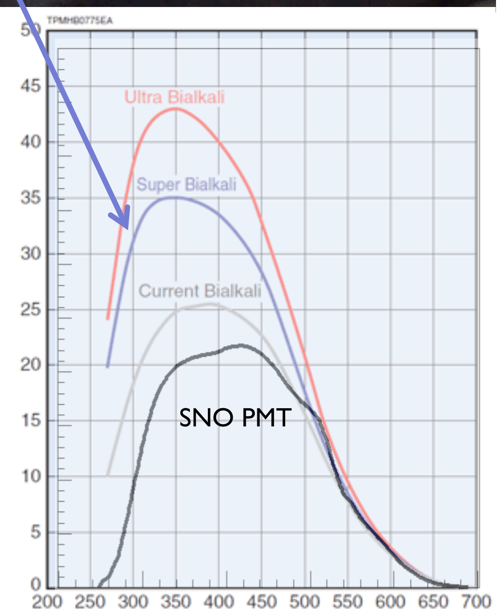
12” HQE (Hamamatsu) | 11” HQE (ETL) | 10” HQE (Hamamatsu) | 8” standard (ETL) | 8” HQE (Hamamatsu) | SNO PMT



Chage (pC)



Time residuals (ns)

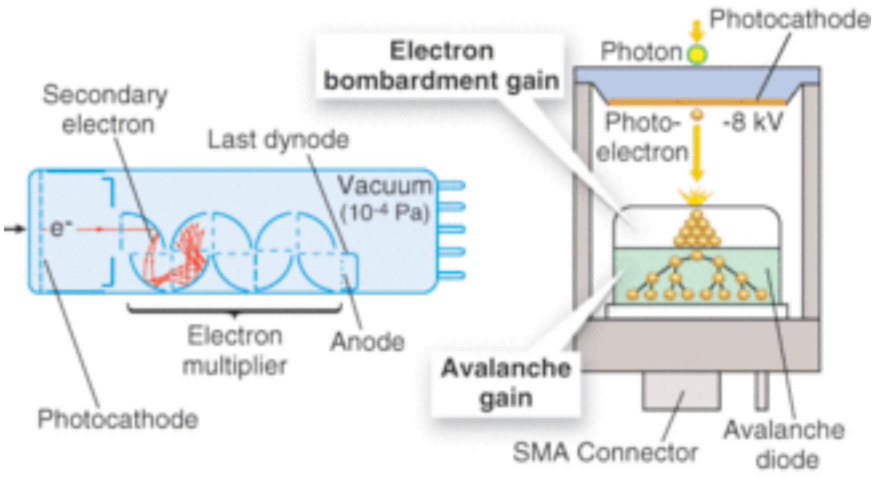


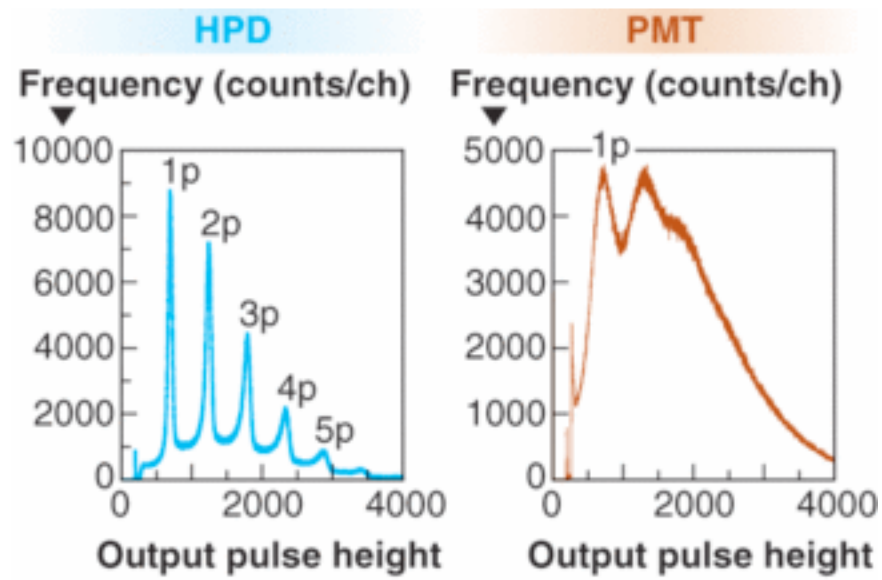
T. Kaptanoglu, Penn

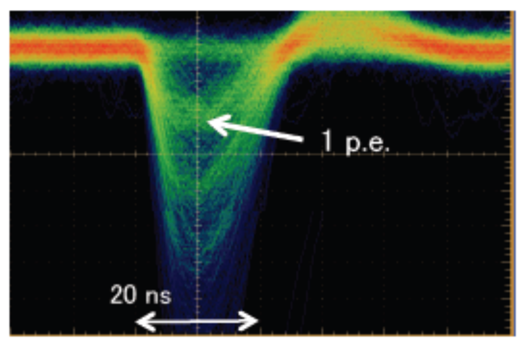
Water-based Liquid Scintillator

Improved Photon Sensors

Hybrid PMT+avalanche photodiodes give much better charge and timing response…







Hirota et al, Nuc. Phys. B PS00, 2012

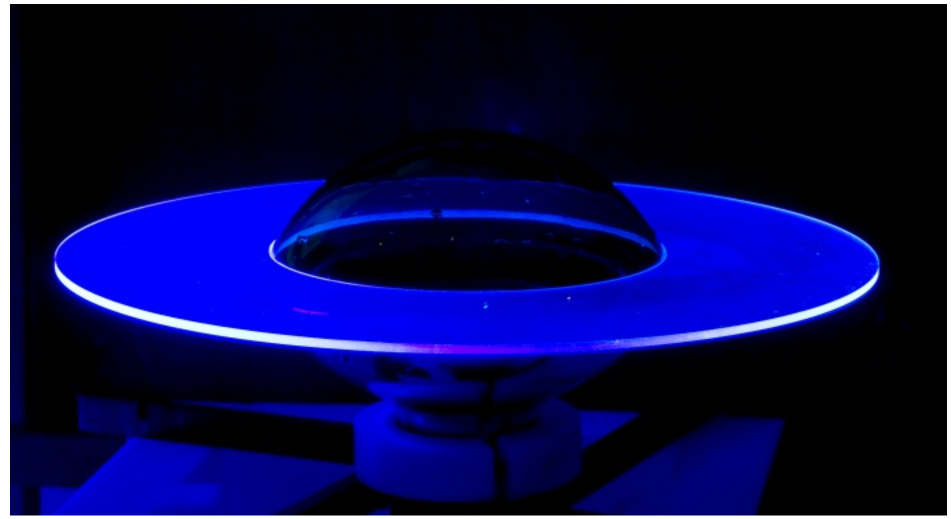
At the expense of lower gain and increased noise (and possibly cost).

Water-based Liquid Scintillator

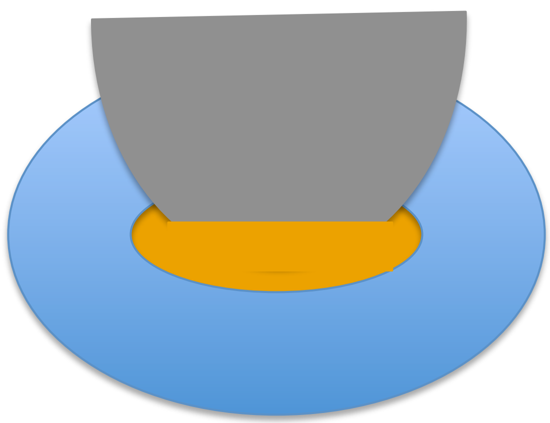
Improved Photon Sensors

Light concentration via Winston reflectors and WLS plates

LBNE-WCD (Drexel)



LBNE-WCD (CSU)



?

Water-based Liquid Scintillator

Improved Photon Sensors

Multi-anode PMTs (11” versions exist) would increase pixels for same photocathode coverage.

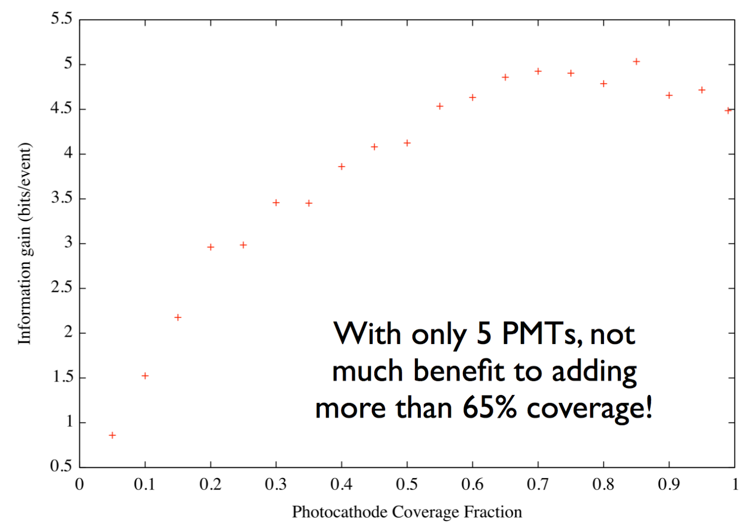
(What wins: pixels or photons?

S.R. Seibert, “information theory” calculation:

- Define: $p(x) = \int p(x|\theta)p(\theta)\ d\theta$ *(PDF of experimental outcomes given your prior knowledge)*
- Then, the information gain from the experiment is:

$$g = \int \int \left[\log p(x|\theta) - \log p(x) \right] \underbrace{p(x,\theta)}_{\text{Joint PDF of parameter values (from prior) and experimental outcomes}}\ dx d\theta$$

Uses defiinition of ``Shannon Entropy”



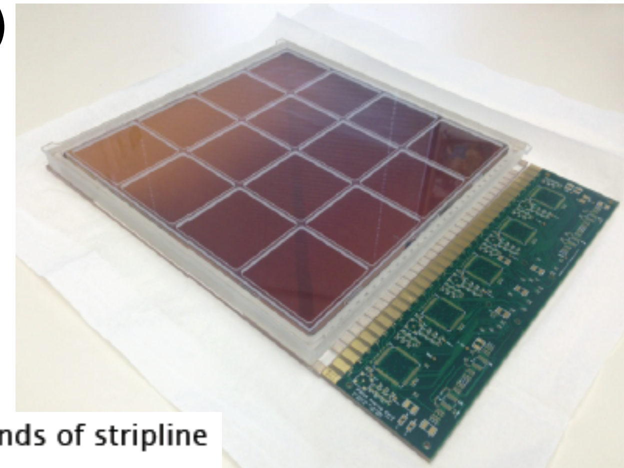
)

