The SoLid experiment

Short baseline Oscillation search with Lithium-6 Detector

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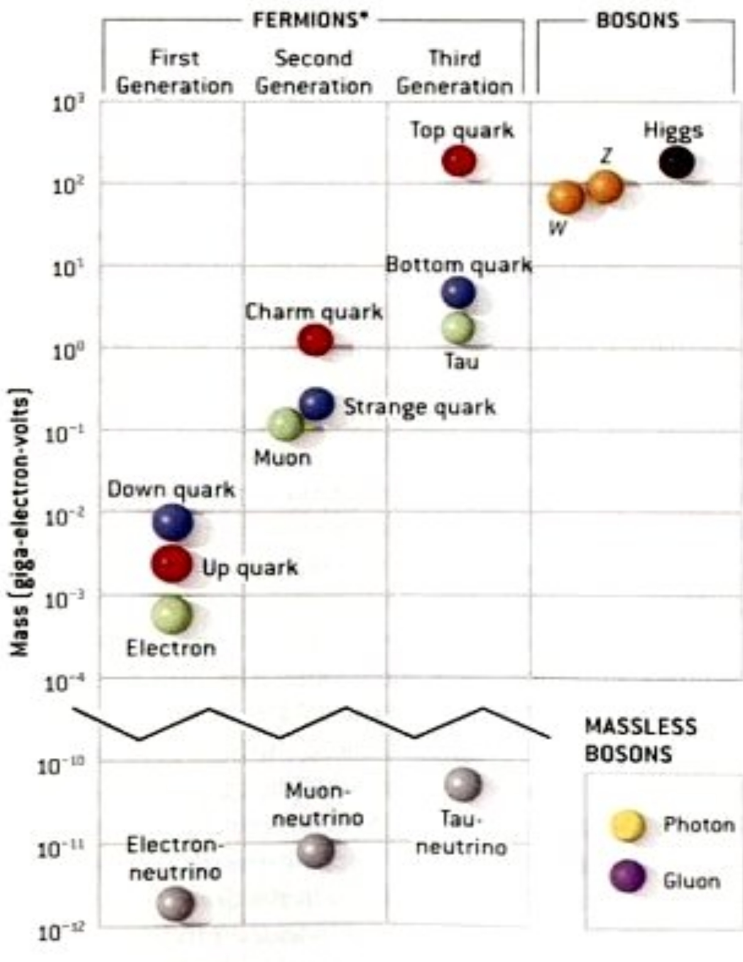
for the SoLid collaboration

March 2, 2017

Introduction

- The recent emergence of the *Reactor Antineutrino Anomaly* has revived the interest in very 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
  - ~ 6.0 - 9.0 m from the BR2 research reactor core in SCK•CEN (Belgium)
  - Volume segmentation and robust neutron identification capabilities
  - Synergy with reactor monitoring, nuclear non-proliferation efforts
- SoLid (phase I) is currently under construction
  - Scan the allowed parameter region within a year of data taking

Neutrinos

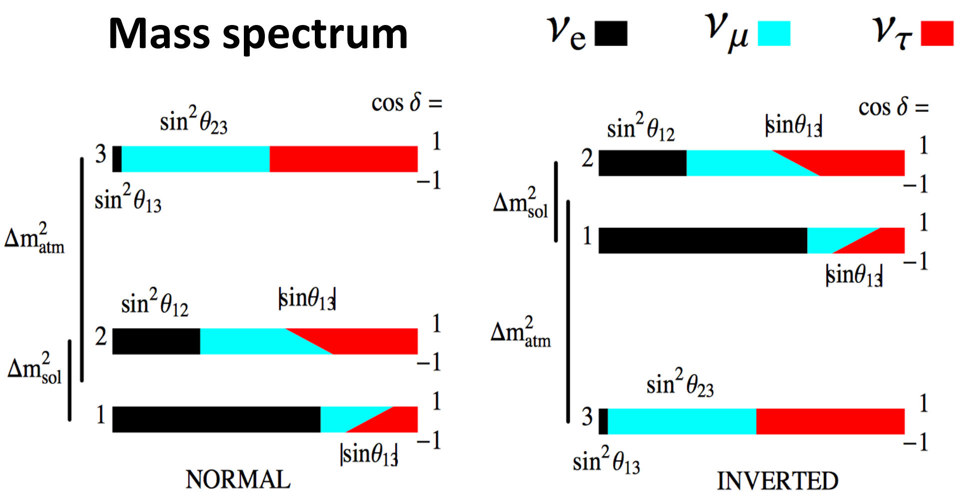


- Originally, incorporated as massless particles in the Standard Model (SM) of particle physics
  - Left-handed helicity states only
- Neutrino oscillations first discovered in 1998 by Super-Kamiokande
  - Now confirmed by several experiments
  - Solar and atmospheric oscillations

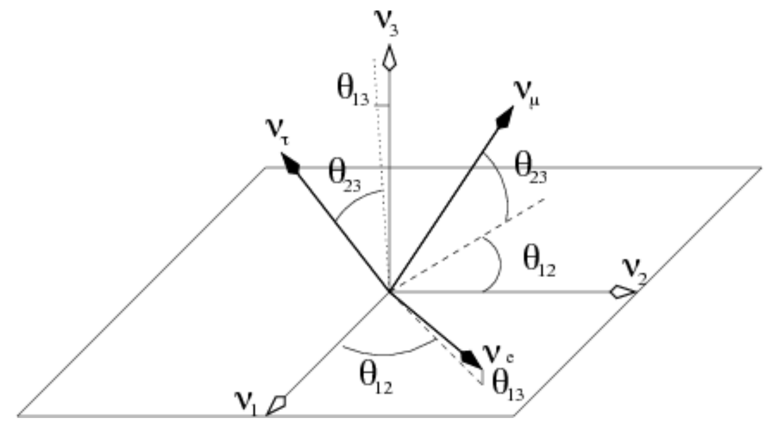
Open questions

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

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

$$\mathcal{U} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times diag\{e^{i\alpha_1}, e^{i\alpha_2}, 1\}$$

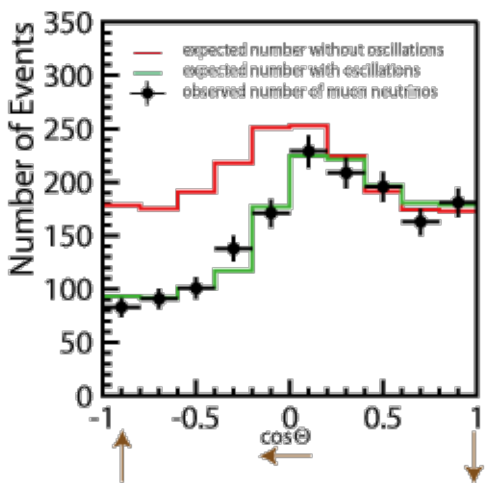
Atmospheric | 1-3 | Solar | 0ν2β

Lepton flavor violation through neutrino oscillations

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

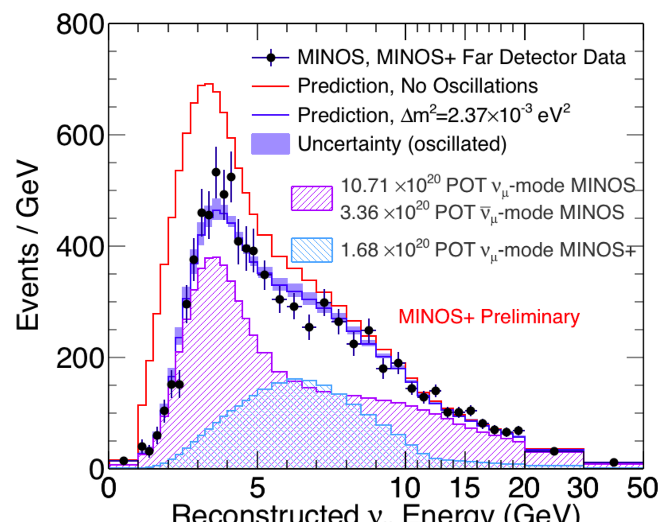
– Oscillation patterns driven by the squared-mass differences, Δm^2_{ij}
– The formula depends on the neutrino energy (E) and distance (L)

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



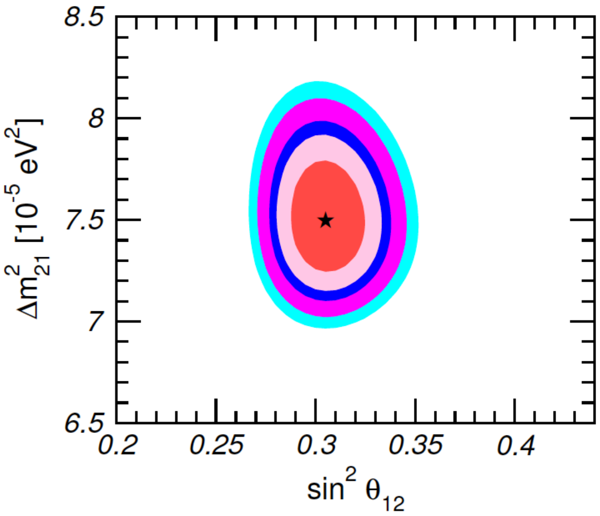
13000 km 20 km

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



Current picture

Solar sector



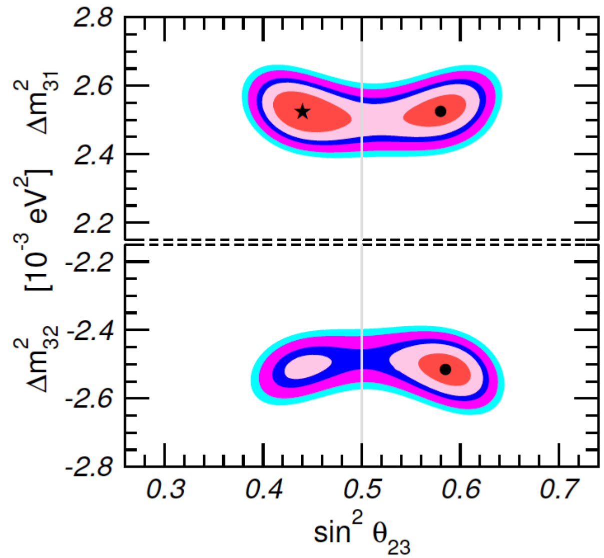
Solar exp. and KamLAND

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

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

(large mixing angle)

Atmospheric sector



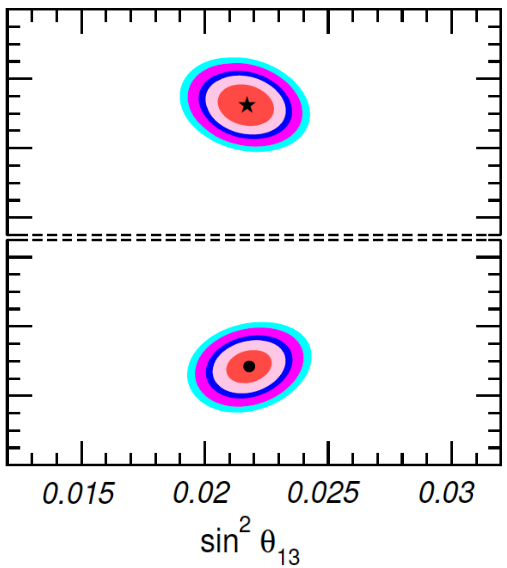
Super-K, MINOS, T2K *et al.*

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

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

(almost maximal mixing)

1-3 sector



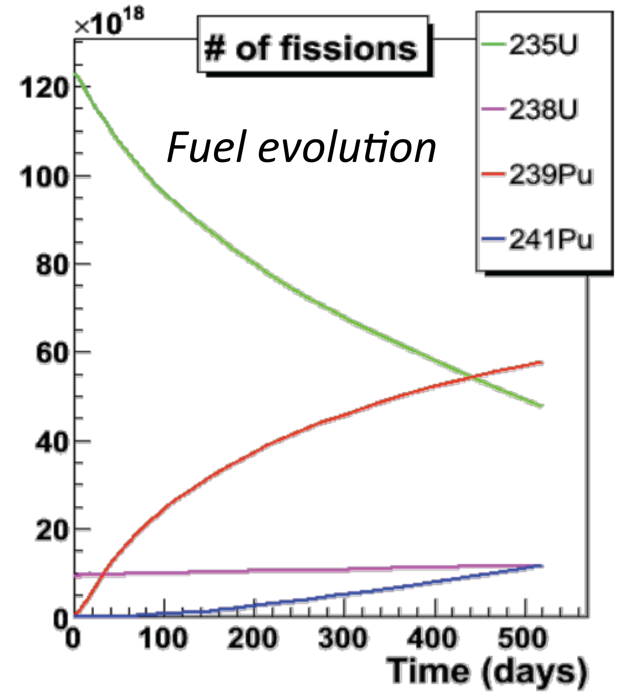
Daya Bay, Double Chooz, RENO, T2K and Nova

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

I. Esteban et al., arXiv:1611.01514

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)

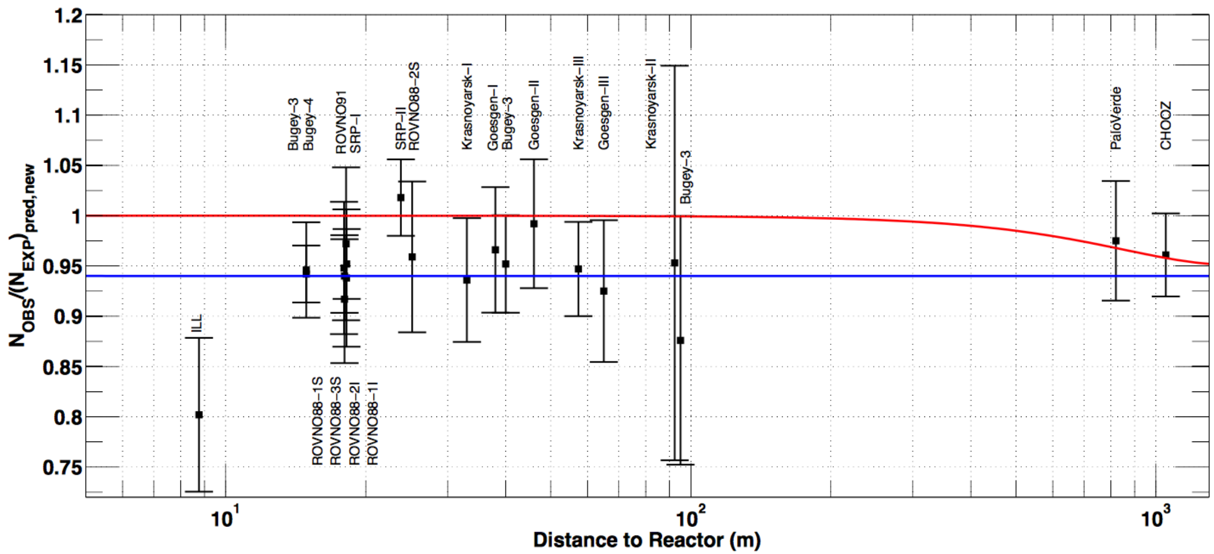
$$\sigma_f^{pred} = \sum_k f_k \sigma_{f,k}^{pred}$$

	old [3]	new
$\sigma_{f,^{235}\mathrm{U}}^{\mathrm{pred}}$	$6.39\pm1.9\%$	$6.61\pm2.11\%$
$\sigma_{f,^{239}\mathrm{Pu}}^{\mathrm{pred}}$	$4.19\pm2.4\%$	$4.34\pm2.45\%$
$\sigma_{f,^{238}\mathrm{U}}^{\mathrm{pred}}$	$9.21\pm10\%$	$10.10\pm8.15\%$
$\sigma_{f,^{241}\mathrm{Pu}}^{\mathrm{pred}}$	$5.73\pm2.1\%$	$5.97\pm2.15\%$
σ_f^{pred}	$5.824\pm2.7\%$	$6.102\pm2.7\%$

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

Reactor Antineutrino Anomaly

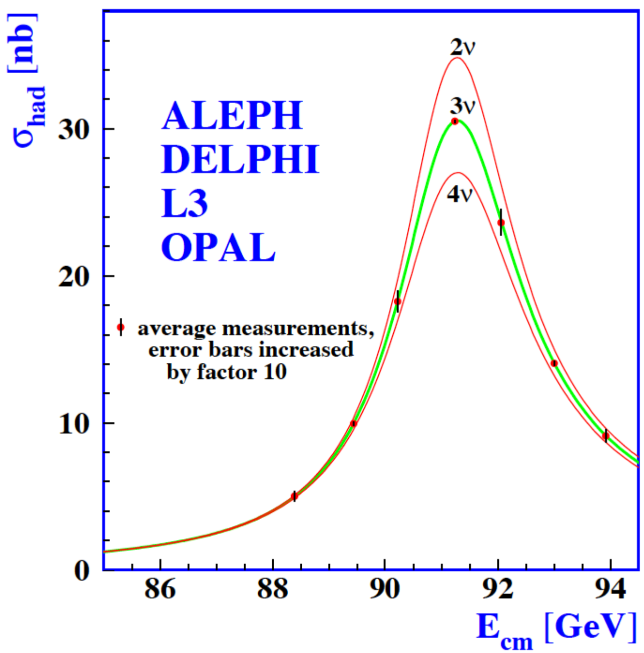
Mention et al., Phys. Rev. D **83** 073006 (2011)



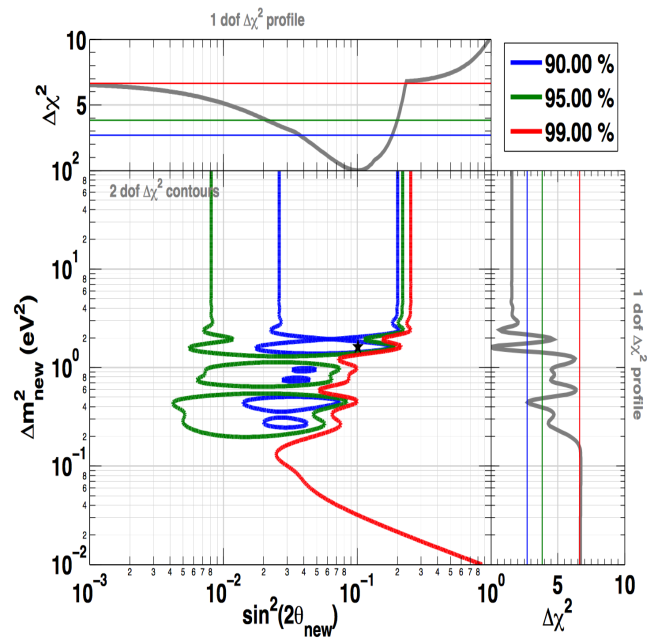
- All previous experiments short baselines (<100m) shifted with respect to re-evaluated spectra
  - Updated observed/predicted averaged event ratio: R = 0.938 ± 0.023 (2.7σ)
- Possible explanations:
  - Wrong estimation of antineutrino spectrum
  - A possible hint for new physics …

