The SoLid experiment

Short baseline Oscillation search with Lithium-6 Detector

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for the SoLid collaboration

February 18, 2016

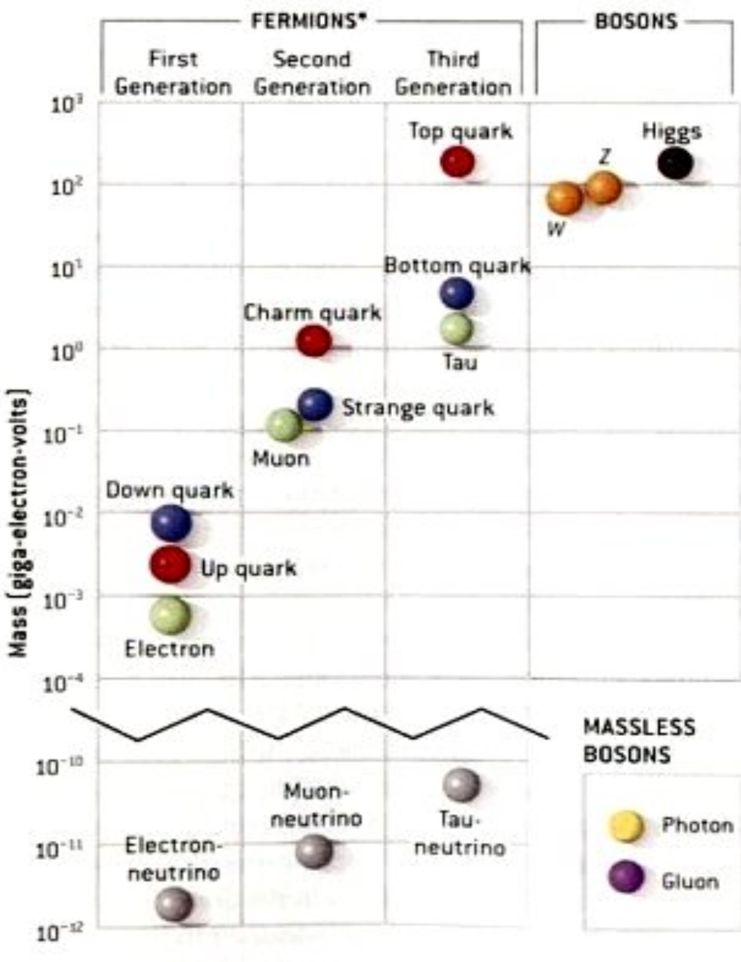
Introduction

- The recent observation of the *Reactor Antineutrino Anomaly* has now revived the interest in short-baseline experiments probing the disappearance of ν_e and $\bar{\nu}_e$
  - Source experiments using high intensity neutrino and antineutrino emitters coupled with large-scale detectors
  - Very short-baseline reactor experiments

- SoLid is a reactor project that aims to resolve the anomaly employing a novel detector design
  - ~ 5 - 10 m from the BR2 research reactor in SCK•CEN (Belgium)
  - Cube segmentation and robust neutron identification capabilities
  - Synergy with reactor monitoring, nuclear non-proliferation efforts

- SoLid (phase I) is expected to start construction in 2016
  - Scan the allowed parameter region within a year of data taking

Neutrinos

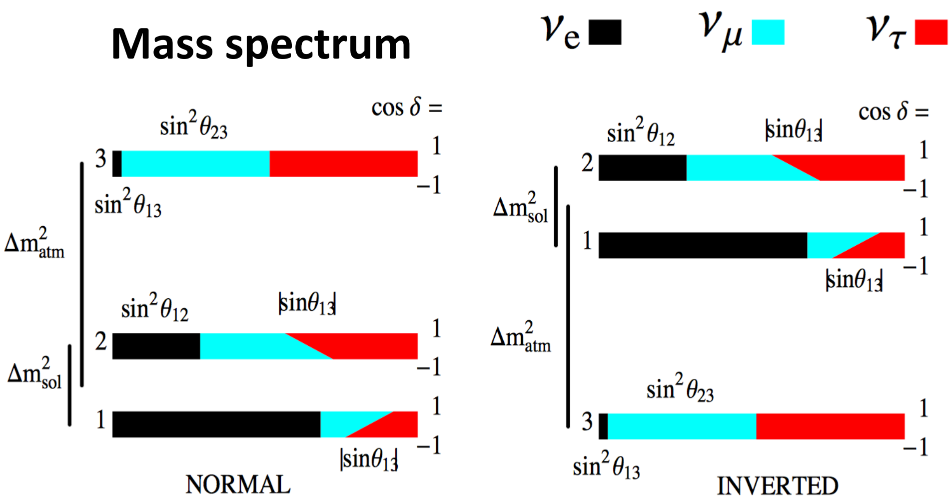


- Originally, incorporated as massless particles in the Standard Model (SM) of particle physics
  - Left-handed helicity states only
- Neutrino oscillations first discovered in 1998 by Super-Kamiokande
  - Now confirmed by several experiments
  - Solar and atmospheric oscillations

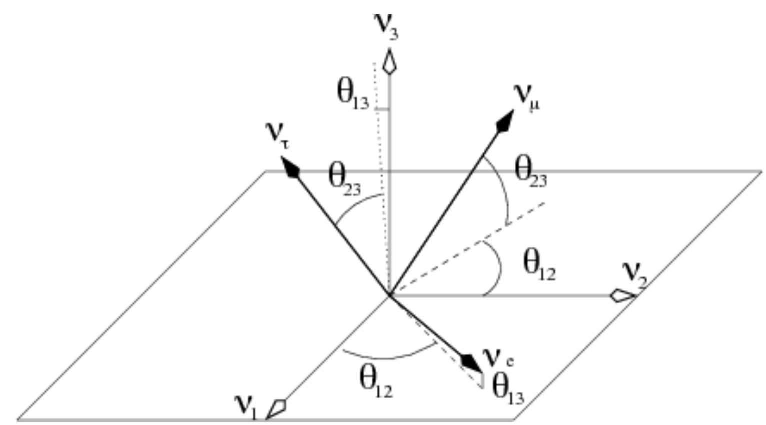
Open questions

- *What are their masses ?*
- *Are they Majorana particles ?*
- *Is there CP violation in the ν sector ?*
- *Do sterile neutrinos exist ?*

Neutrino masses and mixing



O. Mena and S. Parke Phys. Rev. D 69, 117301 (2004)



Neutrino mixing through
a rather simple schematic

- Lepton mixing matrix ($c_{ij}=\cos\theta_{ij}$, $s_{ij}=\sin\theta_{ij}$) :

$$|\nu_\alpha> = \sum_{i=1}^{3} \mathcal{U}^*_{\alpha i}\, |\nu_i>$$

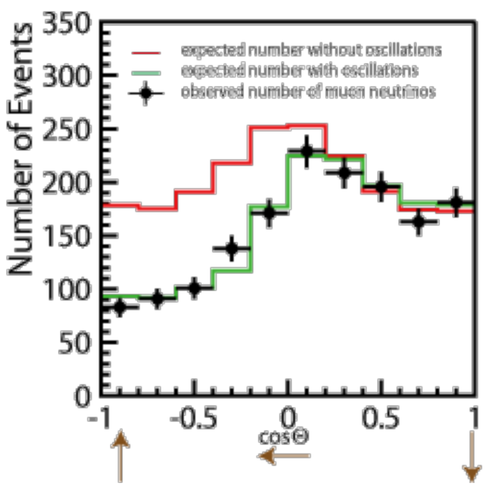
$$\mathcal{U} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospheric}} \times \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{1-3}} \times \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar}} \times \underbrace{diag\{e^{i\alpha_1}, e^{i\alpha_2}, 1\}}_{0\nu2\beta}$$

Lepton flavor violation through neutrino oscillations

$$P_{\nu_\alpha \to \nu_\beta} = \sum_{i,j} \mathcal{U}^*_{\alpha i}\, \mathcal{U}_{\beta i}\, \mathcal{U}_{\alpha j}\, \mathcal{U}^*{}_{\beta j}\; e^{-i\frac{\Delta m^2_{ij} L}{2E}}$$

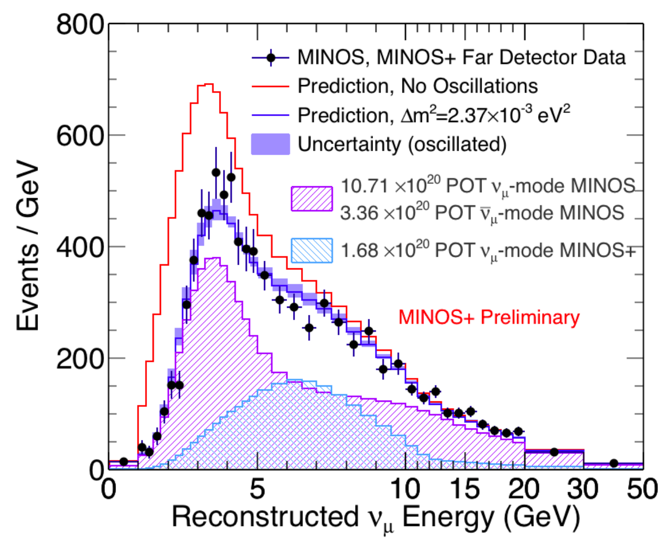
- Oscillation patterns driven by the squared-mass differences, Δm^2_{ij}
- The formula depends on the neutrino energy (E) and distance (L)

Super-Kamiokande,
http://www-sk.icrr.u-tokyo.ac.jp/sk/sk/atmos-e.html



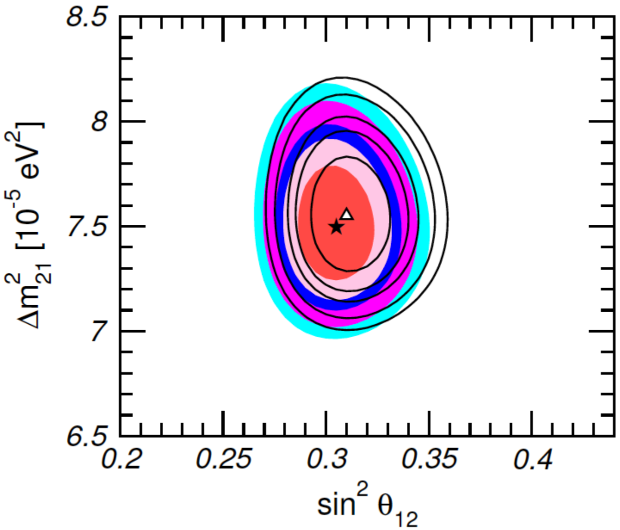
13000 km 20 km

MINOS and MINOS+,
http://www-numi.fnal.gov/PublicInfo/forscientists.html



Current picture

Solar sector



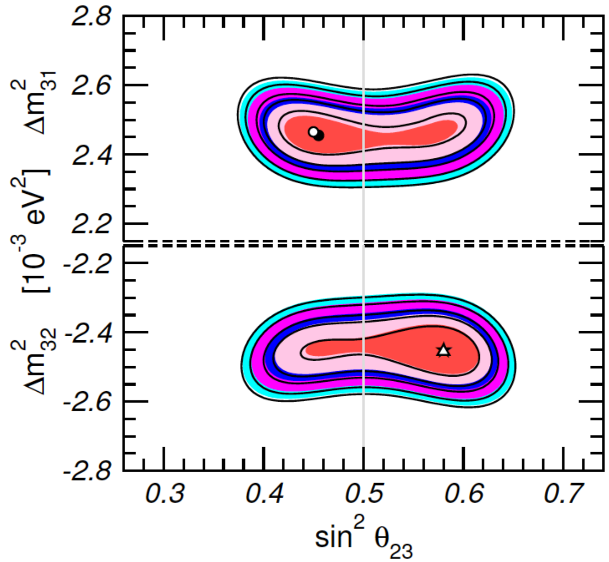
Solar exp. and KamLAND

$\Delta m^2_{12} \approx 7.6\ 10^{-5}$ eV^2

$\sin^2(2\theta_{12}) \approx 0.85$

(large mixing angle)

Atmospheric sector



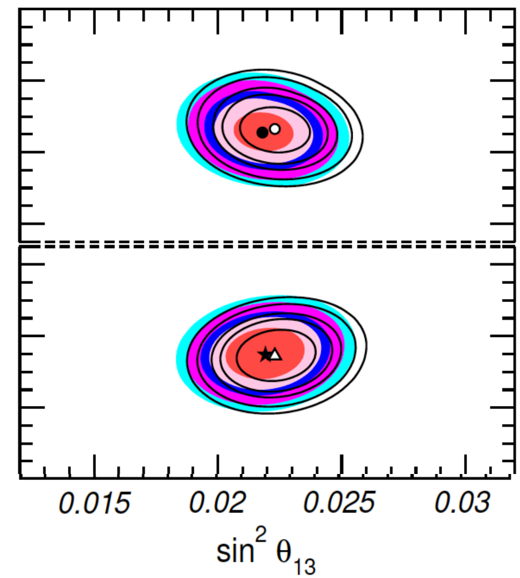
Super-K, MINOS, T2K *et al.*

$\Delta m^2_{23} \approx 2.4\ 10^{-3}$ eV^2

$\sin^2(2\theta_{23}) \approx 1.0$

(almost maximal mixing)

1-3 sector



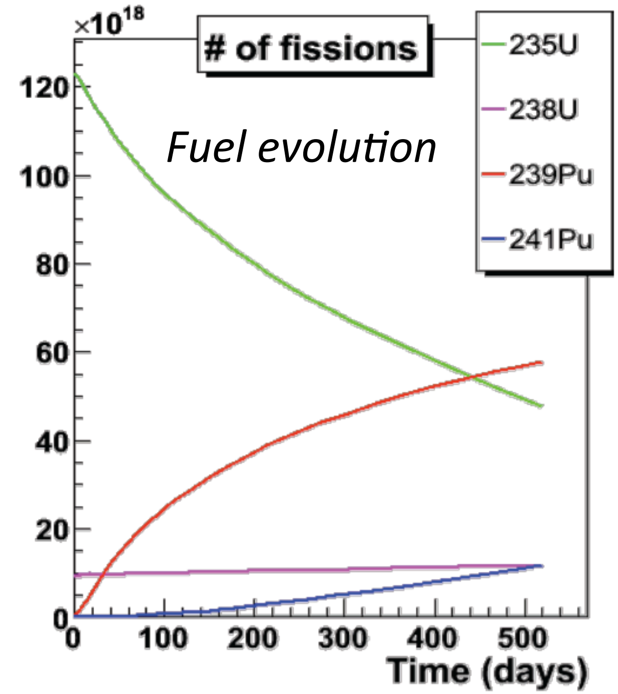
Daya Bay, Double Chooz, RENO, T2K and Nova

$\sin^2(2\theta_{13}) \approx 0.1$

Gonzalez-Garcia et al., arXiv:1409.5439

Reactor antineutrinos

- Reactors are copious sources of $\bar{\nu}_e$
  - Beta decays of fission fragments
  - Low energy antineutrinos; isotropic flux
  - An 1 GW_{th} power reactor emits 2 10^{20} $\bar{\nu}_e$/sec



- The most common detection channel is inverse beta decay (IBD):

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- Number of events detected:

$$n = \frac{1}{4\pi R^2} \frac{P_{th}}{< E_f >} N_p \, \sigma_f \, \epsilon$$

Cross-section per fission

$$\sigma_f = \int_0^\infty S(E_\nu)\sigma_{V-A}(E_\nu)dE_\nu$$

Reactor spectrum re-evaluation

- New reactor antineutrino spectra pioneered by Saclay
  - Work stimulated by Double Chooz, Phys. Rev. C **83**, 054615 (2011)
- Conversion with "*true*" distribution reproducing >90% of ILL data and five effective branches to the remaining 10%
  - 3% net increase wrt old spectrum for ^{235}U, ^{239}Pu and ^{241}Pu
  - Off equilibrium effects increase neutrino yield
  - Decrease of neutron life-time

A ~6 % increase (confirmed by P. Huber)