Water-based Liquid Scintillator

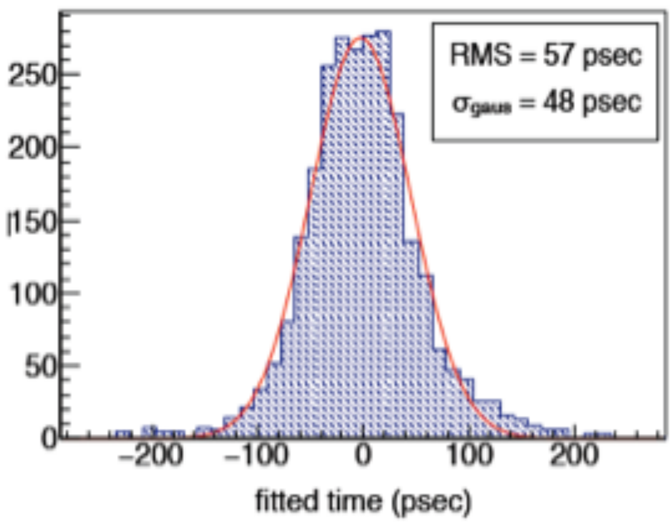
Improved Photon Sensors

Large Area Picosecond Photodetectors (LAPPDs)

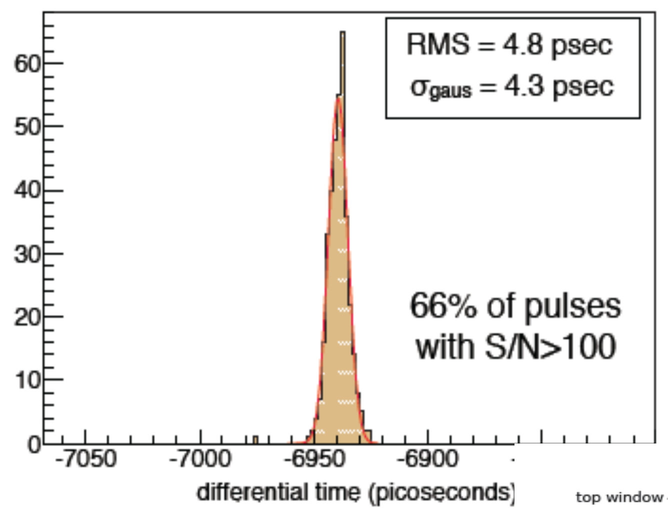
- Large, flat-panel MCP-based photosensors
- 50-100 ps time resolution (<1cm spatial)
- working readout system