Forth neutrino hypothesis

arXiv:0509008



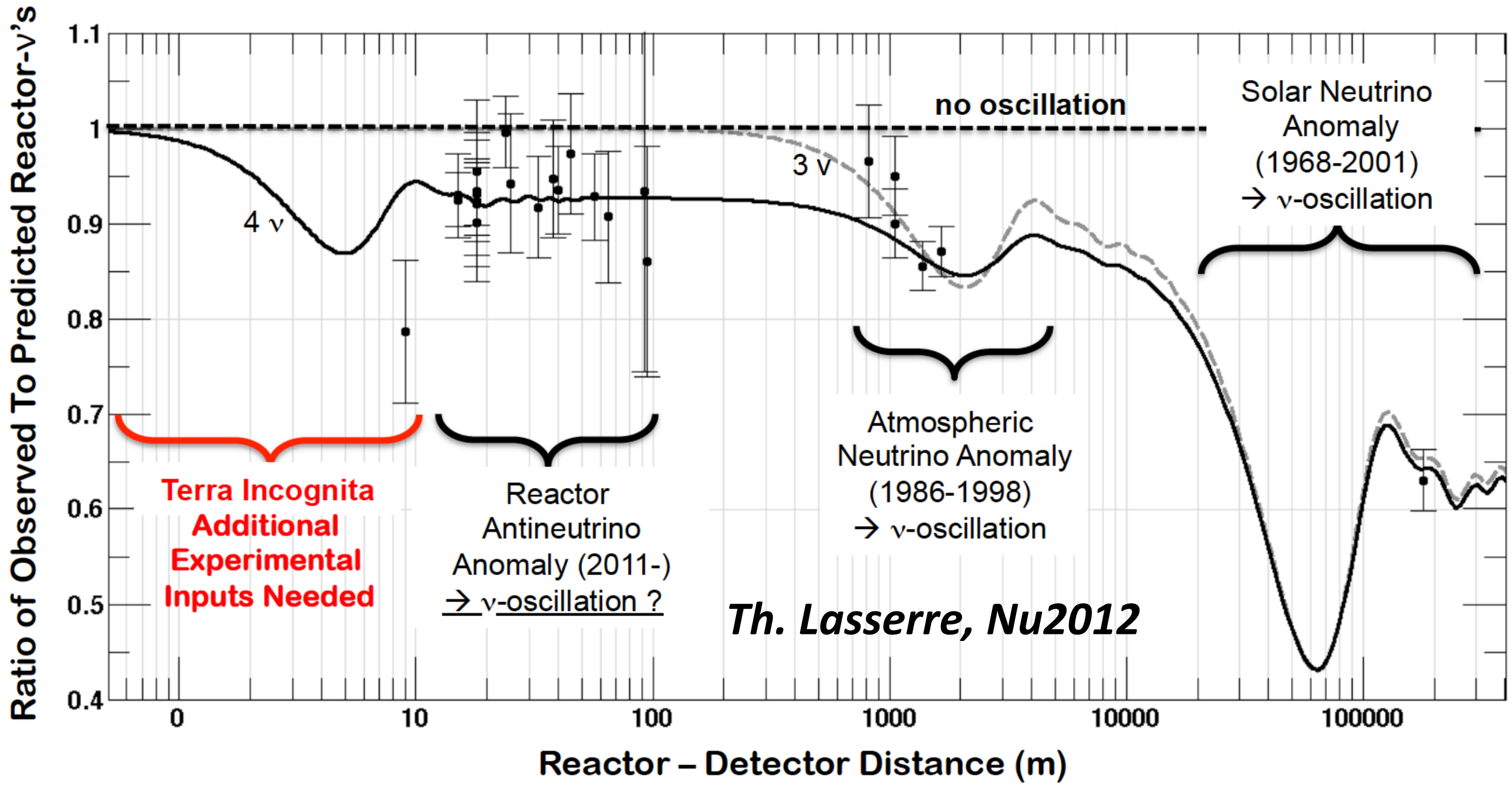
$$P_{\nu_e \to \nu_e} = 1 - \sin^2(2\theta_{ee}) \sin^2(\frac{\Delta m^2_{41} L}{E})$$



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

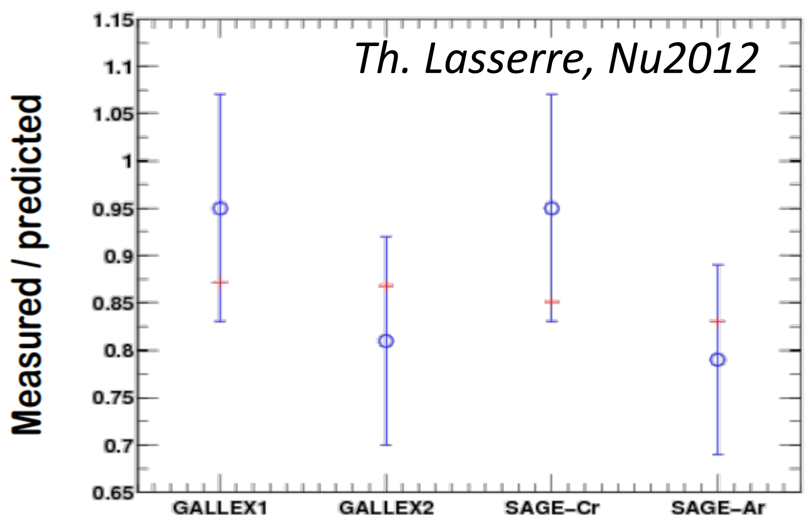


- Oscillations due to an (additional) sterile neutrino are not excluded from other data sets
  - Hints from other experiments in the same channel
  - Further input is needed ! Very short-baseline reactor experiment

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

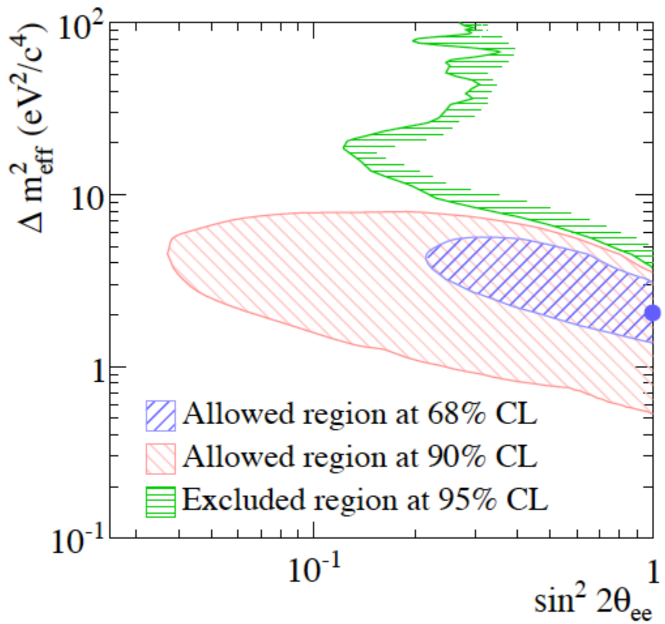


  - Low counted rates in all runs

Tokai to Kamioka (T2K)

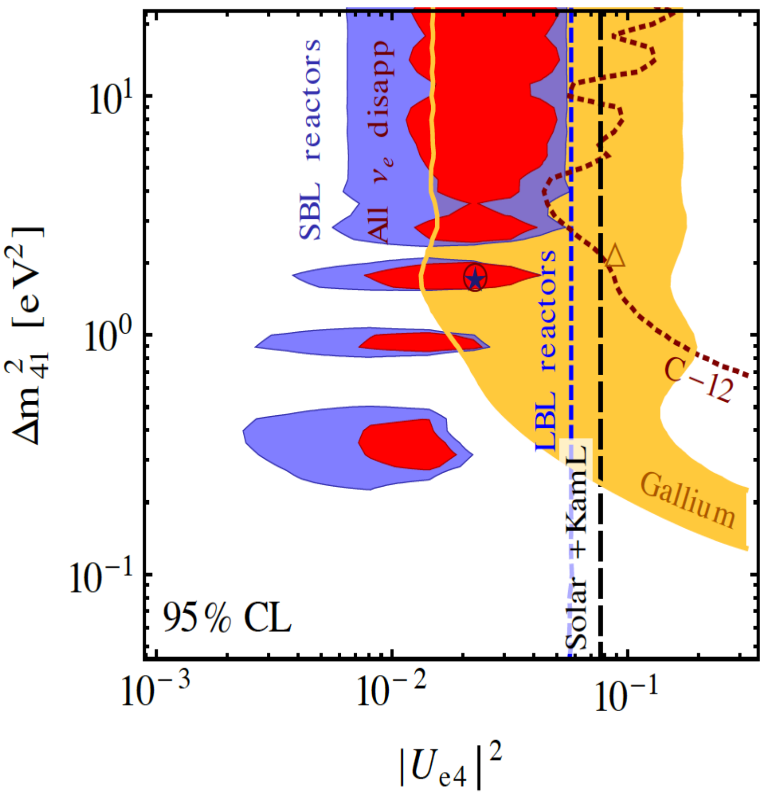
- Analysis using the beam ν_e contamination at near detector

Phys. Rev. D 91 051102 (2015)



Global ν_e disappearance analysis

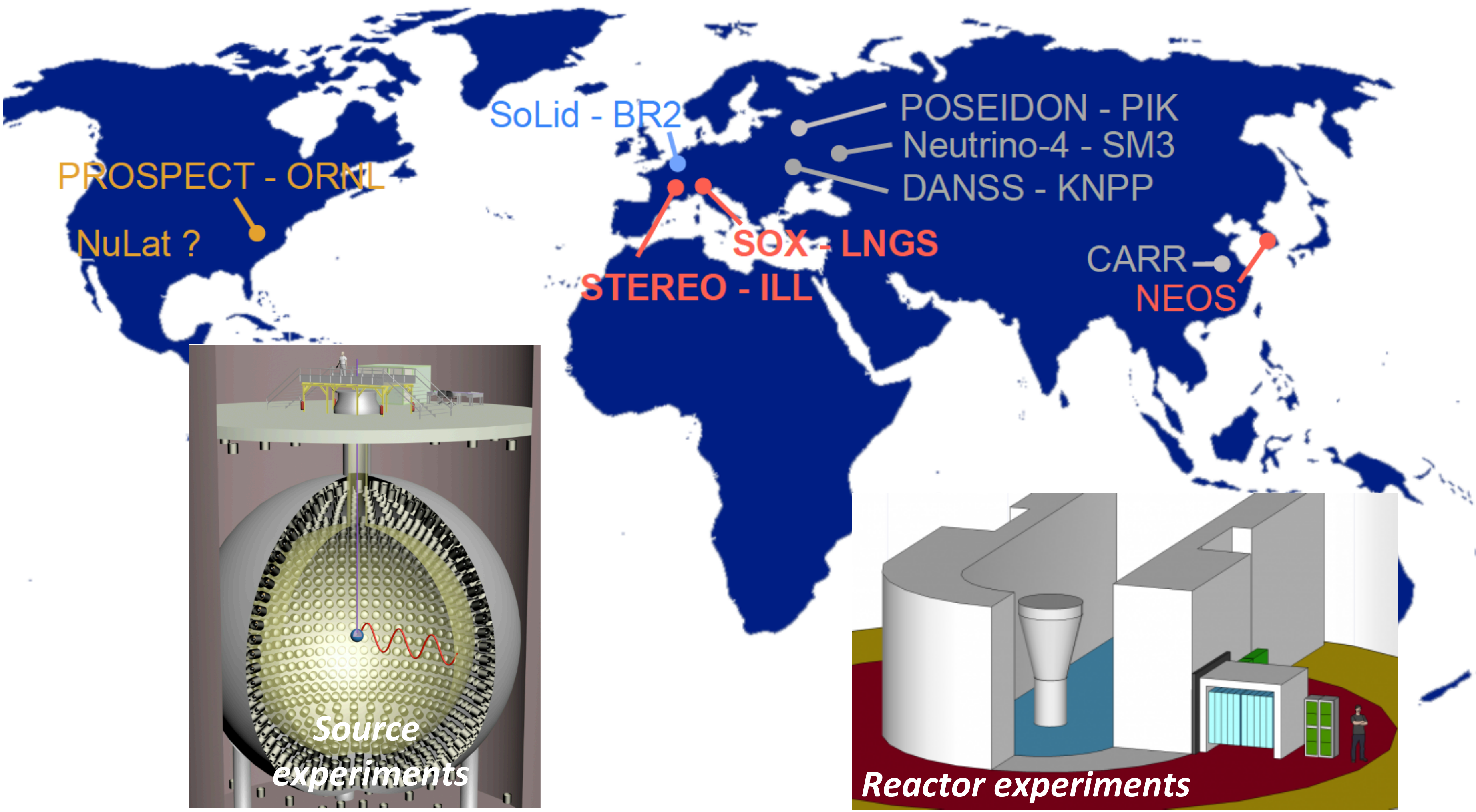
$$\sin^2 2\theta_{ee} \equiv 4|U_{e4}|^2(1 - |U_{e4}|^2)$$



JHEP 1305, 050 (2013)

- 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 results from Daya Bay, NEOS and IceCube*

New experimental tests needed

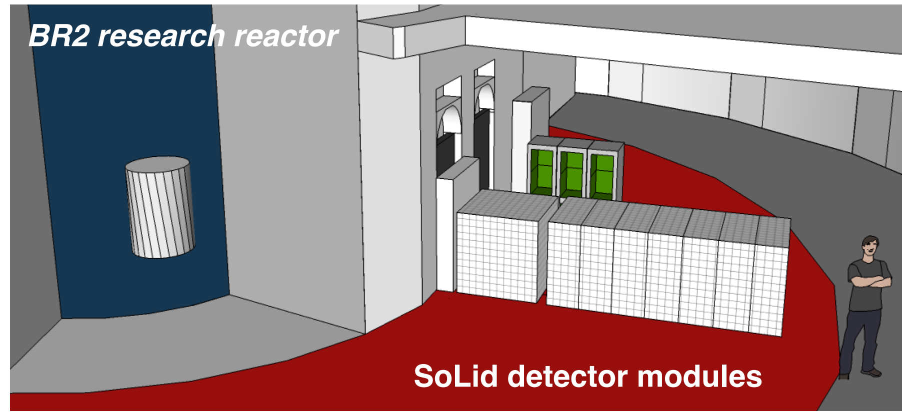


Also: Tritium decay experiments, ie., KATRIN

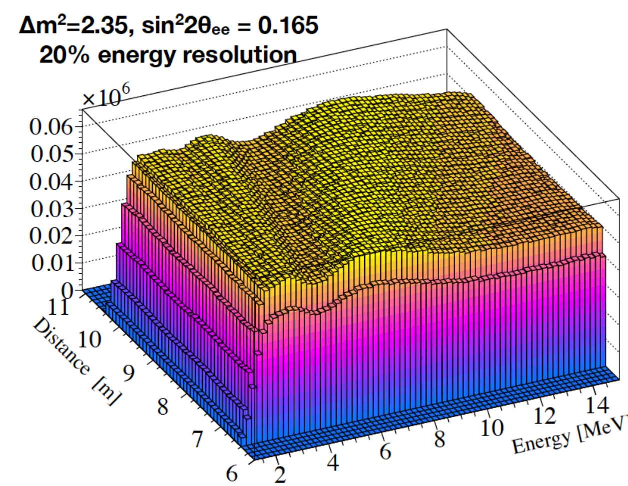
The SoLid collaboration

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

Experimental layout



- Detector modules installed at a distance of ~ 6.0 - 9.0 m from the BR2 reactor
  - Precise reactor antineutrino oscillometry
- ^{235}U flux measurement
  - Improve reactor flux prediction
  - Demonstrate reactor monitoring



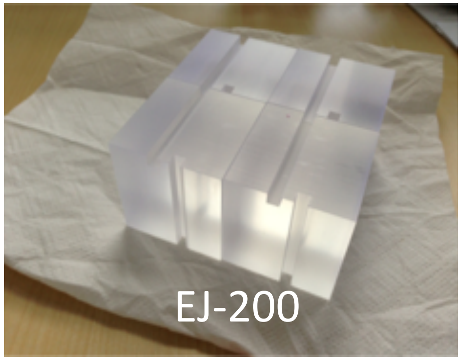
Challenges

- **Small oscillation effect (10%)**
  - Large statistics, good understanding of systematics
- **Requires compact reactor core (d < 1 m)**
  - A few meters oscillation length
- **Cover a large baseline range (6.0 - 9.0 m)**
  - Good vertex and energy resolution
- **Control of background is the key**
  - Close proximity to a nuclear reactor
  - Low overburden (almost on surface)

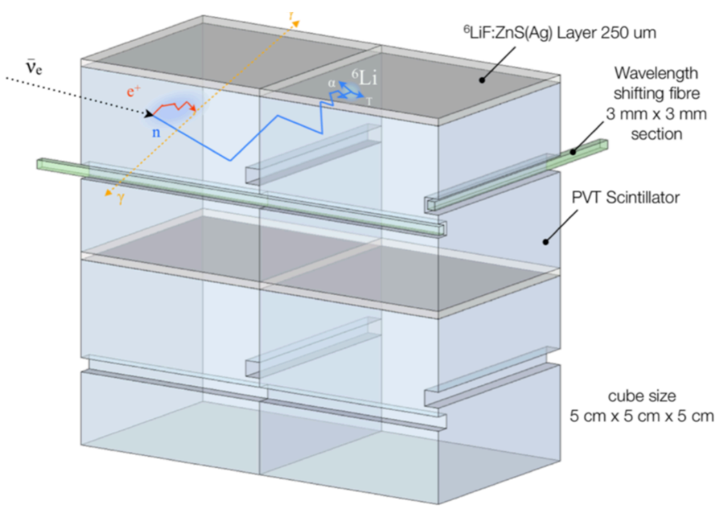
BR2 reactor at SCK•CEN

- 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*

Detector concept

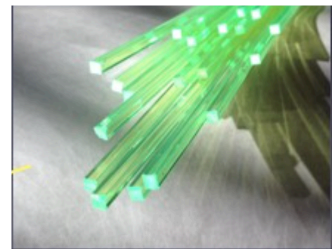


- $5 \times 5 \times 5$ cm^3 PVT cubes
- Non-flammable scintillator

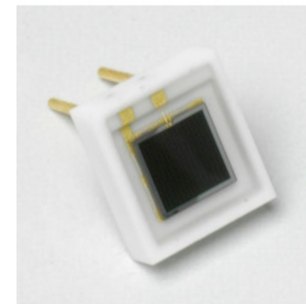


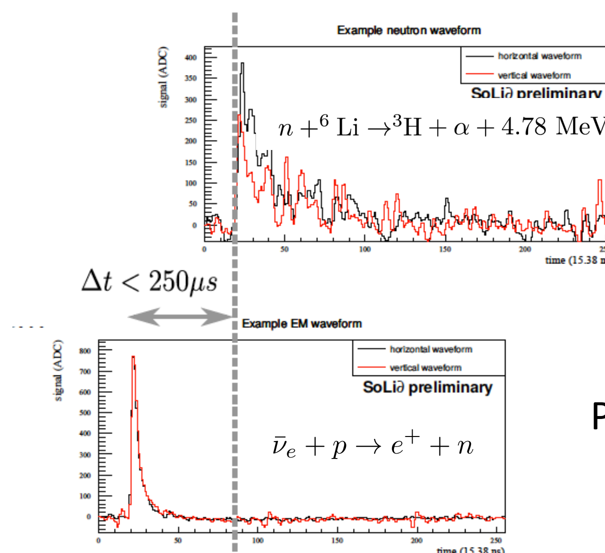
- Adjacent planes of cubes

- Cubes are optically separated (wrapped in Tyvek)
- ^{6}LiF:ZnS(Ag) for neutron identification
- Light collected through optical fibers and silicon photomultipliers (SiPMs require low-voltage)