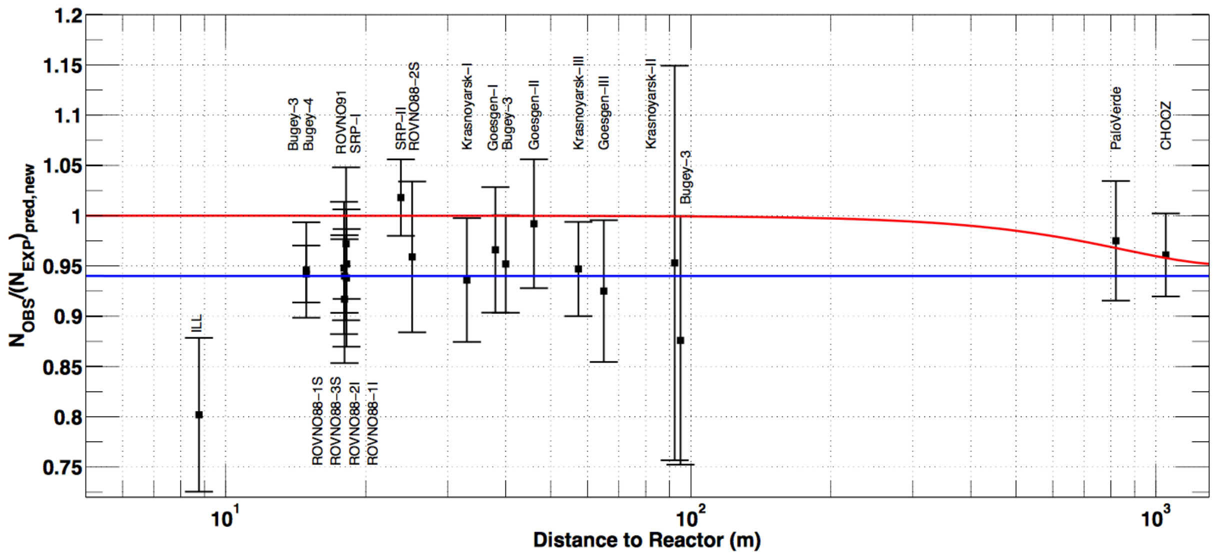
$$\sigma_f^{pred} = \sum_k f_k \sigma_{f,k}^{pred}$$

	old [3]	new
$\sigma_{f,^{235}\mathrm{U}}^{\mathrm{pred}}$	6.39±1.9%	6.61±2.11%
$\sigma_{f,^{239}\mathrm{Pu}}^{\mathrm{pred}}$	4.19±2.4%	4.34±2.45%
$\sigma_{f,^{238}\mathrm{U}}^{\mathrm{pred}}$	9.21±10%	10.10±8.15%
$\sigma_{f,^{241}\mathrm{Pu}}^{\mathrm{pred}}$	5.73±2.1%	5.97±2.15%
$\sigma_{f}^{\mathrm{pred}}$	5.824±2.7%	6.102±2.7%

Phys. Rev. D **83** 073006 (2011)

The *Reactor Antineutrino Anomaly*

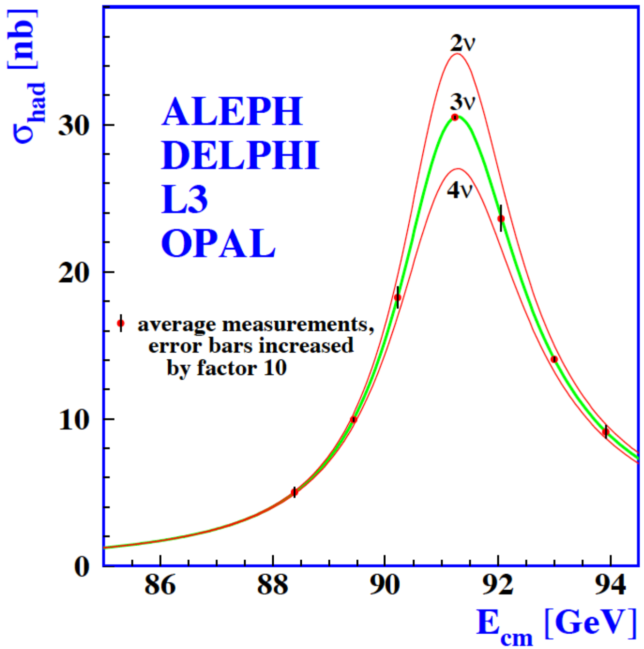
Mention et al., Phys. Rev. D **83** 073006 (2011)



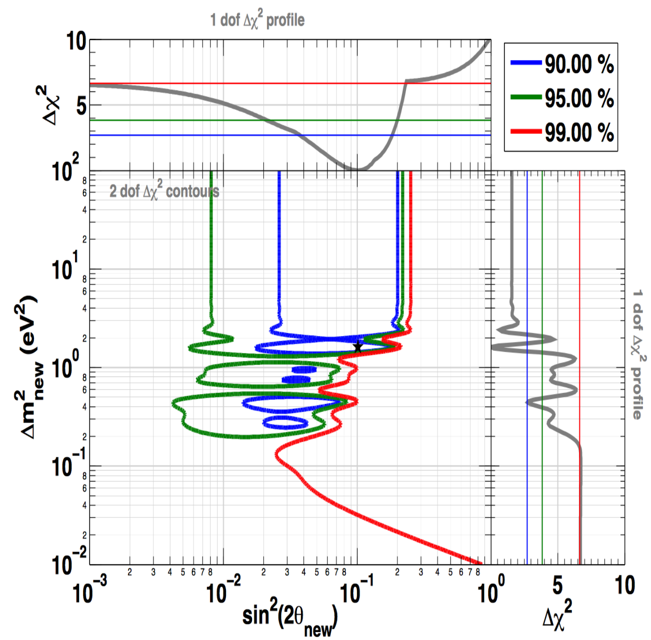
- All previous experiments short baselines (<100m) shifted with respect to re-evaluated spectra
  - Updated observed/predicted averaged event ratio: R = 0.938 ± 0.023 (2.7σ)
- Possible explanations:
  - Wrong estimation of antineutrino spectrum
  - A possible hint for new physics …

Forth neutrino hypothesis

arXiv:0509008



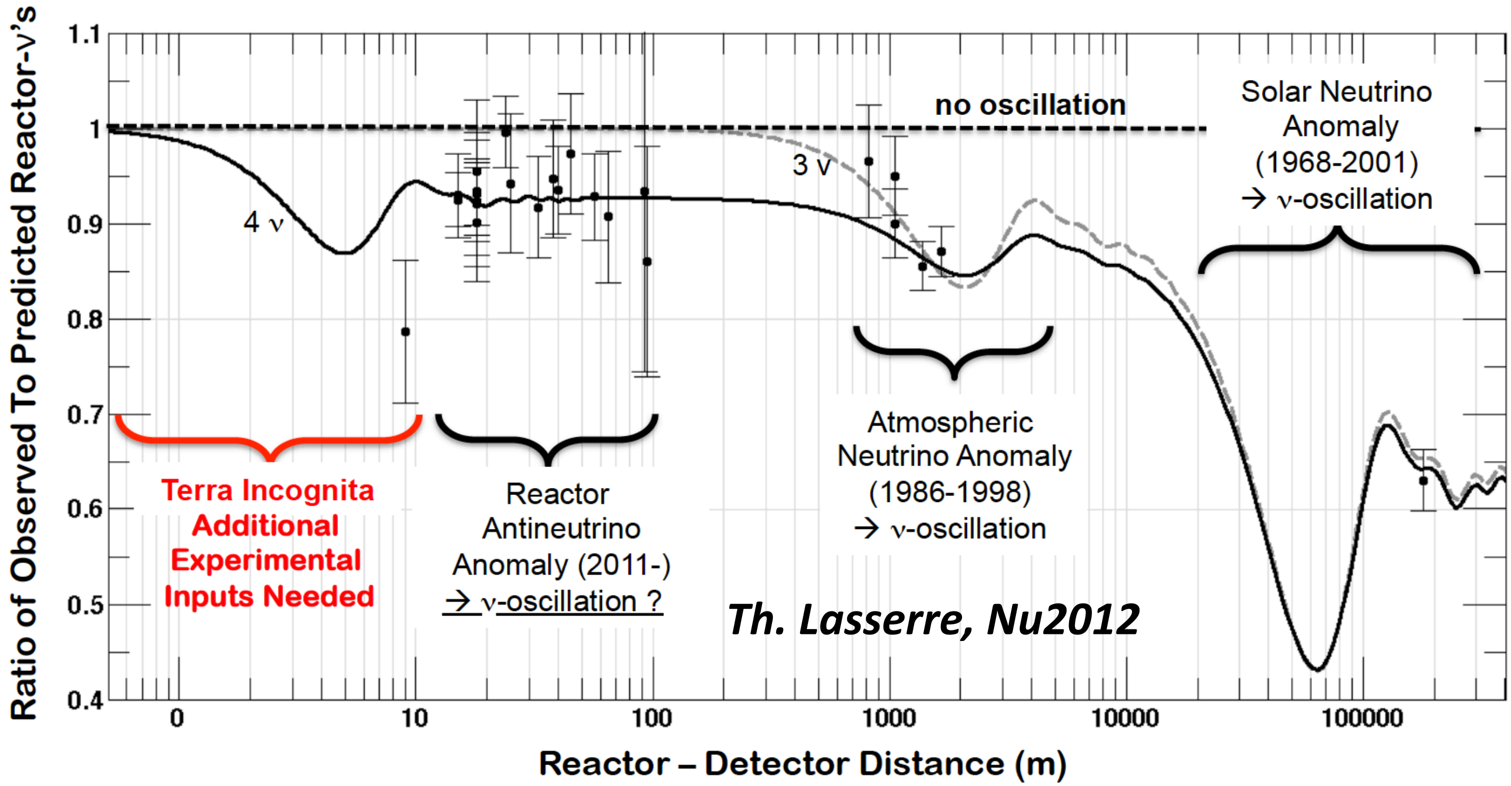
$$P_{\nu_e \to \nu_e} = 1 - \sin^2(2\theta_{ee}) \sin^2(\frac{\Delta m^2_{41} L}{E})$$



Best fit: $\sin^2(2\vartheta) \approx 0.1$ and $\Delta m^2 \approx 1.5$ eV^2

- LEP has constrain the number of (active) neutrinos that couple the Z boson
  - Open possibilities for very heavy or sterile neutrinos
- Sterile neutrinos invoked to explain the LSND excess

Terra incognita

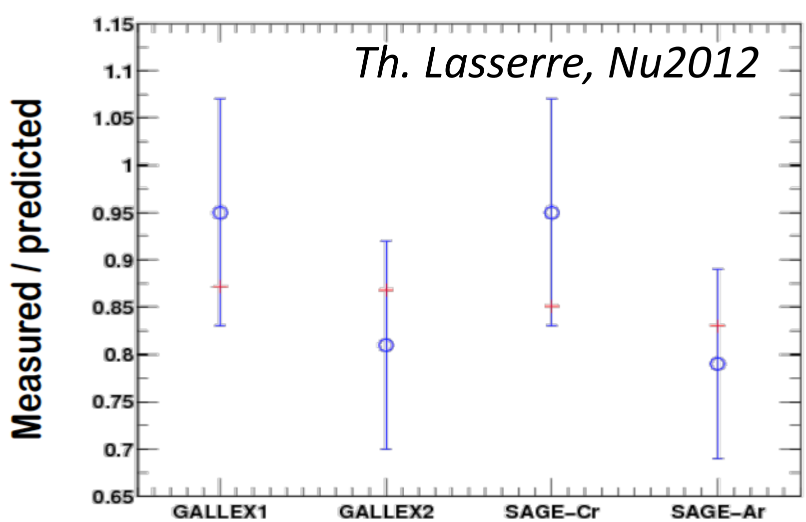


- Oscillations due to an (additional) sterile neutrino are not excluded from other data sets
  - Hints from other experiments in the same channel
  - Further input is needed ! Very short-baseline reactor experiment

The Gallium anomaly and the T2K ν_e disappearance result

Gallex and SAGE

- Four calibration runs with intense MiC neutrino sources
  - ^{51}Cr source, 750 keV ν_e emitter
  - ^{37}Ar source, 810 keV ν_e emitter

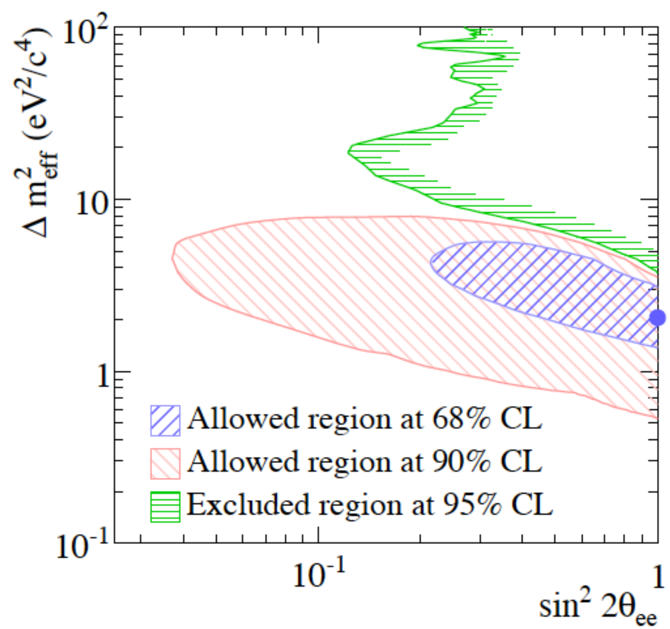


  - Low counted rates in all runs

Tokai to Kamioka (T2K)

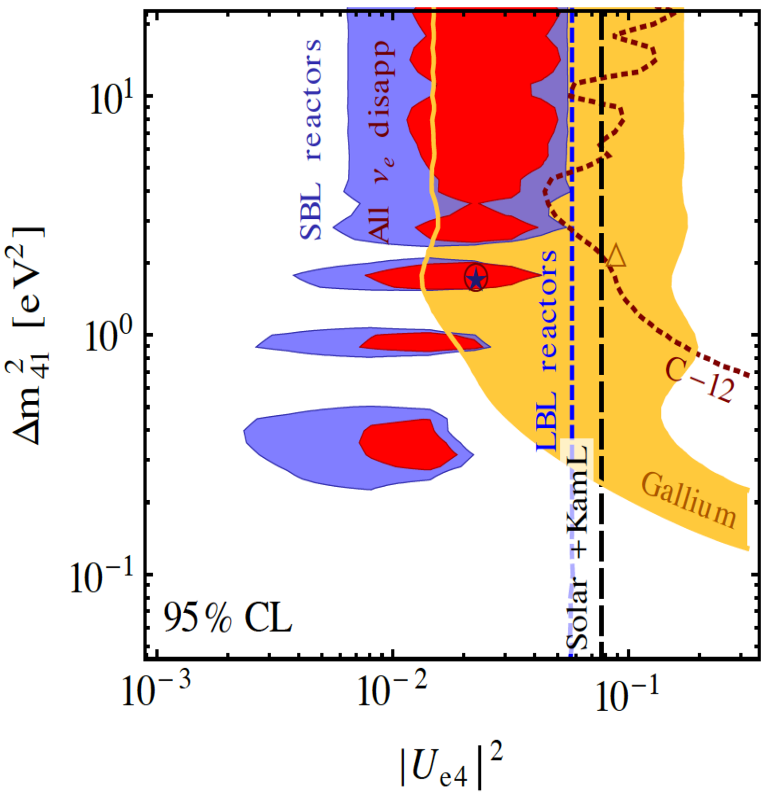
- Analysis using the beam ν_e contamination at near detector

Phys. Rev. D 91 051102 (2015)



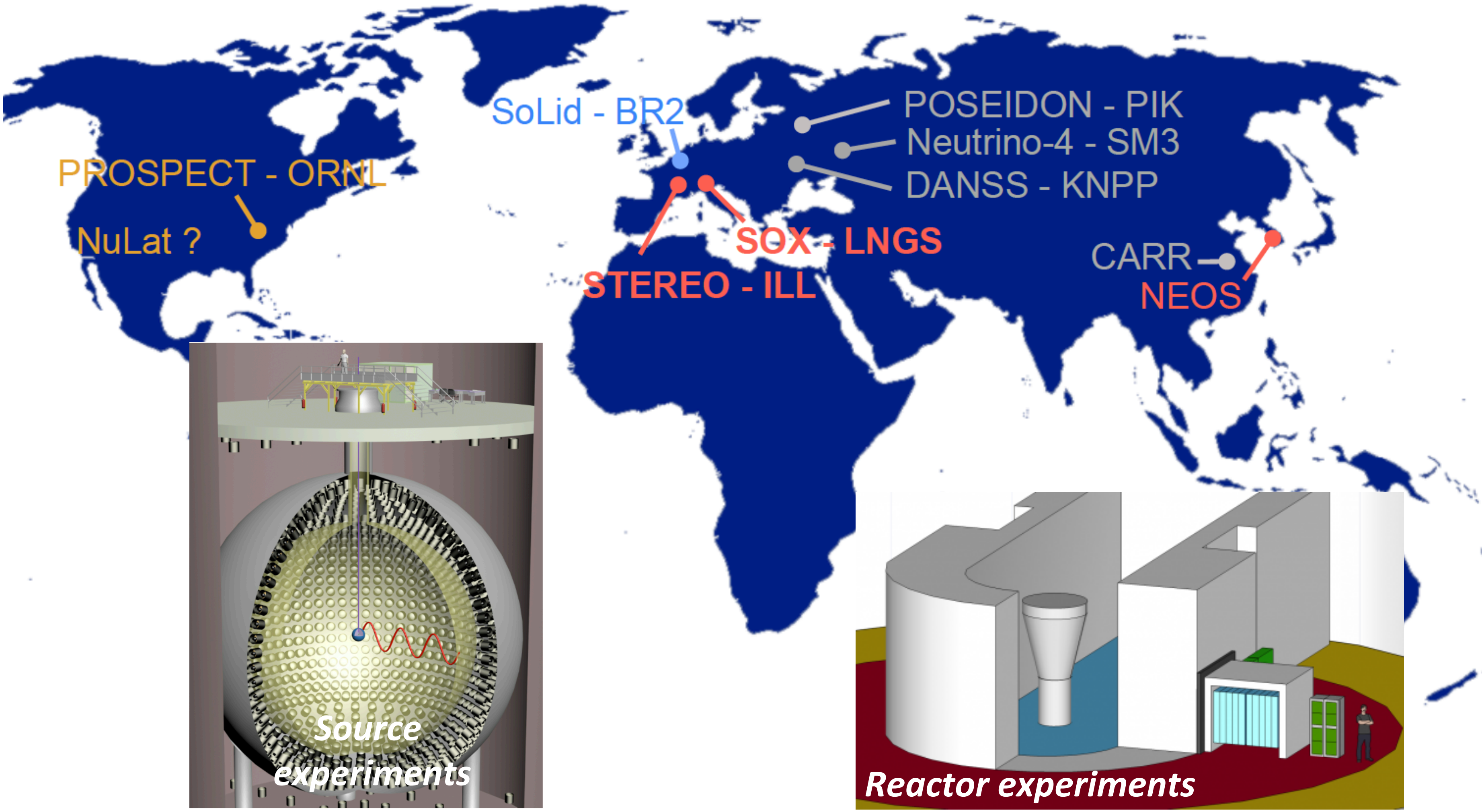
Global ν_e disappearance analysis

$$\sin^2 2\theta_{ee} \equiv 4|U_{e4}|^2(1 - |U_{e4}|^2)$$



- Reactor and Gallium anomalies appear to be quite compatible with each other
- Constraints from:
  - LSND and KARMEN ^{12}C data
  - Medium baseline reactor exp. (Chooz, Palo Verde, etc …)
  - Solar experiments and KamLAND
- Tension between appearance and disappearance experiments
  - No ν_μ disappearance
  - *Recent result from IceCube*