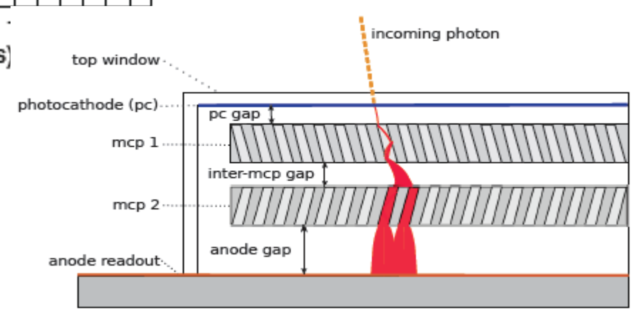


single photoelectron absolute time resolution



differential time resolution between 2 ends of stripline



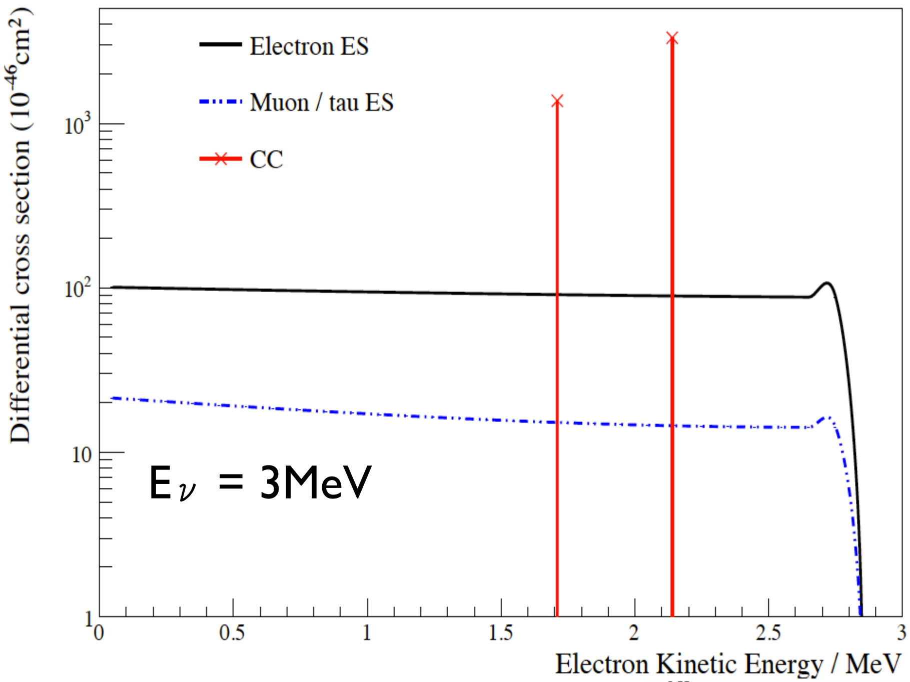


M. Wetstein

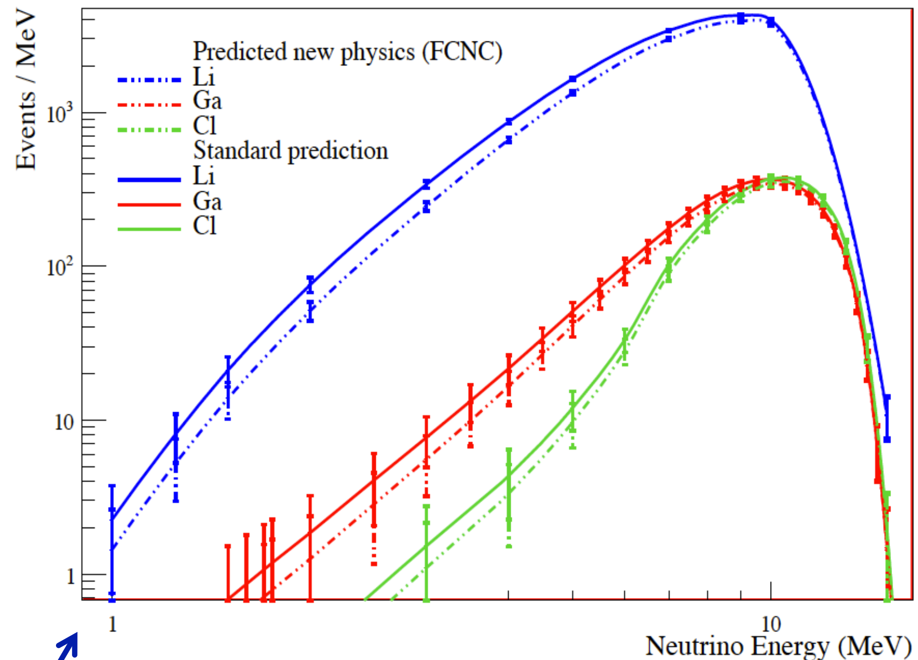
Water-based Liquid Scintillator

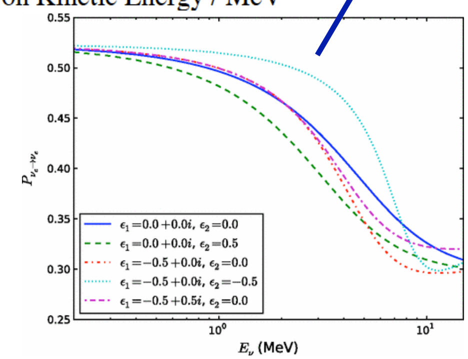
Isotopic Loading

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



Makes models easy to distinguish



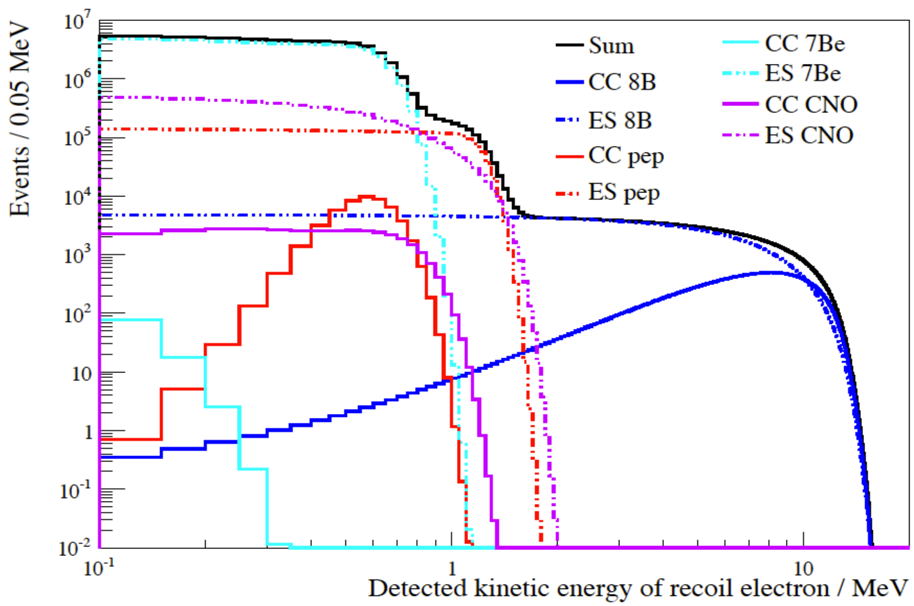


G. D. Orebi Gann (Berkeley)

Water-based Liquid Scintillator

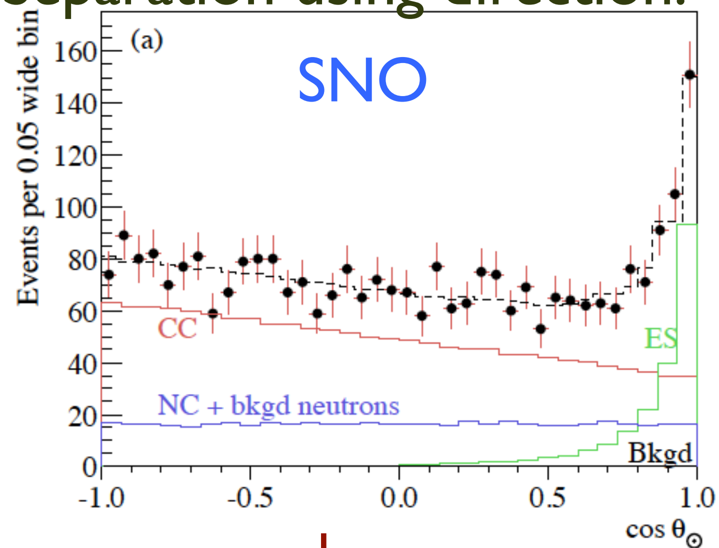
Isotopic Loading

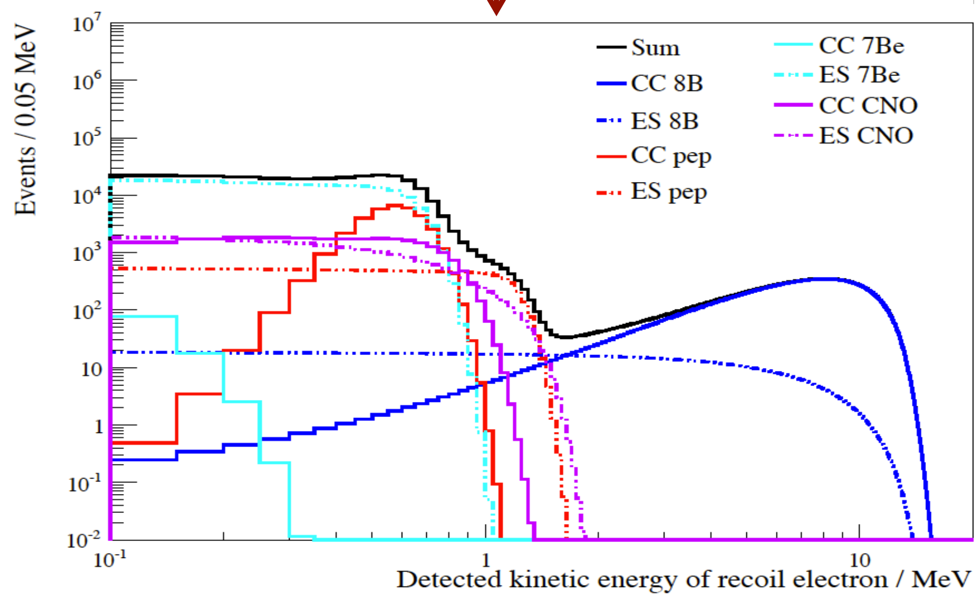
Low-energy solar νs also now possible via both CC and ES:



G.D. Orebi Gann

Separation using direction:



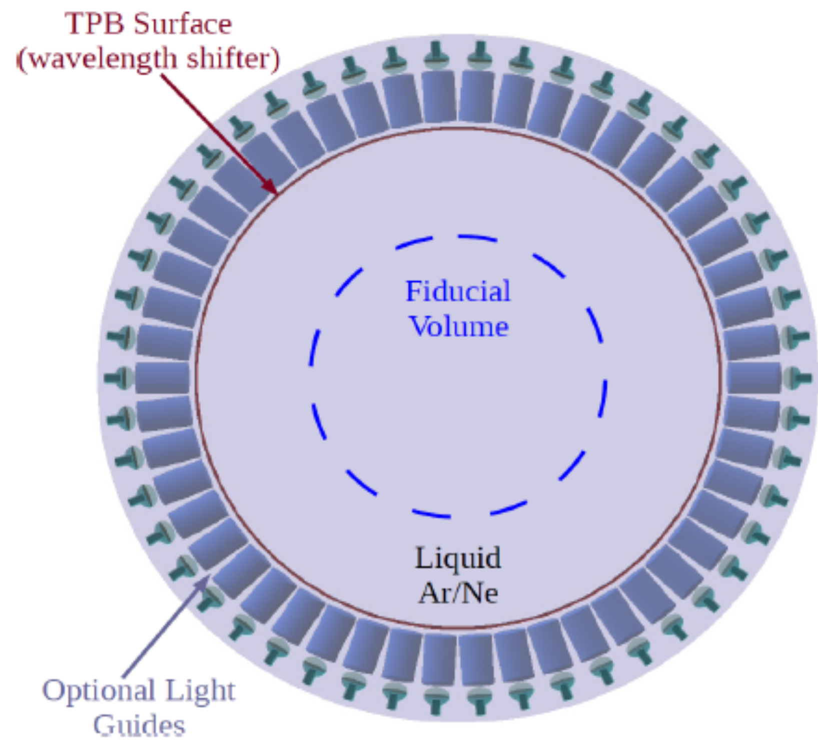


CC+ES also yields total flux via NC component of ES

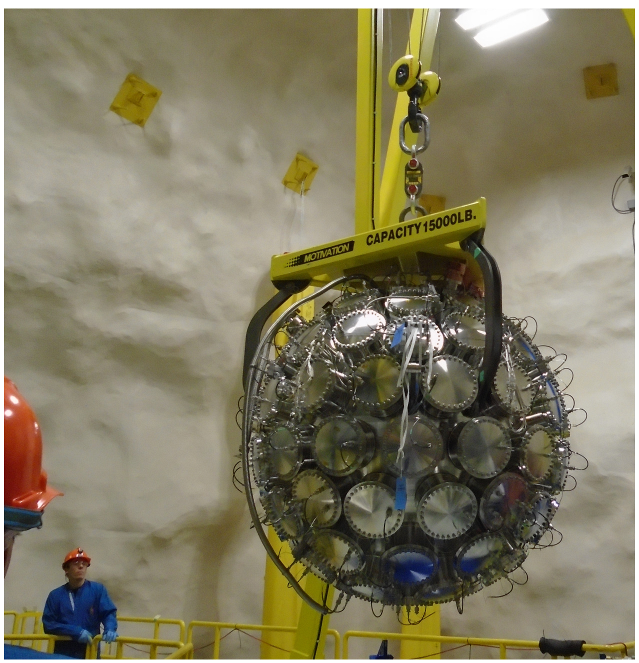
Noble Liquid Scintillation

Physics topics:

1. "Low energy" solar ν (*pp*)
2. Supernova bursts
3. (Dark Matter)



MiniCLEAN



LNe has virtually no intrinsic backgrounds…at 50 tonnes, could make *pp* measurement with precision that could test luminosity constraint.

Noble Liquid Scintillation

Physics topics:

1. "Low energy" solar ν (*pp*)
2. Supernova bursts
3. (Dark Matter)

LAr has sensitivity to SN ν_es:

LAr

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{K}^* + \mathrm{e}^-$$

$$\bar{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{Cl}^* + e^+$$

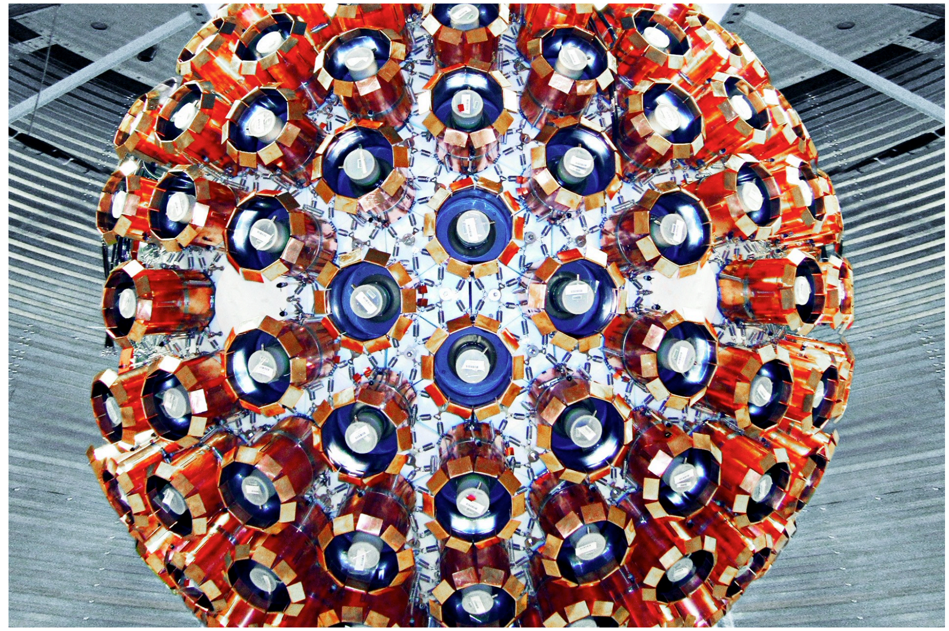
$$\nu_\alpha + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{Ar}^* + \nu_\alpha$$

$$\hookrightarrow {}^{40}\mathrm{Ar} + \gamma_1 + \ldots \gamma_n$$

$$\nu_e + e^- \rightarrow \nu_e + e^-$$

$$\overline{\nu}_e + e^- \rightarrow \overline{\nu}_e + e^-$$

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

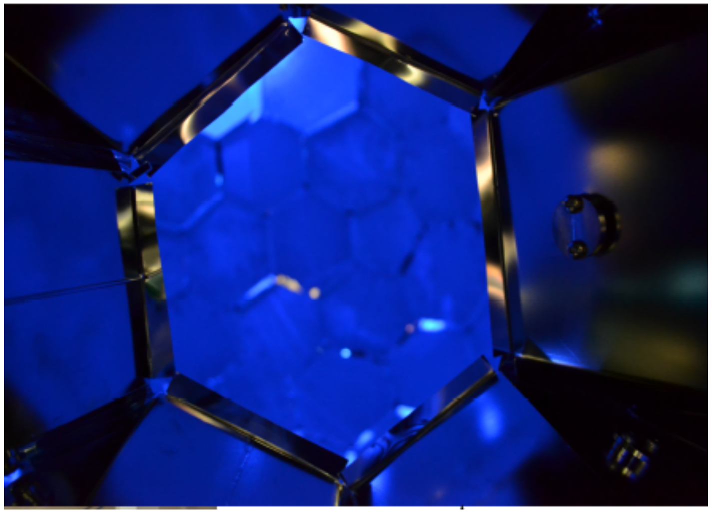


DEAP-3600

By definition, H_2O and LAr are complementary here: highest cross sections have *complementary* lepton numbers

Noble Liquid Scintillation

Technical challenge is building something big enough:



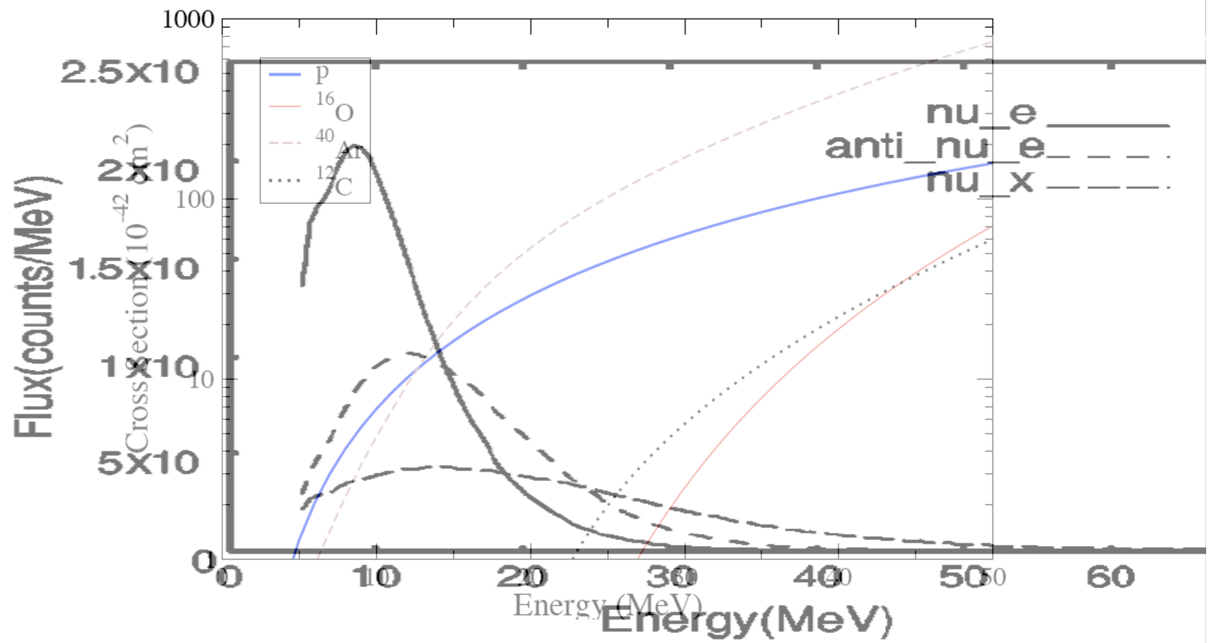
EUV light from scintillation requires wavelength-shifter to see with existing large-area PMTs

- Cryogenic versions have very low efficiency (~16%!)
- "Warm" solutions require long lightguides
- Need ~100% coverage to get enough light for background rejection
- Can doping of one noble with another wavelength-shift light?
- Is there something better than TPB??