Squared BCF-91A fiber

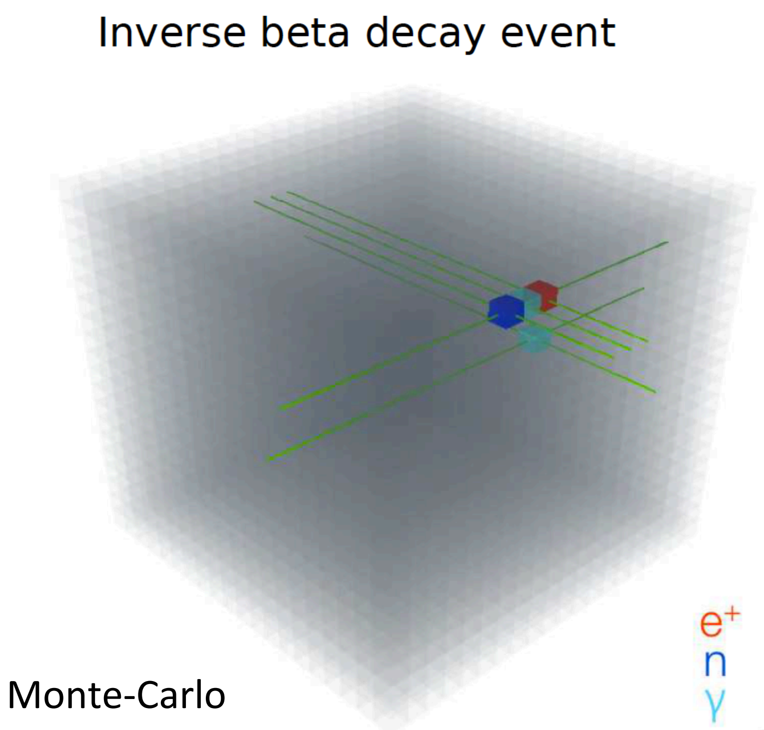


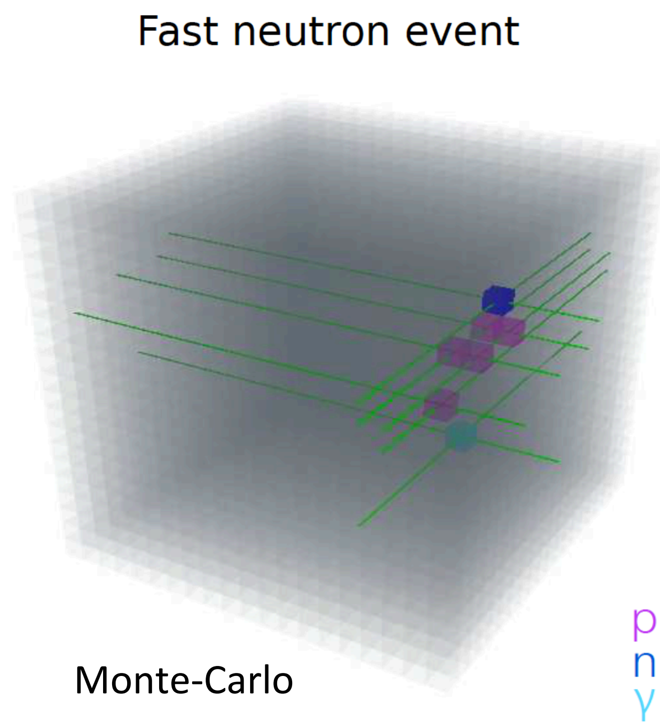


Delayed signal

Prompt signal

Event topology in SoLid

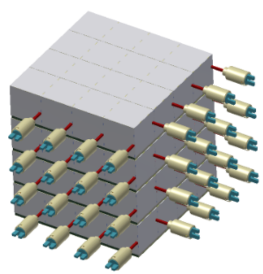




- High granularity allows for signal localization and thus enhances significantly background rejection
- Fast neutron rejection possible through event topology

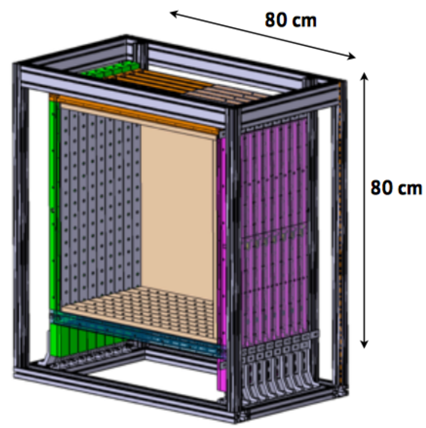
Detector development

NEMENIX, 2013



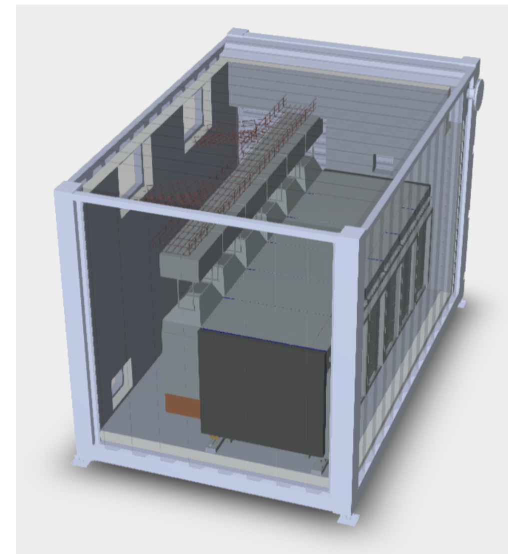
64 cubes totally
8 kg active mass

SM1 prototype,
2014 -2015



9 planes of 16 × 16 cubes
288 kg active mass

Phase I detector, 2017



60 planes of 16 × 16 cubes
2.0 tons active mass

Proof of principle

- Validate neutron identification
- Demonstrate prompt-delayed signal selection
- Background measurement

First large scale prototype

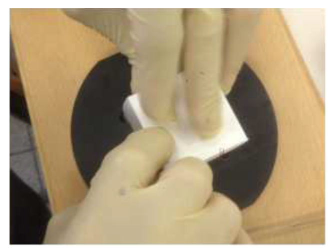
- Demonstrate scalability and test production schedule
- Probe background rejection
- Analysis tools, physics results

Real scale system

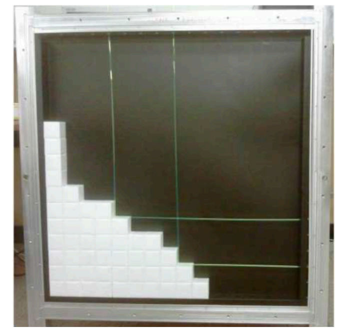
- Improved design
- Implement neutron trigger
- Perform high precision measurements

SM1 prototype

- 2304 cubes machined and assembled
  - Wrapped with Tyvek and carefully weighted
  - Number of protons determined with better than 1 % accuracy

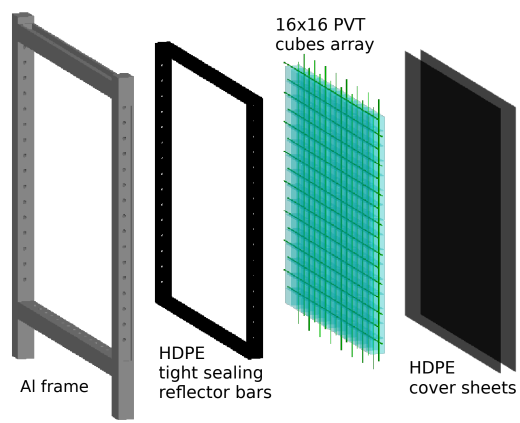


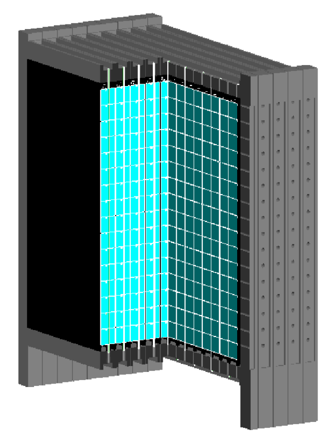
Plane under construction



Assembled plane

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





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

Deployment at BR2


SM1 at Gent

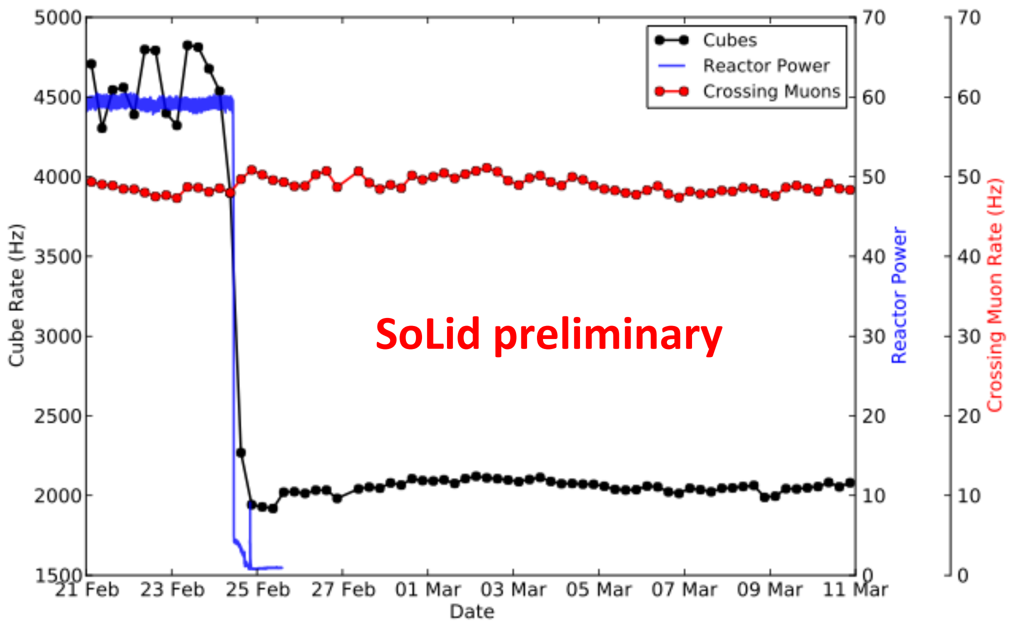

Eppur si muove


Installation at BR2

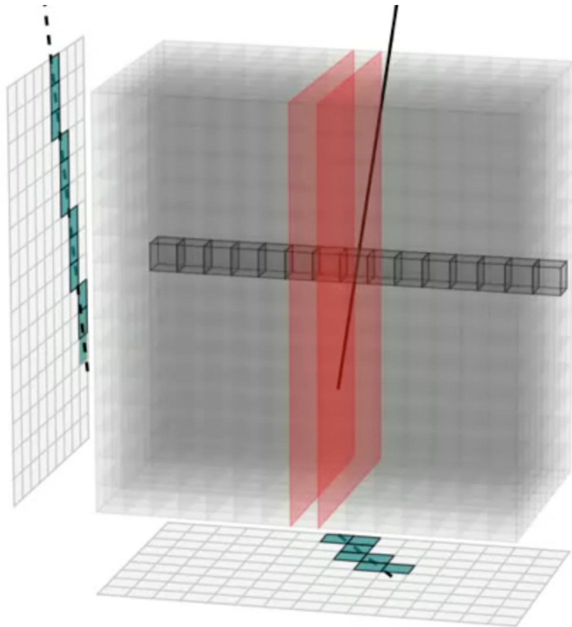

November 2014

Data taking

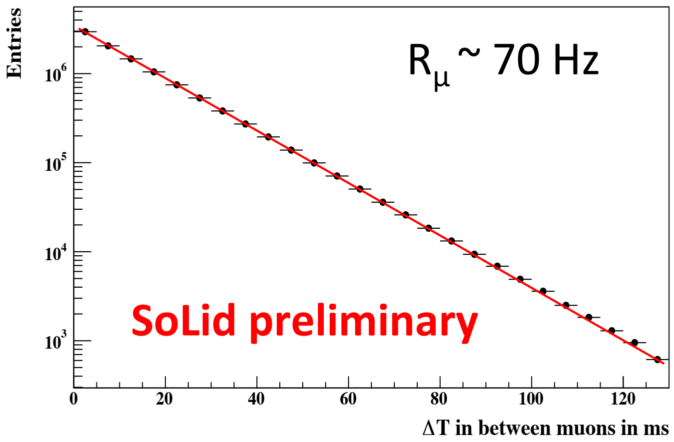
- SM1 run at 12/14 - 03/15
  - Detector commissioning
  - 3 - 4 days reactor on
  - ~ 1 month reactor off
- Detector calibration
  - ^{60}Co and AmBe (04/15)
  - ^{252}Cf in situ (08/15)

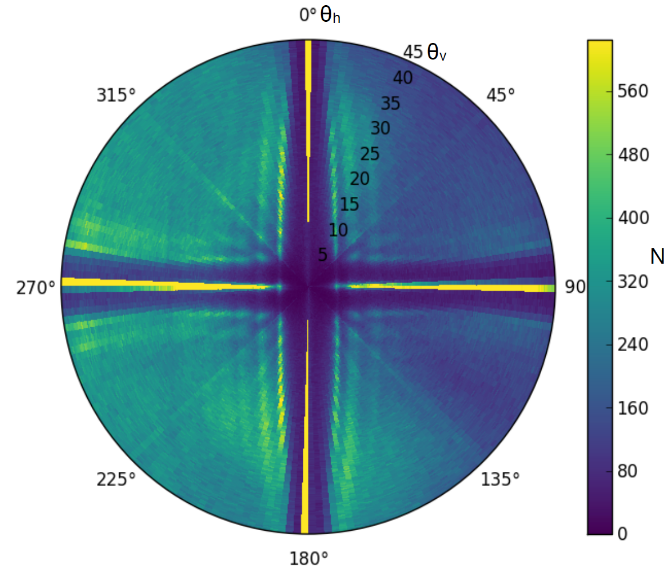


Cosmic muons



Crossing muon event

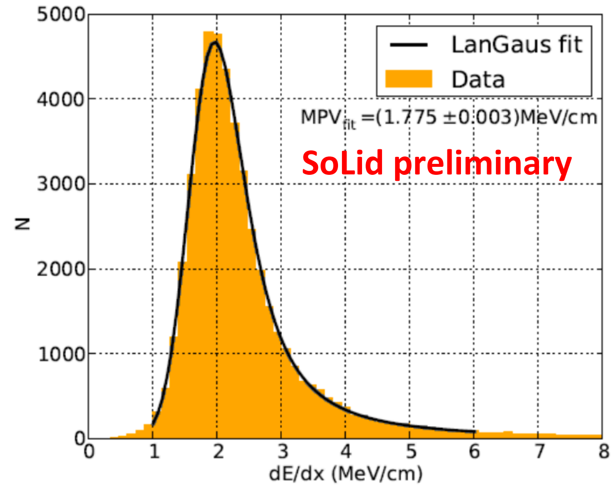


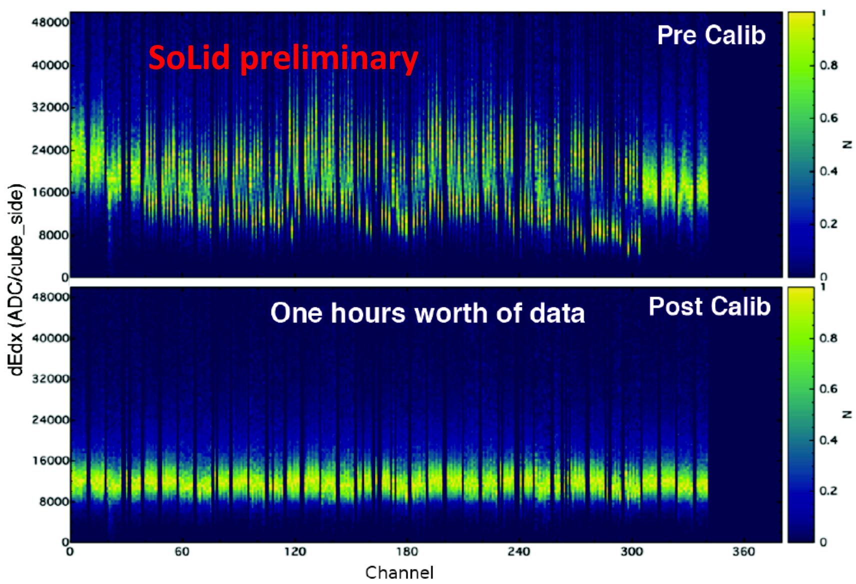


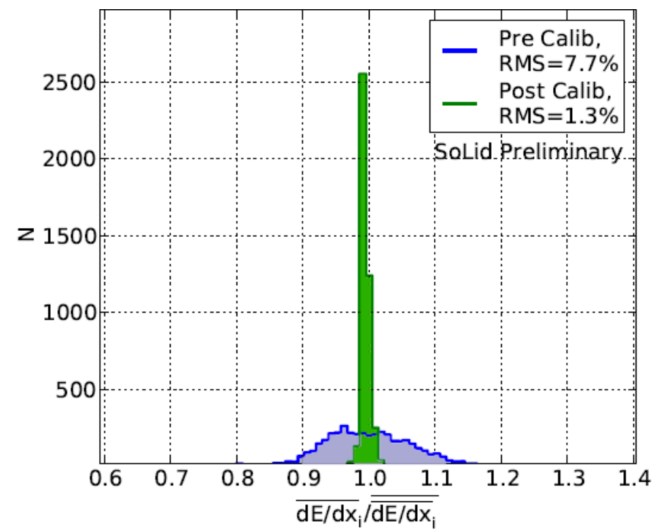
- Excellent muon tracking due to detector segmentation
- Detector calibration and stability monitoring using cosmic muons
- Provides handle on muon correlated background rejection

Calibration with cosmics

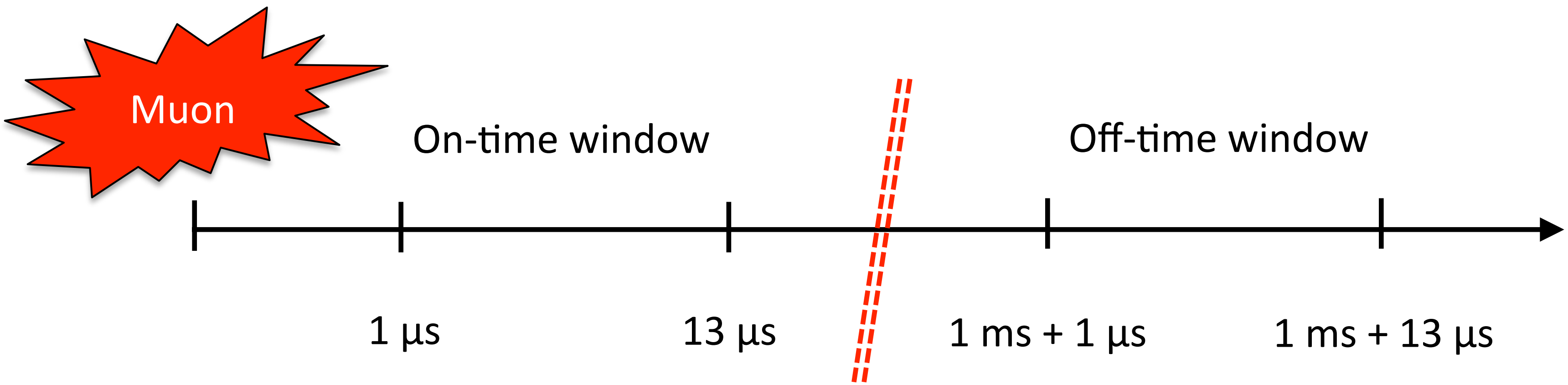
- In-situ energy calibration using dE/dx
  - Channels inter-calibration
  - Cube response equalization
- Light yield measured: 25 PA/cube
- SiPM gain measured with dark rate
  - No need for light injectors