New experimental test needed

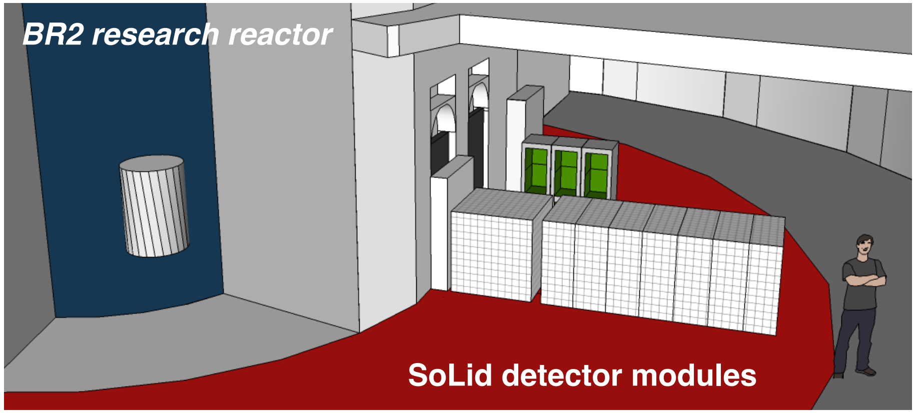


Also: Tritium decay experiments, ie., KATRIN

The SoLid collaboration

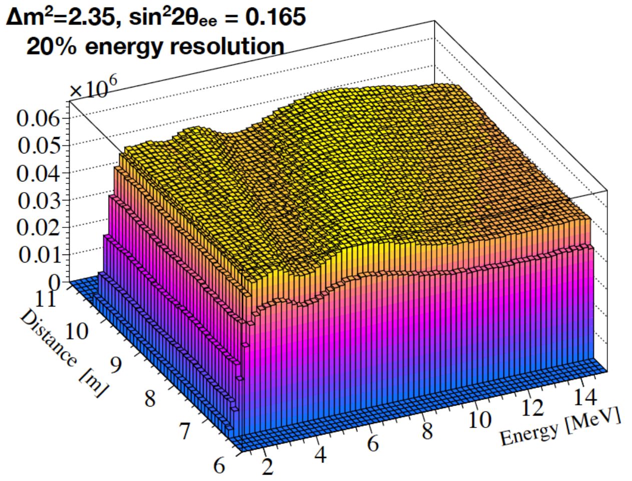
SCK•CEN
Universiteit Antwerpen
Vrije Universiteit Brussel
UNIVERSITEIT GENT
LAL Laboratoire de l'Accélérateur Linéaire
LPC Caen
Subatech
University of Oxford
University of Bristol
VirginiaTech Invent the Future

Experimental layout



- Detector modules installed at a distance of ~ 5 - 10 m from the BR2 reactor
  - Precise reactor antineutrino oscillometry

- ^{235}U flux measurement
  - Improve reactor flux prediction
  - Demonstrate reactor monitoring



Challenges

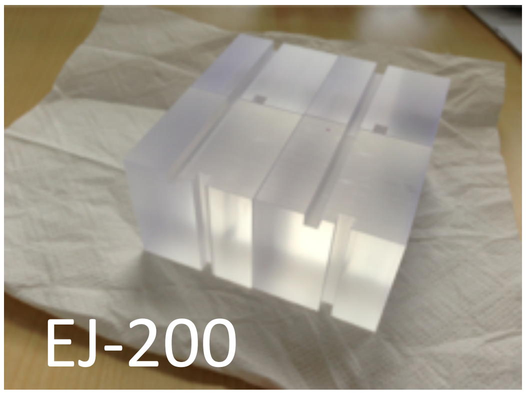
- Small oscillation effect
  - Large statistics, good understanding of systematics
- Requires small reactor core (<1m)
  - A few meters oscillation length
- Cover a large baseline range
  - Good vertex and energy resolution
- Control of background is the key
  - Close proximity to a nuclear reactor
  - Low overburden (almost on surface)

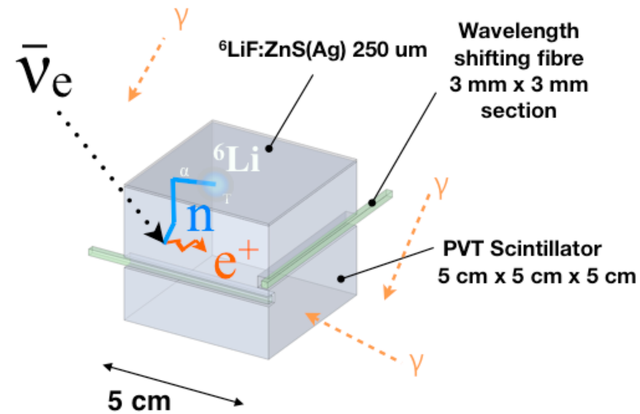
BR2 reactor at SCK•CEN

- Research nuclear reactor
  - Highly enriched in ^{235}U
- High operating thermal power
  - Typical values between 40 and 80 MW
- Compact antineutrino source
  - 50 cm effective core diameter
- 150 days per year duty cycle
  - Reactor off running data for background understanding and subtraction
- Low reactor correlated background rate (compared with other sites)
- Large available space covering baselines of 5.5 to 12 m
- *Good collaboration with SCK•CEN*

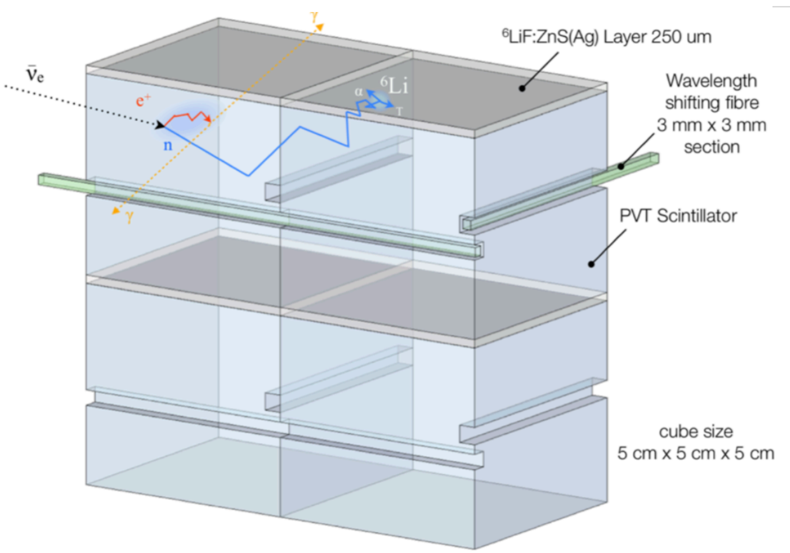
The SoLid detector design

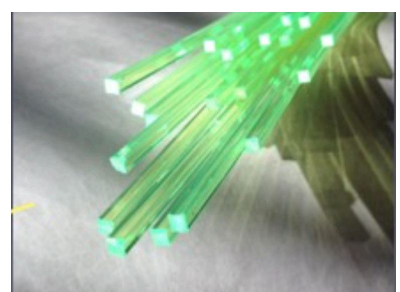
- 5 × 5 × 5 cm PVT cubes
- Non-flammable scintillator



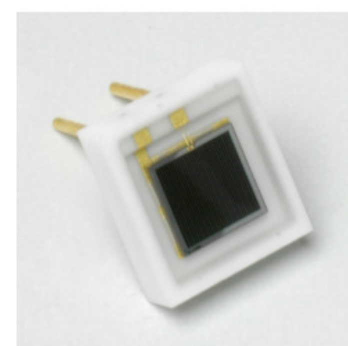


- Cubes are optically separated
- ^{6}LiF:ZnS(Ag) for neutron identification
- Light collected WLS fibers and multi-pixel photon counters (MPPCs)





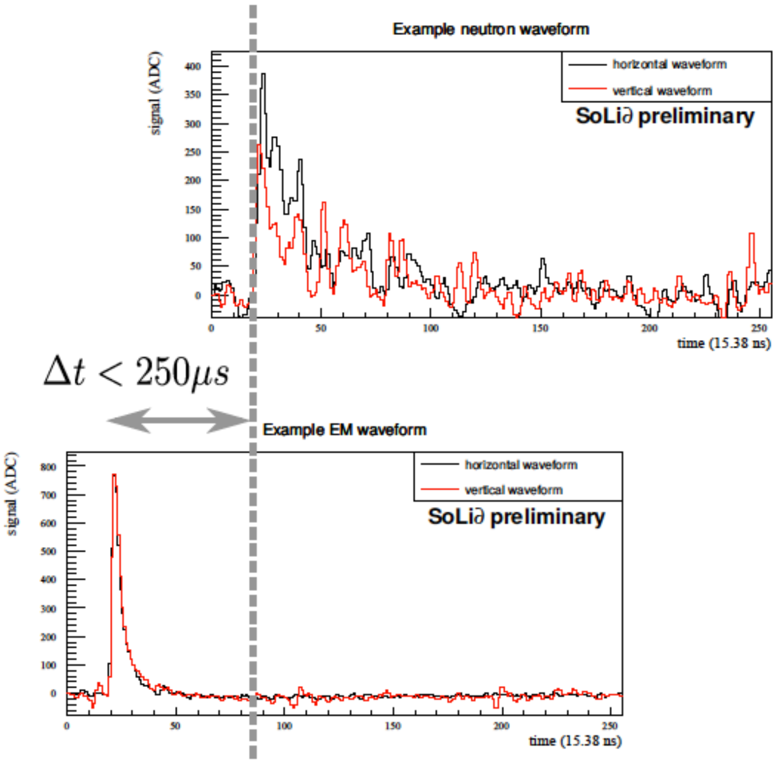
Squared BCF-91A fiber



$\bar{\nu}_e$ detection: *Inverse Beta Decay (IBD)*

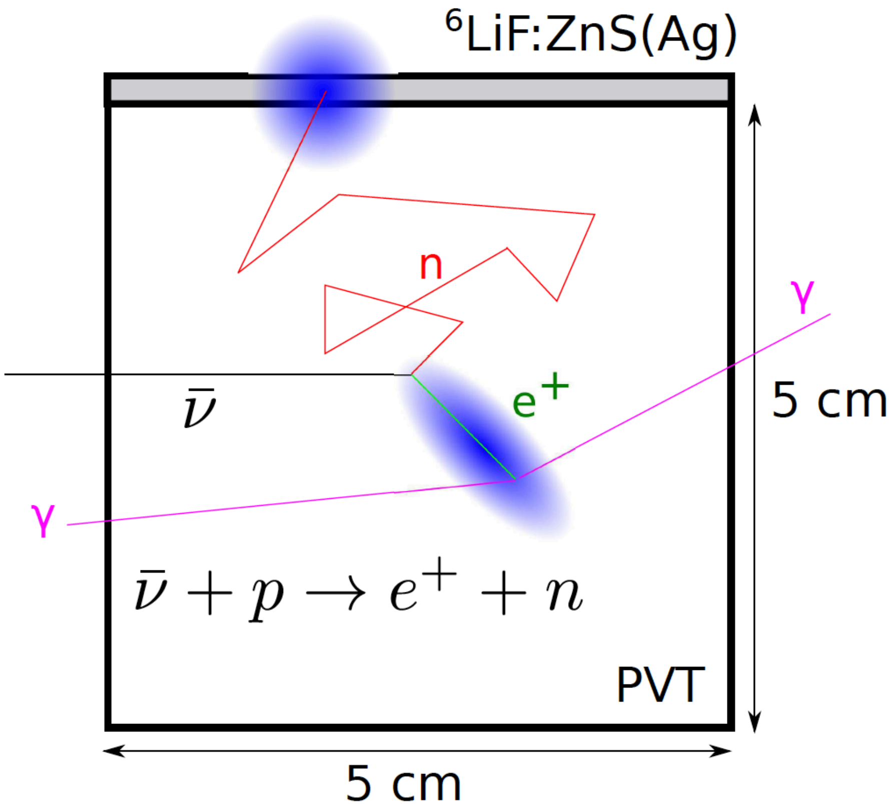
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- High cross-section
- Threshold at 1.8 MeV
- Prompt-delayed coincidence

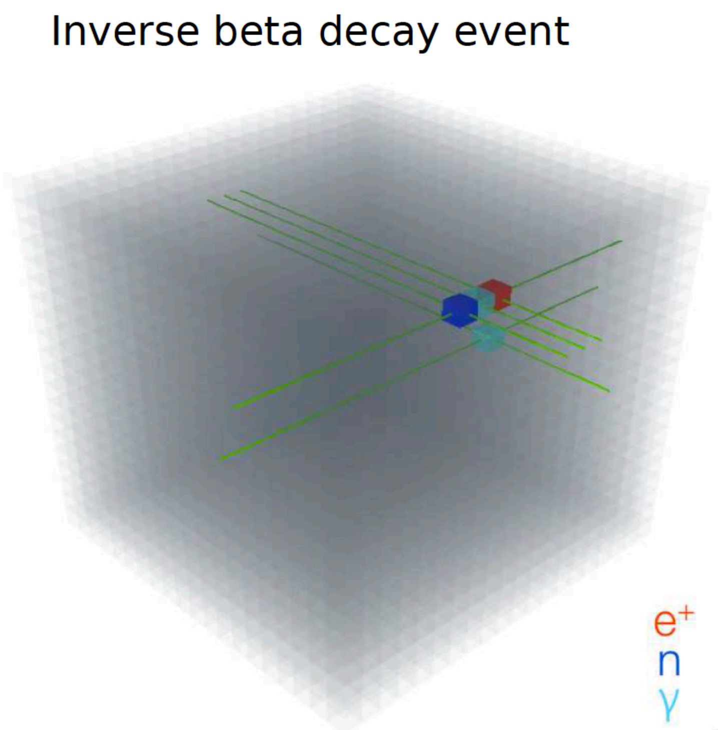


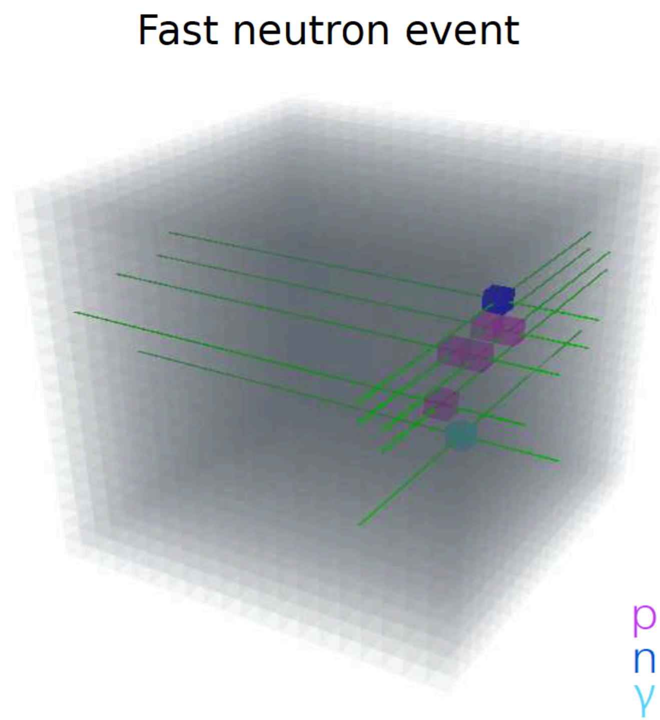
Pulse shape discrimination (PSD) in ^{6}LiF:ZnS(Ag) screens

$$n + ^6\mathrm{Li} \rightarrow ^3\mathrm{H} + \alpha + 4.78\ \mathrm{MeV}$$



Event topology in SoLid

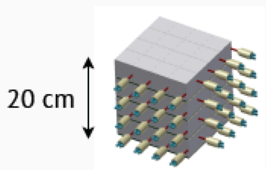




- High granularity allows for signal localization and thus enhances significantly the background rejection
- Possible fast neutron rejection through event topology

Detector development

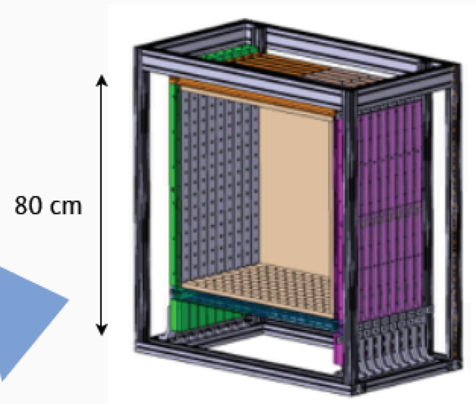
2013



- NEMENIX **8kg**
64 voxels, 32 chan.