LAr-TPC

Physics topics:

1. Supernova bursts
2. DSNB
3. “High energy” solar ν (^{8}B, hep)



Channel	Events, “Livermore” model	Events, “GKVM” model
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$	1154	1424
$\bar{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$	97	67
$\nu_x + e^- \rightarrow \nu_x + e^-$	148	89
Total	1397	1580

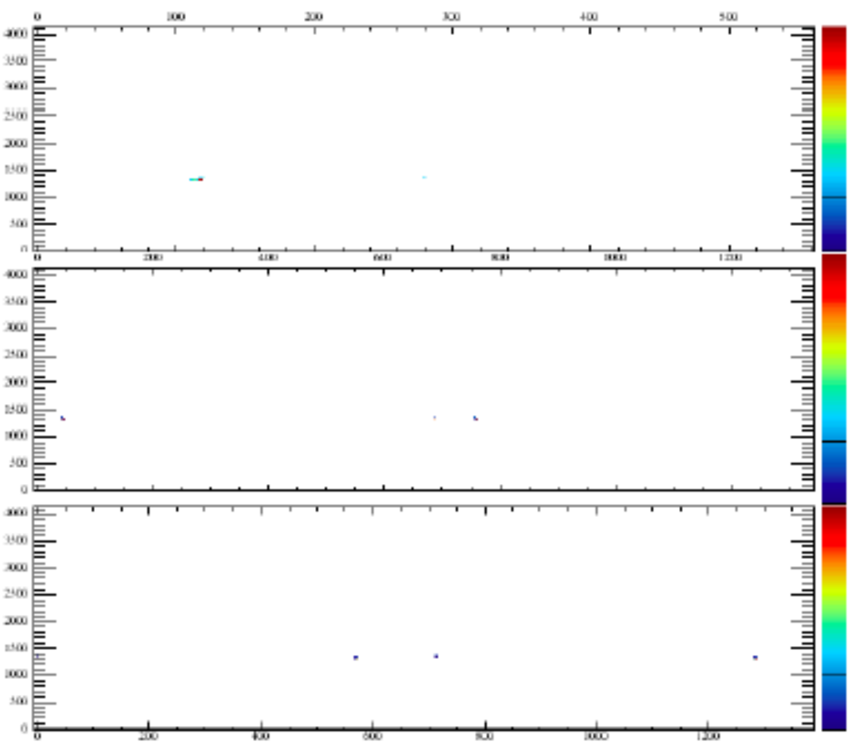
17kt of LAr, 10 kpc supernova burst

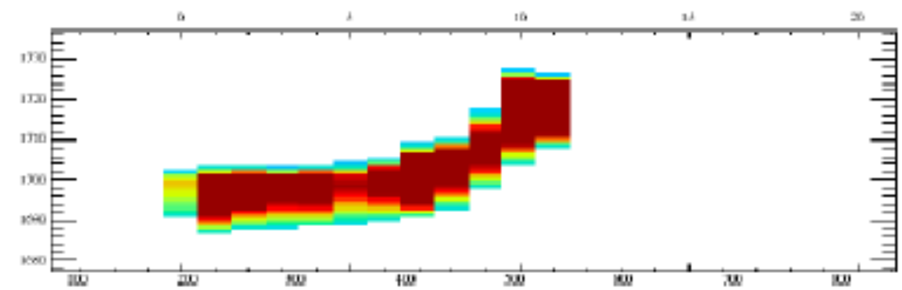
DUNE

C. Volpe* and J. Welzel†

LAr-TPC

Single-Phase TPC





At SN energies, plenty of wires hit

Challenges are

- T0 for drift correction
- "Fast" turn-around trigger

K. Scholberg

These are complicated by ^{39}Ar background

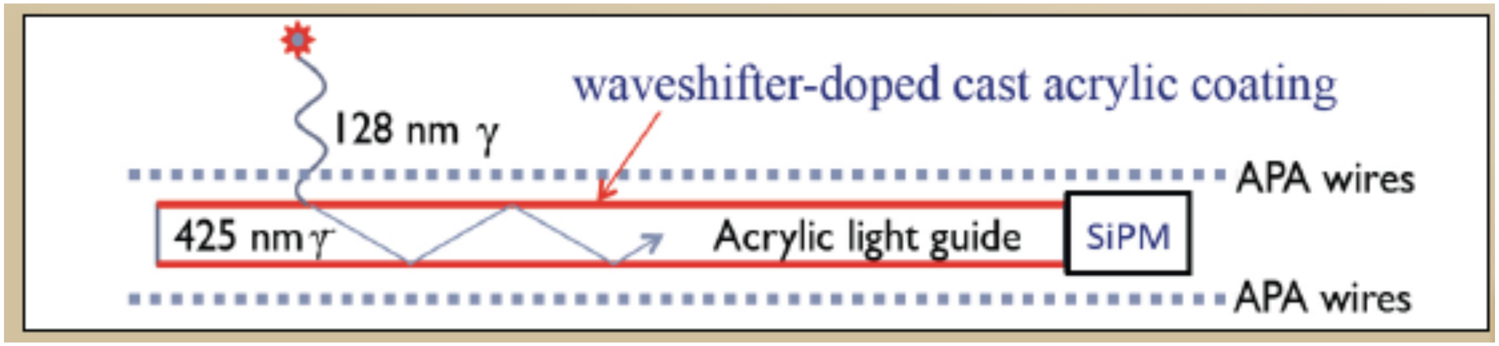
DUNE

DUNE

LAr-TPC

Single-Phase TPC

T0 comes from photon system, currently TPB-coated lightguides readout by SiPMs



N. Buchanan

Without good T0, event energy resolution ~2x worse

But

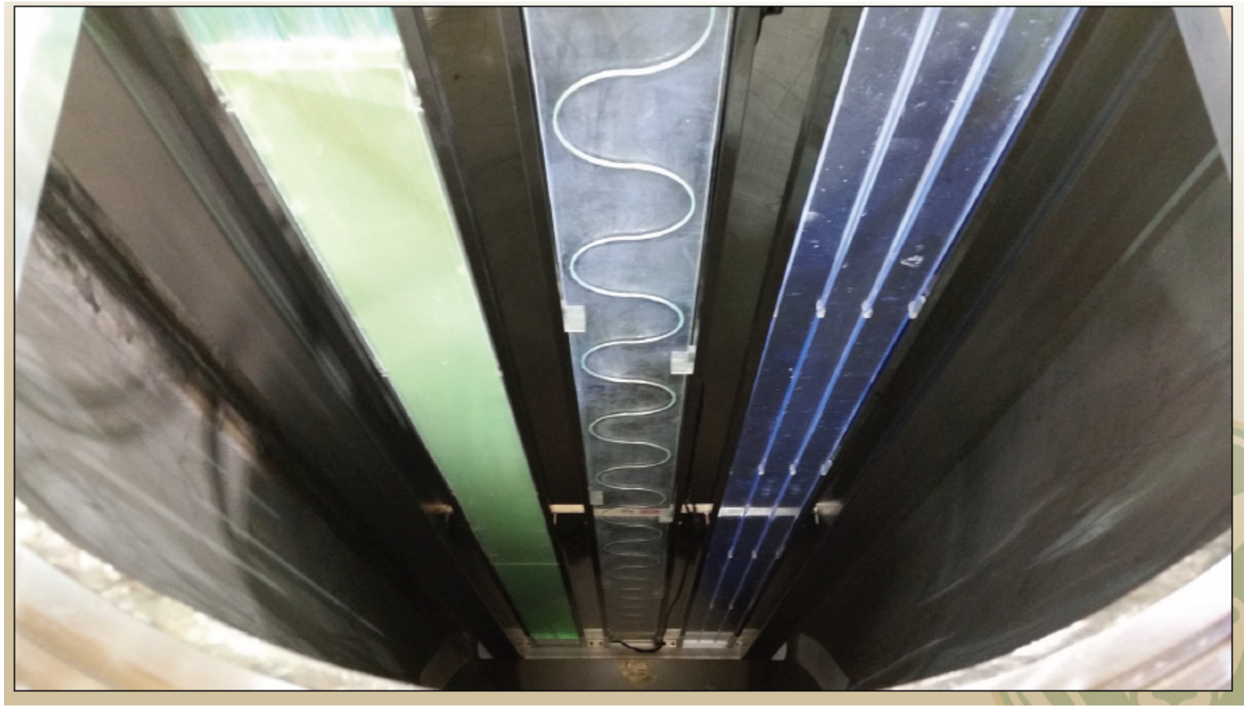
- photon yield is low
- "glow" from ^{39}Ar is non-trivial background

Breakthrough technology would be much improved photon collection

LAr-TPC

Single-Phase TPC

Multiple designs under study



Differ by use (or not) of WLS fibers, methods of TPB coating.

LAr-TPC

Single-Phase TPC

Triggering on burst in principle can be done “nearline” or offlline as zero-suppressed data stream will be stored temporarily…

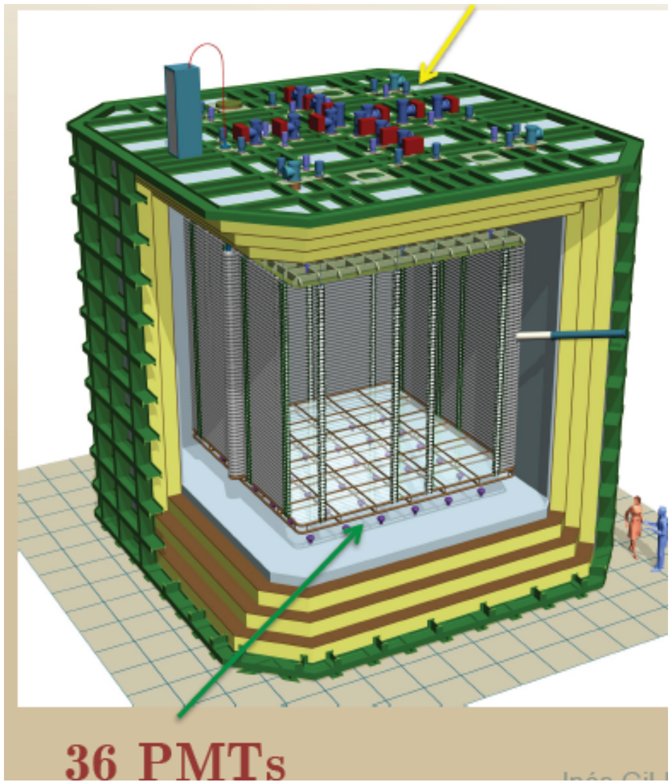
But would be nicer to have a faster trigger that can distinguish ^{39}Ar and pileup from supernova burst events.

