Sterile : Short Baseline Neutrino Experiments

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Outline

- Anomalies and sterile hypothesis
- Disappearance experiments: Testing antineutrino deficit and potential oscillation
- Experimental parameters and environment of a Short Baseline experiment
- Short Baseline reactor experiments
- Conclusion

Physics Beyond the 3-ν SM?

• Experimental anomalies ranging in significance (2.8-3.8σ) have been reported over the past 20 years from a variety of experiments studying neutrinos at baselines less than 1km.

Experiment	Type	Channel	Significance
LSND	DAR	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	3.8σ
MiniBooNE	SBL accelerator	$\nu_\mu \to \nu_e$ CC	3.4σ
MiniBooNE	SBL accelerator	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	2.8σ
GALLEX/SAGE	Source - e capture	ν_e disappearance	2.8σ
Reactors	Beta-decay	$\bar{\nu}_e$ disappearance	3.0σ

K. N. Abazajian et al. "Light Sterile Neutrinos: A Whitepaper", arXiv:1204.5379 [hep-ph], (2012)

$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ appearance

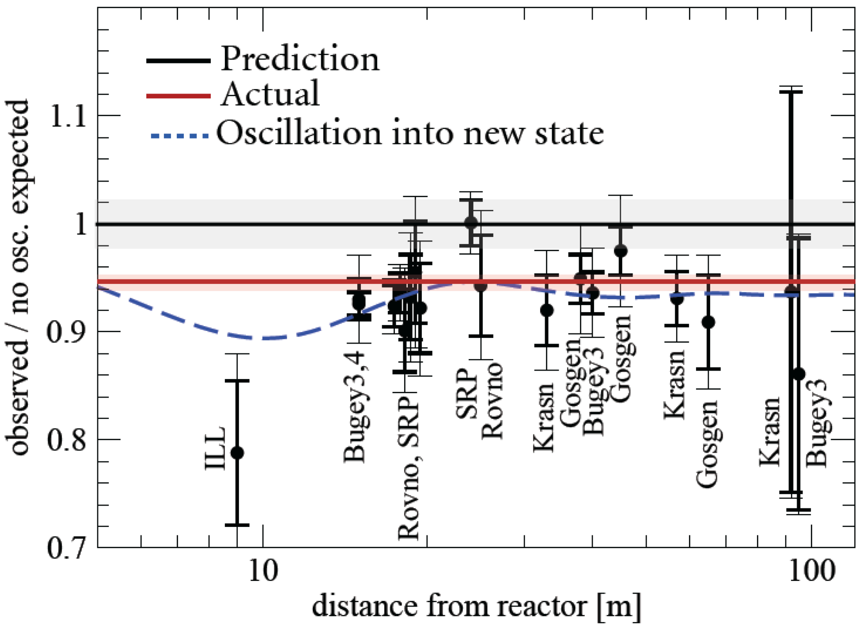
$\overset{(-)}{\nu}_e$ disappearance

• **Combined no oscillation disfavored at more than 99.9% C.L. (3.3σ)** Common interpretation is as evidence for one or more additional, mostly **"sterile" neutrino states driving oscillations at $\Delta m^2_{new} \approx 1$ eV^2** and a relatively small $\sin^2(2\theta_{new})$.

• Confirmation of the sterile neutrino hypothesis would be a major discovery, physics beyond the SM

• A definite null result would settle a long-standing open question with possible implications in future experiments (better predictions) and in nuclear physics.

Reactor Anomaly

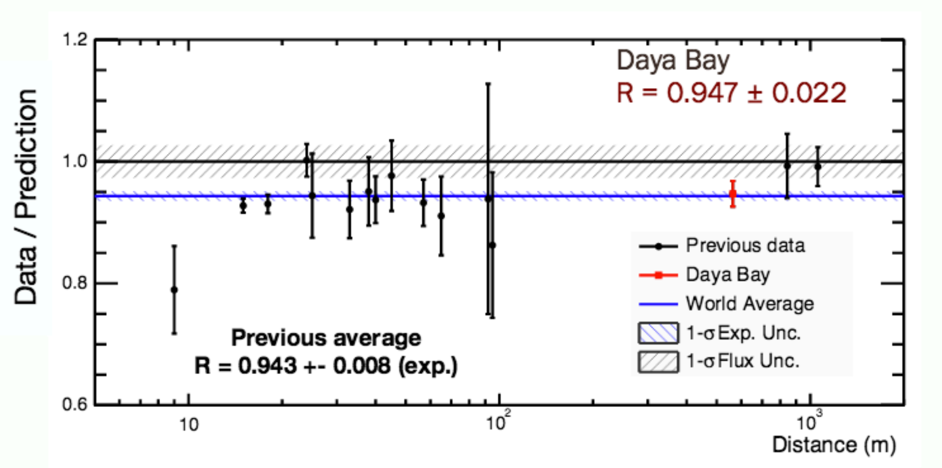


↓ 2.7σ deficit

Reanalysis of reactor SBL experiments
G. Mention et al., Phys. Rev. D83, 073006 (2011)

current rate anomaly due to unknown effect, to some prediction issues or to new physics ?

Daya Bay's reactor flux measurement is consistent with previous SBL experiments



arXiv:1508.04233

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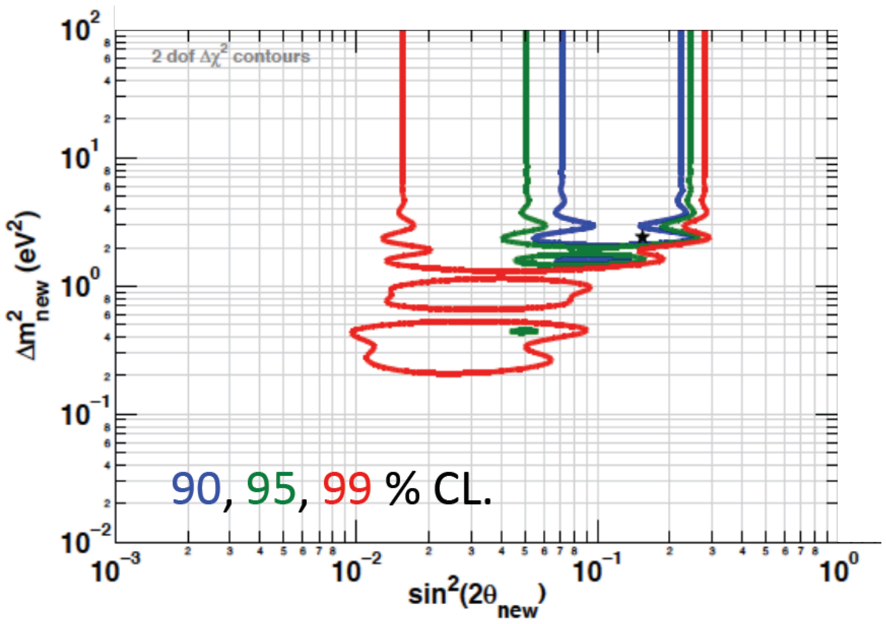
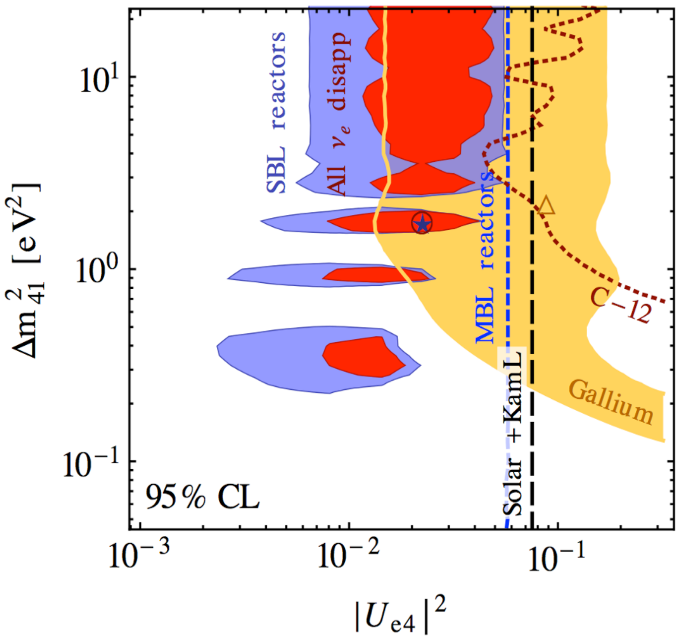
Sterile neutrinos

The measured anomalies can be explained by a sterile neutrino state with Δm^2 around eV^2