20x

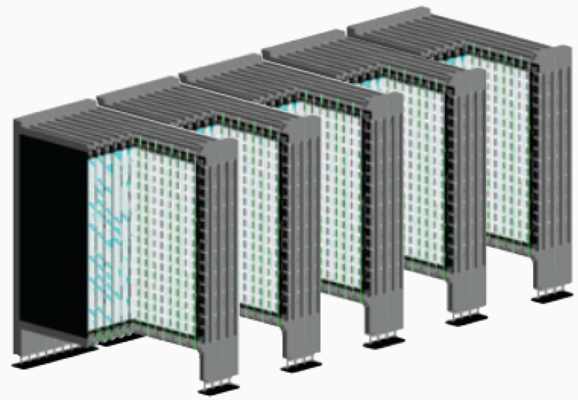
2014-2015



- SoLid Module 1 (SM1)
288kg
9 Detector planes
2304 voxels, 288 chan.

5x

2016



- 5x modules **1.440 tonnes**
11520 voxels, 1920 chan.
needs 2-3 tonnes for SoLid

Proof of concept **TRL 2-3**

1. demonstrate neutron PID
2. Measure bkgs
3. measure PVT-n concidence

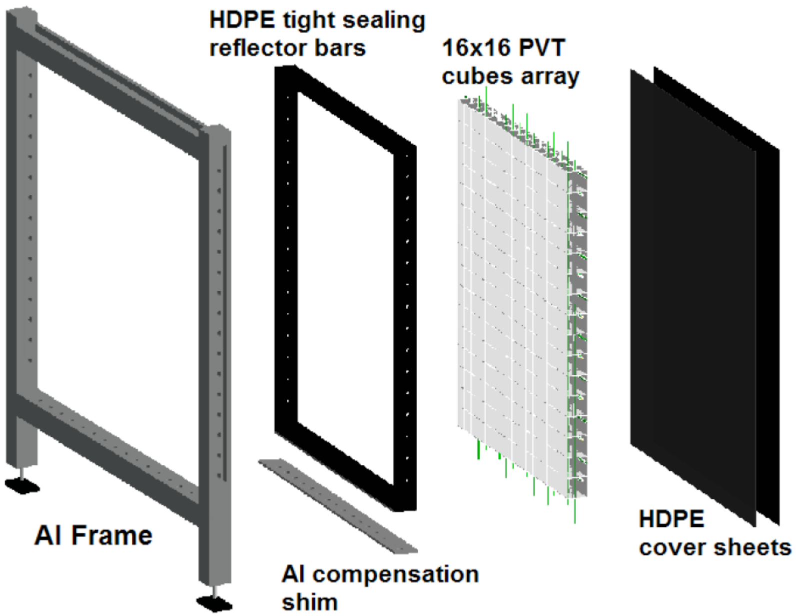
Real scale system **TRL 3-5**

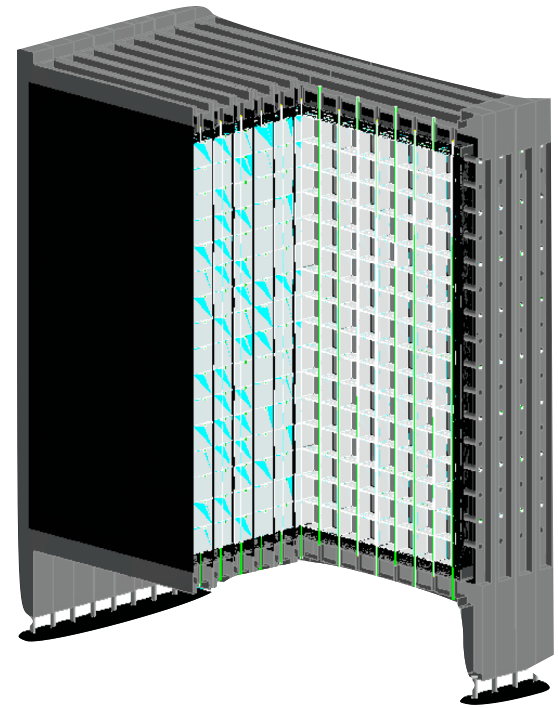
1. demonstrate scalability and test production schedule
2. demonstrate segmentation capability
3. do some physics ?

Build multiple modules

1. upgrade trigger to use neutron
2. optimised performance
3. improve cost-effectiveness

SoLid Module 1 (SM1)



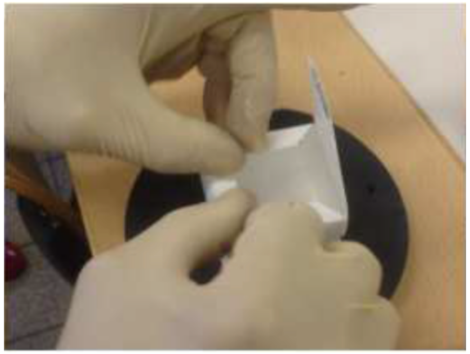


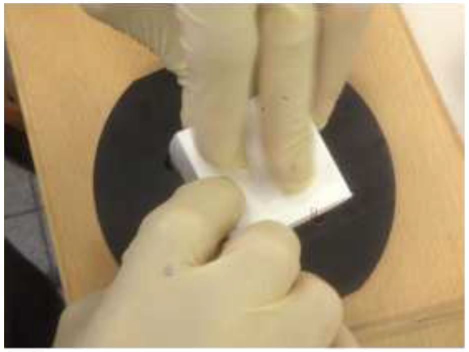
- 16 × 16 PVT cubes grouped together to form a single *detector* plane
  - Mechanical support with aluminum frame
  - HPDE to reduce neutron dissipation

9 planes totally, 288 kg
288 readout channels
80 × 80 × 45 cm

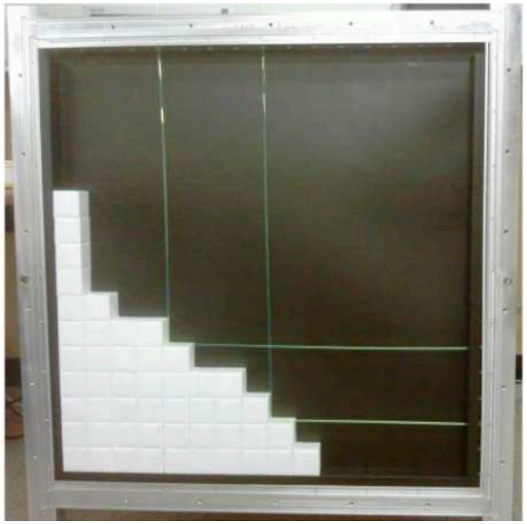
SM1 construction

- 300 cubes machined and assembled
  - Wrapped with tyvek and carefully weighted
  - Number of protons determined with better than 1 % accuracy





Single detector plane under construction



Assembled planes

Deployment at BR2

SM1 at Gent

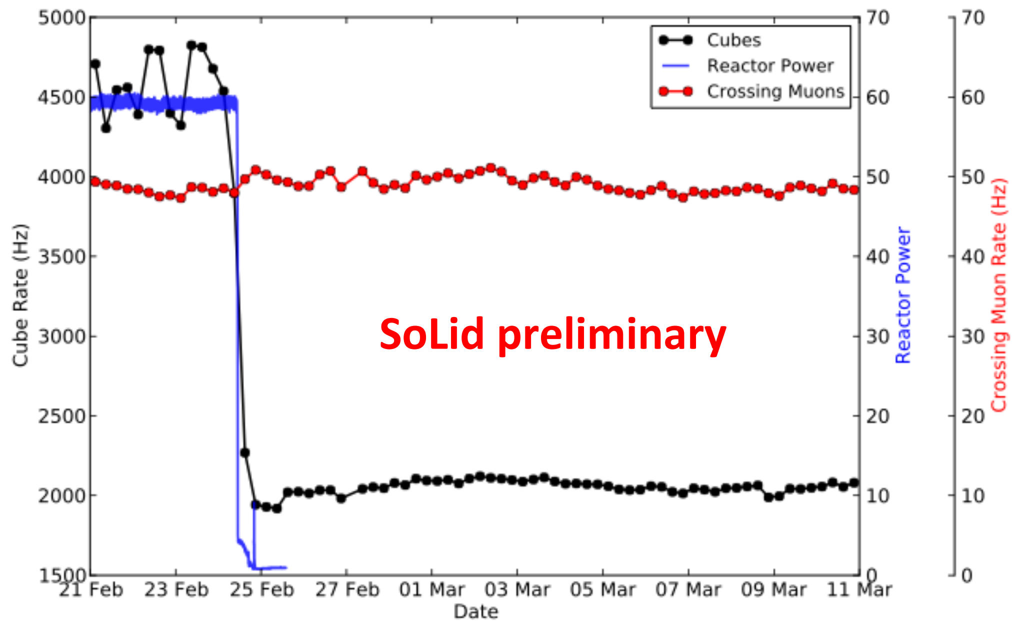
Eppur si muove

Installation at BR2

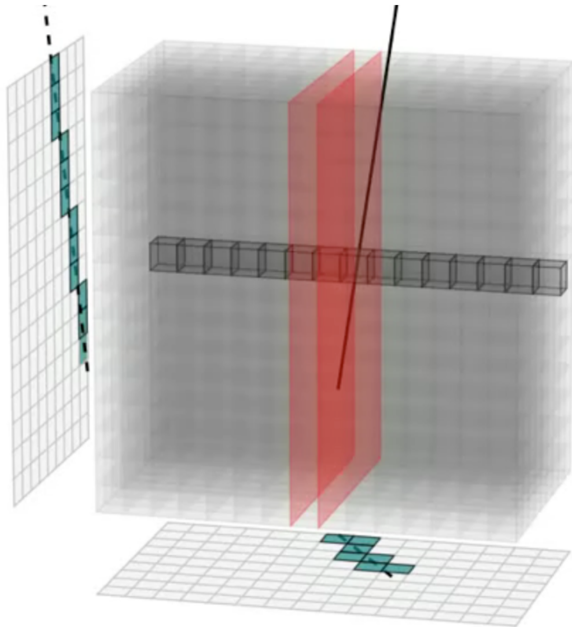
November 2014

Data taking

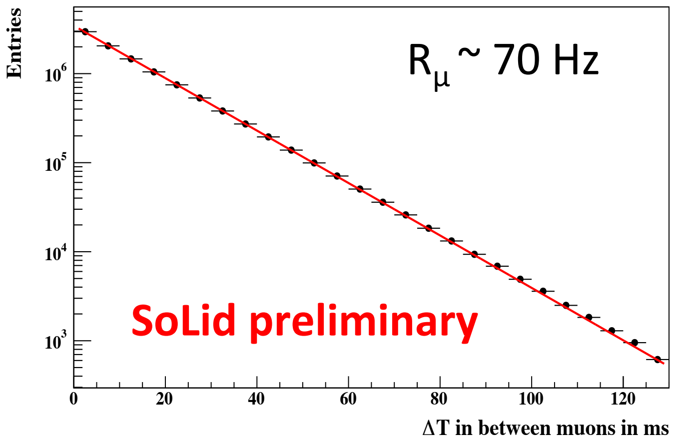
- SM1 run at 12/14 - 03/15
  - Detector commissioning
  - 3 - 4 days reactor on
  - ~ 1 month reactor off
- Detector calibration
  - ^{60}Co and AmBe (04/15)
  - ^{252}Cf in situ (08/15)

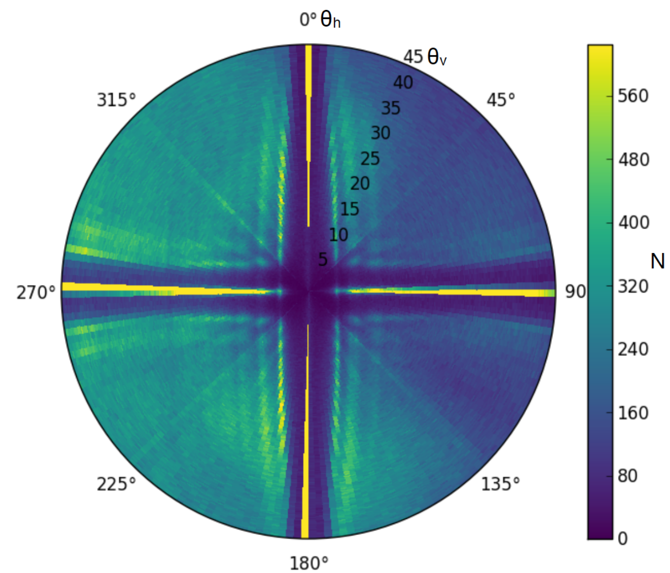


Cosmic muons



Crossing muon event

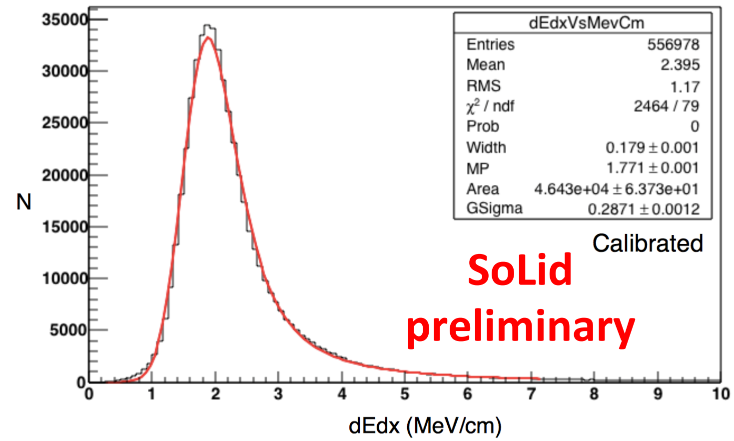


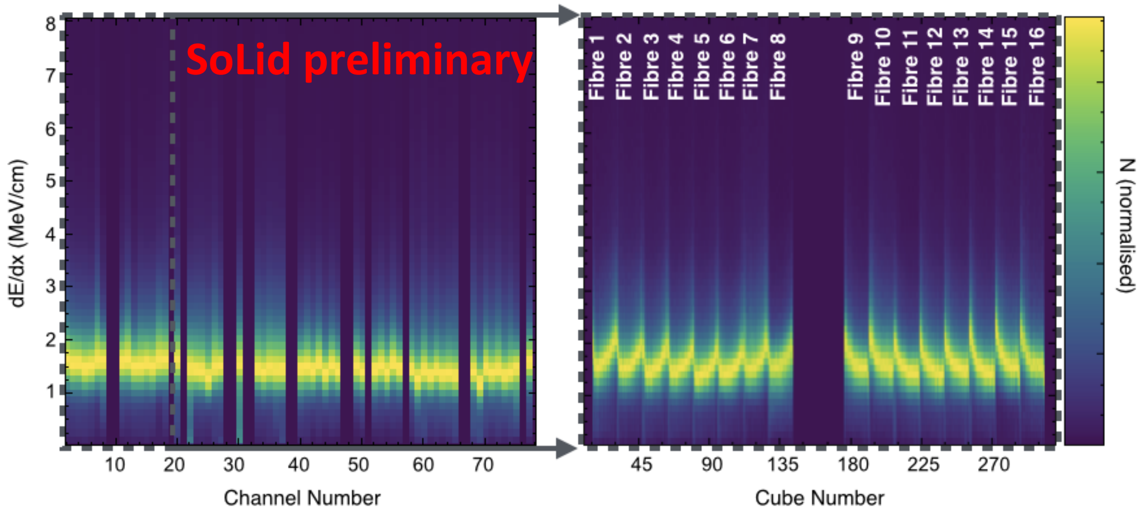


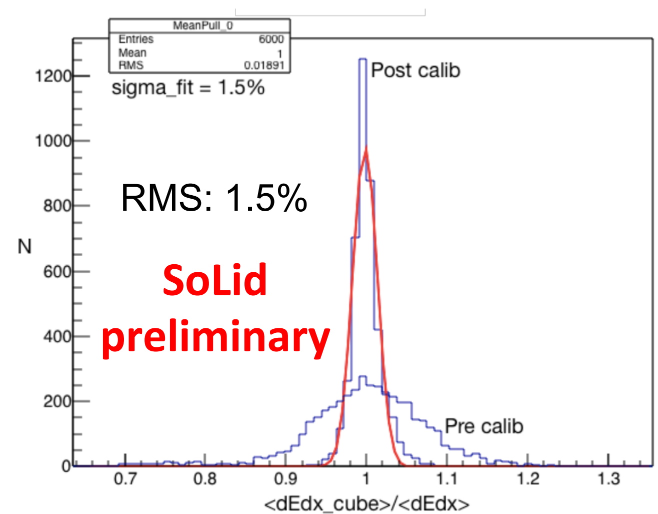
- Excellent muon tracking due to detector segmentation
- Detector calibration and stability monitoring using cosmic muons
- Provides handle on muon correlated background rejection