Breakthrough technology:
Robust FPGA or ASIC with ability for channel-to-channel correlated triggers
---use front-end distributed processing to alert central DAQ that event is interesting.
---allow gating of nearby wires to keep hits that otherwise are below zero-suppression threshold

DUNE

LAr-TPC

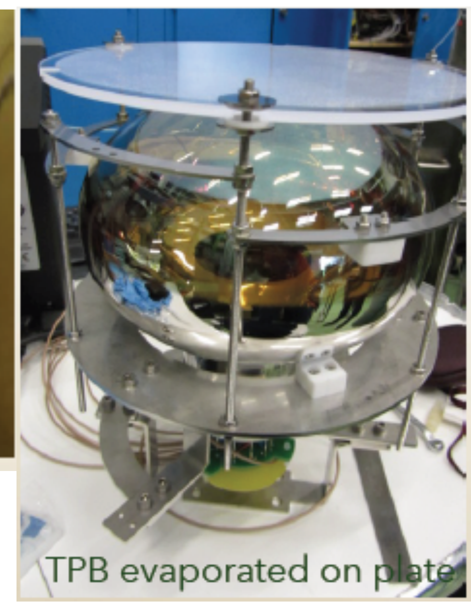
Dual-Phase TPC



WA105 prototype

- Simpler reconstruction
- (More) monolithic design
- Low threshold

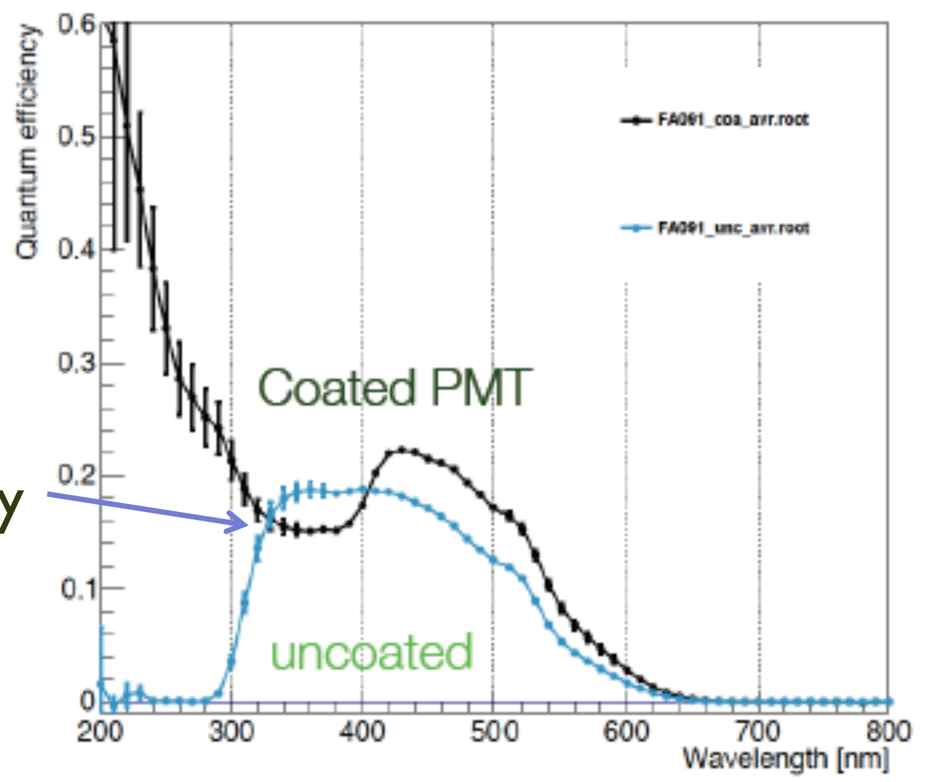
For scintillation light, challenges similar to noble liquid scintillation experiments



LAr-TPC

Dual-Phase TPC

So crappy



Breakthrough technology:

- Large-area cryo PMTs sensitive to EUV light, with HQE photocathodes….

Summary

- Lots of interesting neutrino physics and astrophysics to do with astrophysical sources
- New technologies being developed:
  - Loading of H_2O and scintillator for neutron detection or low-energy neutrino interactions
  - Water-based liquid scintillator (and loading)
  - Nobel liquid scintillation detectors and TPCs for low-energy ν detection
- Instrumentation needed:
  - Large-area, low-cost, fast, high-efficiency photosensors
  - Large-area cryogenic photosensors with EUV sensitivity
  - Front-end ASICs or robust FPGAs for fast local TPC triggers

[redacted]

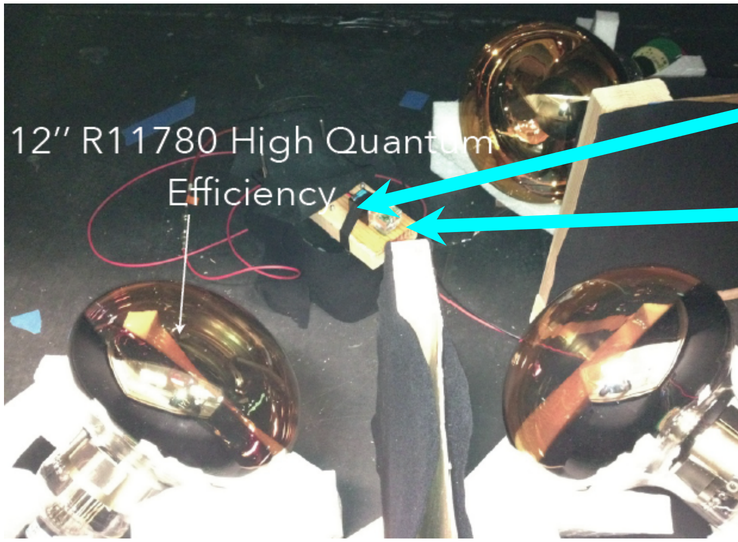
Broadening the Program

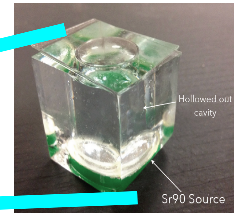
But requirements for various physics goals are in tension:

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-νs	>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

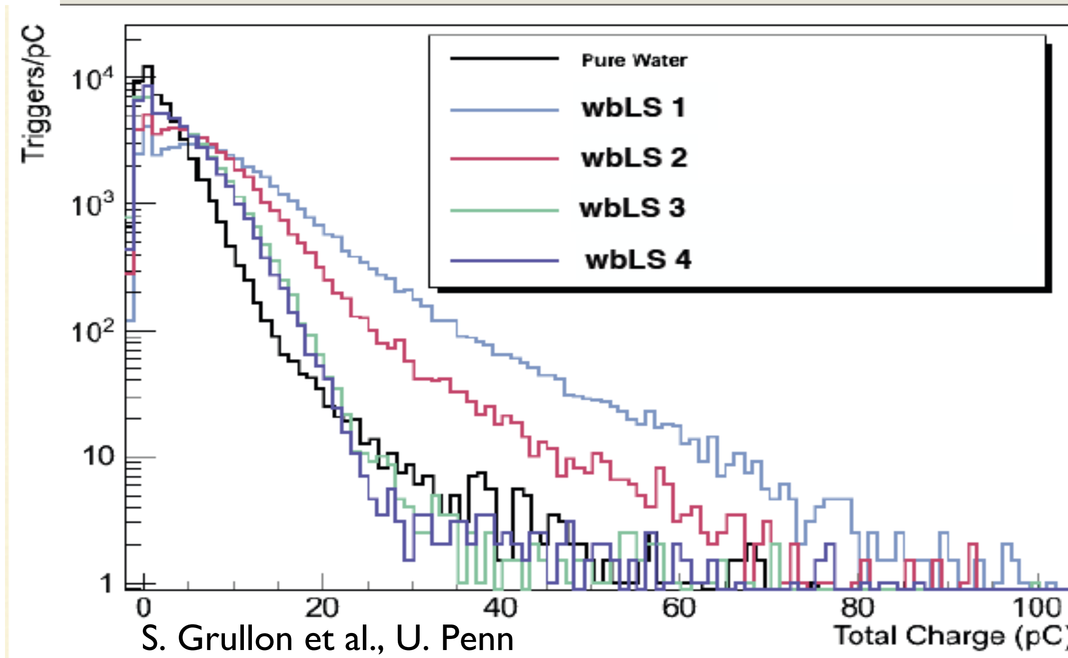
Water-based Liquid Scintillator





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

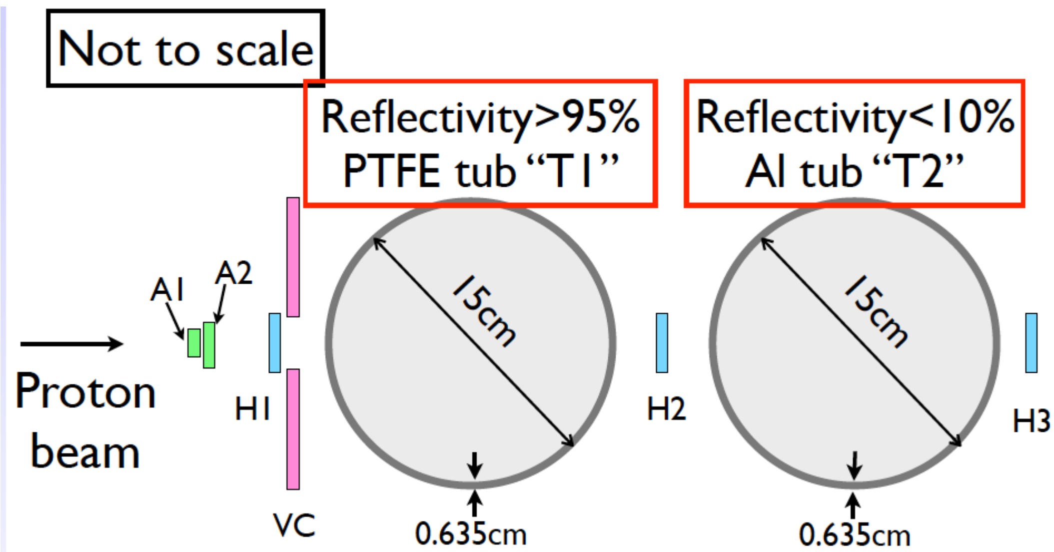
At low energies, intrinsic light yield scales with scintillator fraction.