Sterile neutrino white paper arXiv:1204.5379



J. Kopp et al., hep/ph: 1303.3011

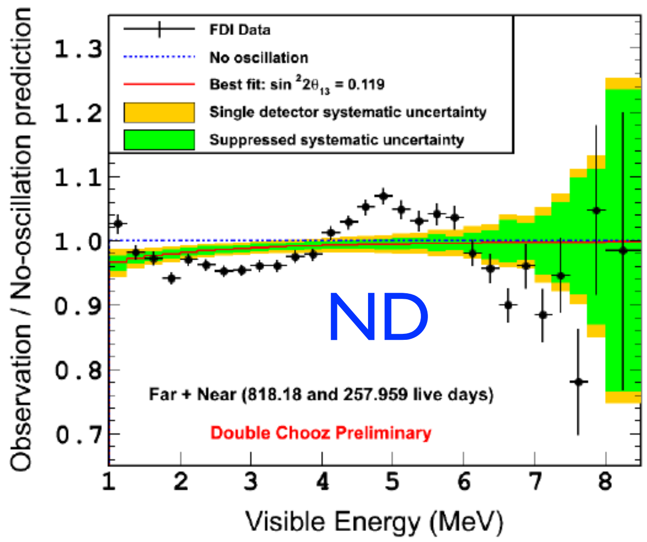
Two techniques in ν_e disappearance to address this on a short timescale:

1. Large source, large detector experiments
2. very short baseline [5-20] m reactor experiments

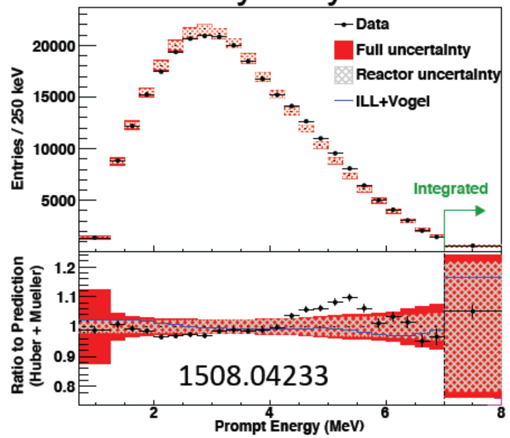
Recent reactor data: Anomalous Reactor Spectrum Results

- Distortion in e+ spectrum observed / predicted at all three experiments (Double Chooz, Daya Bay, RENO)
  - local excess in [4,6] MeV window in Daya Bay data
  - no effect on θ_{13} measurement and reactor anomaly
  - Origin of the excess to be understood: is it a physics effect or a bias in the predictions?

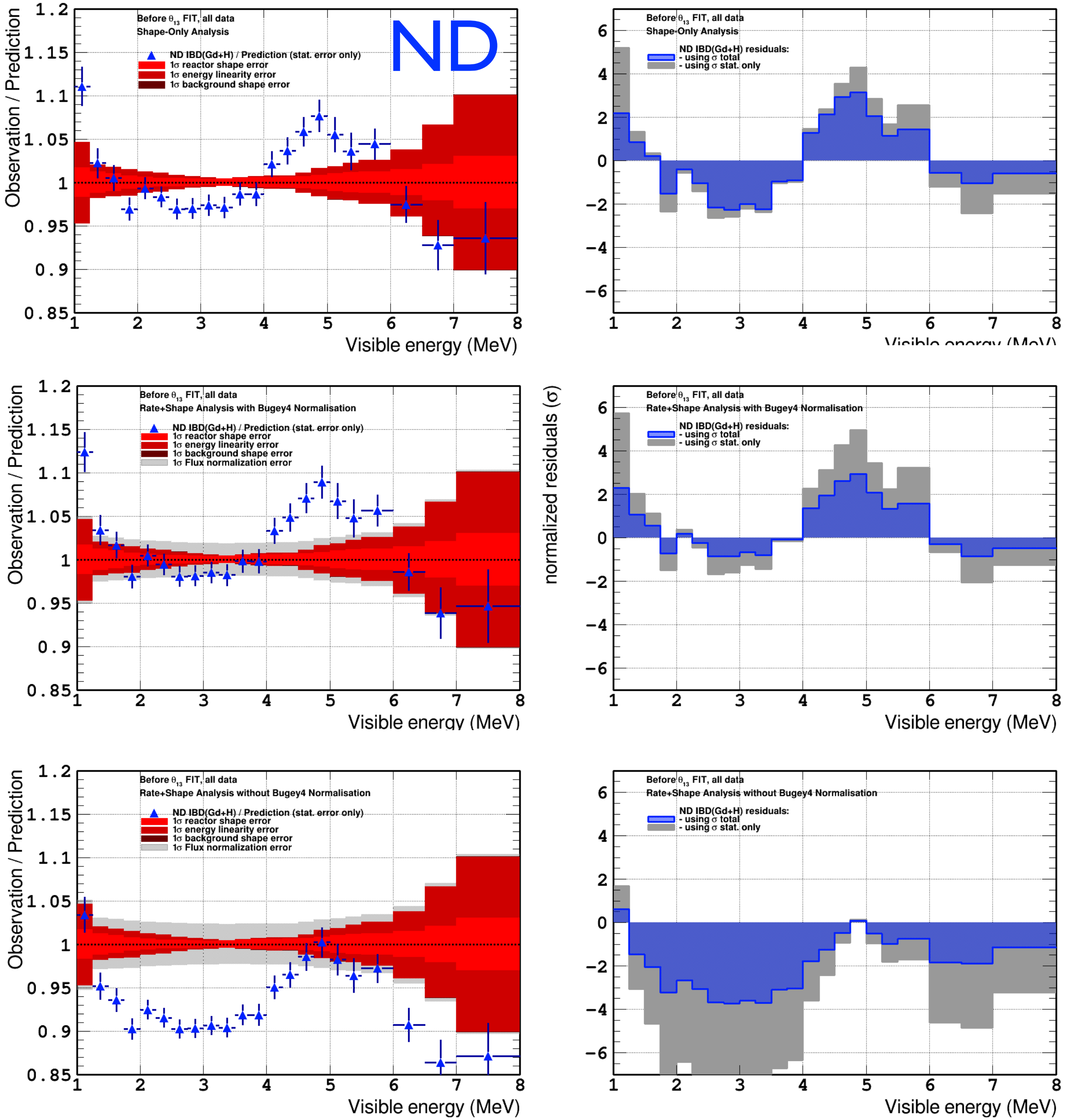
DOUBLE CHOOZ
Ratio data/non oscillation predictions



Daya Bay



Distortion analysis with ND rate+shape (A. Cabrera CERN seminar 09/16)



shape-only

rate via Bugey4

rate via prediction

Test the existence of features not biased by shape-only assumption (i.e. smaller errors)

shape-only≈Bugey4 (consistency of Bugey4?)

non-statical features
- which is deficit?
- which excess?
- which is OK?

$\Rightarrow$ less evident!!

careful analysis before stating the "trouble region" is bump problem really? (maybe no bump whatsoever)

(bias question → bias answer)

Ongoing & Future Short-Baseline Experiments

Accelerator Decay-in-Flight:
Fermilab Short-Baseline (SBND, MicroBooNE, ICARUS) , nuSTORM

Accelerator Decay-at-Rest:
OscSNS, IsoDAR, KDAR/Kpipe, JSNS^2

Sterile Searches that are not Short-Basline:
OPERA, IceCube, MINOS+, Plank, KATRIN

Radioactive Neutrino Sources:
SOX

Reactor Experiments:
CHANDLER, DANSS, Neutrino-4, NEOS, Prospect, NuLAT, Stereo, Solid

Borexino / SOX

Borexino designed to detect solar neutrinos from ^{7}Be via **elastic scattering off electrons** in **highly purified** liquid scintillator

Detection via scintillation light:

✓Very **low energy** threshold

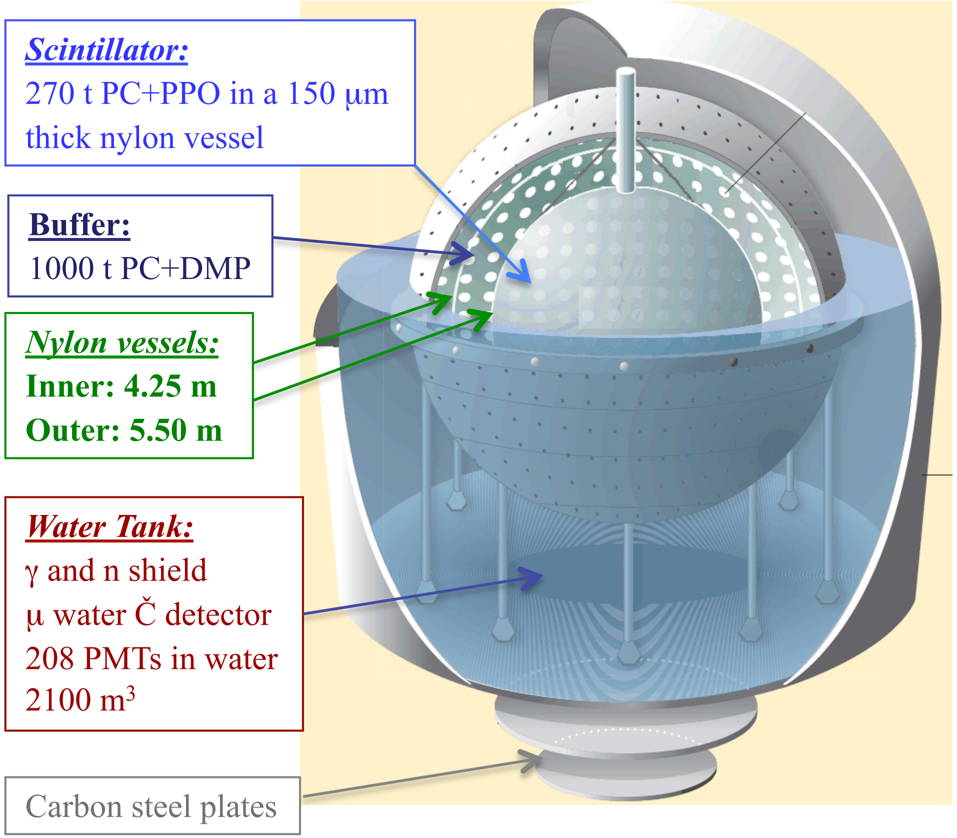
✓Good **position** reconstruction

✓Good energy **resolution**

BUT…

✓No **direction** measurement

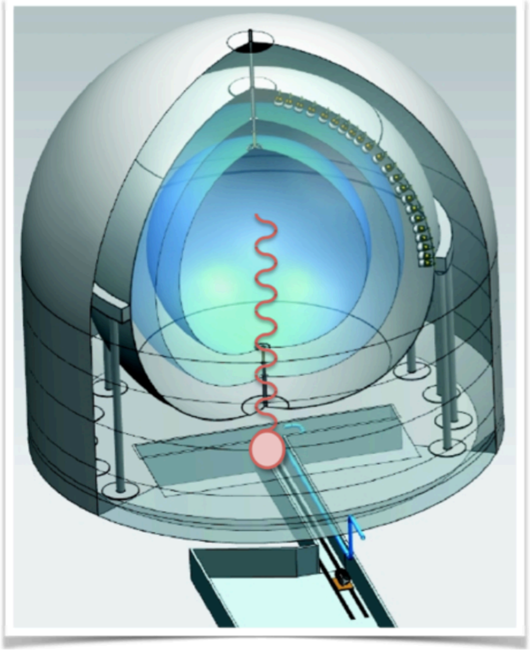
✓The ν induced events can't be distinguished from other background events due to **natural radioactivity**



Extreme radiopurity of the scintillator is a must!

SOX

The ^{144}Ce source

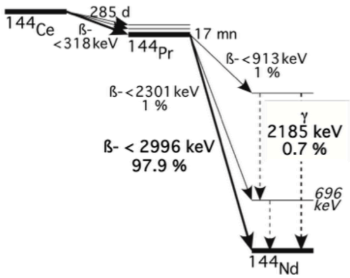


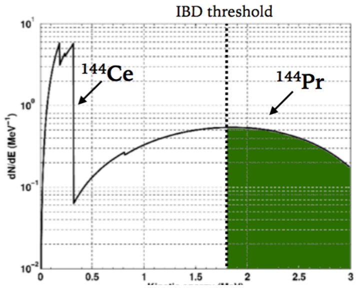
activity: (100-150) kCi ≈ (3.7-5.5) PBq

$^{144}Ce \xrightarrow[T_{1/2}=285d,\ Q\sim0.3\ MeV]{\beta^-} {}^{144}Pr \xrightarrow[T_{1/2}=17min,\ Q\sim 3\ MeV]{\beta^-} {}^{144}Nd$

long life time
- production
- transportation
- measurement

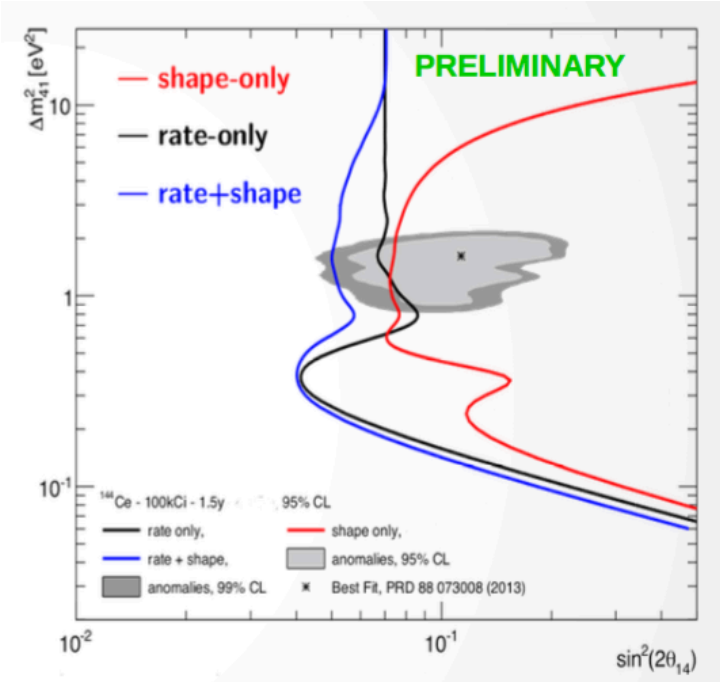
high Q value
- antineutrinos above IBD threshold





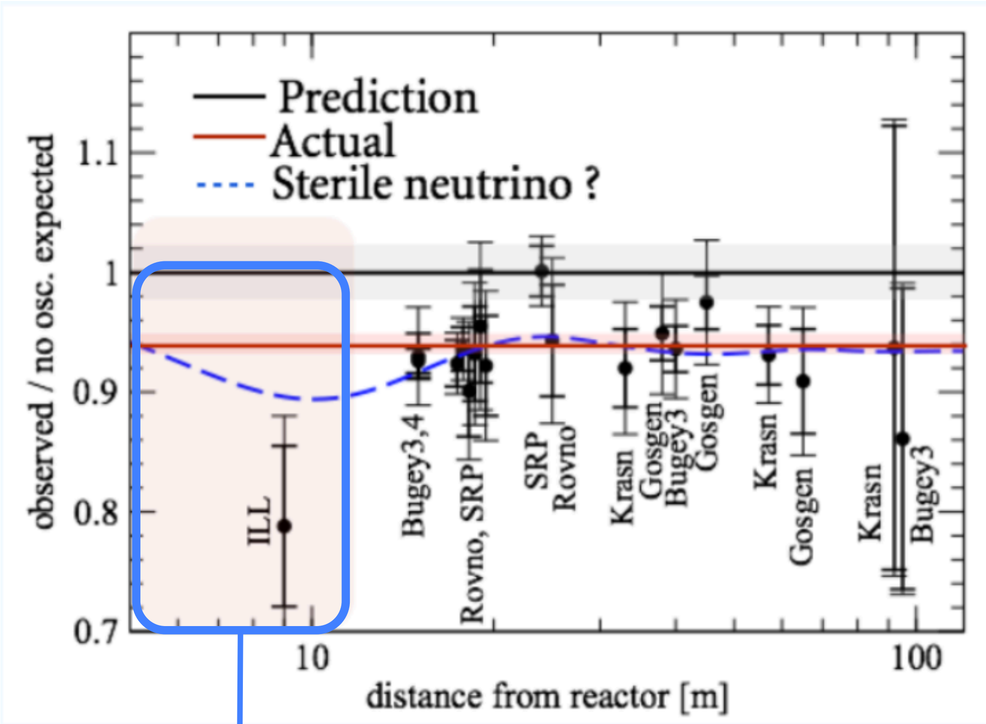
- **Rate analysis**: standard disappearance experiment
- **Shape analysis**: waves inside Borexino!