Calibration with cosmics

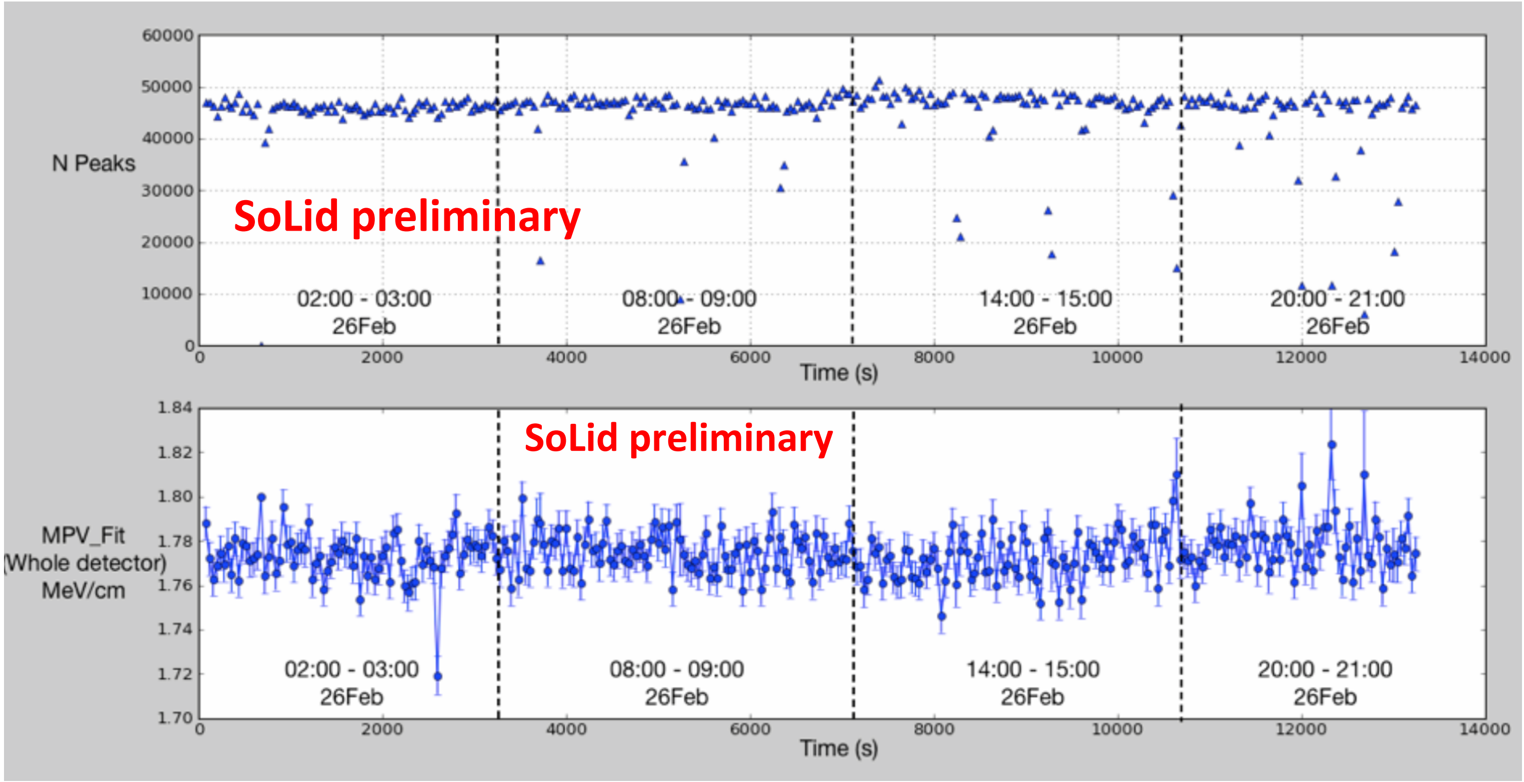
- In-situ energy calibration using dE/dx
  - Channels inter-calibration
  - Cube response equalization
- Light yield measured: 25 PA/cube
- MPPC gain measured with dark cnts rate
  - No need for light injectors





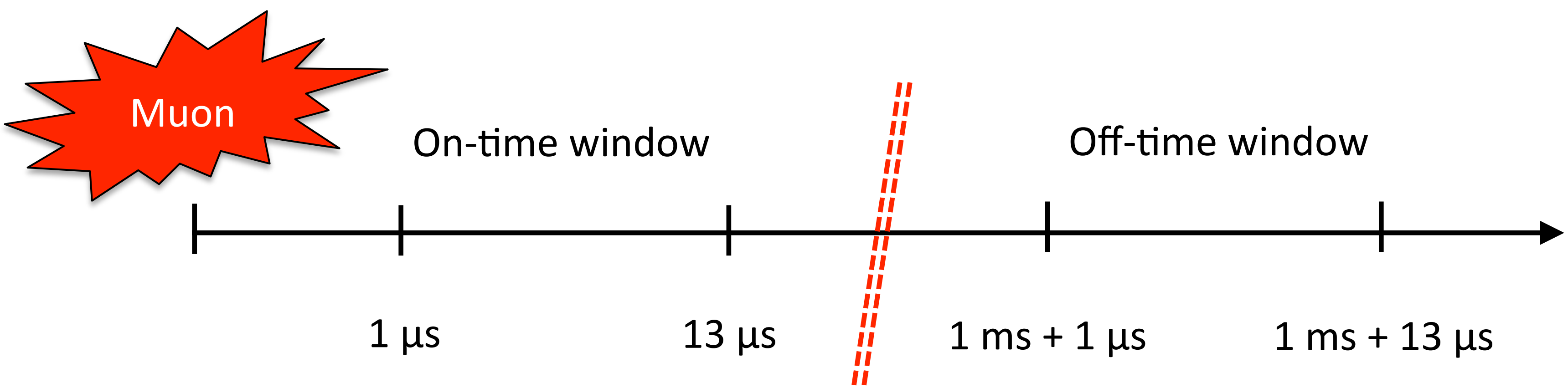


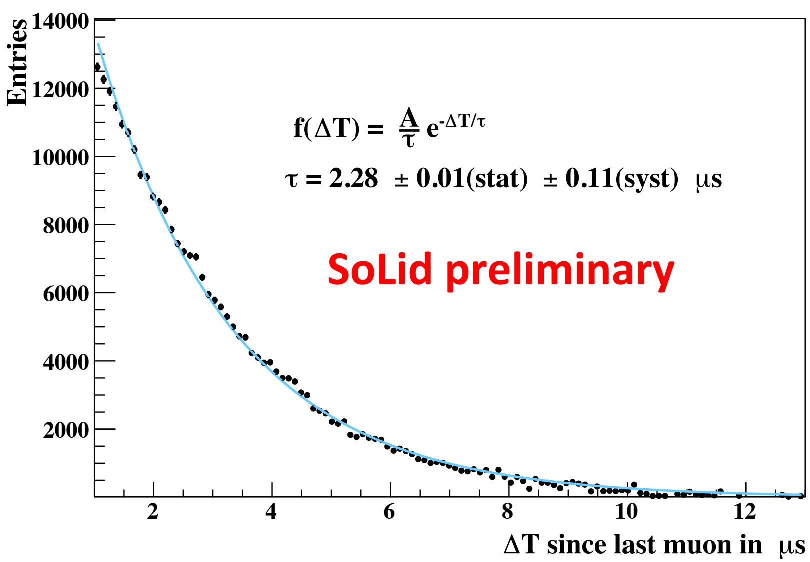
Calibration stability



- First look at the stability over time
  - A few % deviations in the energy scale only
  - Temperature well-controlled in BR2

Muon daughters: michel electrons



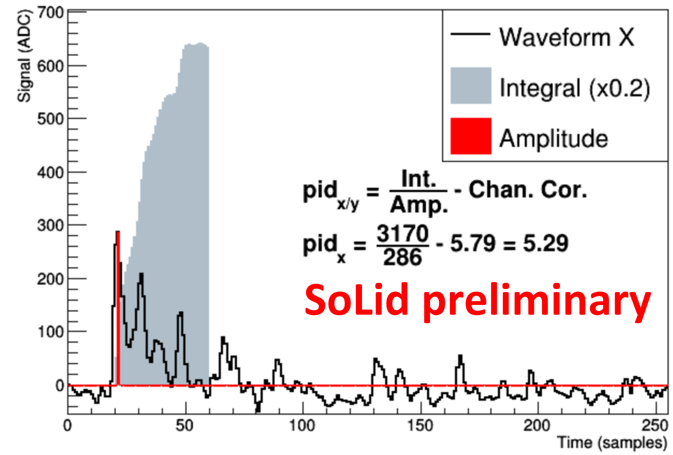


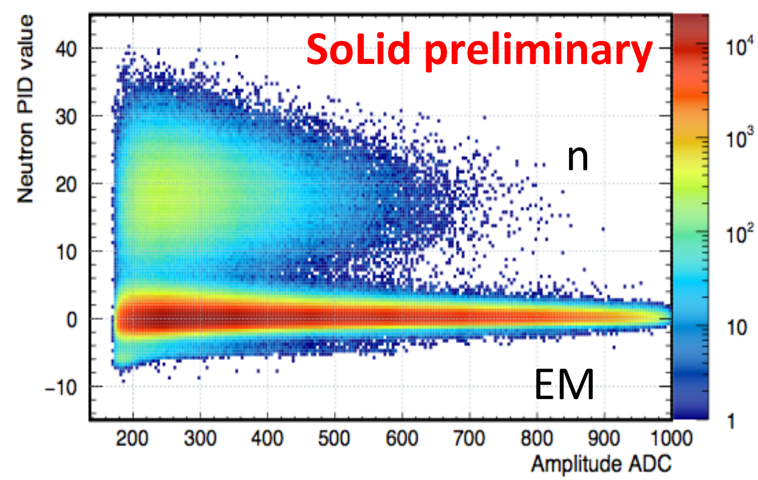
$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$

- Michel decay probes the tagging of prompt-delayed coincidences
  - DAQ is well behaving
- Large sample of michel electrons that can be used for calibration
  - Higher energy range than IBD

Neutron identification

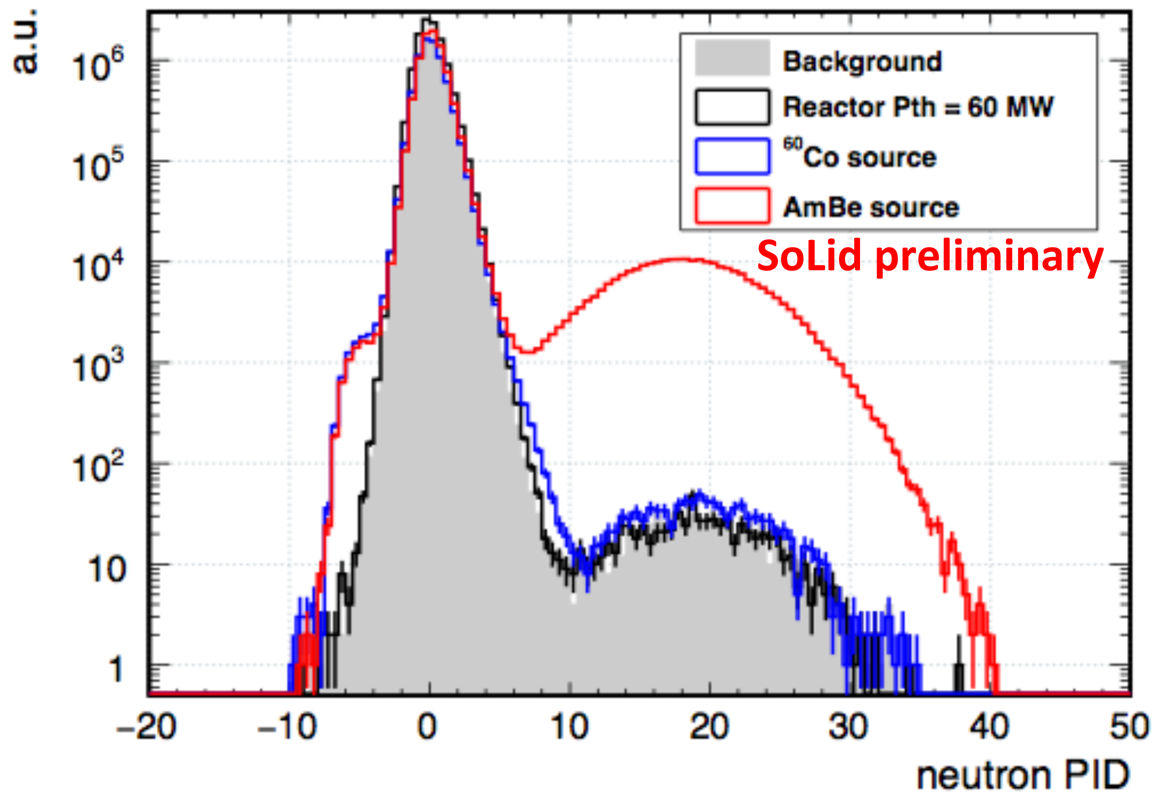
- Neutron identification using pulse shape discrimination
  - Slow scintillation light for neutron captures in with $^6LiF:ZnS(Ag)$
- Method employing the integral and amplitude of the pulses
  - Both fibers (channels) exploited
- Data show impressive EM/n discrimination capabilities
  - To be implemented in the online trigger (data reduction)





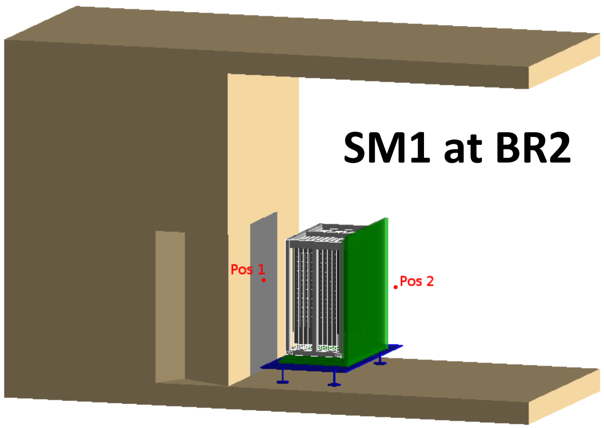
AmBe data

Neutron identification (cont'd)

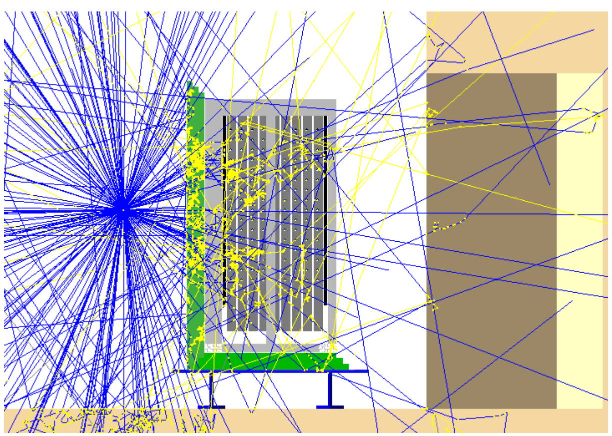


Can distinguish a neutron in millions of signals !

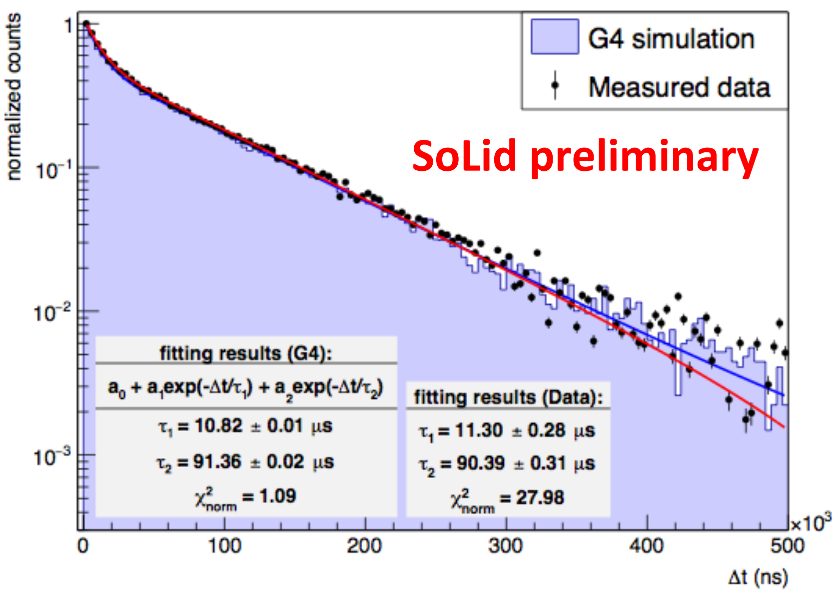
Neutron source calibration



- Calibration runs with AmBe source
  - AmBe is a fast neutron emitter
- Probe detector behavior
- Study prompt-delayed coincidence
  - Time-space correlation, neutron efficiencies, etc…