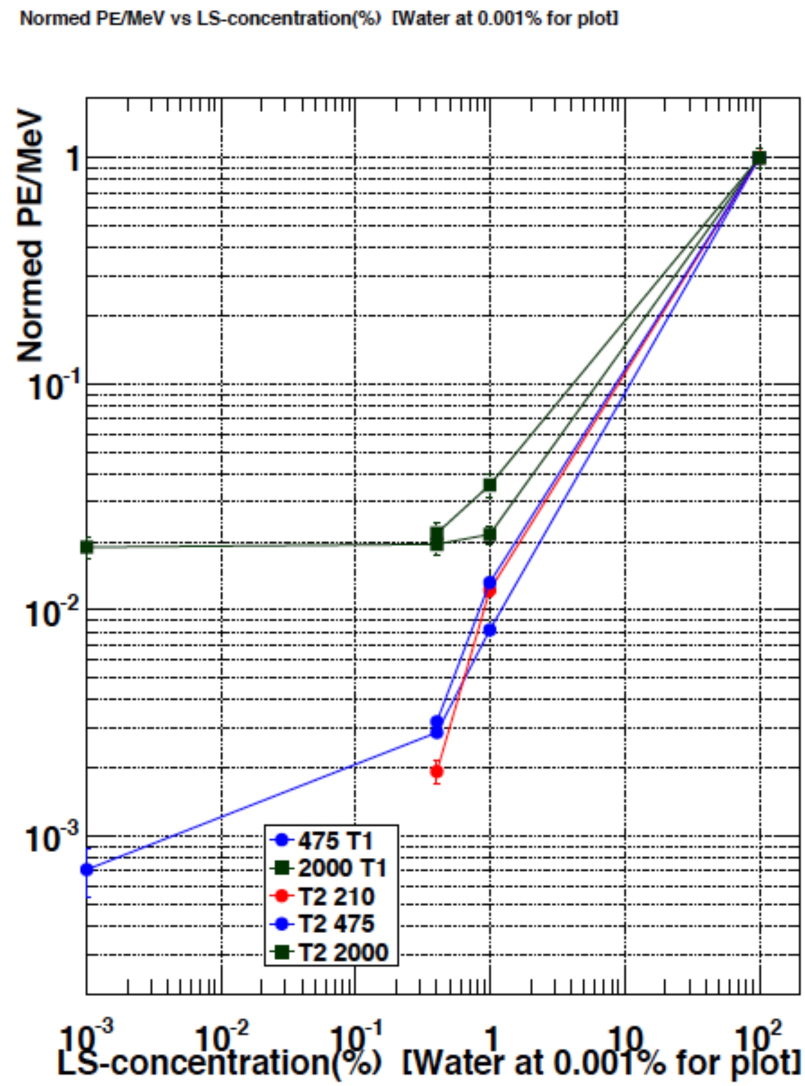


S. Grullon et al., U. Penn

Water-based Liquid Scintillator

And at high energies, until Cherenkov contribution becomes large.





D. Jaffe, BNL

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
$\overline{\nu}_e + p \to n + e^+$	88%	Inverse Beta
$\nu_e + e^- \to \nu_e + e^-$	1.5%	Elastic Scattering
$\overline{\nu}_e + e^- \to \overline{\nu}_e + e^-$	<1%	Elastic Scattering
$\nu_x + e^- \to \nu_x + e^-$	1%	Elastic Scattering
$\nu_e + ^{16}O \to e^- + ^{16}F$	2.5%	Charged Current
$\overline{\nu}_e + ^{16}O \to e^+ + ^{16}N$	1.5%	Charged Current
$\nu_x + ^{16}O \to \nu_x + O^*/N^* + \gamma$	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

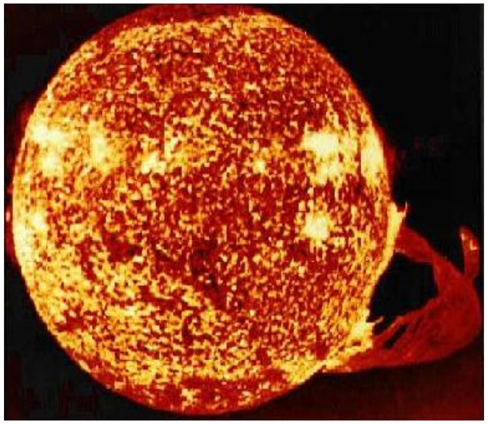
- Detect via IBD+neutron tag---very low background
- Scintillation light has higher efficiency than Gd+H_2O
- Low NC background
  - Atmospheric ν+C → n + fragments
  - WbLS allow rejection of recoils via Cher/Scint
  - "Isotropy" of Cherlight also helps discrimination

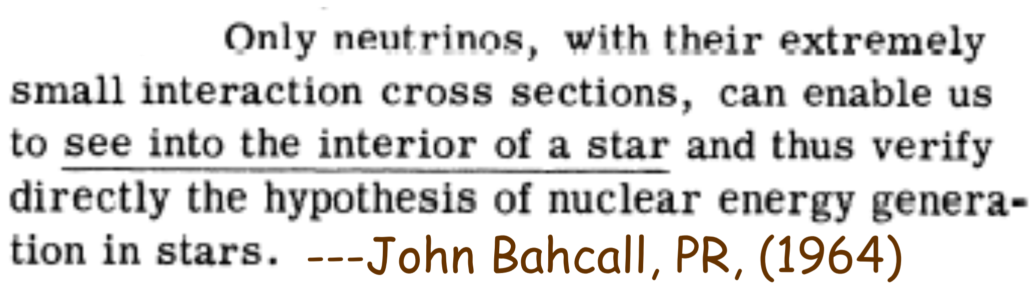
Loading with Cl or Li would allow ν_e detection in same detector.

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

CNO and the Sun

The solar `metallicity problem'





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)

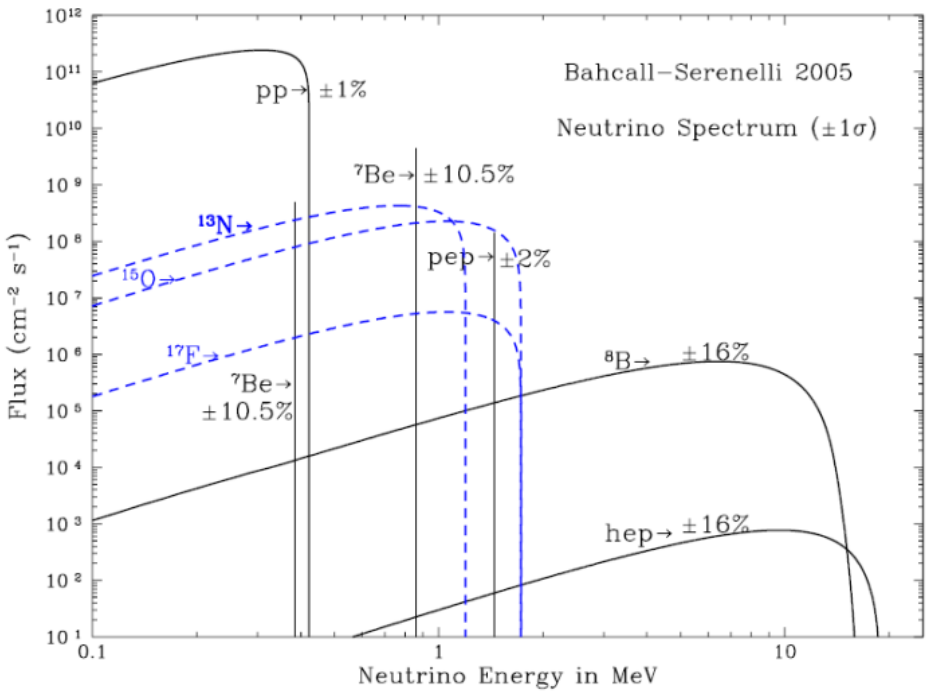
- Helioseismology convinced `everyone' that SSM was correct
- Modern measurements of surface metallicity are lower than before
- Which makes SSM helioseismologic predictions wrong

But! CNO neutrinos tell us metallicity of solar core

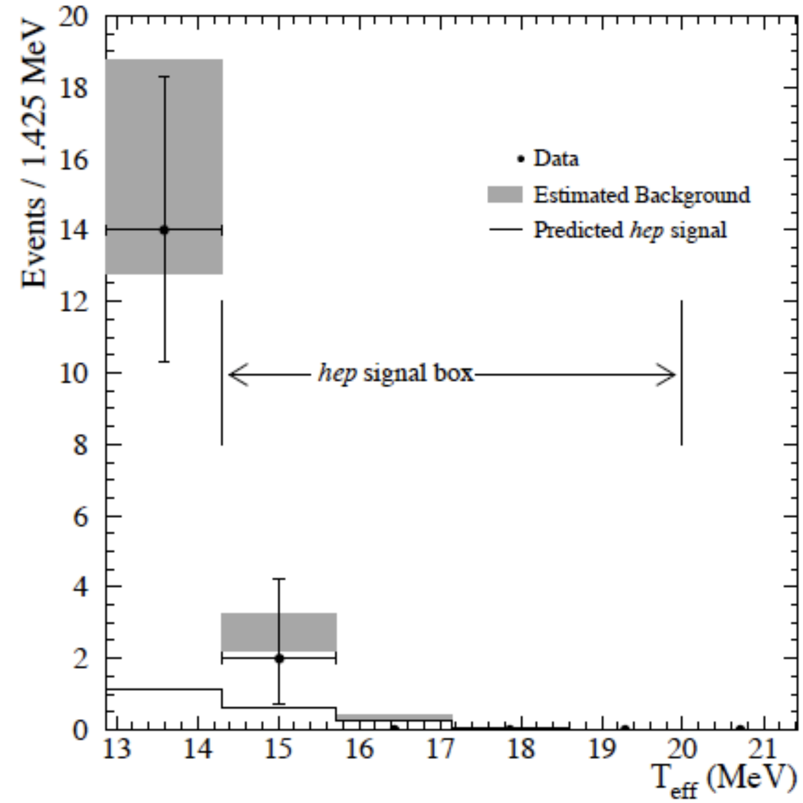
→ Flux may differ by factor of 2 between old/new metallicity