$$P_{ee} = 1 - \sin^2 2\theta_{14} \sin^2 \frac{1.27\,\Delta m^2_{14}(eV^2)\,L(m)}{E(MeV)}$$



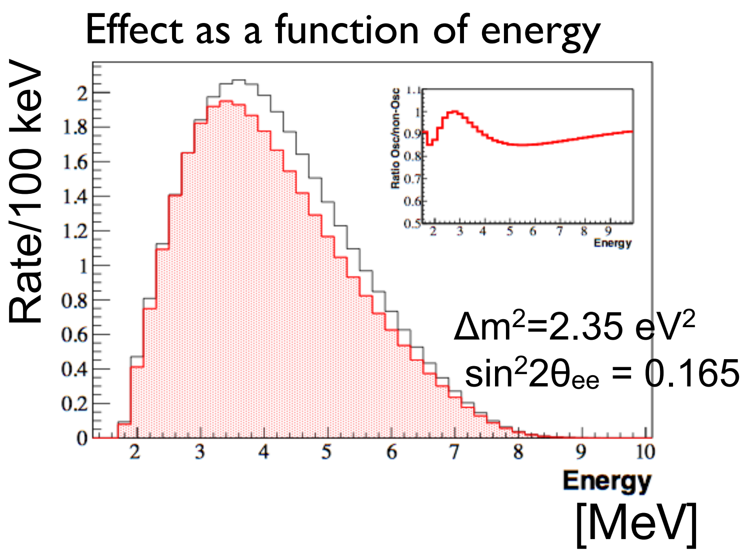
Short Baseline at reactors

Look for rate and energy variations



Data scarce at short distance :

Need better experiments and other data points !



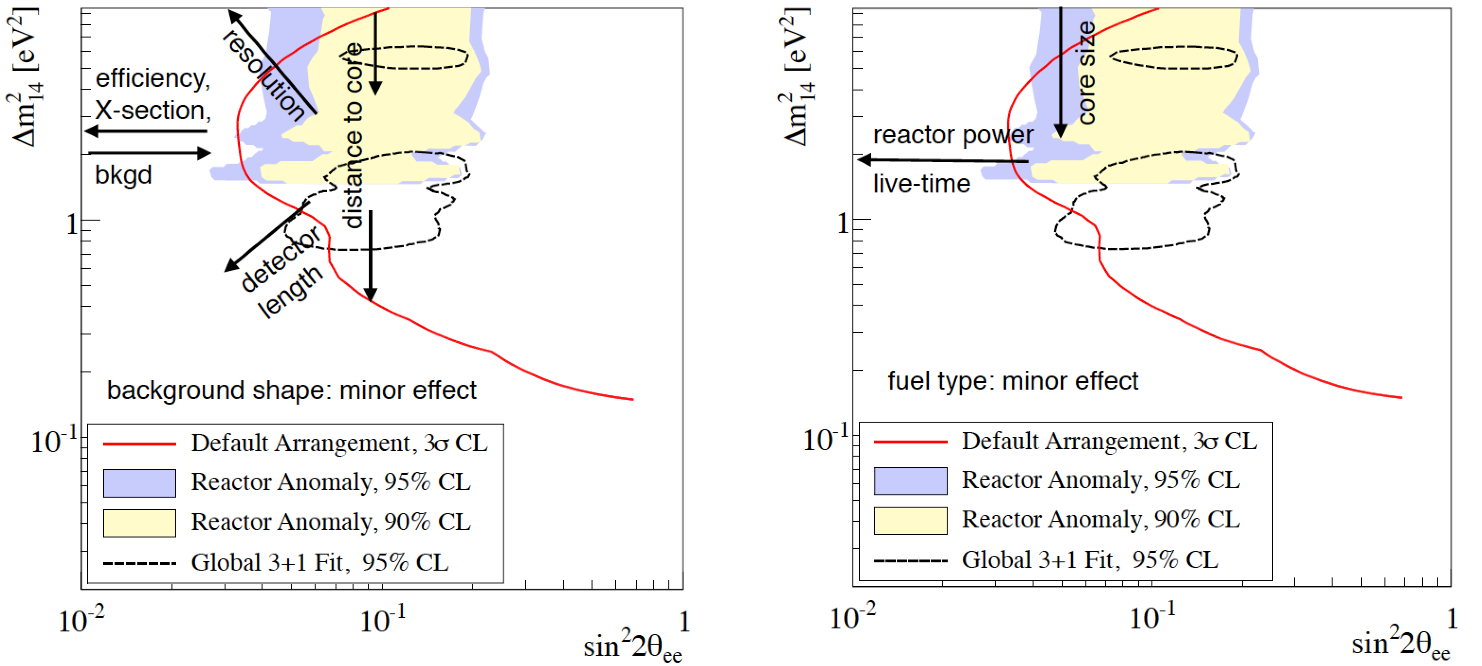
- Good energy resolution experiment
- Good position resolution

- Control of background is key for best sensitivity

Key Experimental Parameters

Reactor and detector parameters relevant for covering the suggested parameter space.

K.M. Heeger et al., arXiv:1212.2182v1



Total Statistics: Highest possible power and a detector with the highest possible efficiency

Detector length: A large detector length increases an experiment's ability to resolve oscillations with position in addition to spectral distortions in energy.

Detector-reactor distance:The closest reactor-detector distance r_{min} determines the Δm^2 range of highest sensitivity.

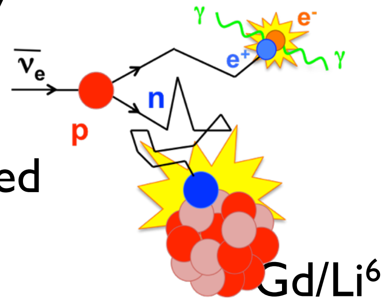
Detector resolution: Oscillations at higher Δm^2 are only visible if resolutions and bin sizing are smaller than the oscillation itself.

Background: The S:B ratio is crucial for the success of the experiment. Small S:B ratios make it difficult to resolve oscillation effects above statistical background fluctuations and uncorrelated background uncertainties

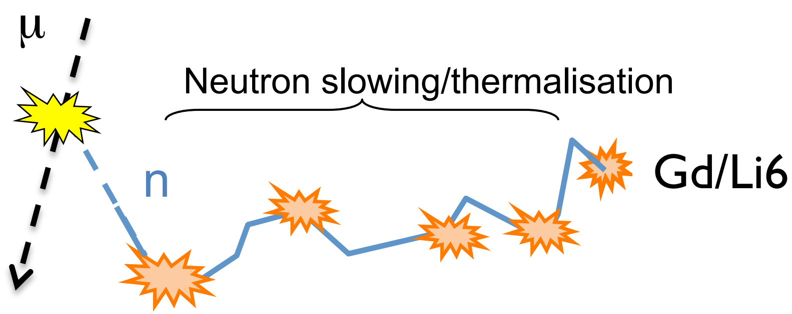
Environmental conditions: Backgrounds

- Inverse beta decay detection
- Low overburden
  - Large muon induced background (FN), difficult to shield
- Close to the reactor core
  - High reactor neutron and gamma accidental background
  - difference reactor ON/OFF data not enough
  - Reactor background conditions can change over the data taking at research reactors
- need high background rejection power, Control of background is key !
  - limit passive shielding to low Z to avoid regeneration of background

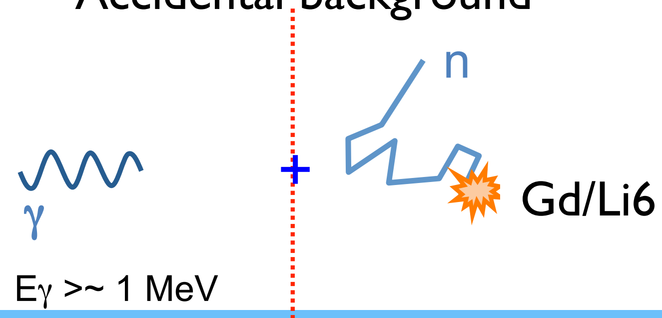
Detection principle: $\bar{\nu}_e + p \rightarrow e^+ + n$
Inverse Beta Decay