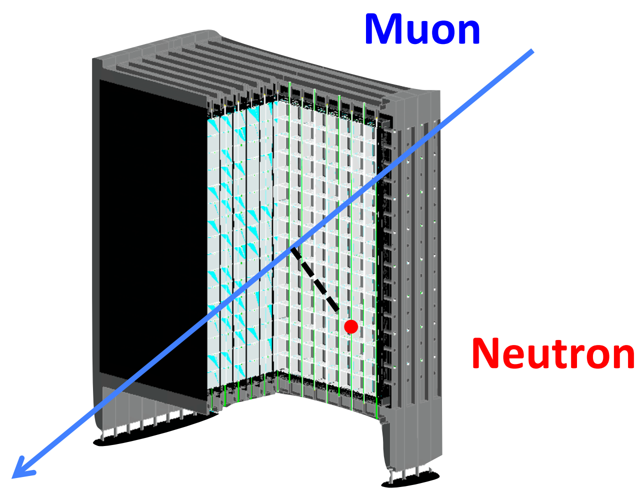


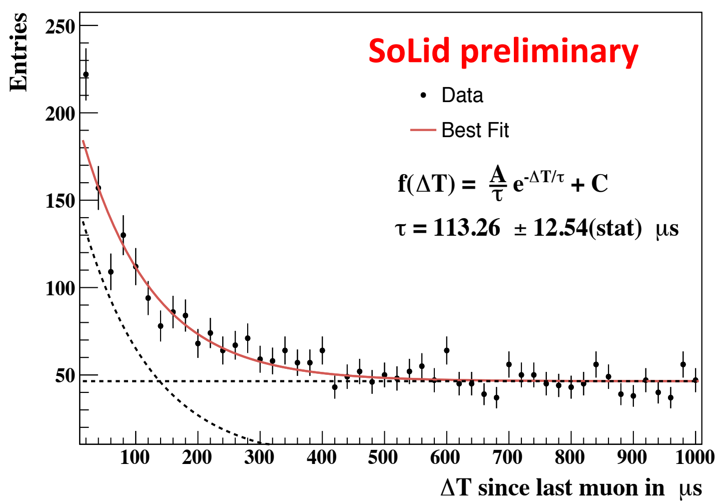
Geant 4 simulation



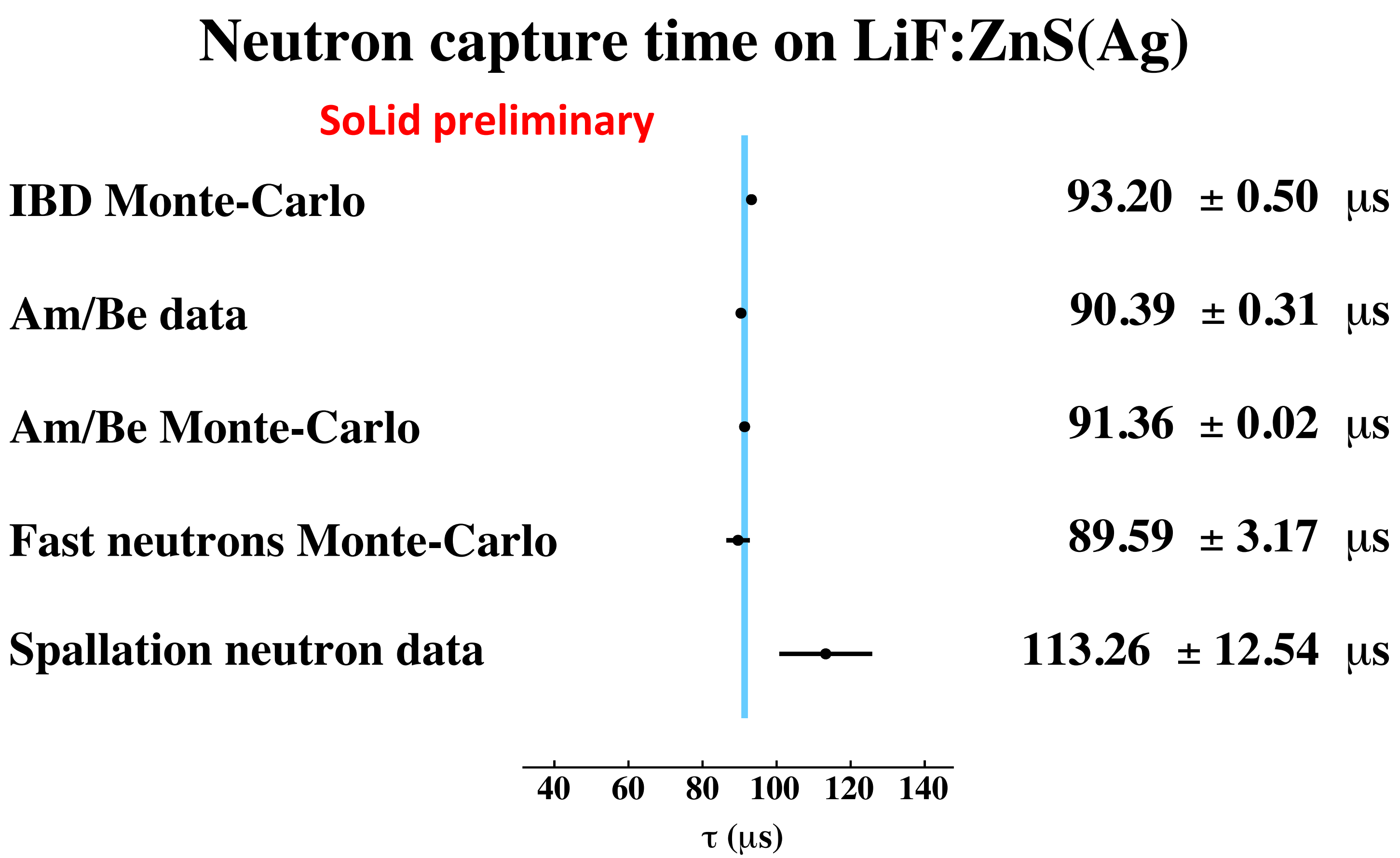
Muon daughters: spallation neutrons

- Muon induced (spallation) neutrons traced in SM1 data
  - Similiar selection as with michels
  - Capture time in good agreement with AmBe data
- Control sample that can serve different purposes:
  - Detector stability versus time
  - Neutron identification studies
  - Tune neutron selection
  - Ongoing analysis, synergies with muon selection and muon products rejection (muon veto)



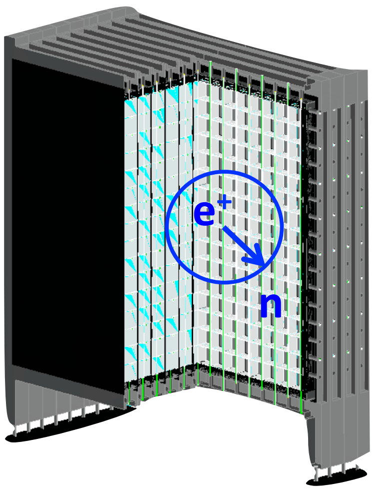


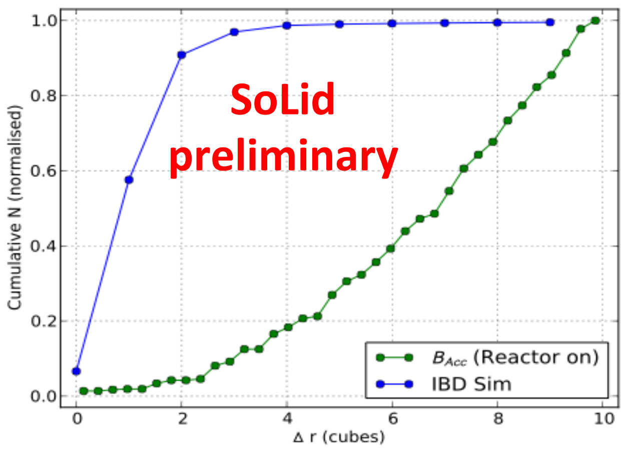
Neutron capture time: summary



IBD analysis

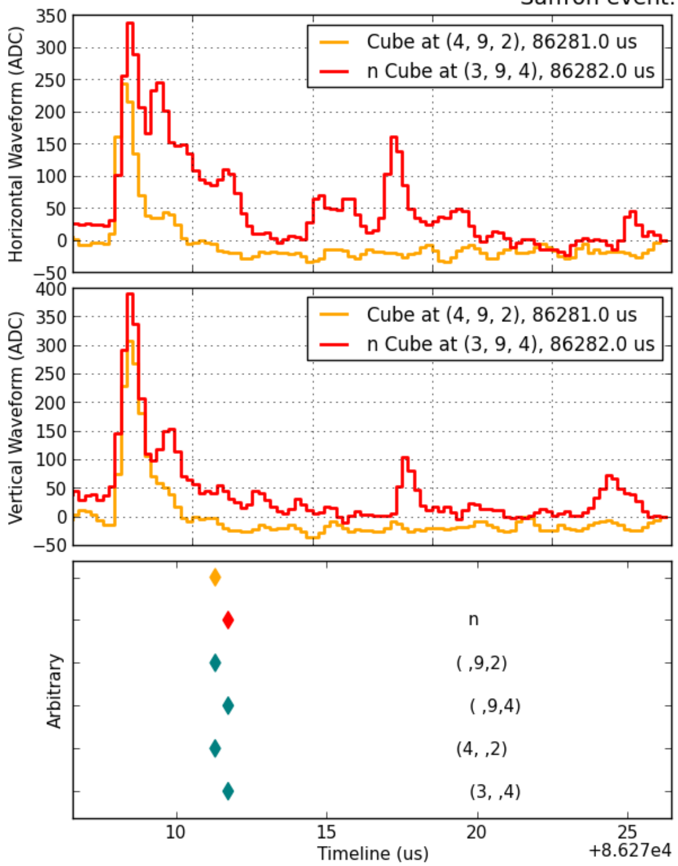
- First data processing completed:
  - Data reduction, filtering, calibration and reconstruction
  - SM1 Monte-Carlo response tuning ongoing
  - Study of background events and selection cuts started
  - Expecting S/N_{acc} around 2 using cube segmentation
- Aim for result early next year
  - ***Stay tuned !***



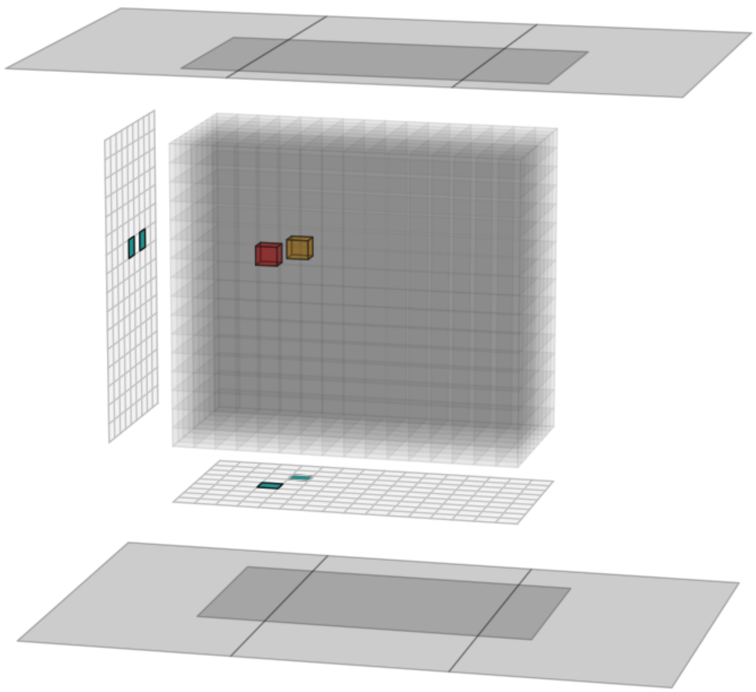


IBD candidate

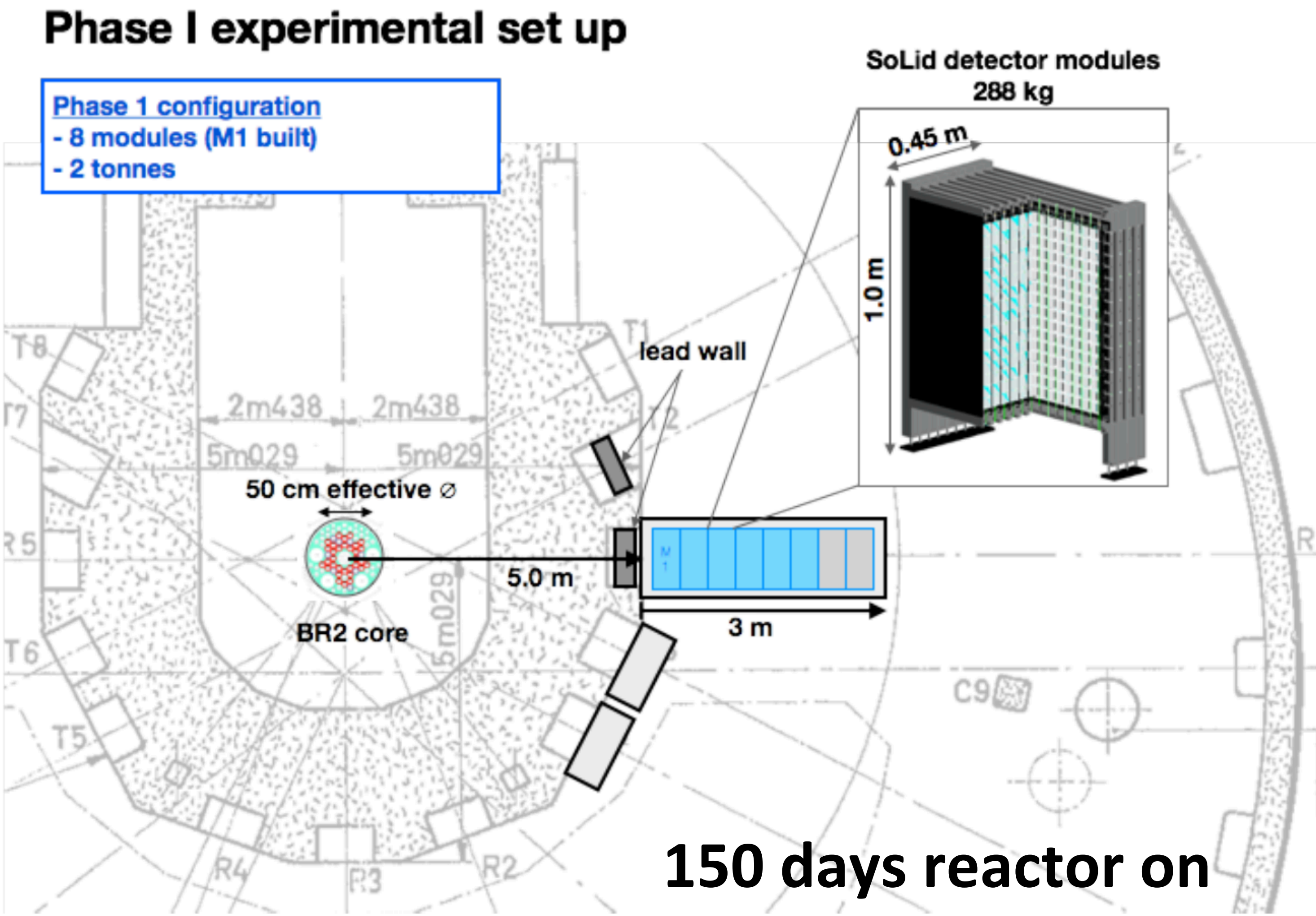
Saffron event: 1087, time range: (86181.0, 86381.0) us