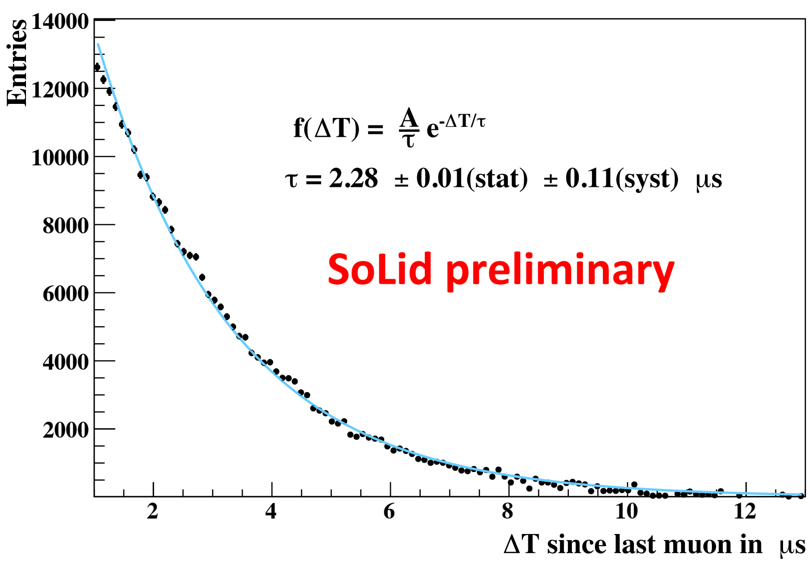






Muon daughters: michel electrons

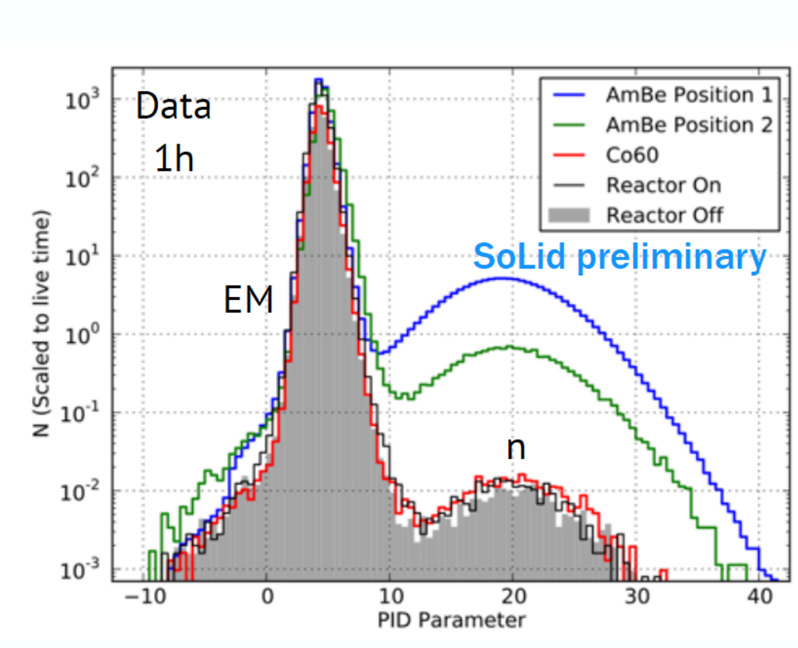


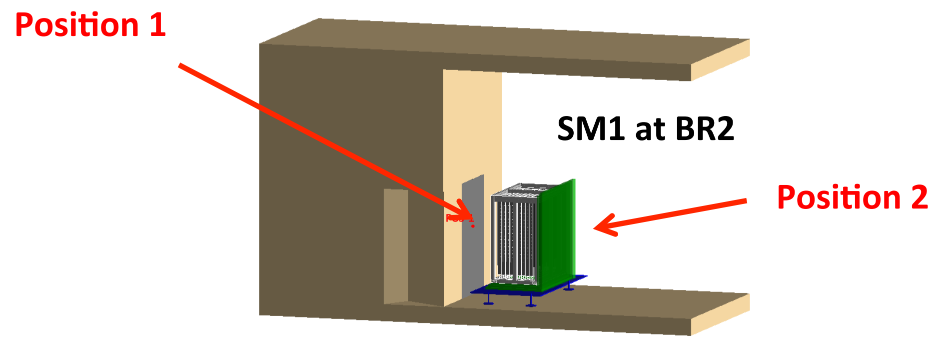


$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$

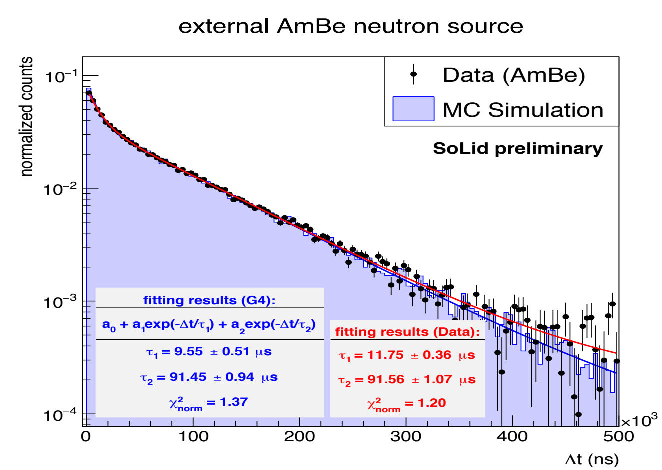
- Michel decay probes the tagging of prompt-delayed coincidences
  - DAQ is well behaving
- Large sample of michel electrons that can be used for calibration
  - Higher energy range than IBD

Neutron identification





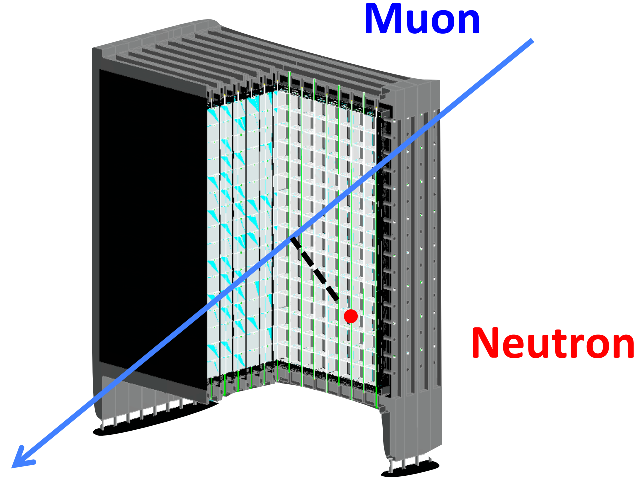
- Calibration runs with AmBe source
  - AmBe is a fast neutron emitter
- Study prompt-delayed coincidence
  - Time-space correlation, neutron efficiency, etc…



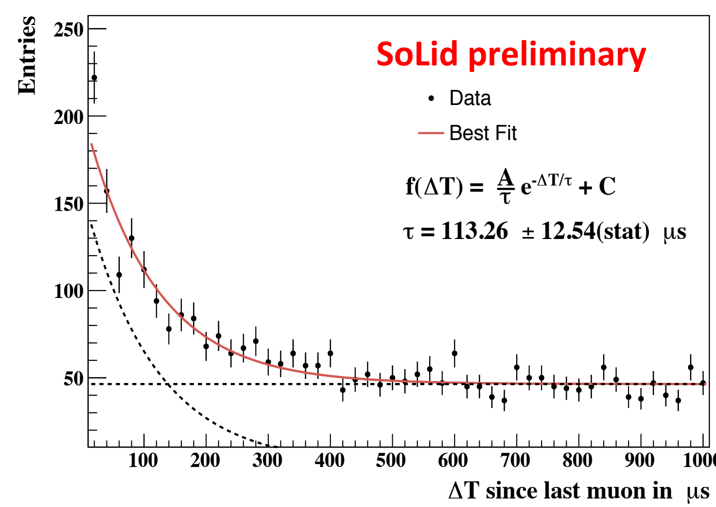
- Excellent neutron identification
  - Tail-to-total algorithm using information from both channels
- Can distinguish a neutron in millions of signals !

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

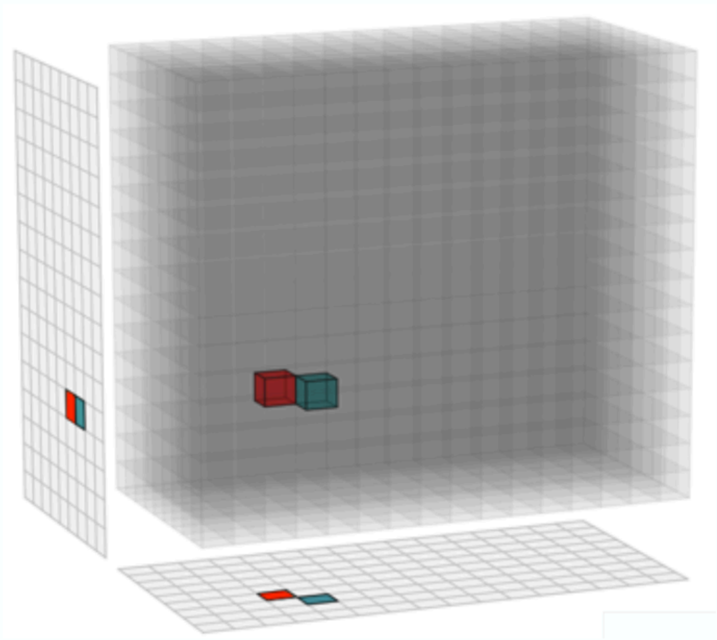


- Control sample that can serve different purposes:
  - Detector stability versus time
  - Neutron identification studies
  - Tune neutron selection

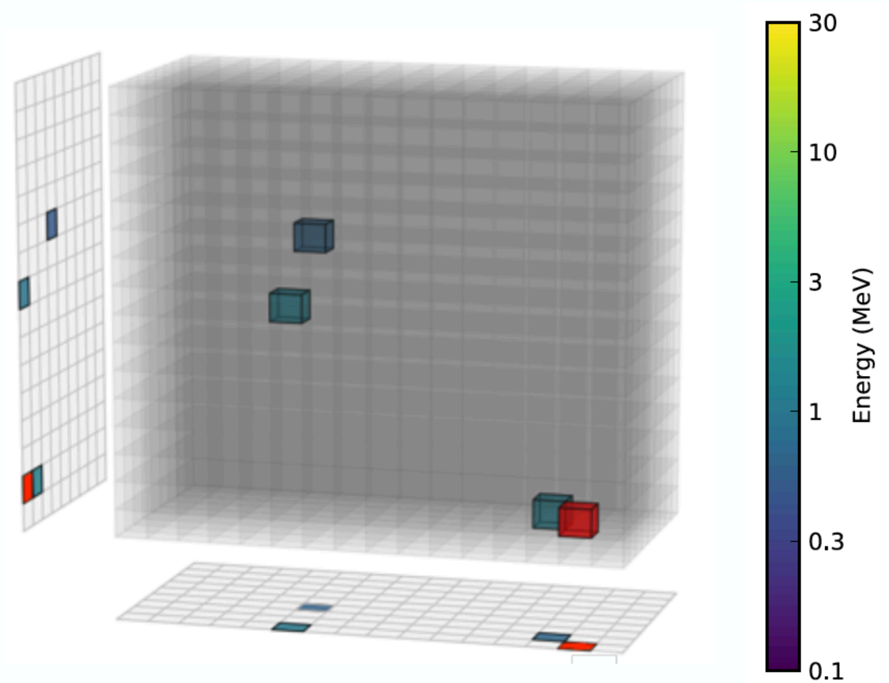


IBD candidates

SM1 data



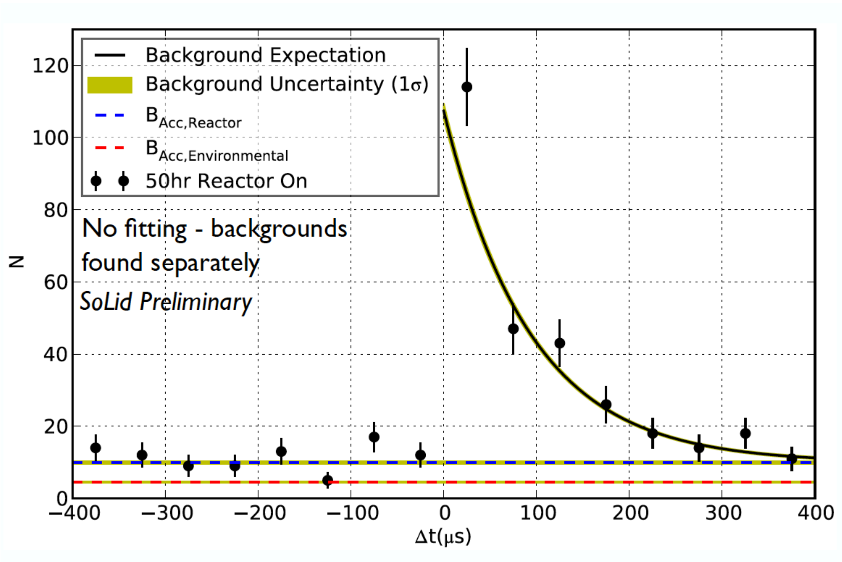
SM1 data



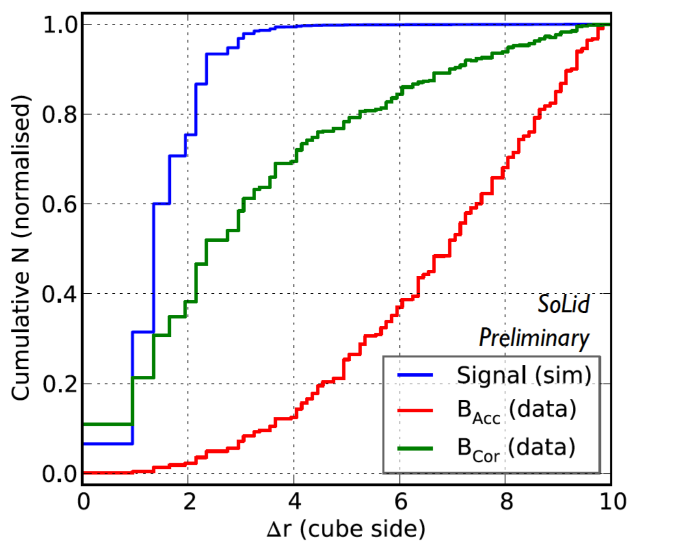
EM signal (prompt) shown in green
Neutrons (delayed) signal are shown in red

IBD selection

- The selection of IBD candidates depends on the time (Δt) and space (Δr) correlation of prompt-delayed coincidences



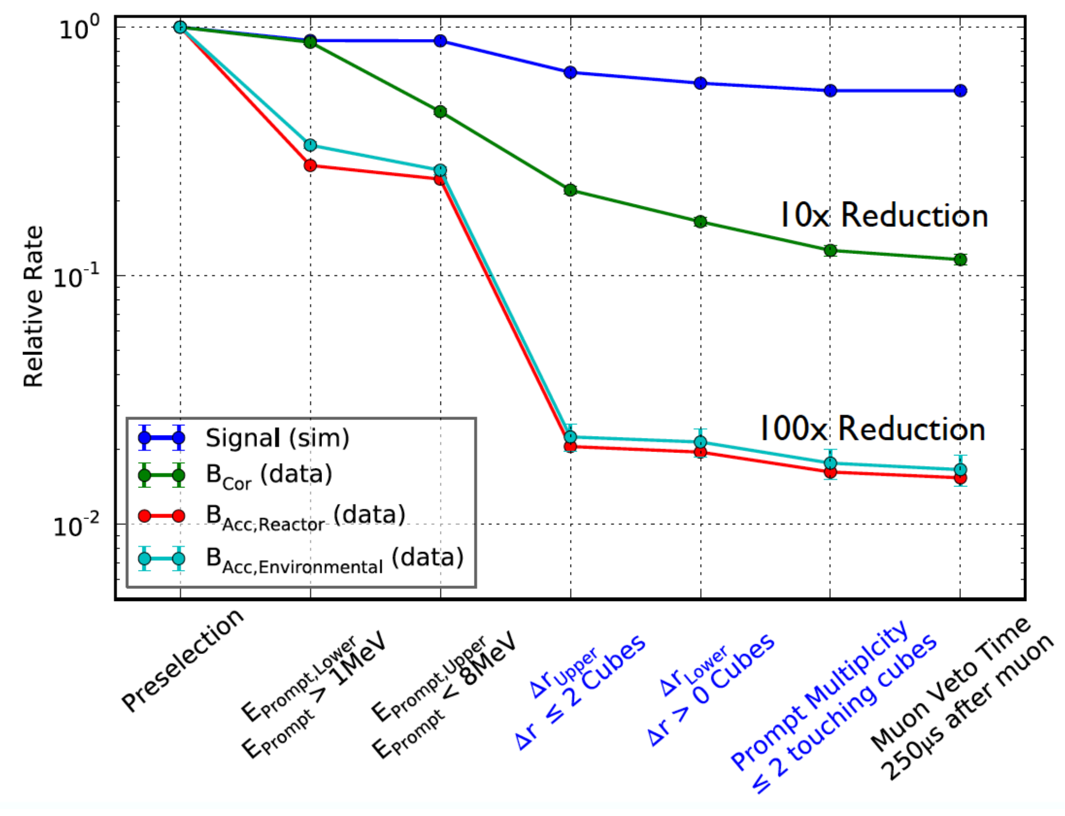
Accidental background has a flat contribution as it was expected



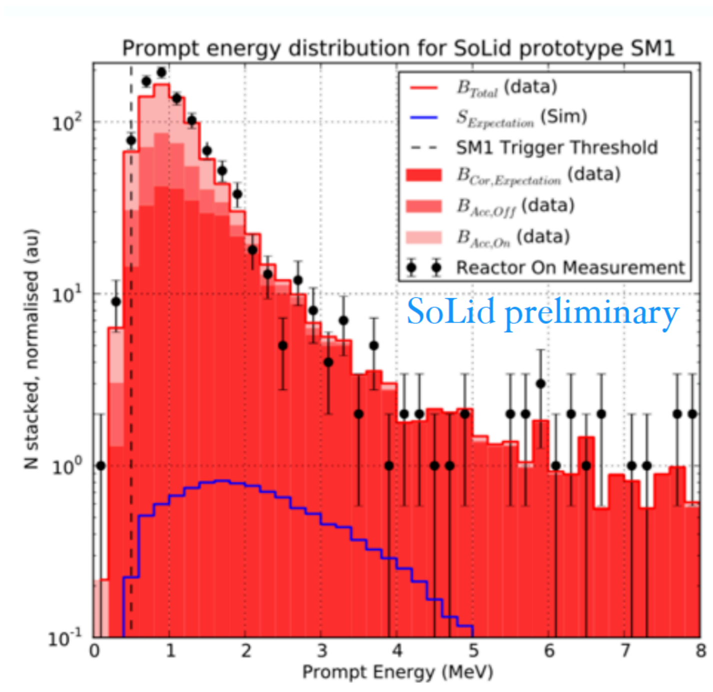
Large background reduction using a Δr cut (volume segmentation)