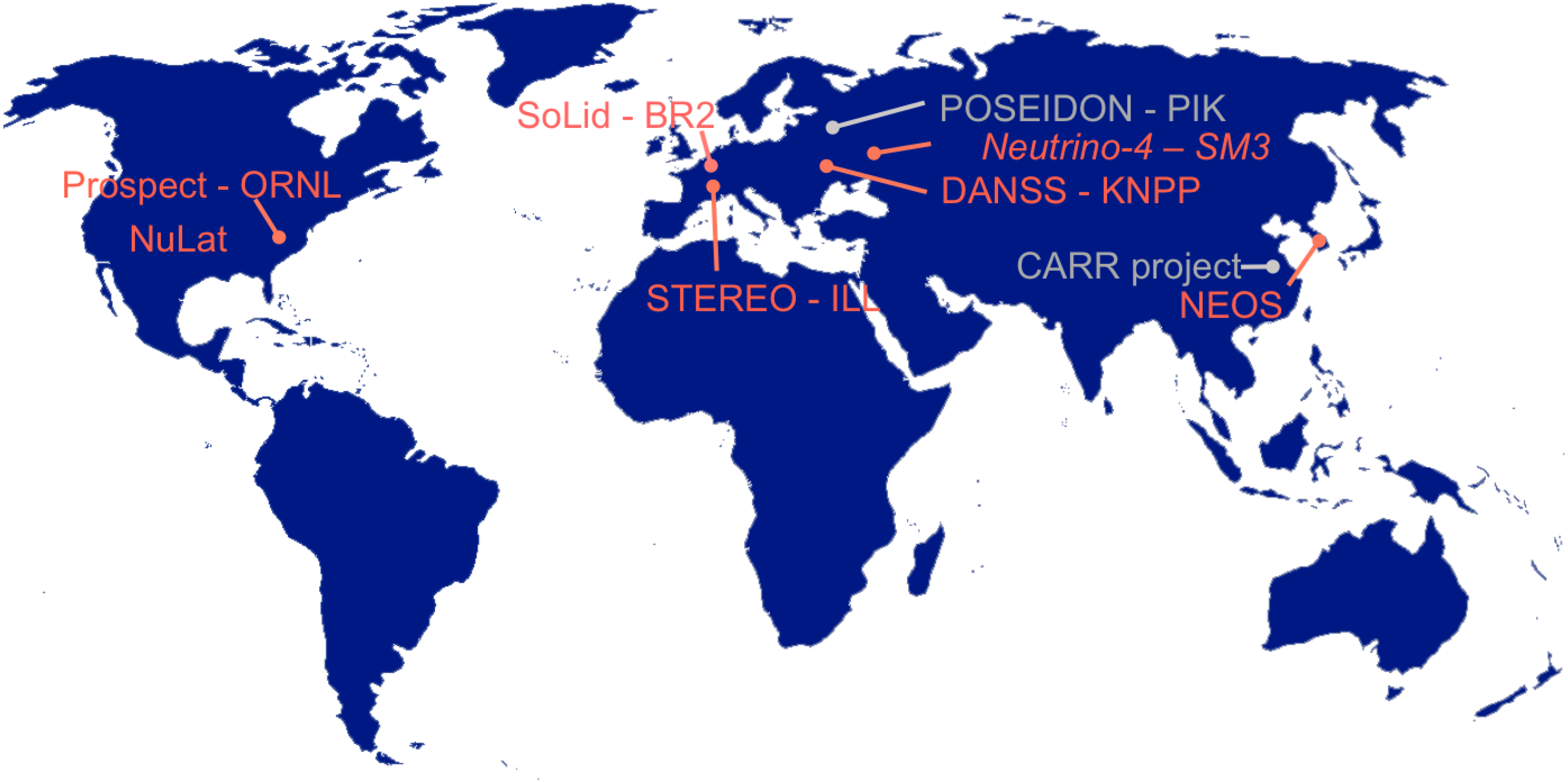
Correlated background from fast neutrons



Accidental background



SBL Reactor experiments

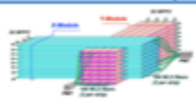
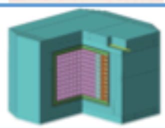
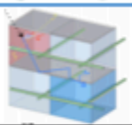
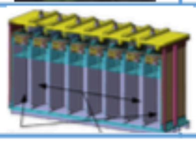


Detection principle:
Inverse Beta Decay

Neutron capture: Gd/Li[6]

Site: research reactor
or power reactor

SBL reactor experiments

Experiment		Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia)		3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only
NEOS (South Korea)		2800 MW LEU fuel	~20	Homogeneous Gd-doped LS	none	Direct double ended PMT	recoil PSD only
nuLat (USA)		40 MW ^{235}U fuel	few	Homogeneous ^{6}Li doped PS	Quasi-3D, 5cm, 3-axis Opt. Latt	Direct PMT	Topology, recoil & capture PSD
Neutrino4 (Russia)		100 MW ^{235}U fuel	~10	Homogeneous Gd-doped LS	2D, ~10cm	Direct single ended PMT	Topology only
PROSPECT (USA)		85 MW ^{235}U fuel	few	Homogeneous ^{6}Li-doped LS	2D, 15cm	Direct double ended PMT	Topology, recoil & capture PSD
SoLid (UK Fr Bel US)		72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm multiplex	WLS fibers	topology, capture PSD
Chandler (USA)		72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm, 2-axis Opt. Latt	Direct PMT/ WLS Scint.	topology, capture PSD
Stereo (France)		57 MW ^{235}U fuel	~15	Homogeneous Gd-doped LS	1D, 25cm	Direct single ended PMT	recoil PSD

Different technolgies, sites, features…

SBL Reactor experiments

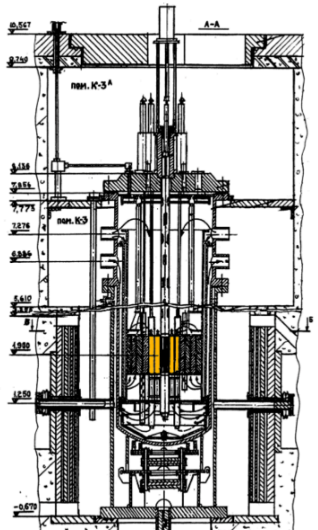
Liquid Scintillator unique target

+Gd-Loaded

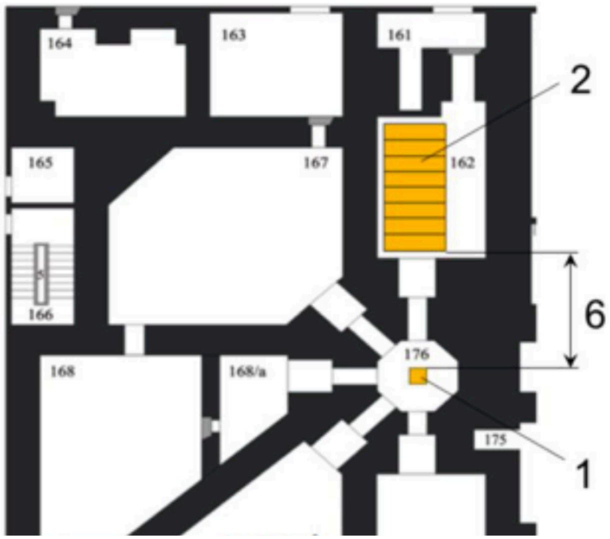
Neutrino-4, NEOS

NEUTRINO-4: 1.5t unique volume target

SM-3 Reactor Dimitrograd, Russia (100 MW)



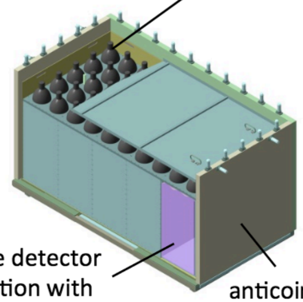
Core size
35 x 40 x 40 cm^3



- Dedicated site at SM-3
- Probe oscillation effect with distance ($1/R^2$)
- homogenous detector design, 1.5 tonnes
- Challenging background conditions
  - 60 tonnes of shielding
- First run with 1 detector unit (400L)

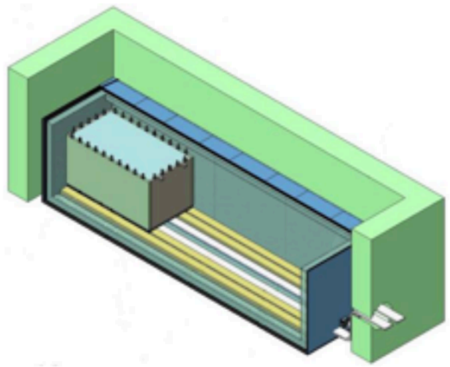
- Intensive background studies vs distance: found variations up to 14%