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

hep neutrinos



SNO Limits



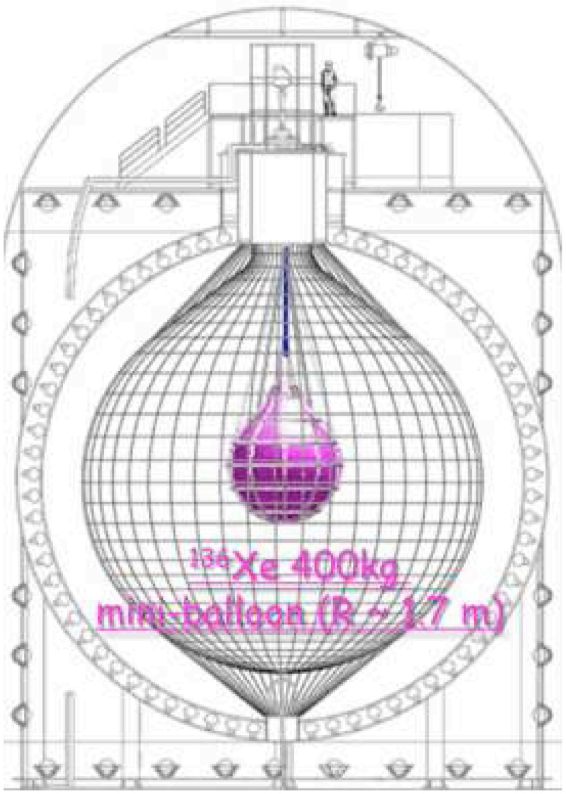
Tough to do with ES and with poorer energy resolution

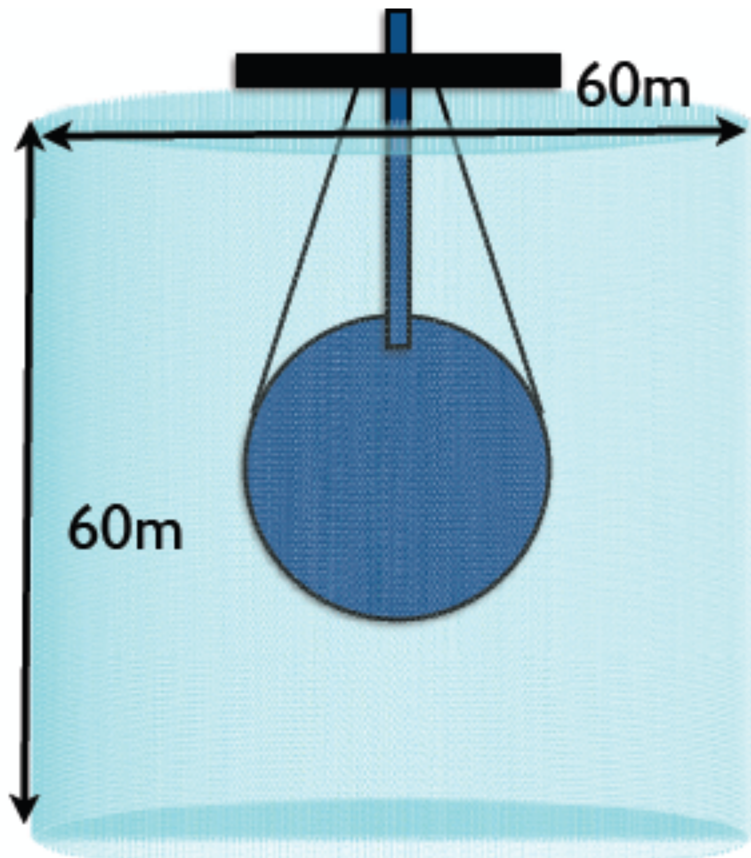
Flexibility

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





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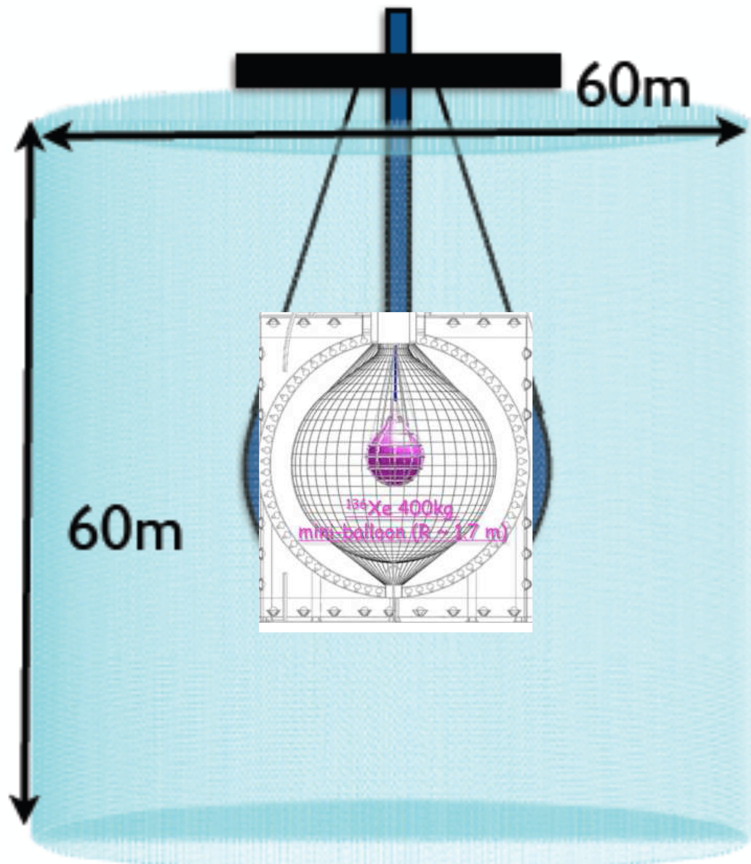
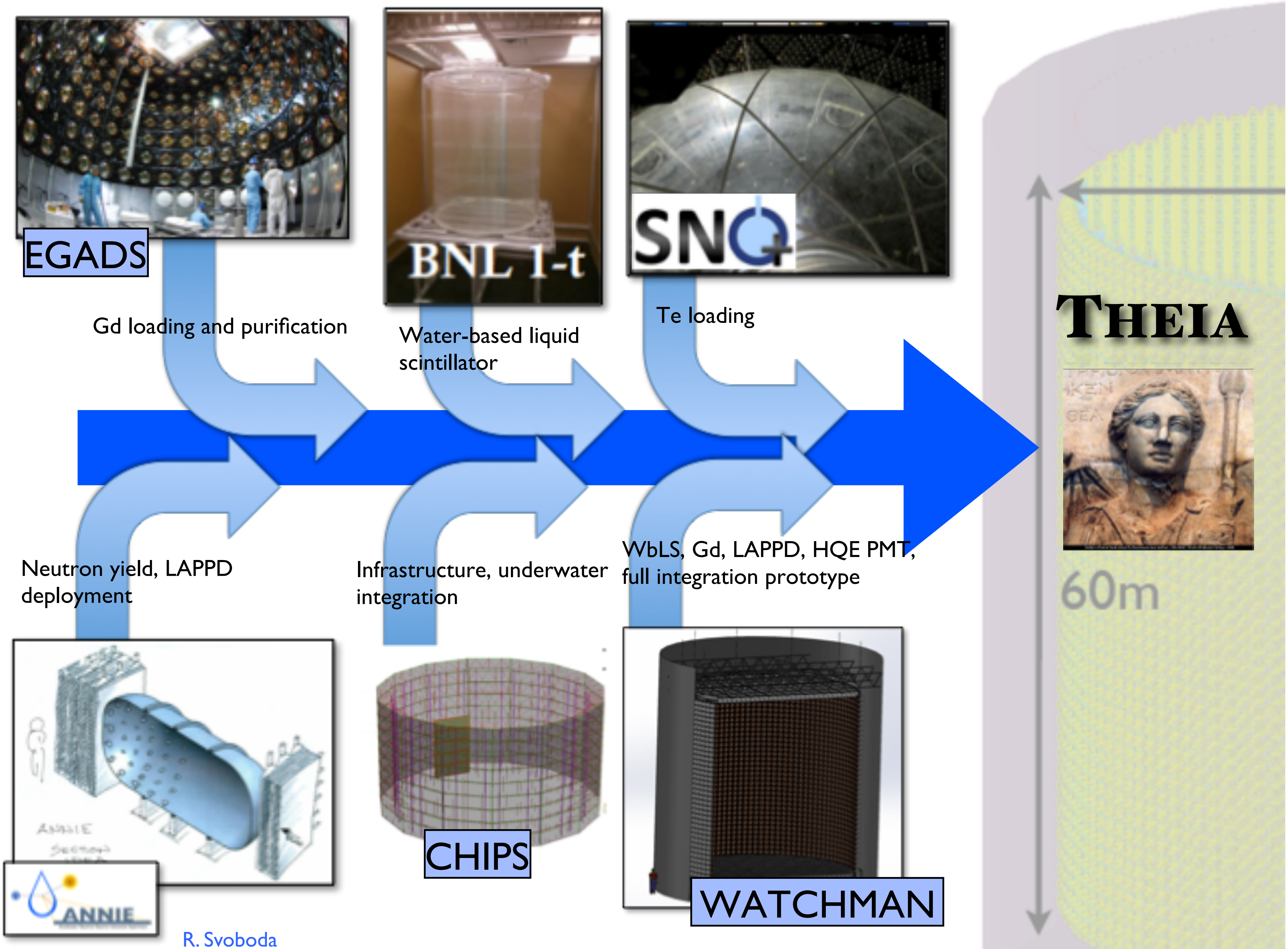


Experiment	Detection Reaction	Targeted Solar νs	Technology	Other Physics	Status
KamLAND	$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$	^{7}Be	Liq. scintillator	Reactor νs, geo-νs	Purification done
SNO+	$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$	pep, CNO	Liq. scintillator	0νββ, geo-νs	Engineering, purification
LENS	$\nu_e + {}^{115}In \rightarrow e^- + 2\gamma + {}^{115}Sn$	pp, ^{7}Be, pep	In-doped liq. scintillator	----------	Prototype bkd studies
XMASS	$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$	pp	Scintillation in cryogenic Xe	dark matter, 0νββ	800 kg stage in design
CLEAN	$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$	pp	Scintillation in cryogenic Ne	dark matter (DEAP/CLEAN)	0.1 and 1 ton engineering
MOON	$\nu_e + {}^{100}Mo \rightarrow e^- + {}^{100}Tc$	pp, ^{7}Be, pep	Scintillator/ Fiber sandwich	0νββ	Prototype for 0νββ
MUNU/TPC	$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$	pp, ^{7}Be, pep, CNO	CF4 TPC	μ_ν (reactor)	μ_ν results, recon studies
XAX	$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$	pp	Scintillation in cryo. Xe+Ar	dark matter, 0νββ	Design and simulation
Mega-H_2O	$\nu_{e(\mu\tau)} + e \rightarrow \nu_{e(\mu\tau)} + e$	^{8}B, hep	H_2O Cerenkov	P-dk, LBL νs	Design, sim.