Background reduction

- Very good signal-background discrimination has been achieved with SM1



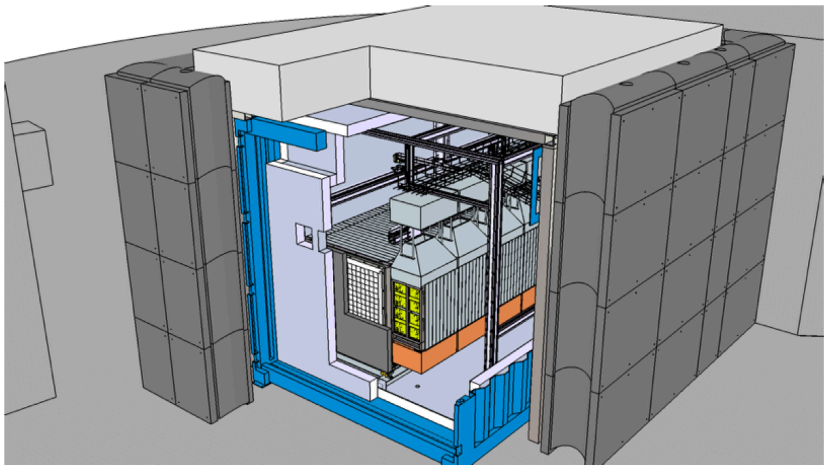
Signal and background



- Correlated background estimated using reactor off data and accidentals using off-time windows
- Good agreement between reactor on data and expectation; Validation of background estimation methods

Phase I detector

Construction phase has started



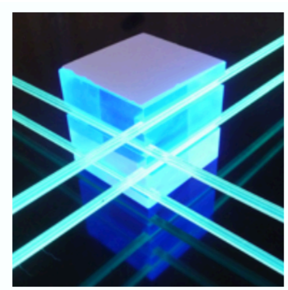
- 6 modules of 10 planes, 16 × 16 cubes
- 60 planes totally, 15360 cubes
- Temperature controlled system
- 3200 readout channels, max 0.5 TB per day

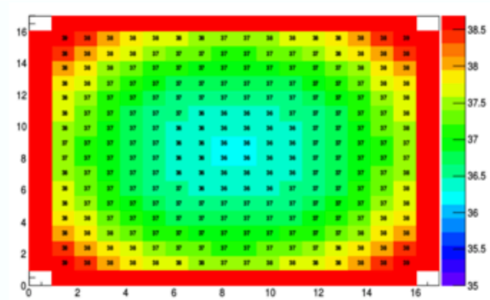
Neutron detection efficiency

- Additional LiF:ZnS sheets
  - Increases ^{6}Li capture efficiency from 51% to 66%
  - Reduces capture time from 105 μs to 66 μs
- New screens with improved transparency

Light yield and uniformity

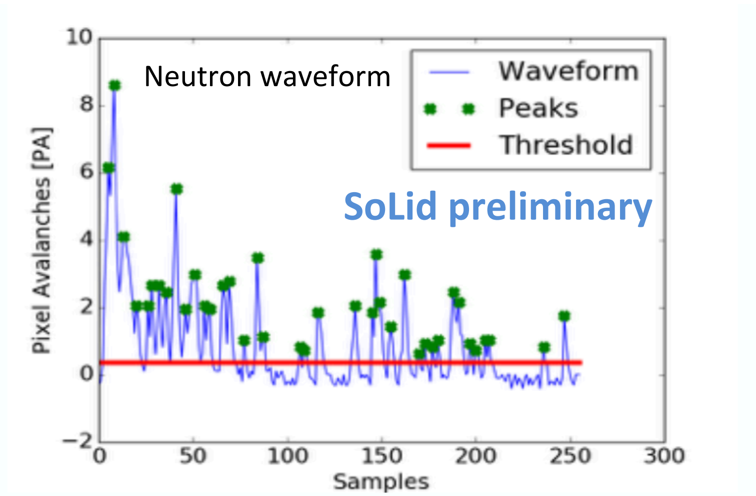
- Four fiber readout
  - 37 PA/MeV, 66% increase with respect to SM1
  - 7% variation of light yield across the detector



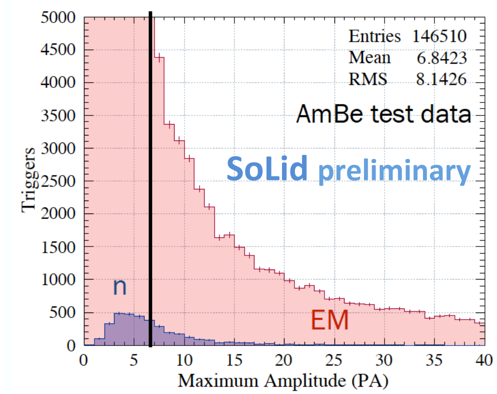


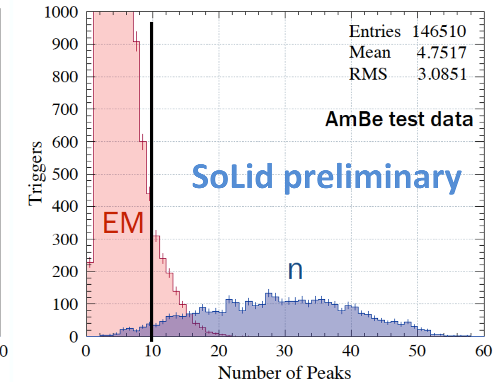
Neutron trigger

- SM1 had a rather low neutron detection efficiency of ~ 5%, due to high trigger threshold (6.5 PA)

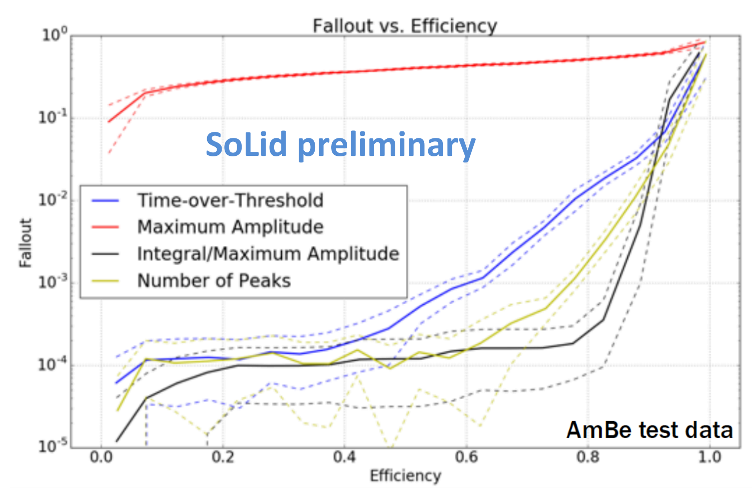


Neutron (n) and electromagnetic (EM) signals





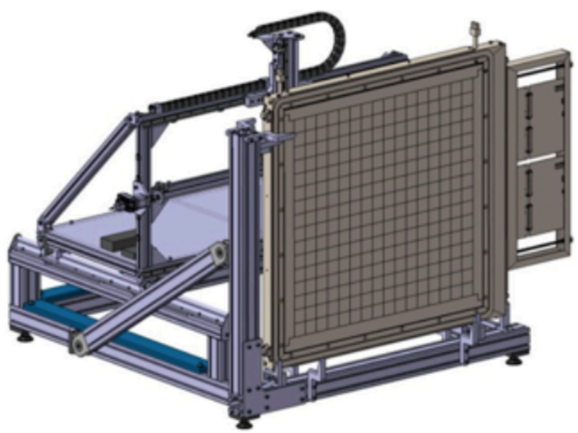
- Phase I detector is designed to have a neutron selection at the trigger level (implemented at the firmware level)
  - Buffer time ± 500 μs and ± 2 planes around a neutron event
  - Zero suppression threshold at 1.5 PA
  - Reduces dramatically the amount of data
  - Retains high IBD efficiency



- We expect n detection efficiency of ~ 70%

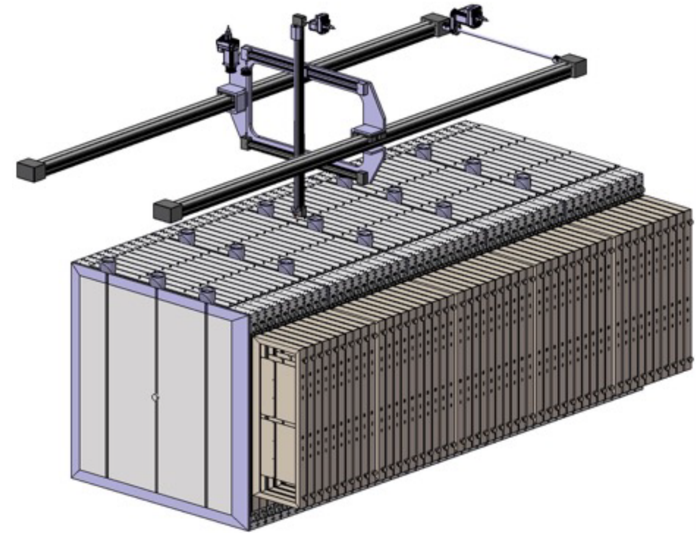
Detector calibration

Off-site calibration system (CALIPSO)



- Plane characterization and commissioning
- Cube to cube equalization
- Neutron and EM signals benchmark

In-situ calibration system (CROSS)

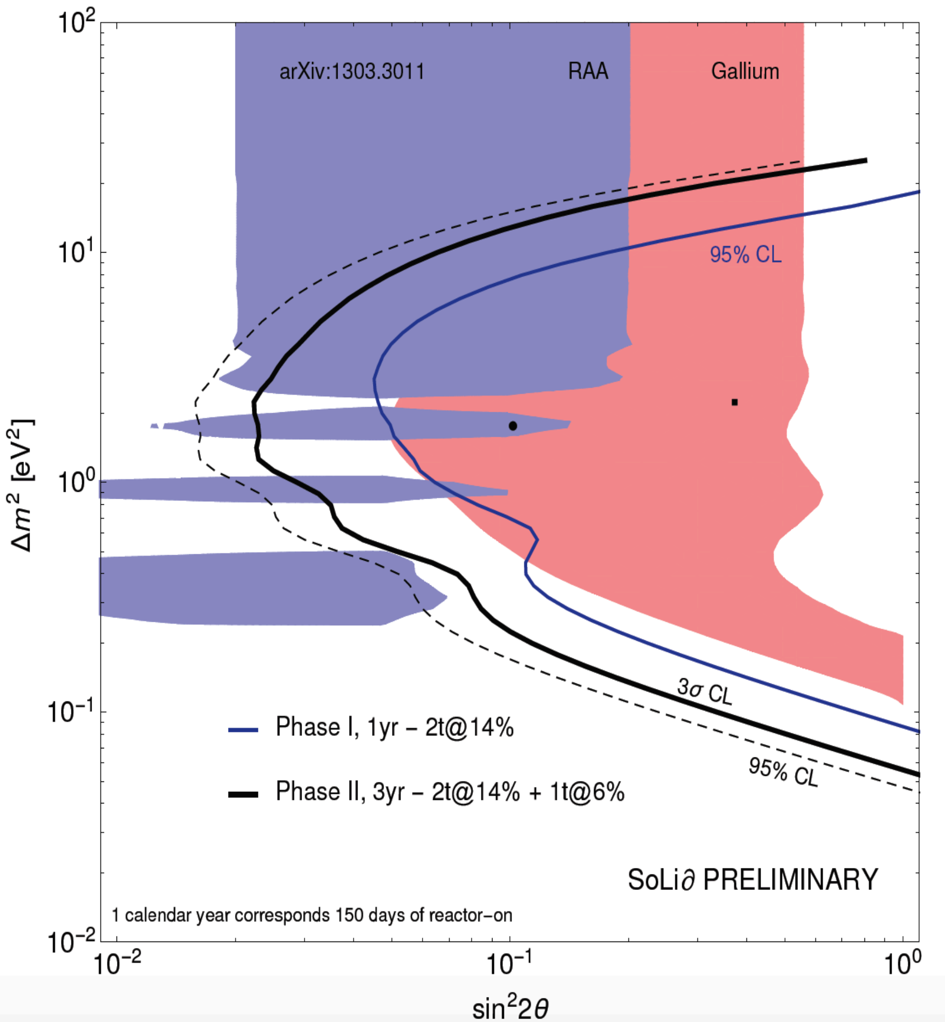


- In-situ radioactive sources deployment
- Precise energy scale and neutron detection efficiency determination

Detector construction

- SoLid detector is under construction !
- Cube production and frame assembly is well underway
- Staged production of electronics
- Trigger firmware implemented and DAQ currently under development
- Container has been built and delivered

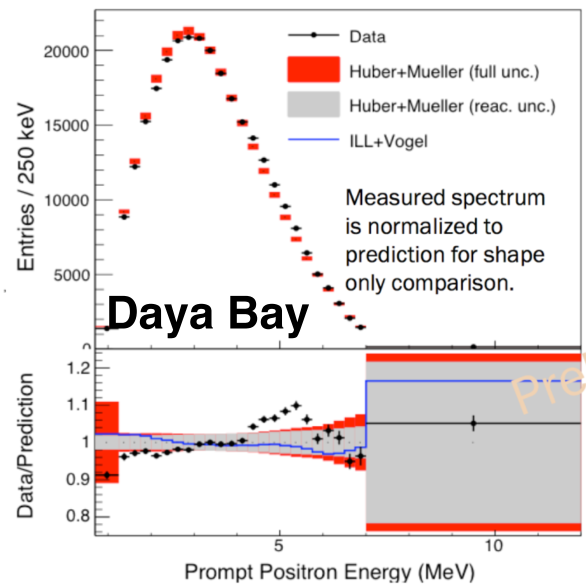
Sensitivity to sterile neutrino

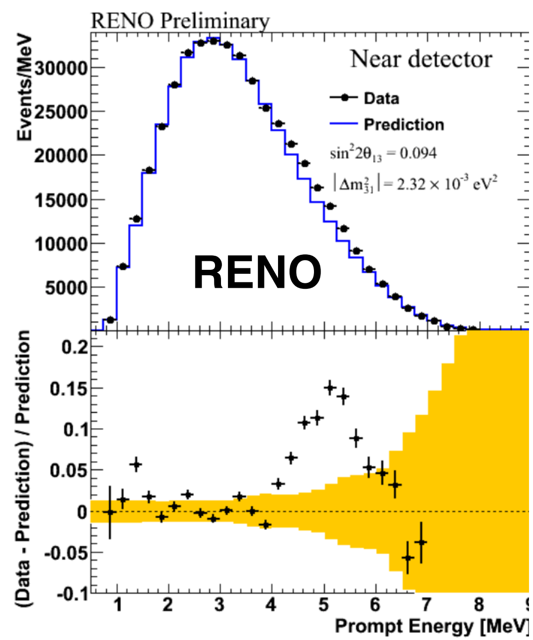


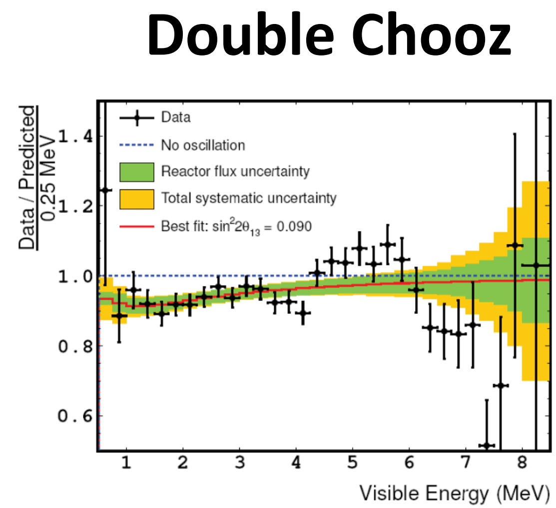
- Two-dimensional fit in energy (E) and distance (L)
  - Good control on detector systematics
  - Energy resolution is crucial
- *Best fit covered within the first year of data taking*

Other physics goals

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







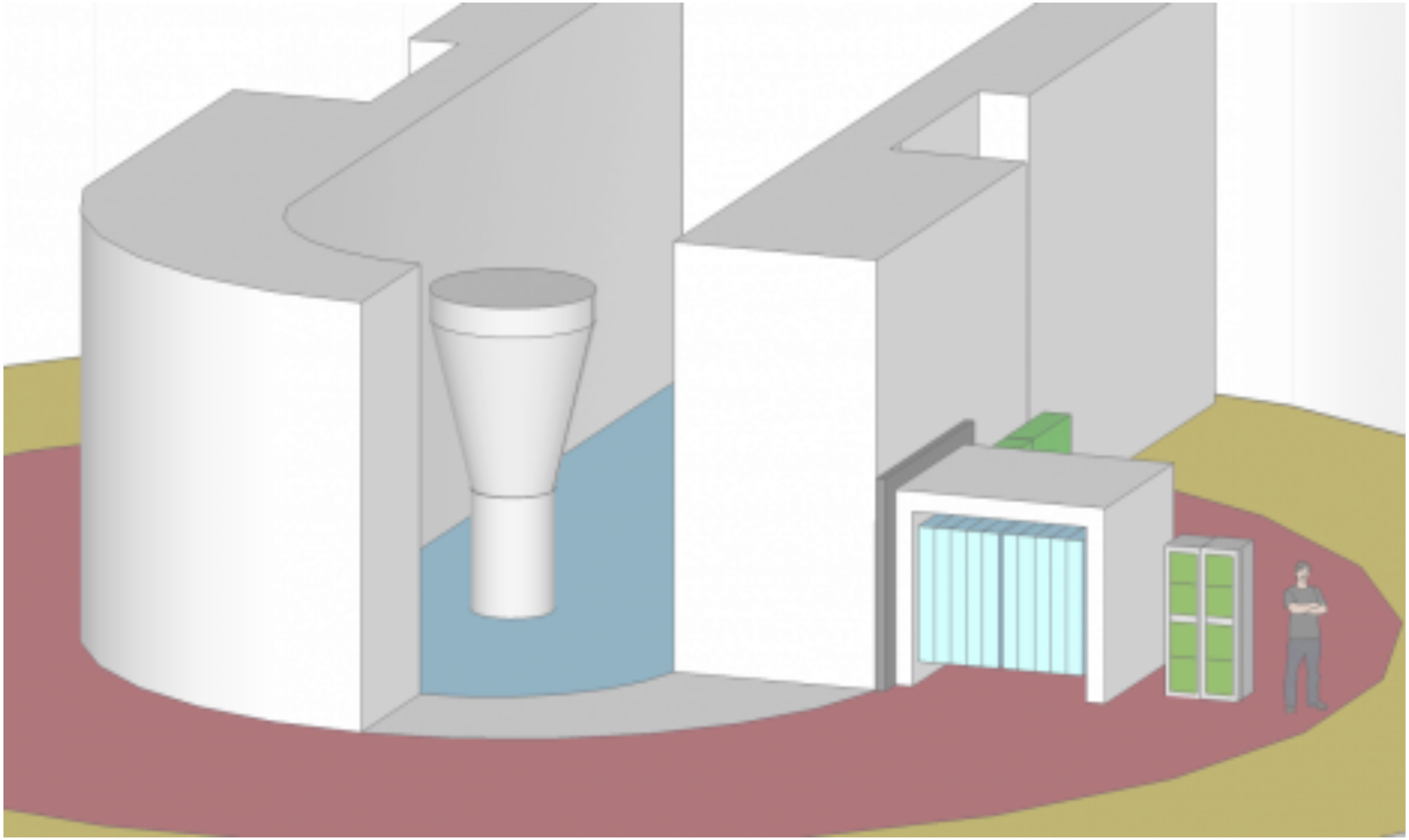
  - Synergy with reactor monitoring and nuclear weapons non-proliferation efforts
  - For instance: Huber *et al.*, PRL **113**, 042503 (2014)

Ending themes

- The SoLid experiment will make a very sensitive search for $\bar{\nu}_e$ disappearance using a novel detector design
- 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%)
- Entered construction phase fro the 2.0 ton detector
  - Funded by FWO, Hercules (BE), ERC (EU) and ANR (FR) grants
  - Increased light yield; more optical fibers
  - Real-time neutron trigger (data reduction)
- Detector commissioned and deployed in BR2 by summer 2017
  - Stay tuned for a high-precision measurement !