SoLid preliminary



Future plans: 2016-2017

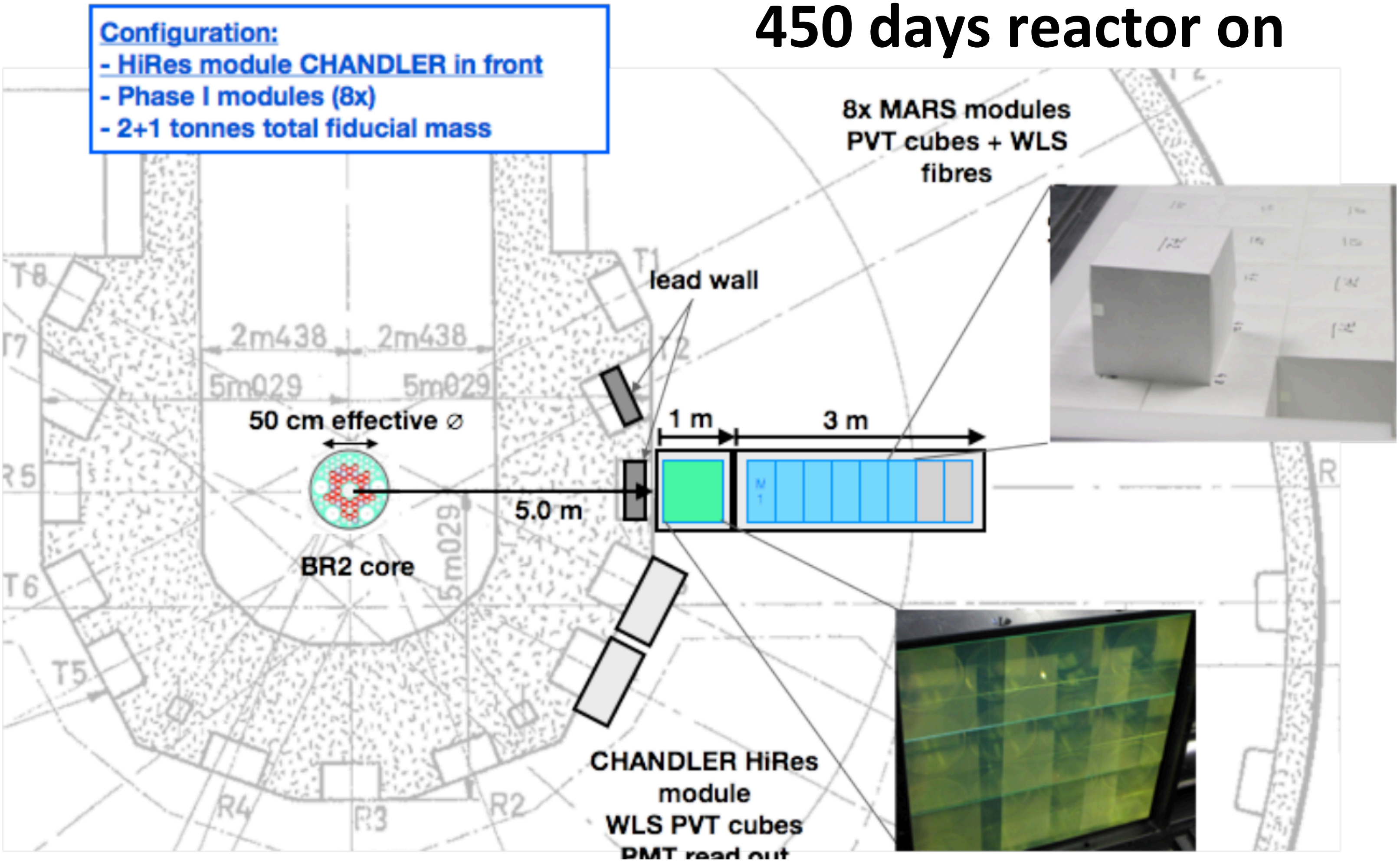


150 days reactor on

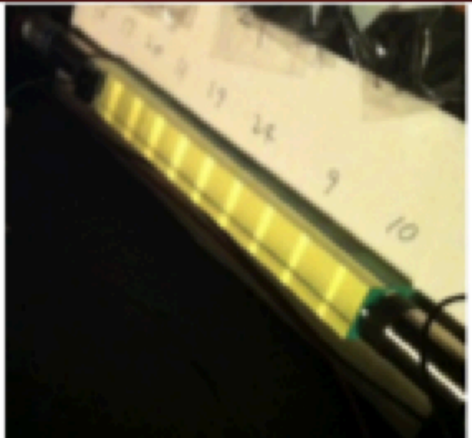
Future plans: 2017-2020

Phase II experimental set up

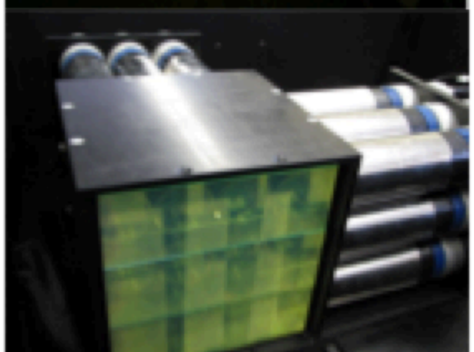
450 days reactor on



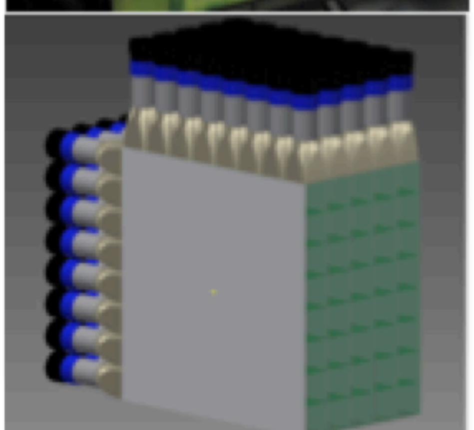
CHANDLER R&D Effort



Cube String Studies have been used to study light production, light collection, light attenuation, energy resolution and wavelength shifter concentration.



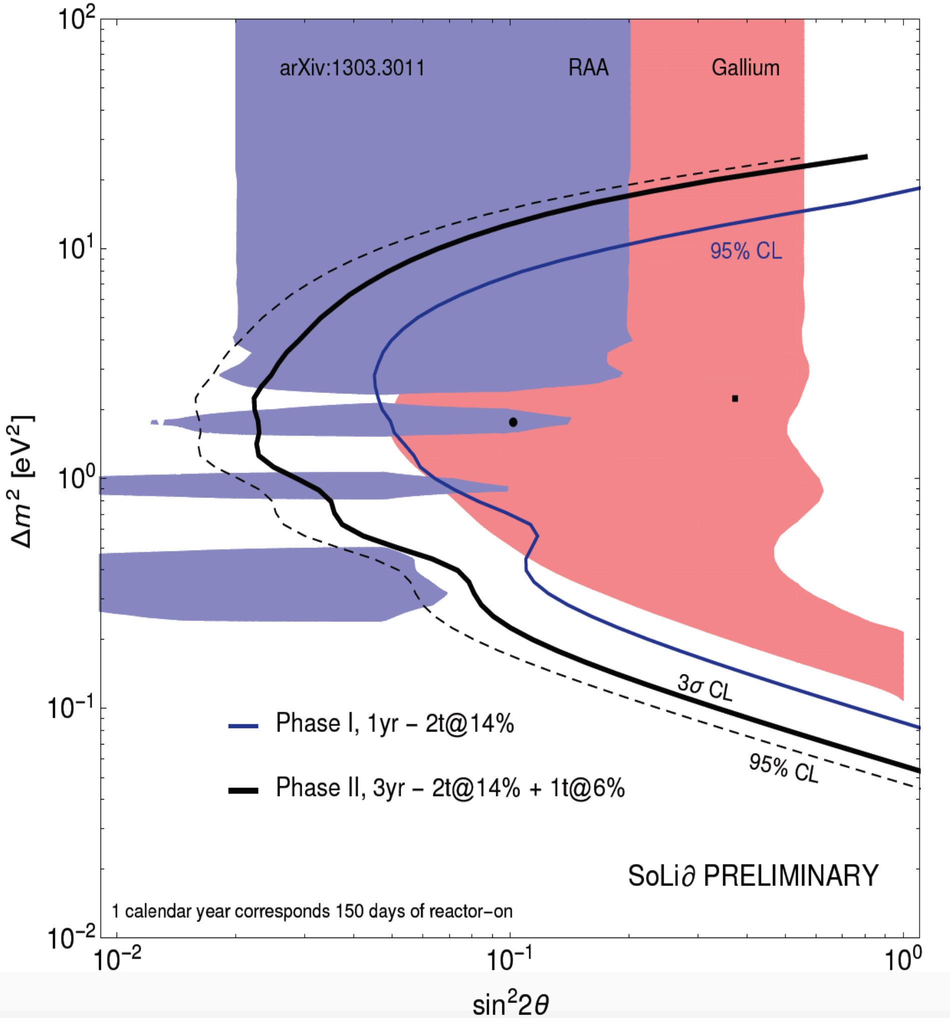
MicroCHANDLER is a 3×3×3 prototype which we are using to test our full electronics chain, develop the data acquisition system, study neutron capture identification and measure background rates.



MiniCHANDLER is a **fully funded** systems test (8×8×5) which is currently under construction and will be deployed at a commercial nuclear power plant. It will be operational winter 2016.

J. Link, Aspen 2016

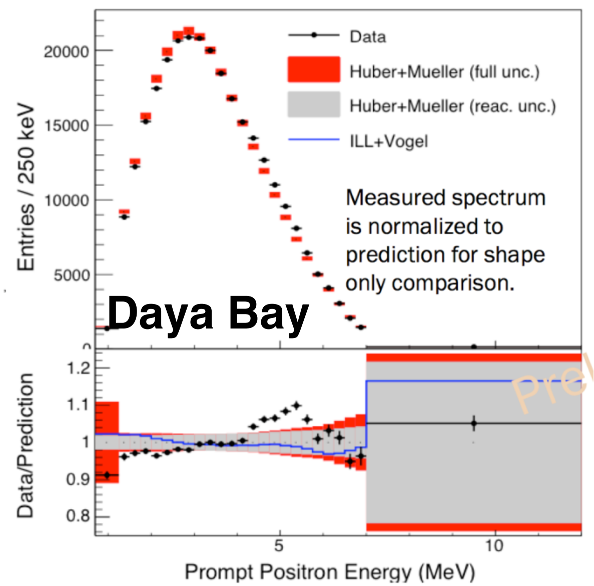
Sensitivity to sterile neutrino

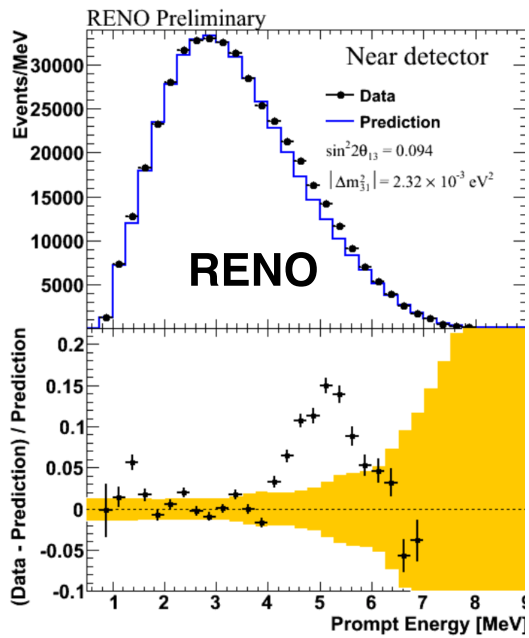


- Analysis independent of the total flux normalization and spectrum
  - Good control on detector systematics
  - Energy resolution is crucial
- *Best fit covered within the first year of data taking*
- Second phase will cover most of the allowed region

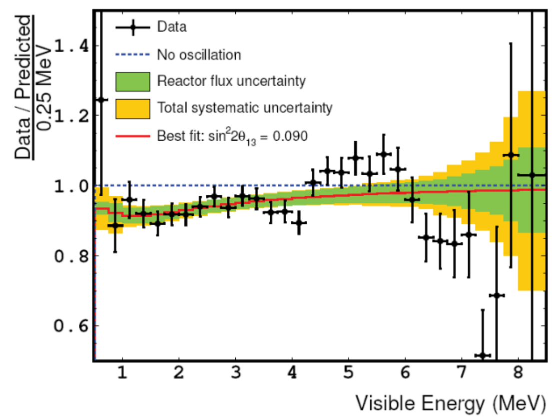
Other physics goals

- Precise measurement of the reactor $\bar{\nu}_e$ spectrum
  - Recent interest after the 5 MeV bump observation





Double Chooz



  - Synergy with reactor monitoring and nuclear weapons non-proliferation efforts
  - For instance: Huber *et al.*, PRL **113**, 042503 (2014)

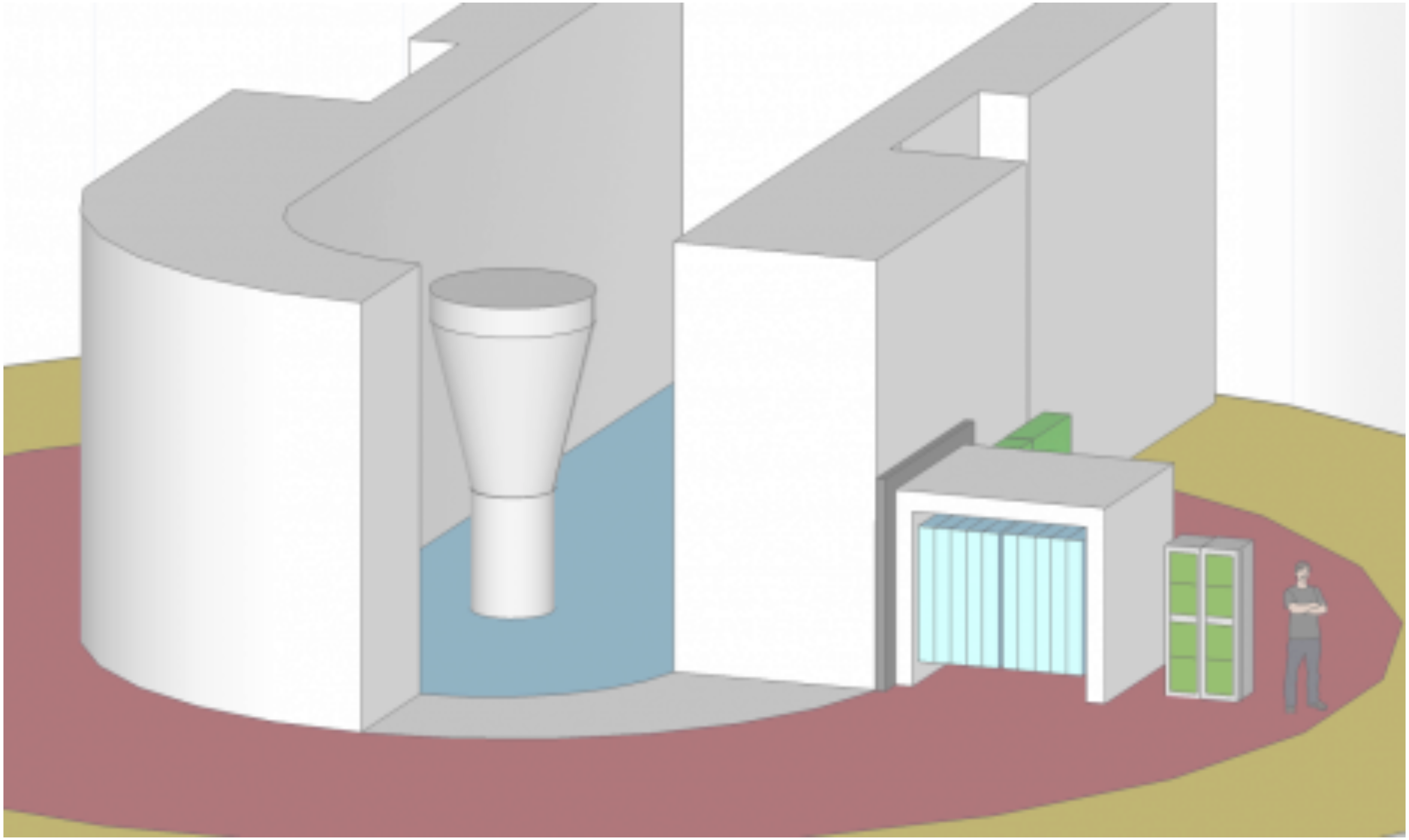
Ending themes

- SoLid experiment will make a very sensitive search for $\bar{\nu}_e$ disappearance using a novel detector
- SM1 operation has been very successful
  - Excellent EM/neutron identification
  - Low background at BR2 has been confirmed
  - Precise calibration with muons (cube equalization ~1.5%)
- ***Further results from SM1 expected this year !***

- R&D phase completed
  - Light yield increase and mechanical design
  - Electronics, neutron trigger
  - Cost estimation ongoing
- ***ERC-SoLid funding has been granted to Antonin Vacheret !***
  - Phase I to start in the second half of 2016

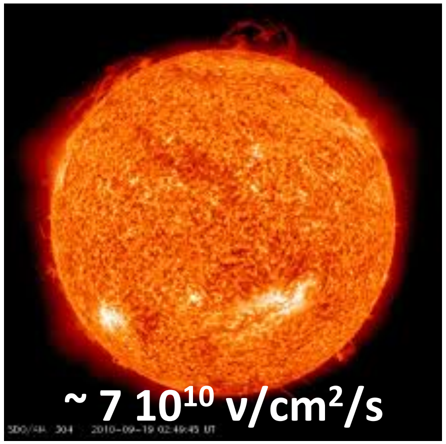
Thank you for your attention !

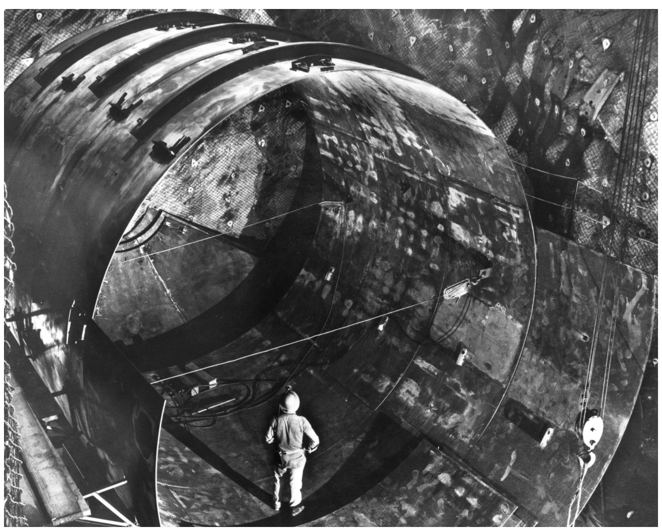
Leonidas N. Kalousis
leonidas.kalousis@vub.ac.be



SPARES

Pioneering experiments



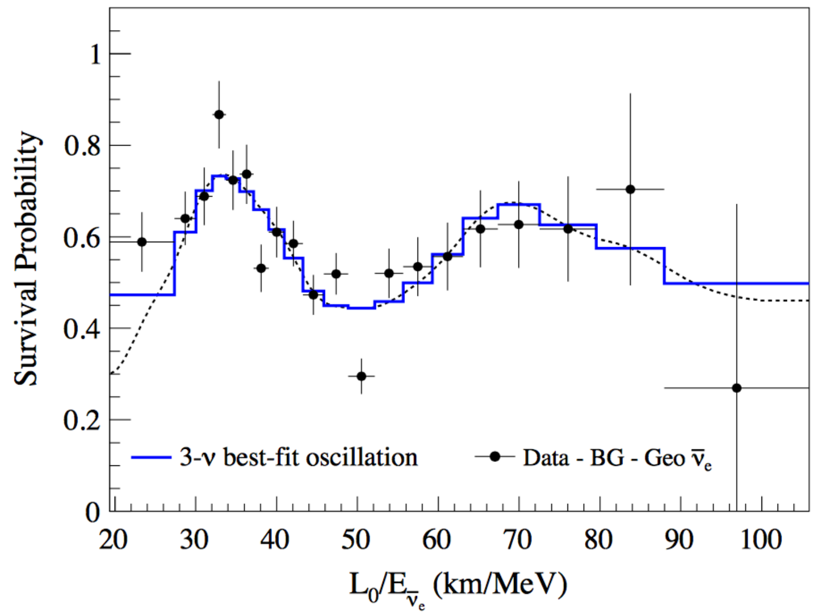


R. Davis' chlorine experiment

Oscillation patterns

KamLAND detector is surrounded by several reactors at different distances

KamLAND, *arXiv:1303.4667*



- Signature of neutrino oscillations seen by many experiments
  - Clear oscillatory patterns that cannot be reproduced by other possible mechanisms (neutrino decay, etc …)

Two flavour approximation

- Three flavour are highly suppressed since $|\Delta m^2_{31}| << \Delta m^2_{21}$ and $\cos^2(2\theta_{13}) \approx 1.0$
- Dominant oscillations are well described by effective two-flavour oscillations.
- One mixing angle no complex phase.