PMT

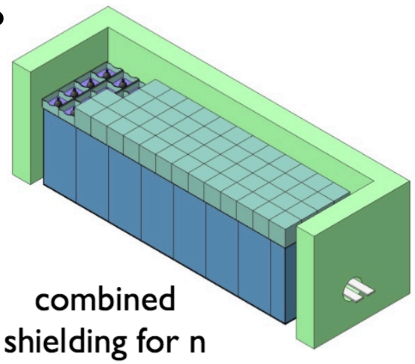


one detector section with scintillator

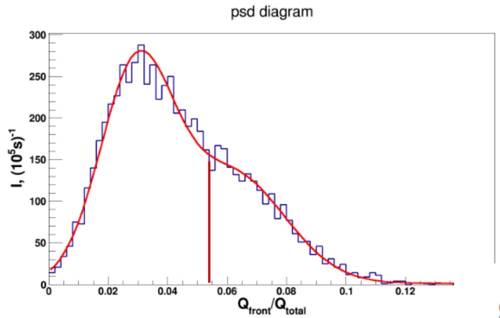
anticoincidence plastic shielding with PMT



moving platform on rails 6m - 12m

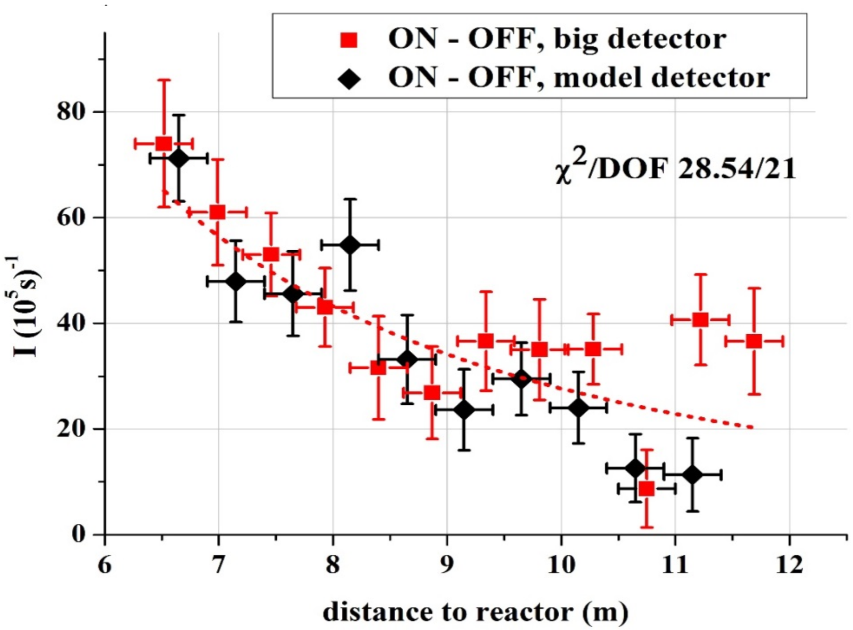


combined shielding for n and gamma-rays



- first measurement in $1/R^2$
  - IBD efficiency 15%, ~130 candidates/day
- next phase:
  - full scale system
  - active shielding around passive shielding

start 3 MeV, stop 3 MeV



Status of Experiment NEUTRINO-4 Search for Sterile Neutrino

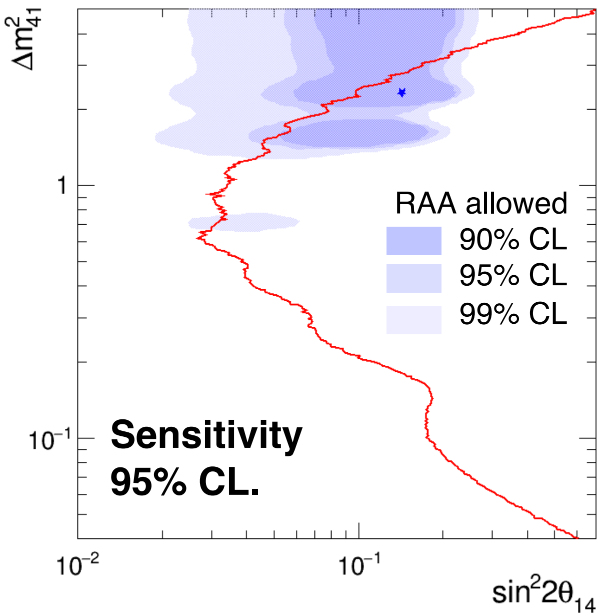
A Serebrov[1], V Ivochkin[1], R Samoilov[1], A Fomin[1], A Polyushkin[1], V Zinoviev[1], P Neustroev[1], V Golovtsov[1], A Chernyj[1], O Zherebtsov[1], V Martemyanov[2], V Tarasenkov[2], V Aleshin[2], A Petelin[3], A Izhutov[3], A Tuzov[3], S Sazontov[3],

In the frame of the available statistical accuracy it is not revealed if there are any reliable deviations of antineutrino flux distance dependence from the law $1/R^2$ where R – distance from the center of reactor core

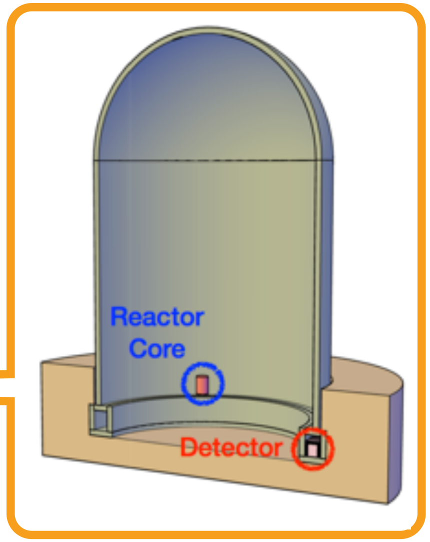
Data taking still ongoing for more precice measurement !

NEOS: Neutrino Experiment for Oscillation at Short baseline

- Hanbit NPP in Younggwang, Korea
- 2.8 GWt commercial reactor
- core size: 3.1 m (ϕ) X 3.8 m (H)
- LEU fuel (~4.6% ^{235}U)
- Tendon Gallery: 24 m baseline, ~20 m.w.e overburden

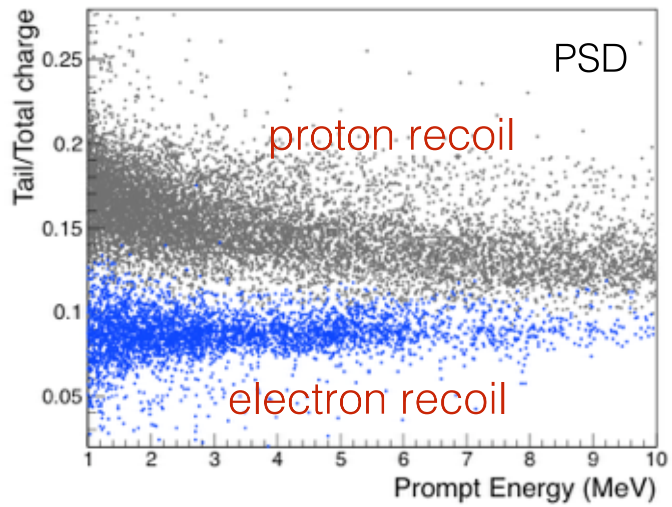


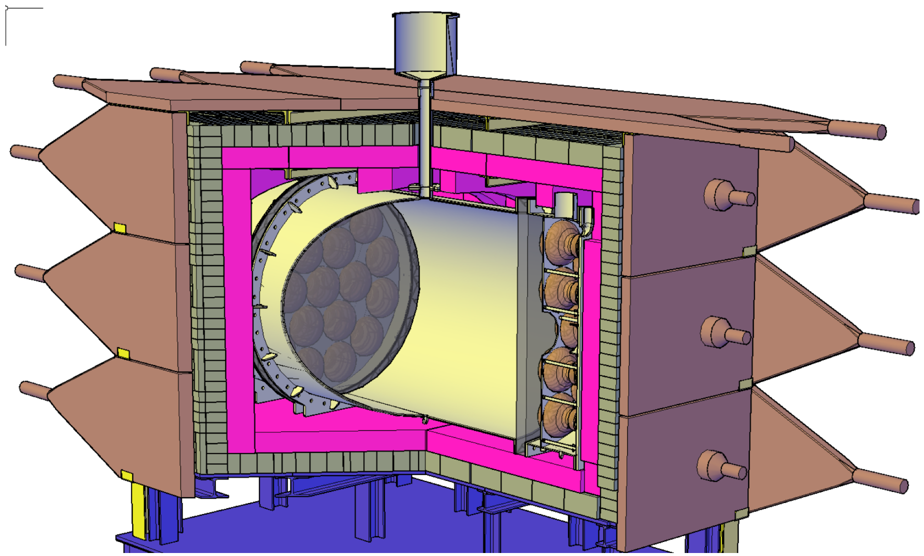
Reactor Unit 5, Hanbit NPP in Younggwang, Korea (Reno Site)