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

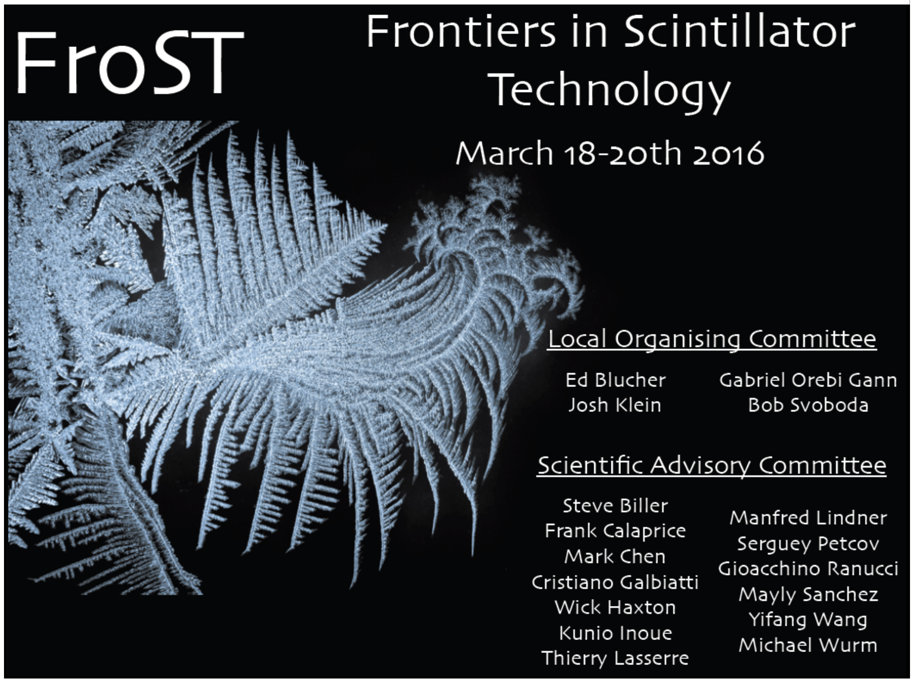
Planned Demonstrations

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

Summary

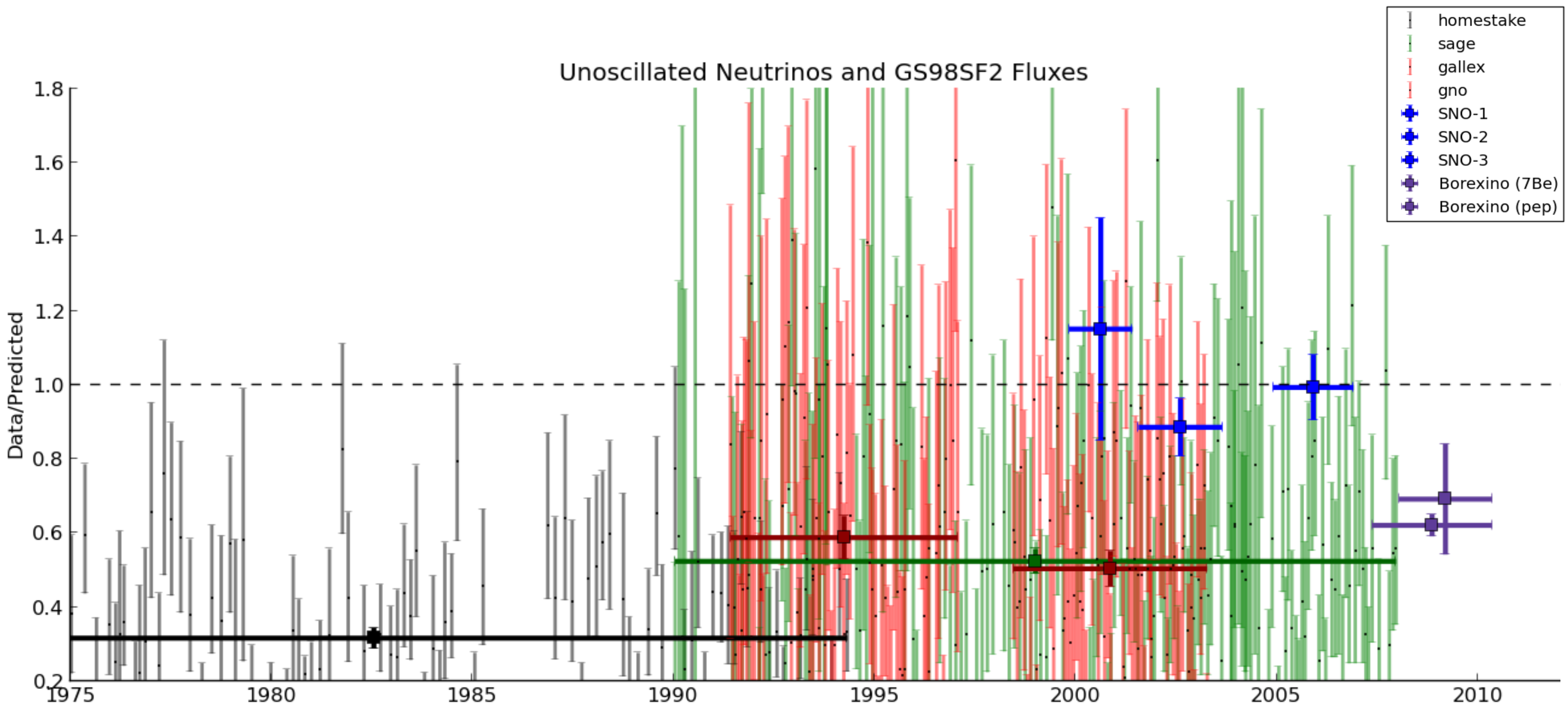
- Great opportunity with LBNF
- Can exploit this with a broad physics program that overlaps with DUNE
- New technologies (WbLS, LAPPDs, isotope loading) make a very broad program possible
- Work on THEIA is proceeding surprisingly rapidly

Workshop at FNAL next year!



The (Very) Recent History of the Solar Core

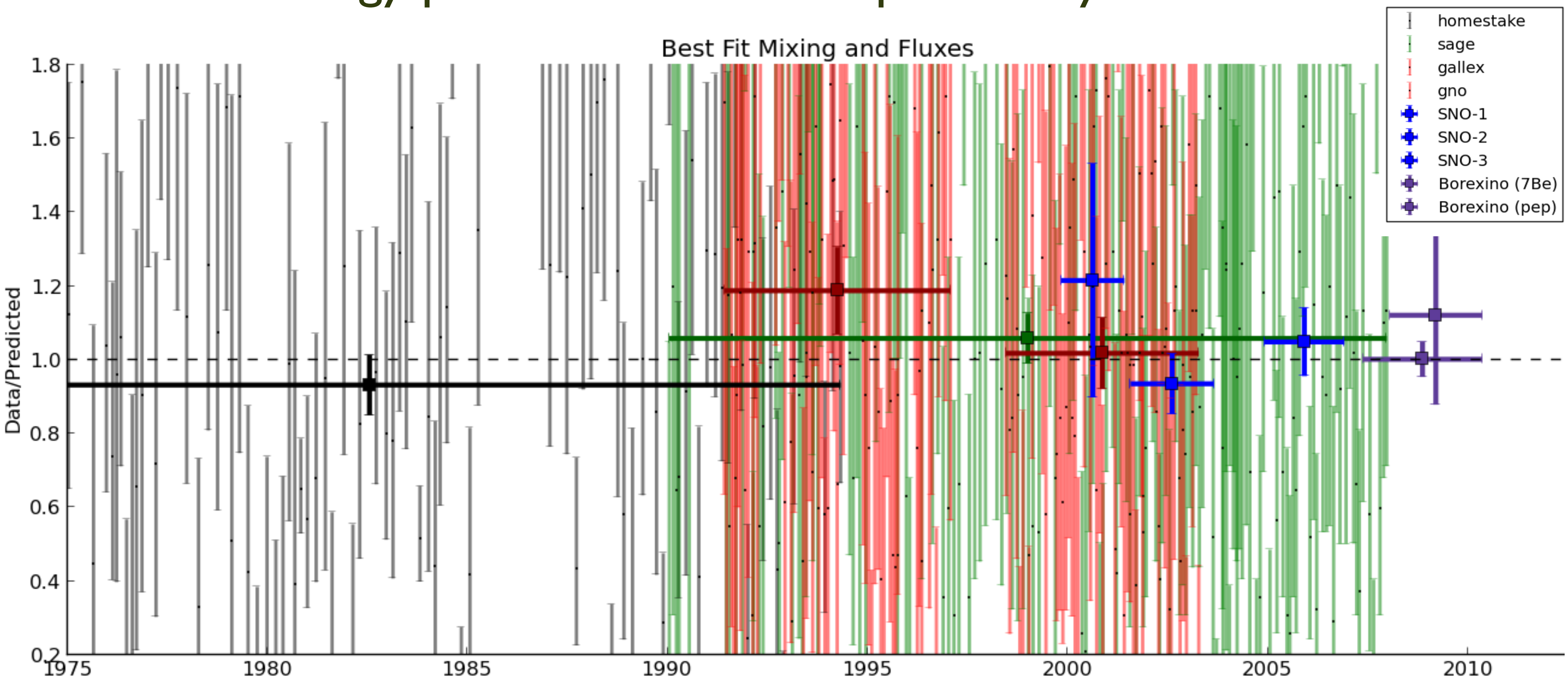
Without mixing correction, this is a history of the Solar Neutrino Problem



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

THEIA

- New materials (water-based liquid scintillator)

+

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

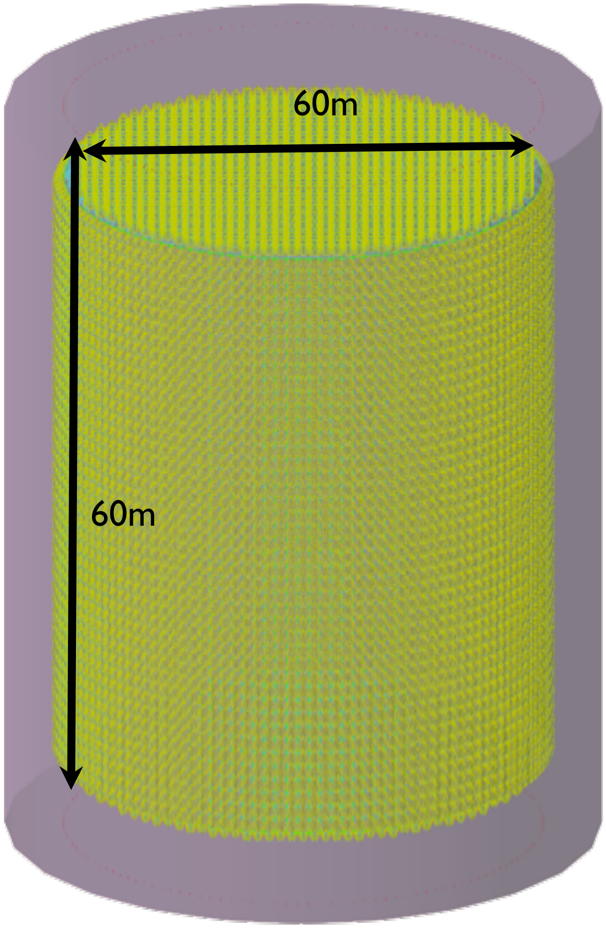
+

- 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”



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!