Thank you for your attention !

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

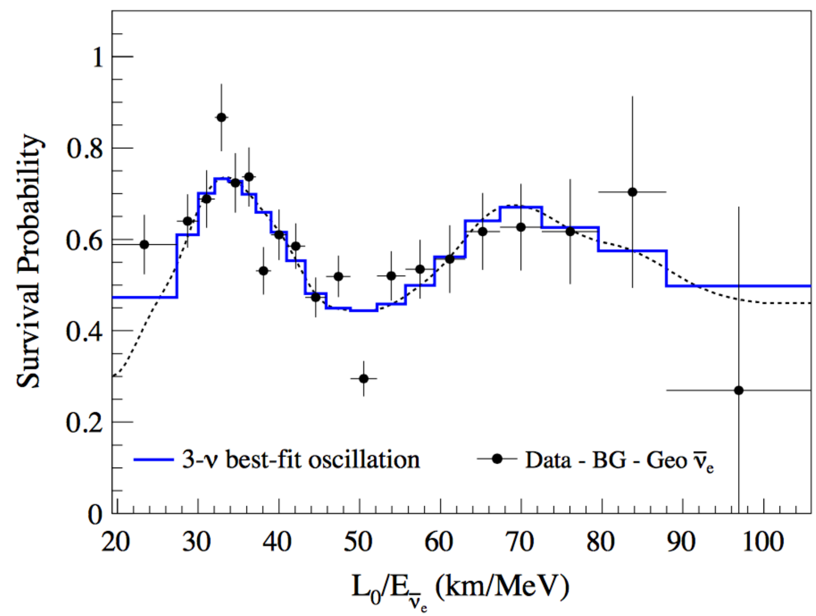


SPARES

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.

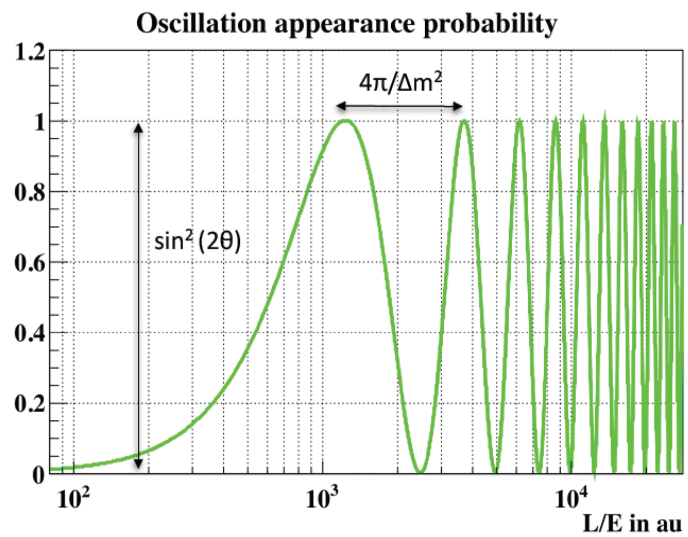
$$\mathcal{U} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

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

Appearance probability

Typical oscillatory behaviour

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



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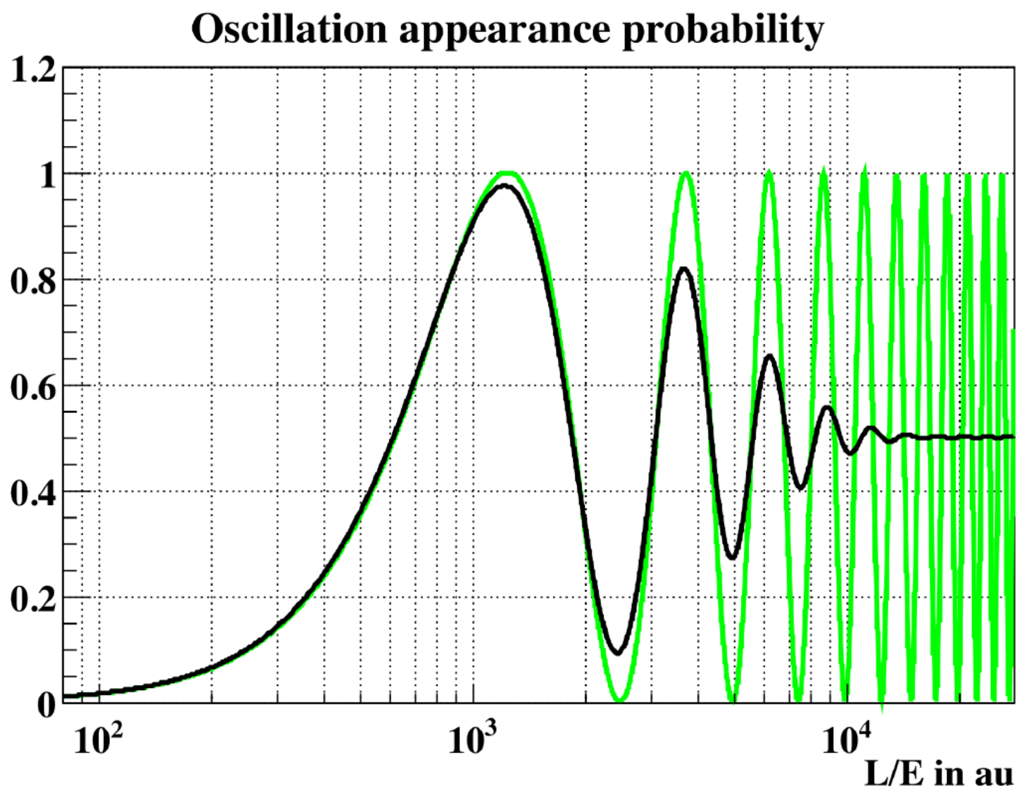

<E> = 1 GeV and ΔE = 0.1 GeV

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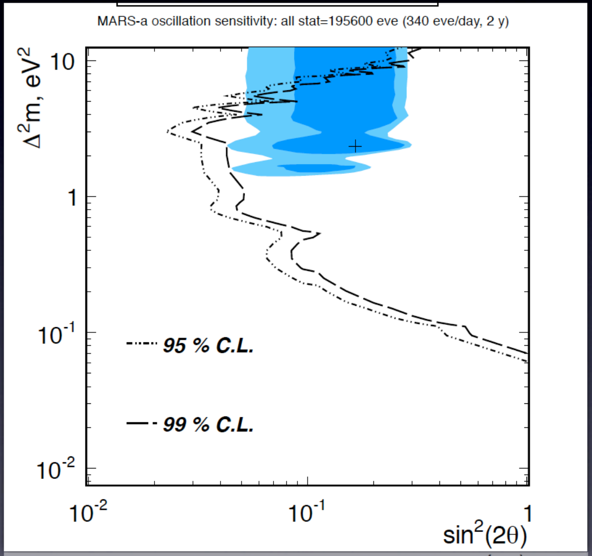
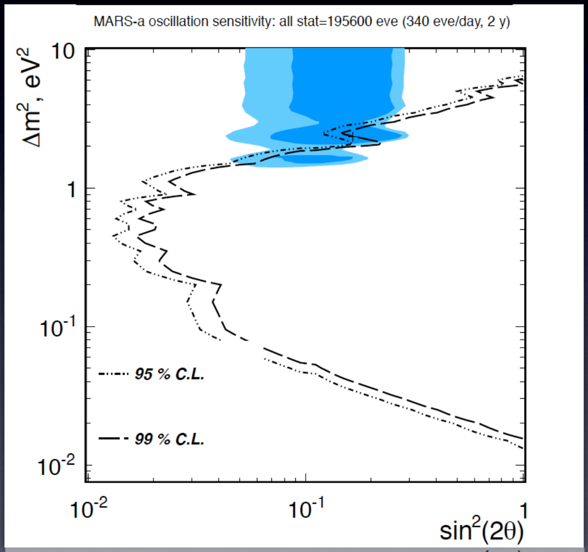
Effect of core size

ILL core 0.4 x 0.8 m @ 6.5 m



Power reactor core 3 m x 3.5 m @ 12 m



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:**

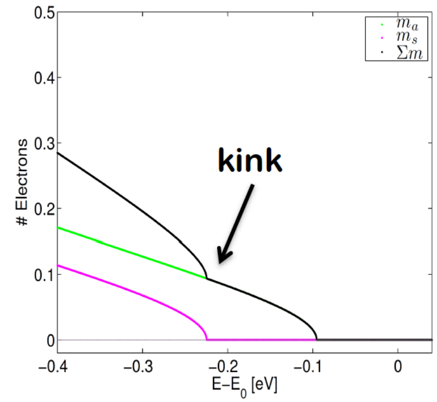
$$\langle m_\beta \rangle = \sqrt{\sum_{1,2,3,..} |U_{ei}|^2 m_i^2}$$

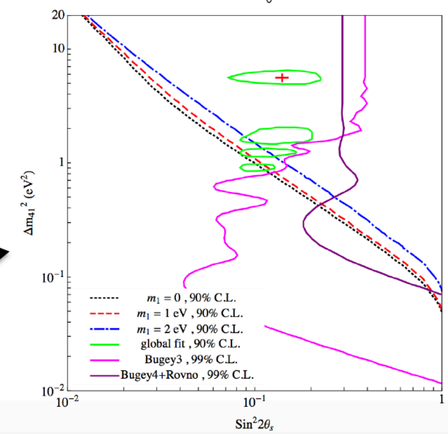
- **Hypothetical 4th ν contribution**

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

→Search for a kink few eV below end point

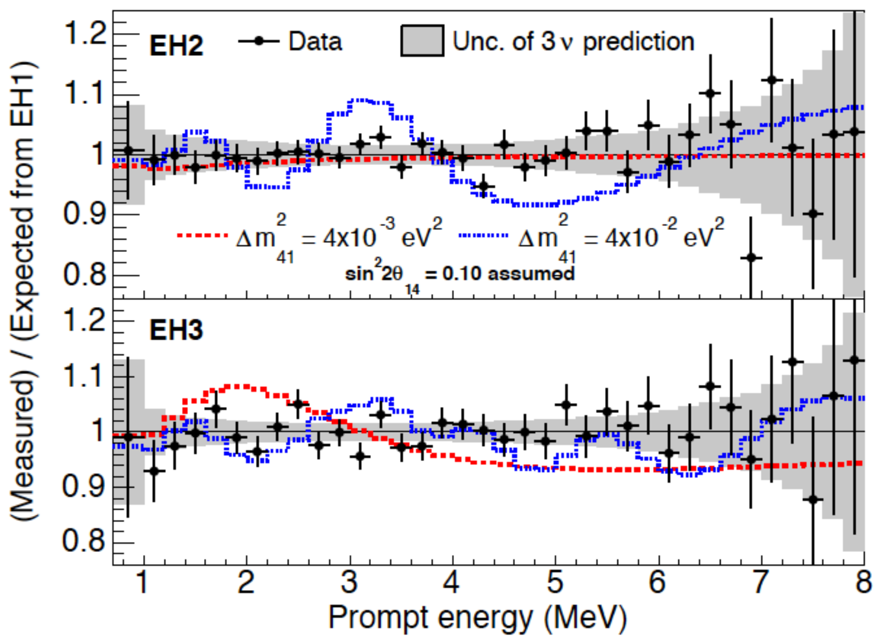
- **KATRIN –as designed – can test the ν_e disappearance anomalies (sensitivity to be assessed with syst.)**

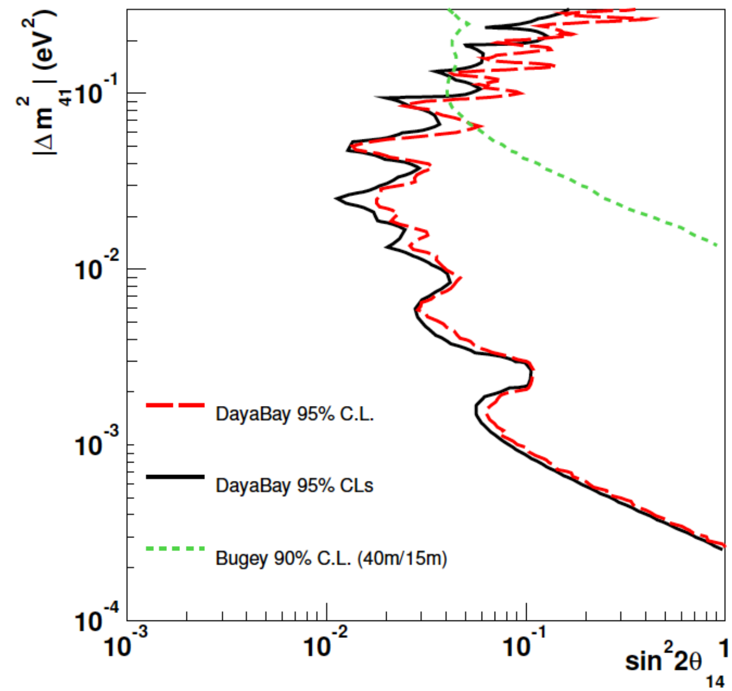




	Tech	Reactor	P [MW]	L (m)	M (tonnes)	Starting dates
Nucifer	LS+Gd	OSIRIS	70	7	0.8	ended 2015
POSEIDON	LS+Gd	PIK	100	5-8	~3	not funded
STEREO	LS+Gd	ILL	57	8.8-11.2	1.75	Aug 2016
Neutrino-4	LS+Gd	SM3	100	6-12	1.5	2014 - ended ?
PROSPECT	LS + Gd/^{6}Li	ORNL HFIR	85	7-18	1 & 10	awaits funding
SoLid	PVT + ^{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

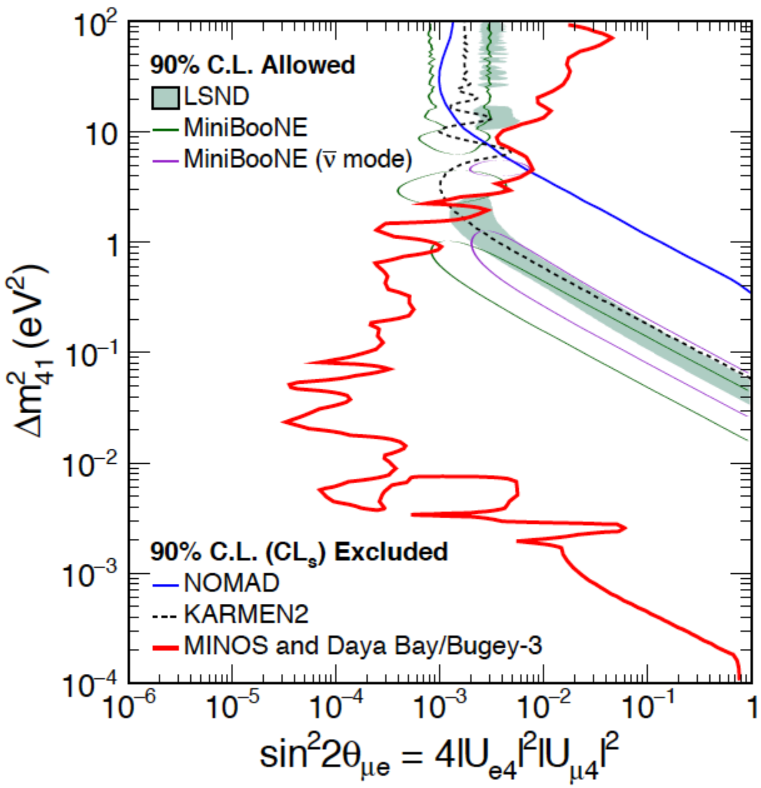
Sterile neutrino search in Daya Bay





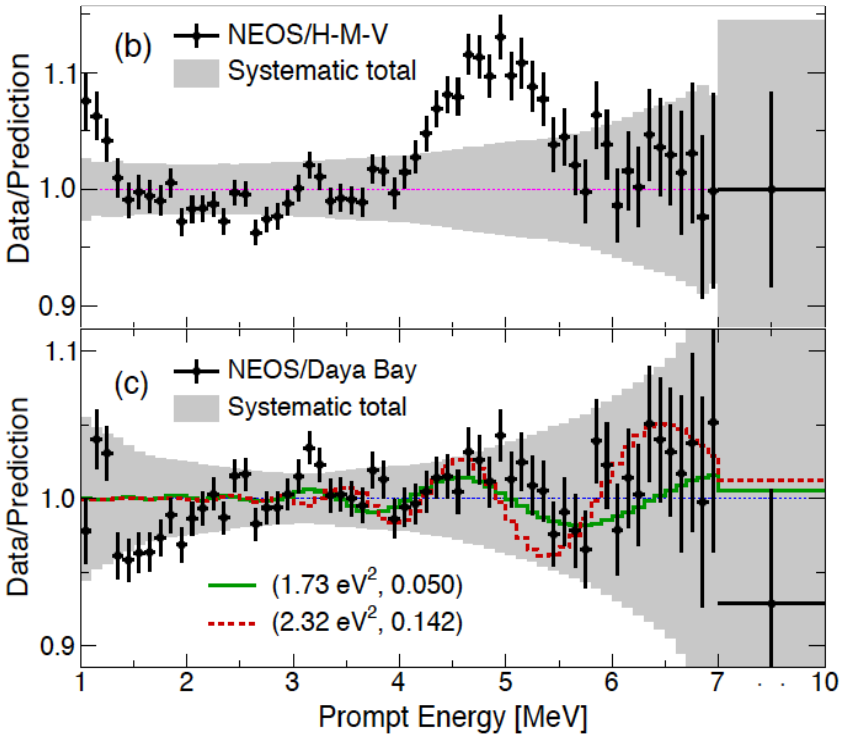
- Compromised sensitivity on the *interesting region* due to the large distance and reactor size
  - Still, important constraints provided by DB
  - Similar analyses put forward by Double Chooz and RENO