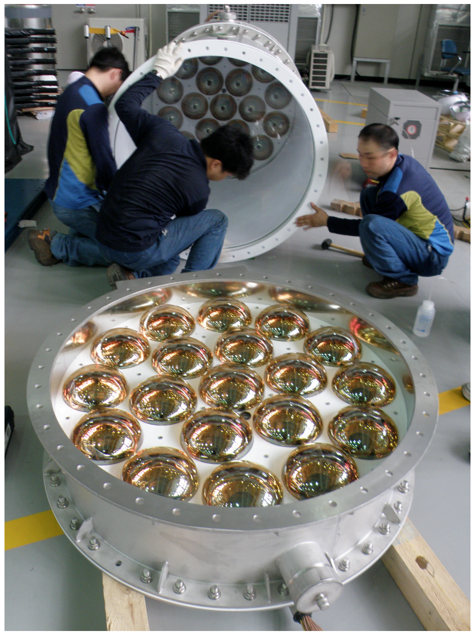


NEOS - detector

- 1000 L of 0.5 Gd LS, homogeneous
  — LAB+DIN for better PSD performance
- 38 8" PMTs for the active target
- 10 cm borated PE, 10 cm Pb passive shields
- muon counters for active veto
- DAQ: 500 MS/s FADC for waveform analysis



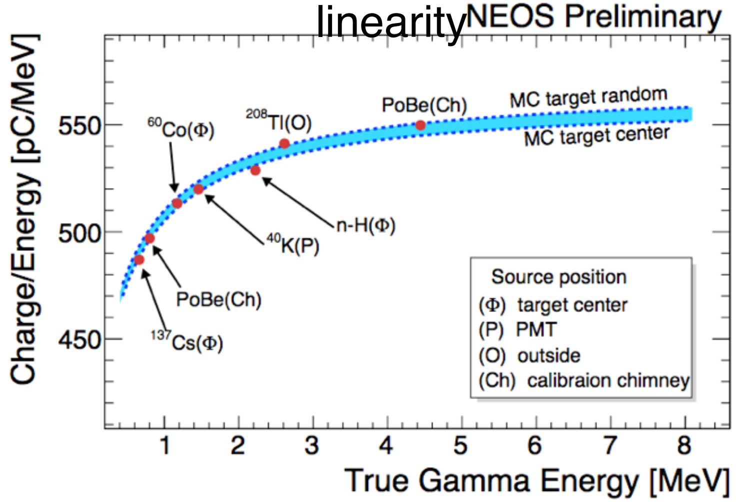


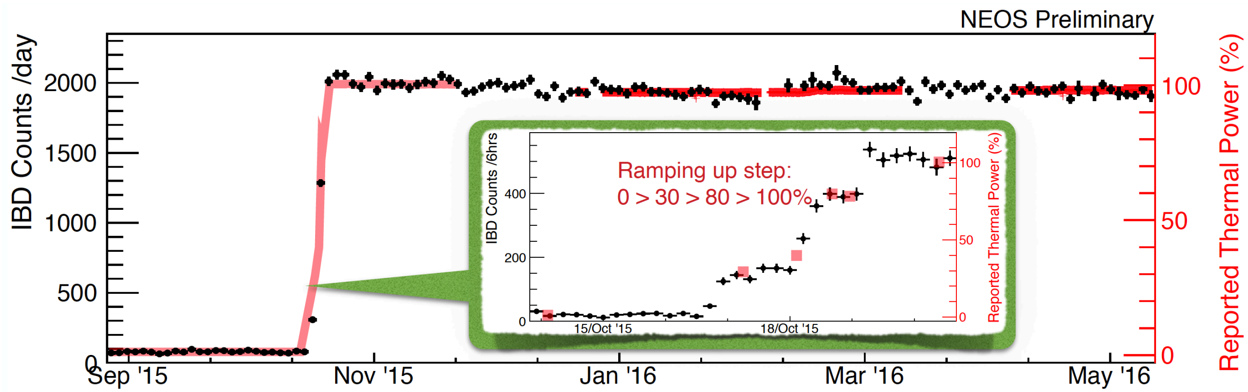


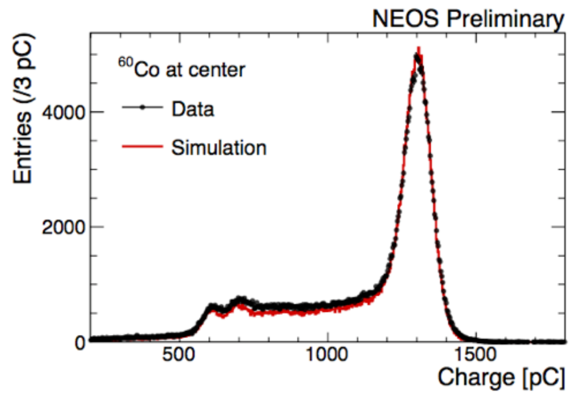
NEOS - status

- data taking completed : Aug 2015 - May 2016
  — ~180 (46) days with the reactor on (off)
  — ~2000 (80) IBD candidates/day for on (off)
- detector & MC simulation
  — 5% energy resolution at 1 MeV
  — 70% background reduction using PSD
  — escaping γ, E resolution, charge response well reproduced by MC.

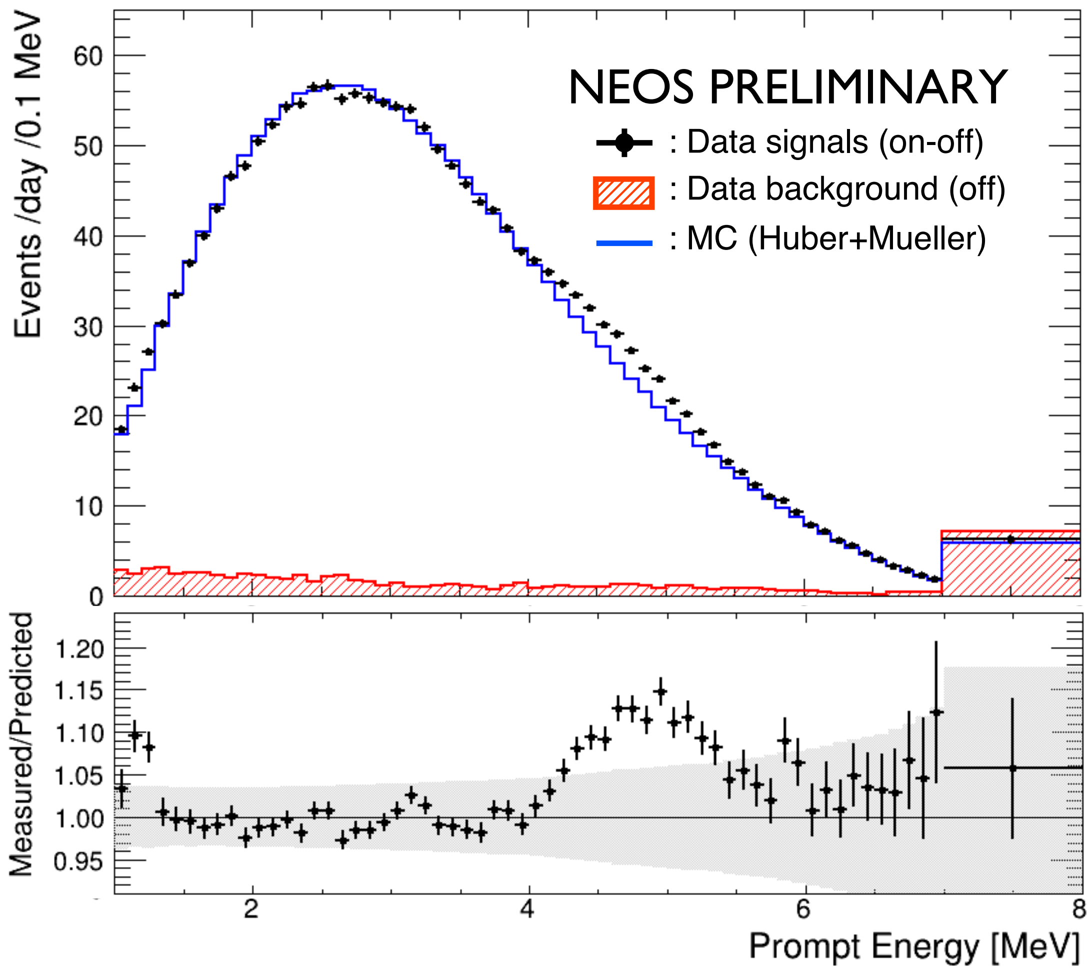
charge vs energy non-linearity







NEOS - prompt energy spectrum



- shape comparison with Huber & Mueller's flux model:
  — excess around 5 MeV
  — another disagreement at
  low energy side.
- result with sterile-ν analysis
  will be published soon.