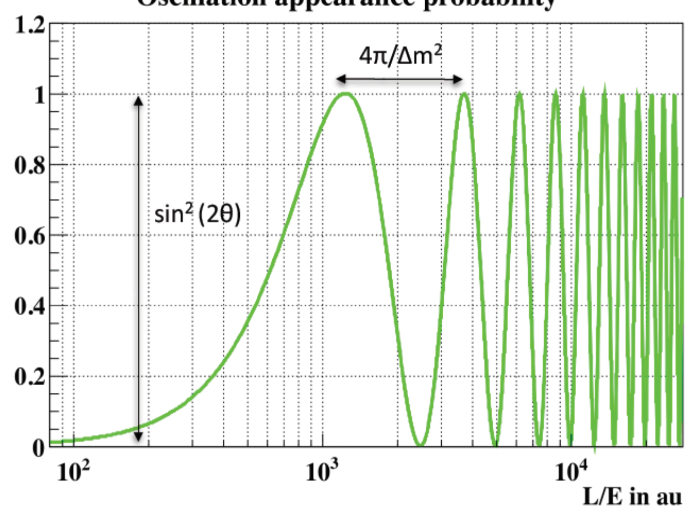
$$\mathcal{U} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

$$p(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \, \sin^2 \frac{\Delta m^2 L}{4E}$$

Appearance probability

Typical oscillatory behaviour

$\theta = \pi/4$, E = 1 GeV and $\Delta m^2 = 0.001$ eV^2



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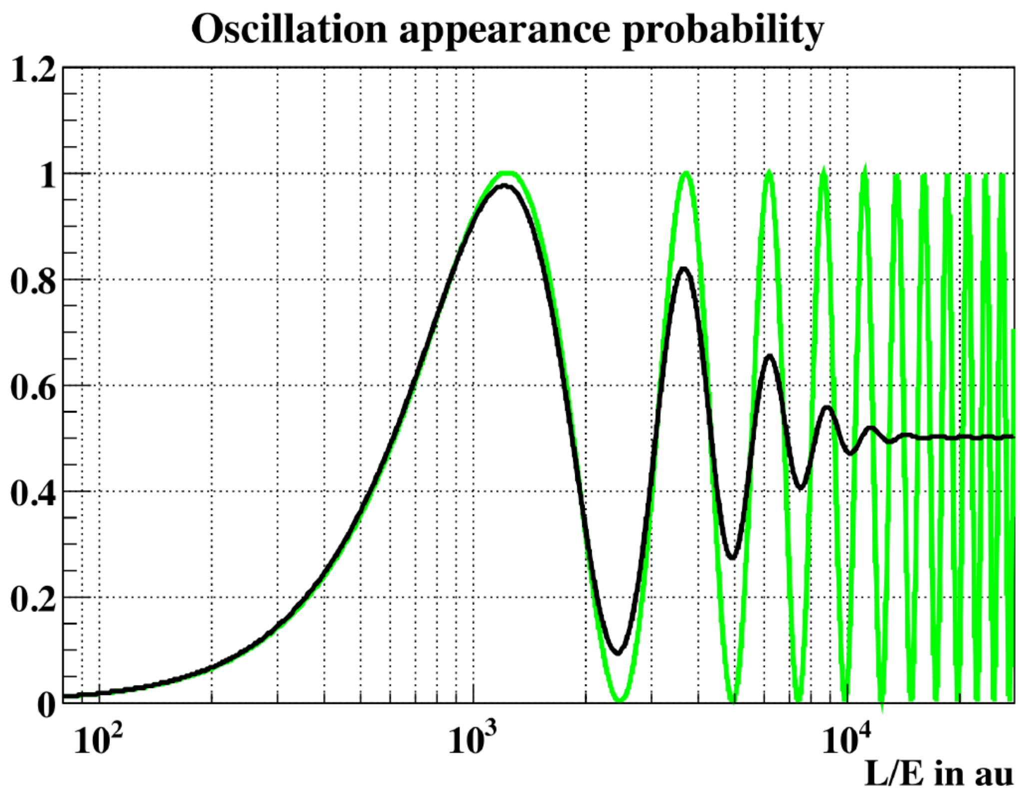
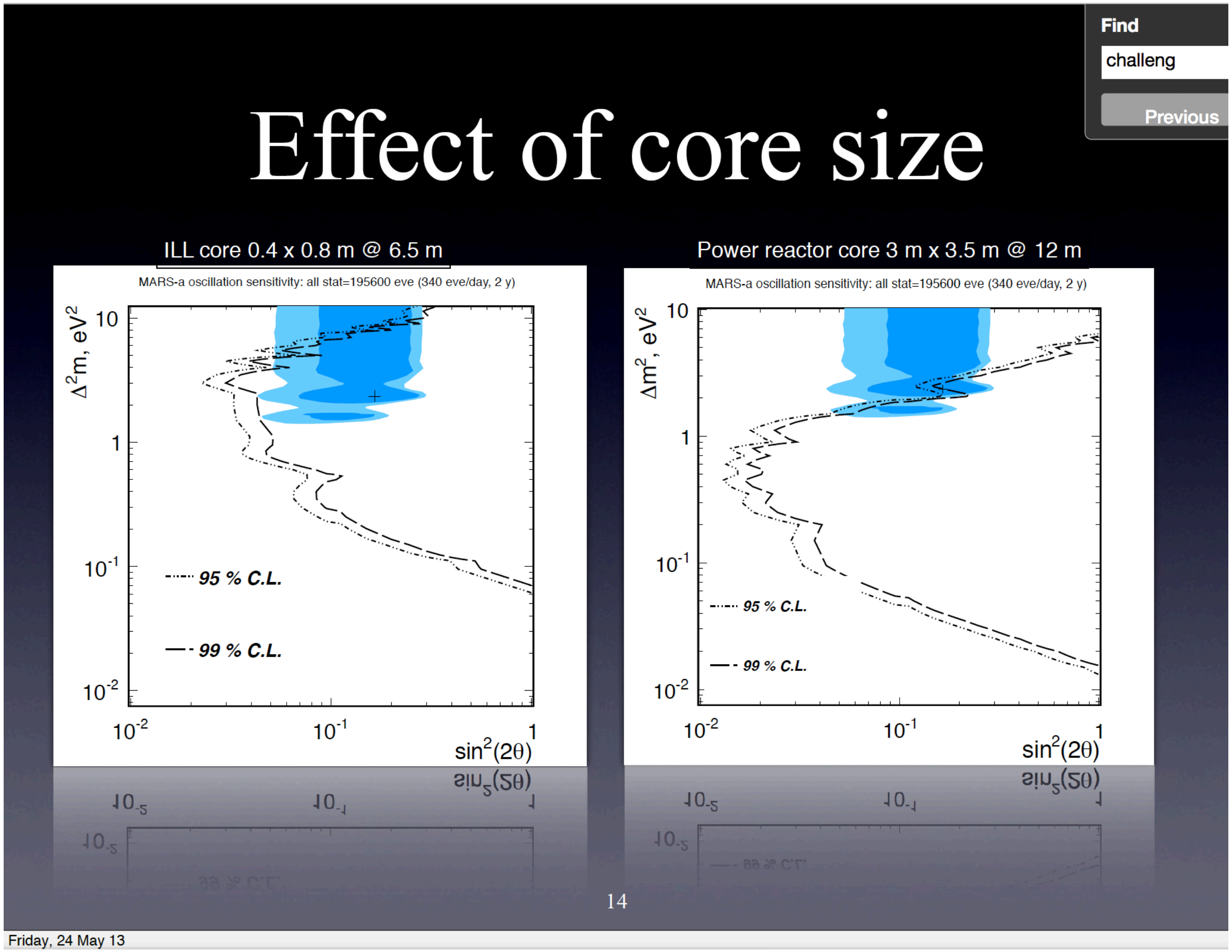


<E> = 1 GeV and ΔE = 0.1 GeV

28


Find
challeng
Previous
Effect of core size
ILL core 0.4 x 0.8 m @ 6.5 m
Power reactor core 3 m x 3.5 m @ 12 m
MARS-a oscillation sensitivity: all stat=195600 eve (340 eve/day, 2 y)
MARS-a oscillation sensitivity: all stat=195600 eve (340 eve/day, 2 y)
$\Delta^2 m$, eV^2
Δm^2, eV^2
10
1
10^{-1}
10^{-2}
10^{-2}
10^{-1}
1
$\sin^2(2\theta)$
95 % C.L.
99 % C.L.
14
Friday, 24 May 13

Search for ν_s with ^{3}H β dec

Find

KATRIN

Previous

- **Source:** $^{3}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + e^{-} + \overline{\nu}_e$
- **β spectrum shape depends on:**

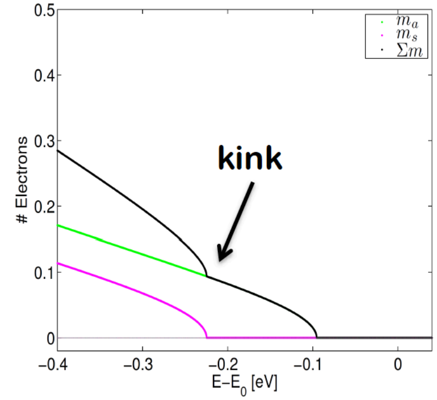
$$\langle m_\beta \rangle = \sqrt{\sum_{1,2,3,..} |U_{ei}|^2 m_i^2}$$

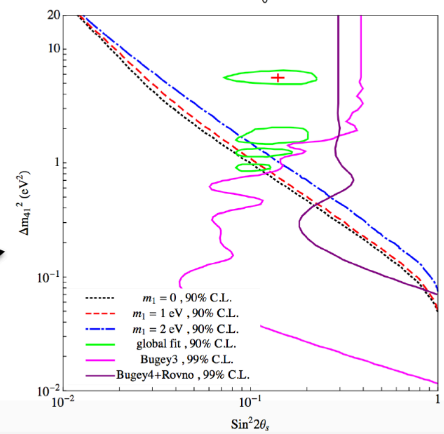
- **Hypothetical 4th ν contribution**

$$\langle m_\beta \rangle_4 = |U_{e4}| \sqrt{\Delta m_{41}^2}$$

→ **Search for a kink few eV below end point**

- **KATRIN –as designed – can test the ν_e disappearance anomalies (sensitivity to be assessed with syst.)**





	Tech	Reactor	P [MW]	L (m)	M (tonnes)	Starting dates
Nucifer	LS+Gd	OSIRIS	70	7	0.8	ended 2015
POSEIDON	LS+Gd	PIK	100	5-8	~3	not funded
STEREO	LS+Gd	ILL	57	8.8-11.2	1.75	Aug 2016
Neutrino-4	LS+Gd	SM3	100	6-12	1.5	2014 - ended ?
PROSPECT	LS + Gd/^{6}Li	ORNL HFIR	85	7-18	1 & 10	awaits funding
SoLid	PVT + ^{6}LiF:ZnS	SCK•CEN BR2	45-80	5.5-11	1.44/2.88	2016
DANSS	PS + Gd	KNPP	3000	9.7-12.2	0.9	2016 ?
NEOS	PS + Gd/^{6}Li	Hanaro/ Younggwa	30-2800	6-?	~1	2015 at PWR
CeSOX	LS	-	N/A	5-14	20	Dec 2016

MicroBooNE

The first phase of the next generation SBN Program begins soon with MicroBooNE coming online later this year!

June 23, 2014

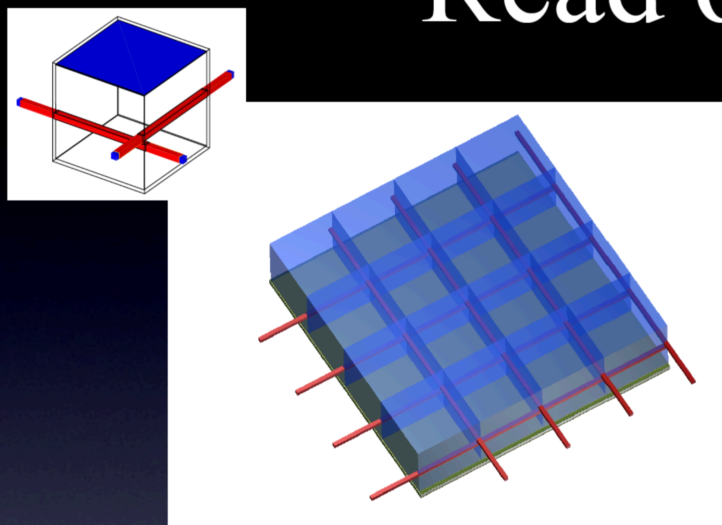
The SoLid detector design

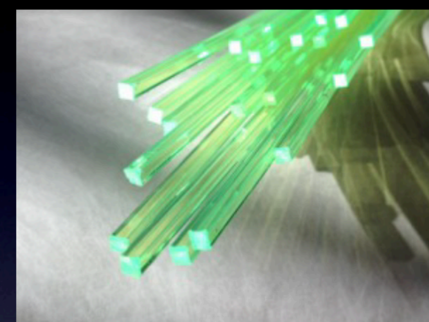
- Segmented detector made of PVT cubes
  - High granularity allows for signal localization and thus enhances significantly the background rejection
  - Non-flammable organic scintillator

- Scintillator cubes intervened with ^{6}LiF:ZnS(Ag)
  - Improves antineutrino signature through neutron identification

- Light collected through wavelength shifting (WLS) optical fibers and multi-pixel photon counters (MPPCs)

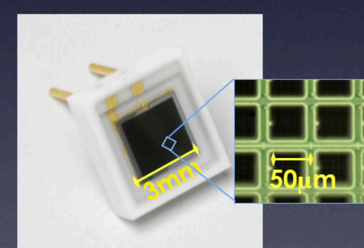
Read out





Squared BCF-91A fibre

- Both scintillator light collected by wavelength shifting fibre
- MPPC read out at both end of fibre

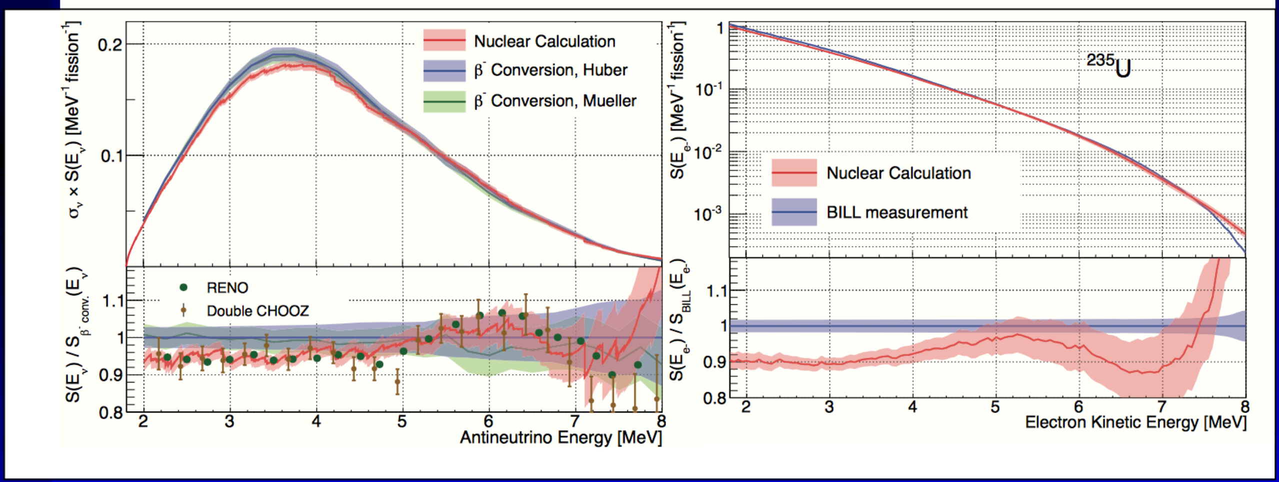


MPPC 3 mm x 3 mm
50 um pixel pitch
60-65% active area
Pixel RC cnst~13 ns
PDE ~ 30-40%

Explanations?

Direct summation of latest ENSDF database, assuming allowed beta-spectrum shape

Dwyer and Langford, 2014



This direct summation, as all other direct summations, does not agree with the Schreckenbach total beta-spectrum.