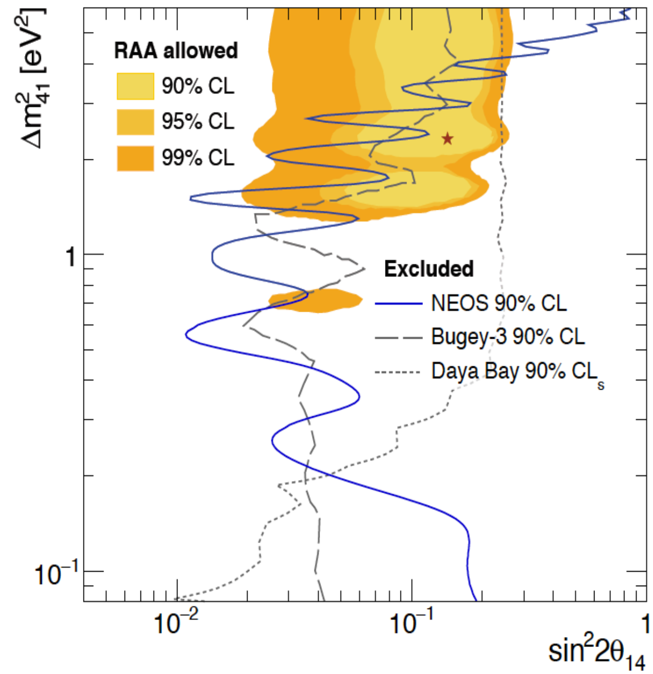
Bougey-3, Daya Bay and MINOS



- Combination of Bougey-3, Daya Bay and MINOS
- Strong constraints imposed on the appearance channel
  - Exclusion contour covers part of the LSND/KARMEN allowed region
  - Complementary information to ICARUS/OPERA

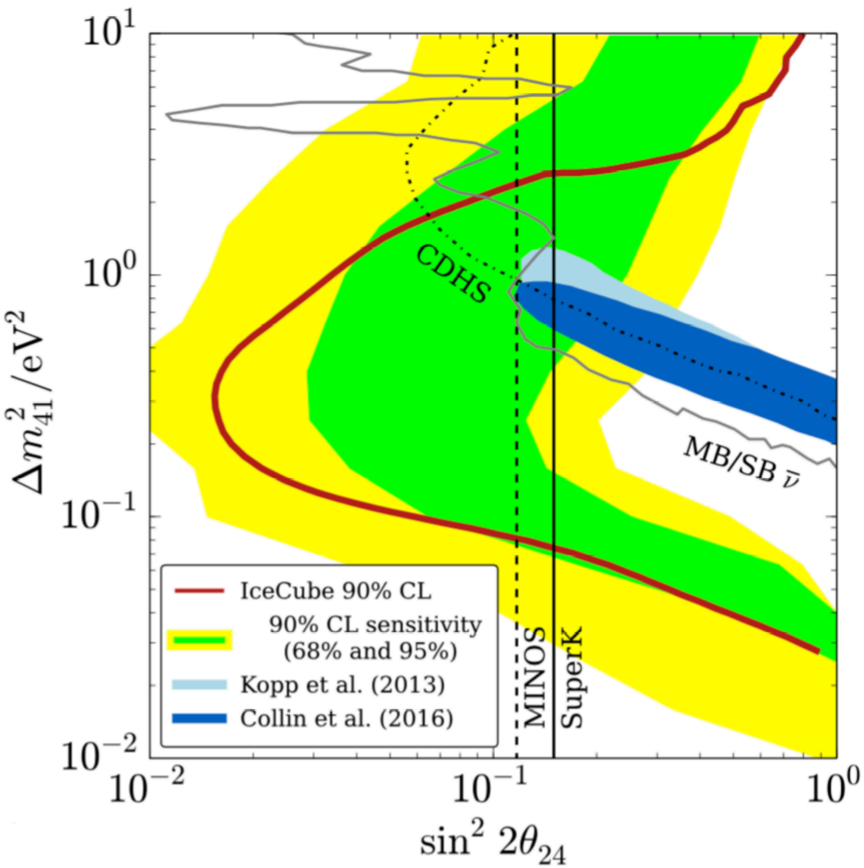
The NEOS experiment in Korea





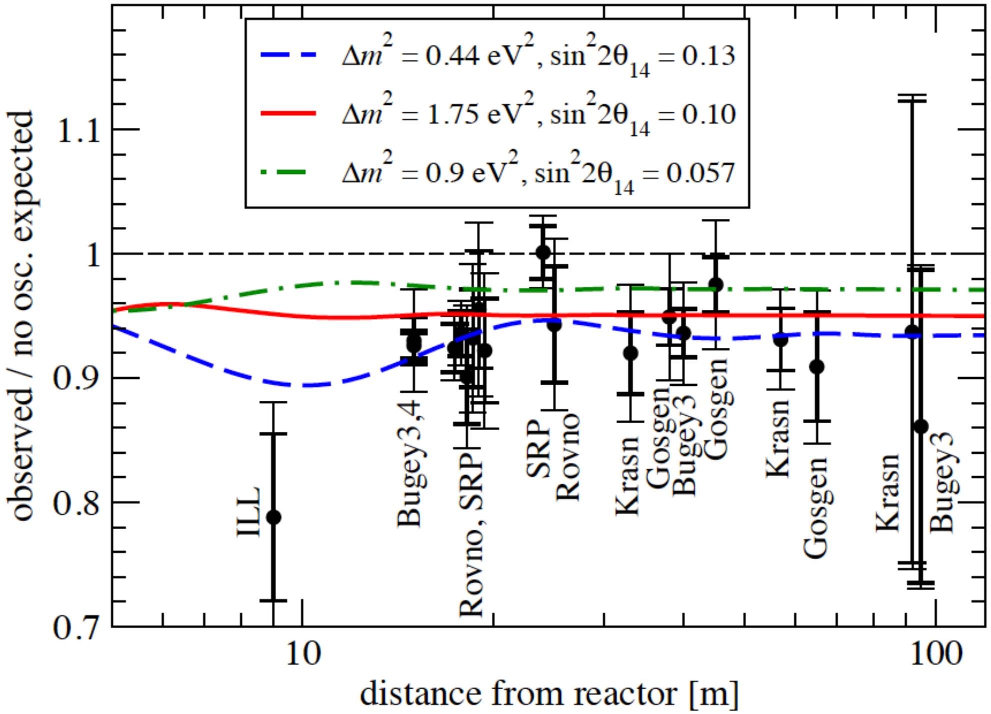
- Experiment in a power reactor
  - Confirmation of the so-called ~ 5 MeV bump seen by Daya Bay, Double Chooz and RENO
  - Lower sensitivity on the large Δm^2

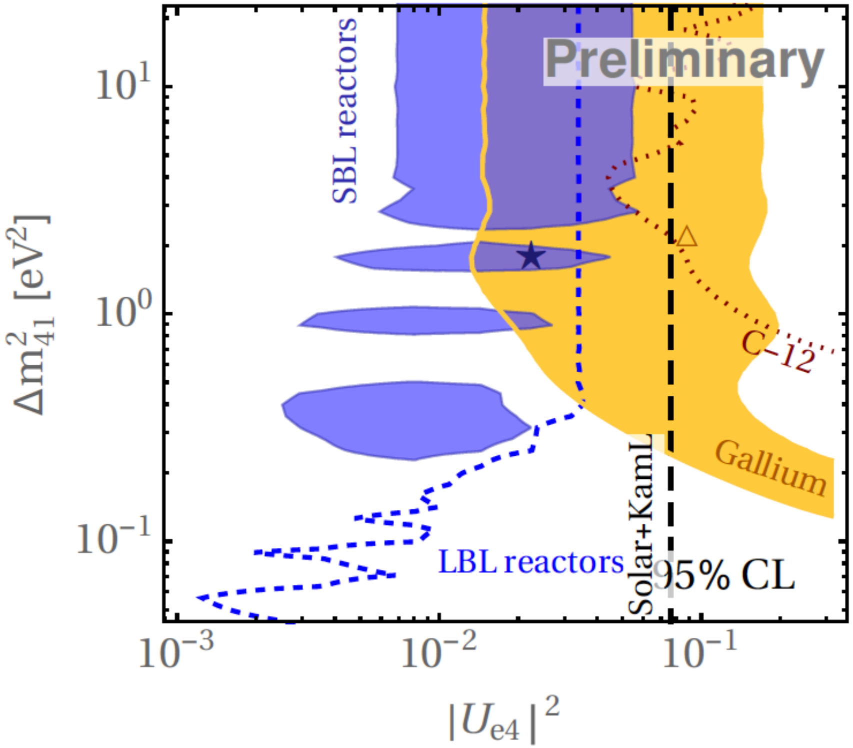
IceCube



- Matter-induced oscillations produced by the *potential existence* of sterile neutrinos

$\overset{(-)}{\nu}_e$ disappearance in the 3+1 scenario





	$\sin^2 2\theta_{14}$	Δm^2_{41} [eV^2]	χ^2_{min}/dof (GOF)	$\Delta\chi^2_{no\ osc}$/dof (CL)
SBL rates only	0.13	0.44	11.5/17 (83%)	11.4/2 (99.7%)
SBL incl. Bugey3 spect.	0.10	1.75	58.3/74 (91%)	9.0/2 (98.9%)
SBL + Gallium	0.11	1.80	64.0/78 (87%)	14.0/2 (99.9%)
global ν_e disapp.	0.09	1.78	403.3/427 (79%)	12.6/2 (99.8%)

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Dentler JK Machado Maltoni Schwetz, in prep.

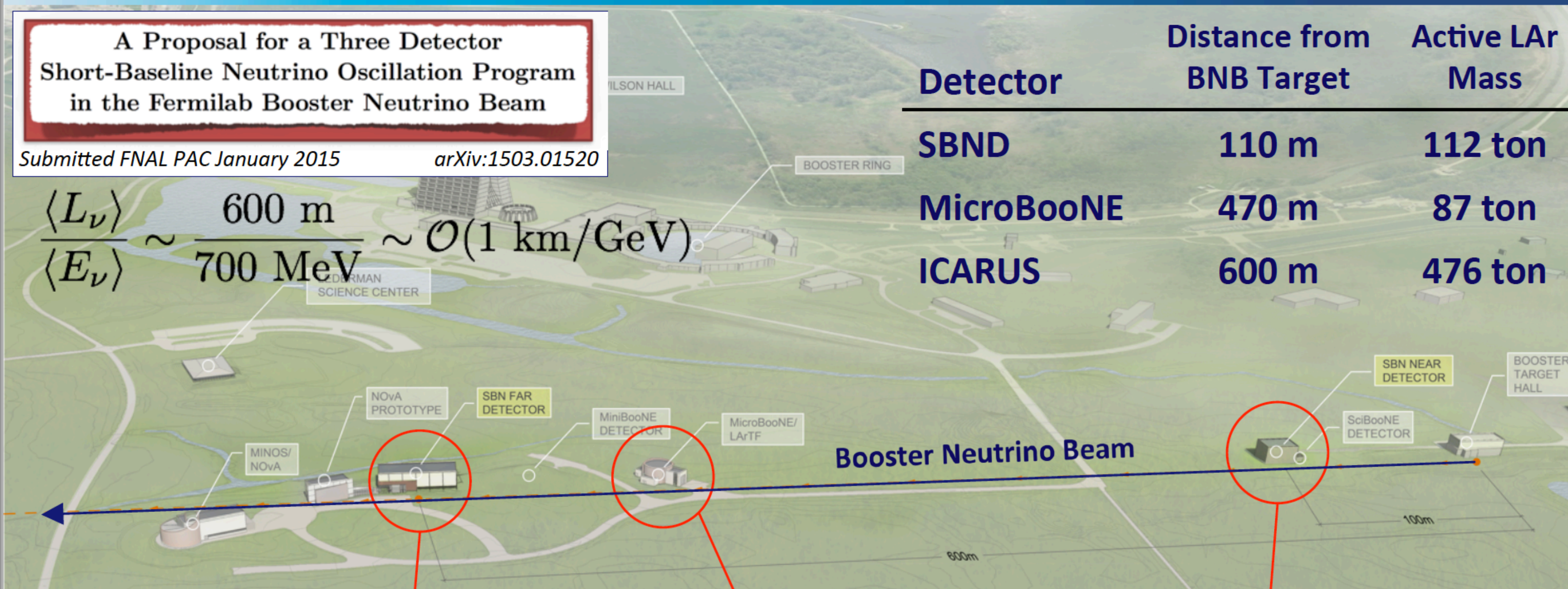
The Three LArTPC SBN Program

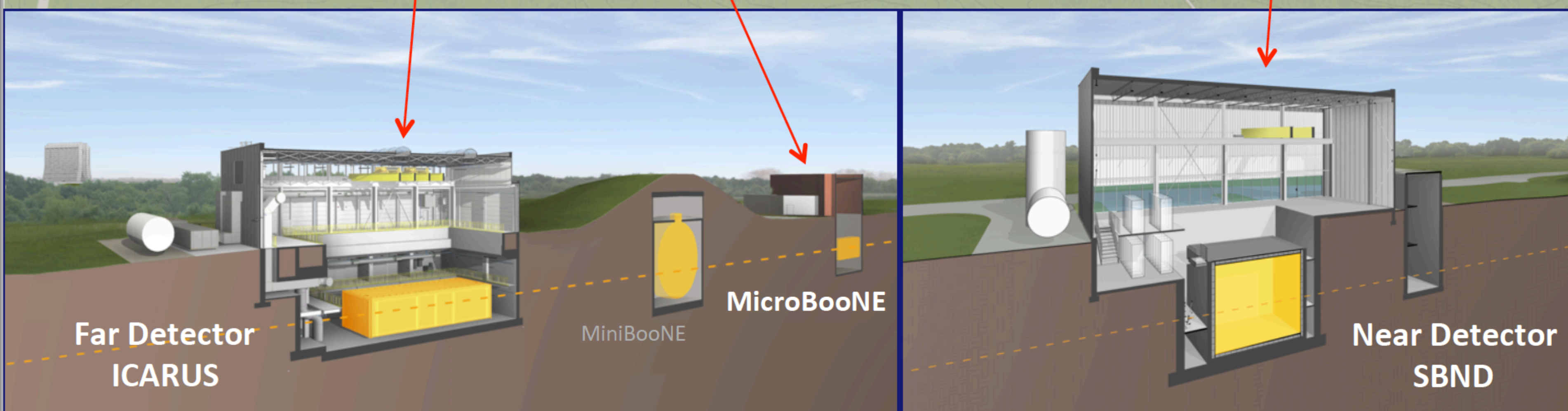
A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam

Submitted FNAL PAC January 2015 *arXiv:1503.01520*

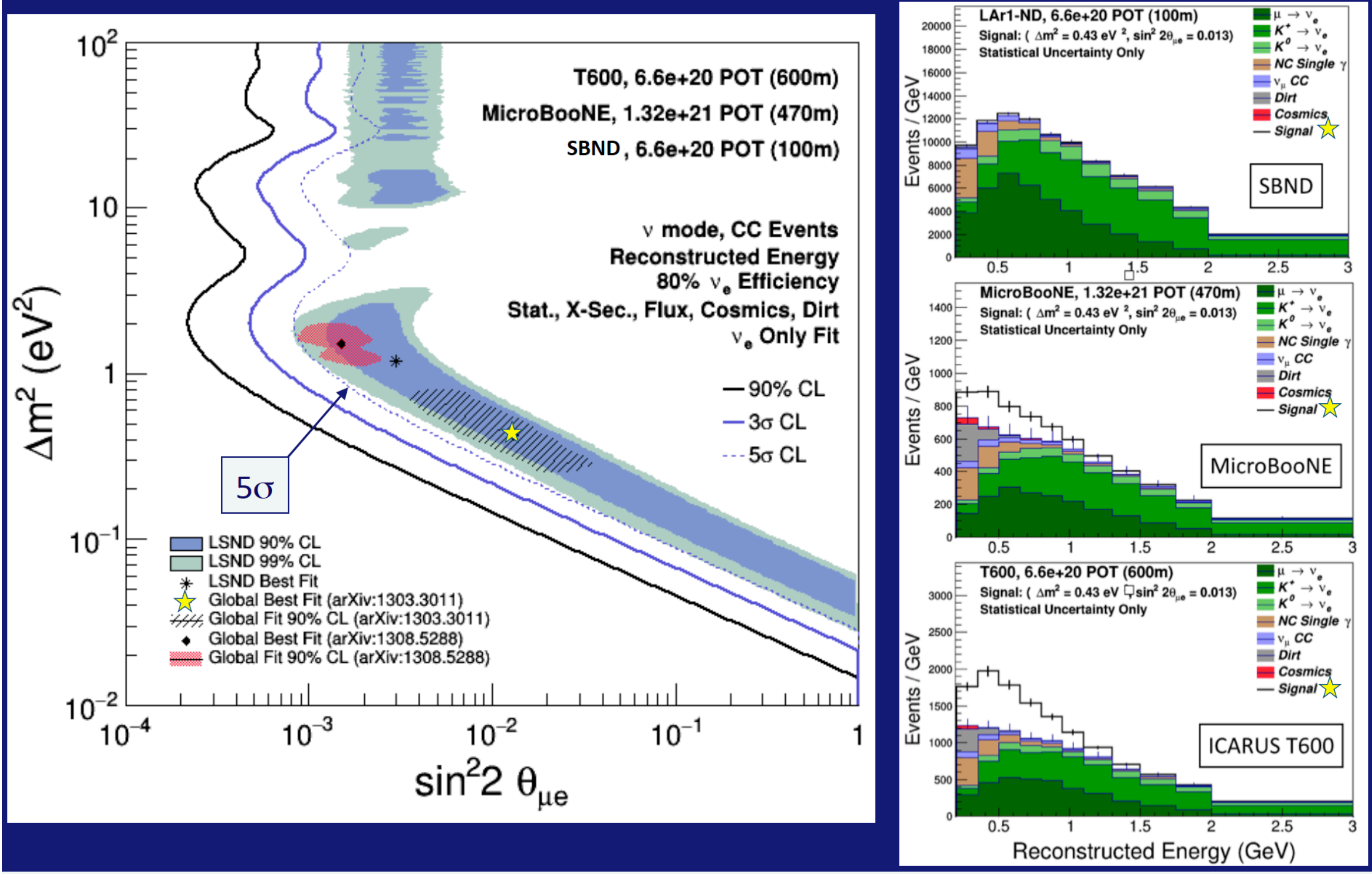
$$\frac{\langle L_\nu \rangle}{\langle E_\nu \rangle} \sim \frac{600\ \text{m}}{700\ \text{MeV}} \sim \mathcal{O}(1\ \text{km/GeV})$$

Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton

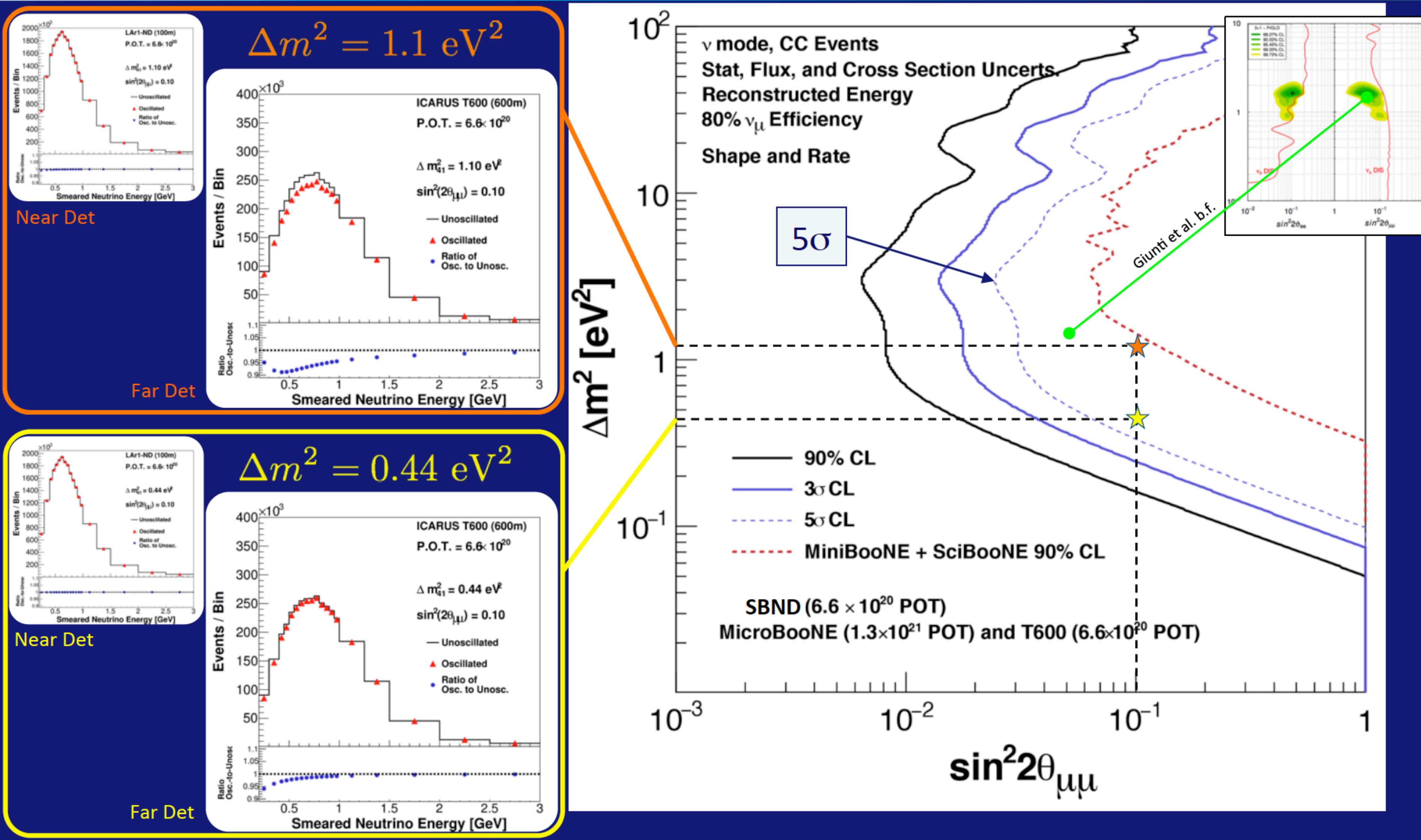




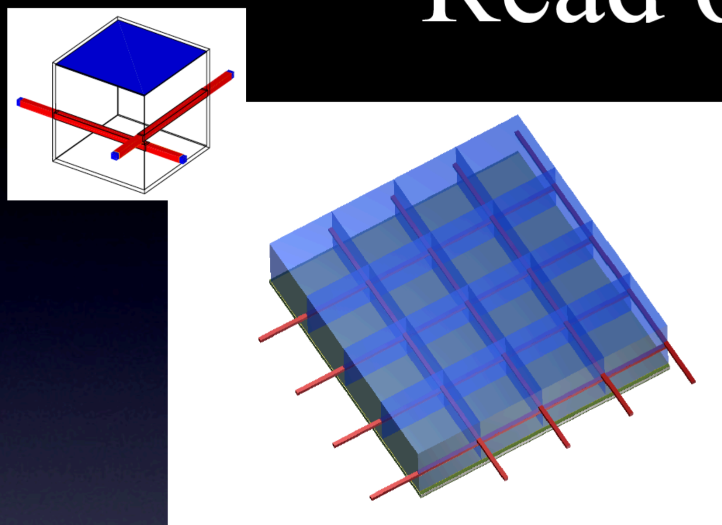
SBN $\nu_\mu \rightarrow \nu_e$ Oscillation Sensitivity

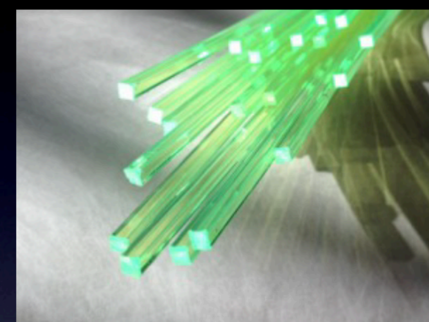


SBN $\nu_\mu \rightarrow \nu_x$ Oscillation Sensitivity

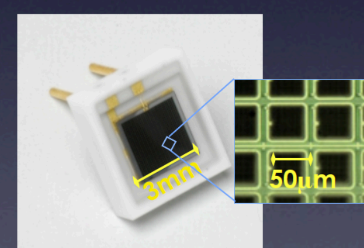


Read out





Squared BCF-91A fibre



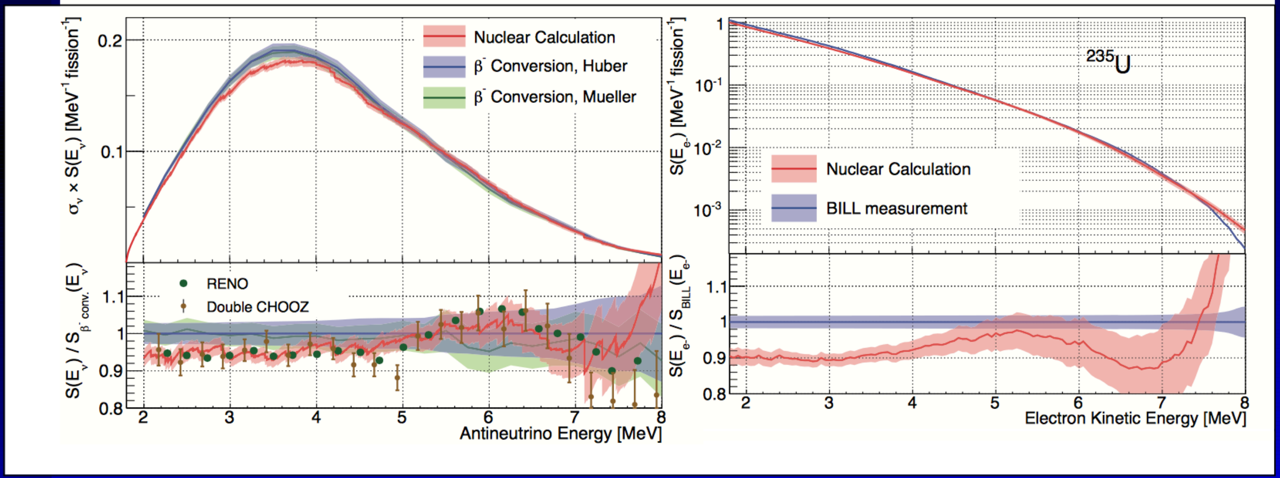
MPPC 3 mm x 3 mm
50 um pixel pitch
60-65% active area
Pixel RC cnst~13 ns
PDE ~ 30-40%

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

Explanations?

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

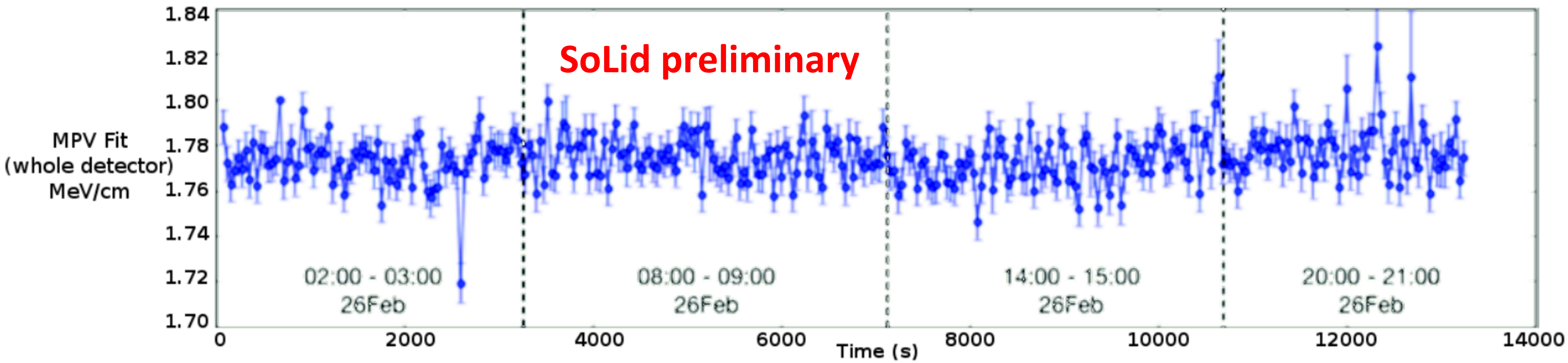
Dwyer and Langford, 2014



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

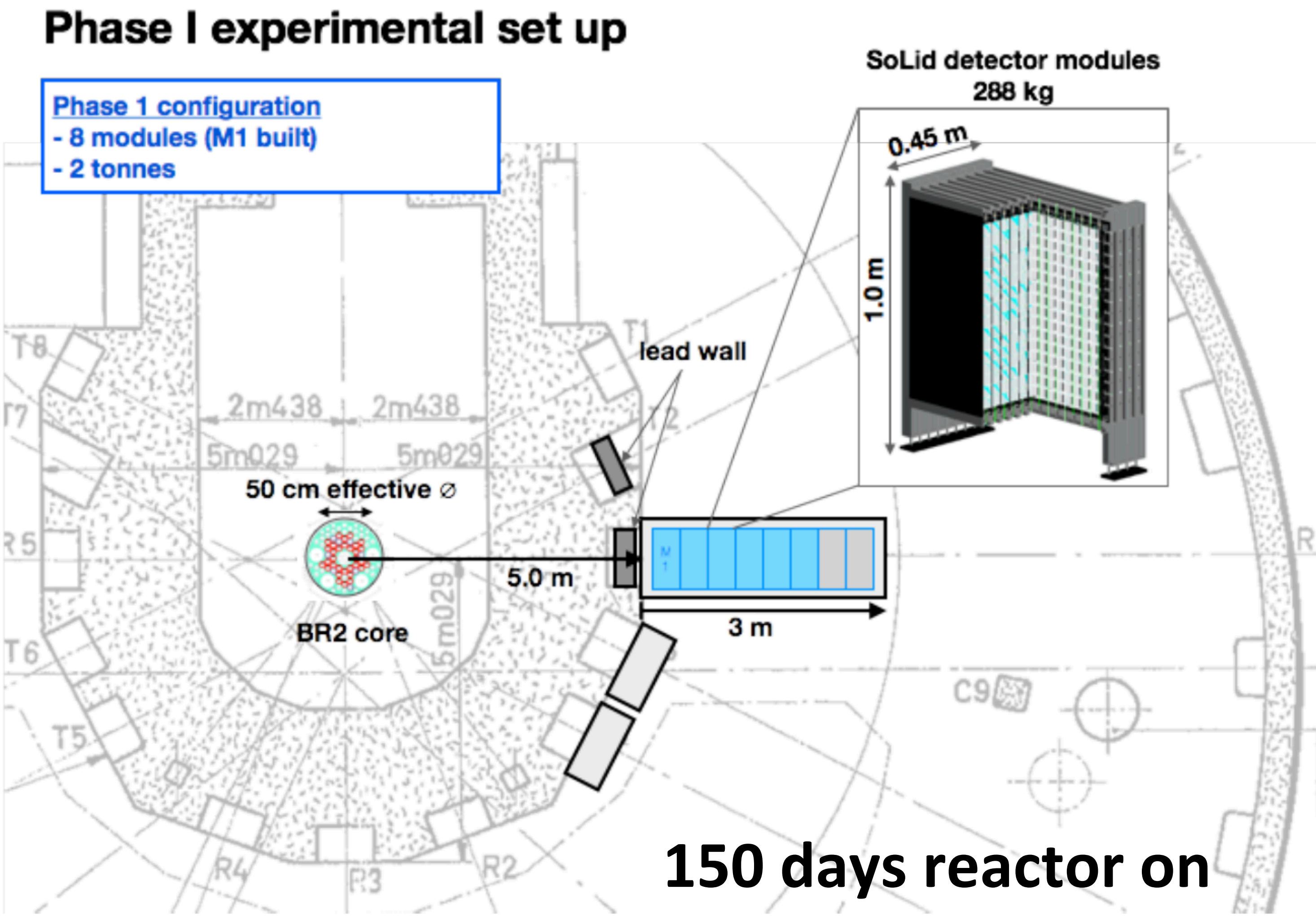
P. Huber – p. 18

Calibration stability



- Very good stability over time
  - A few % deviations in the energy scale only
  - Temperature well-controlled in BR2

Future plans: 2016-2017

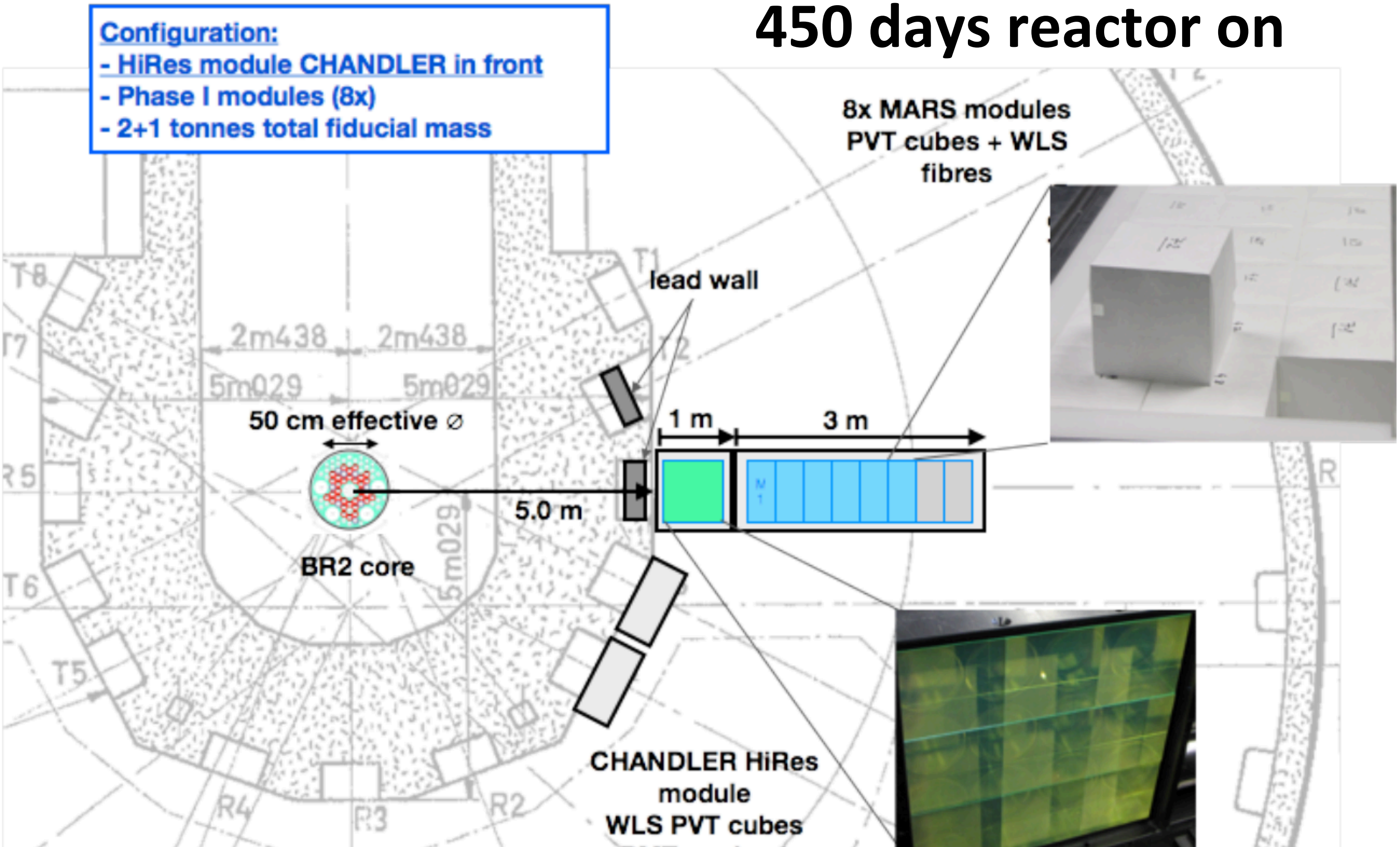


150 days reactor on

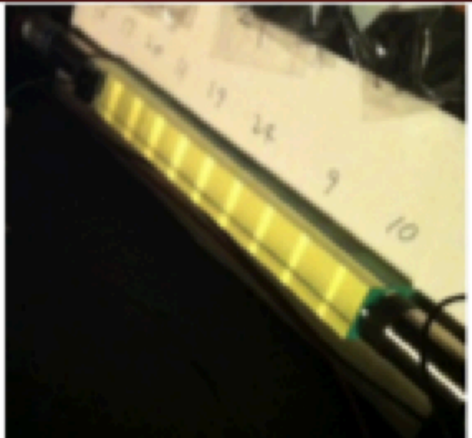
Future plans: 2017-2020

Phase II experimental set up

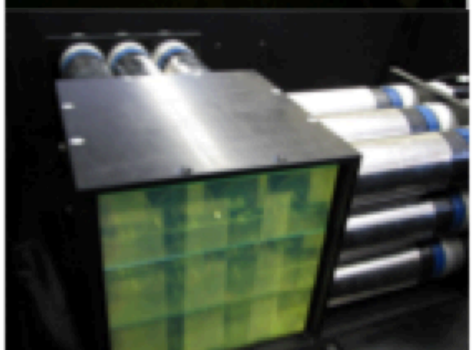
450 days reactor on



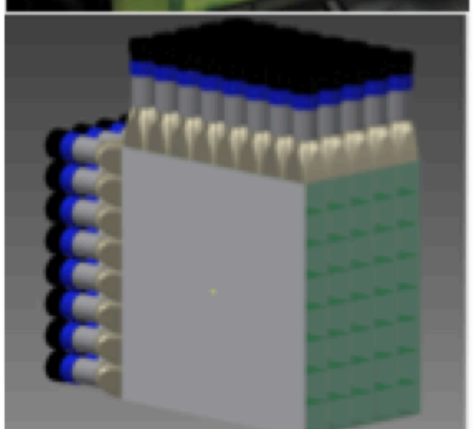
CHANDLER R&D Effort



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