Segmented Liquid Scintillator Target

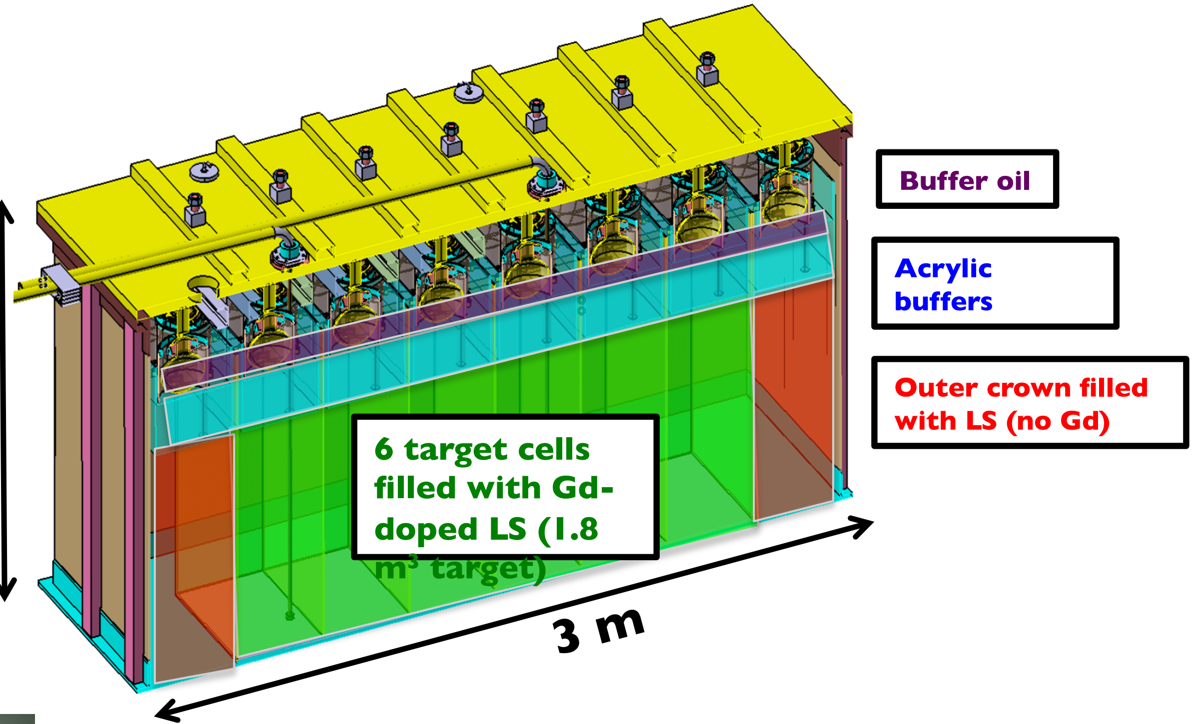
+Gd-Loaded

STEREO

Stereo Setup

Motivations

- Look for a new oscillation pattern in identical detector cells
- New reference ν spectrum from quasi-pure ^{235}U fissions at the compact core of ILL-Grenoble.
- **Data taking has started on Nov 10, 2016 !**



Insertion underneath the ILL water channel

Stereo filling Nov 9-10, 2016

Stereo Setup

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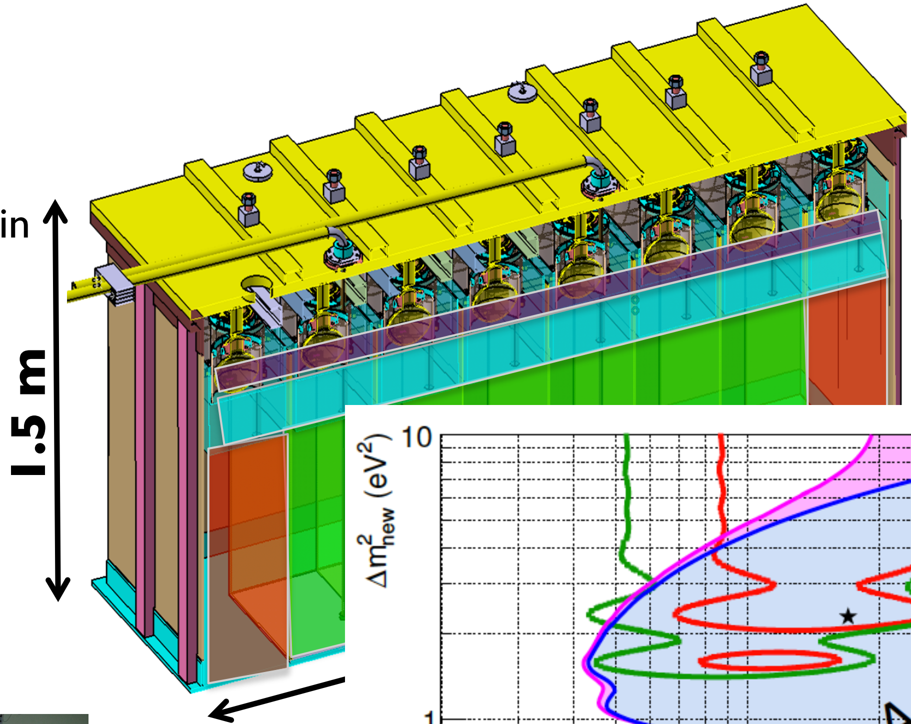
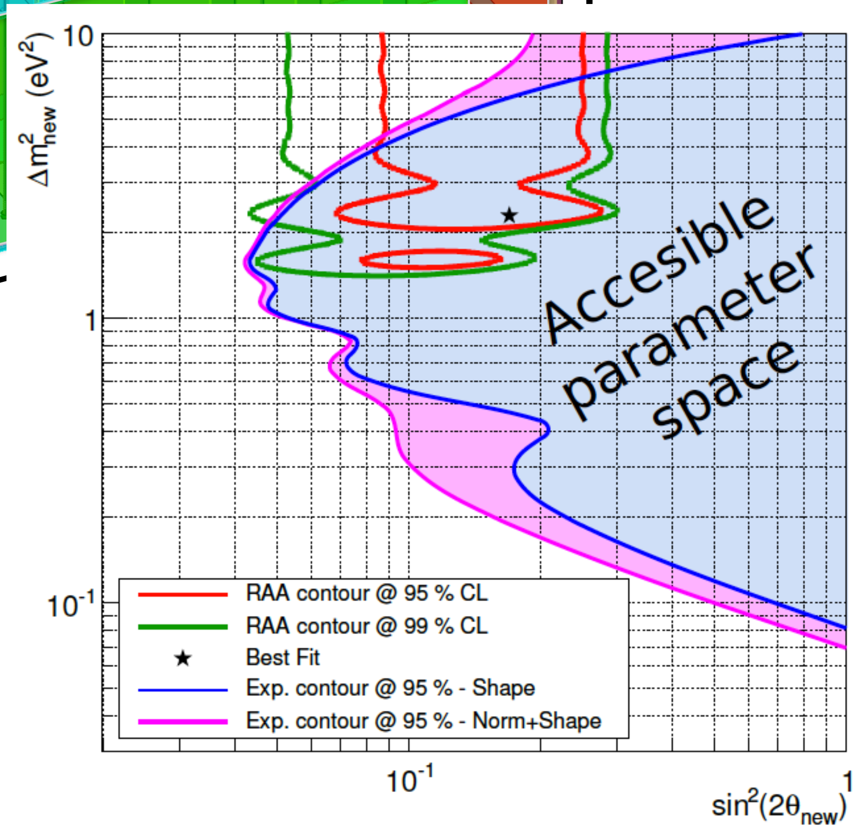


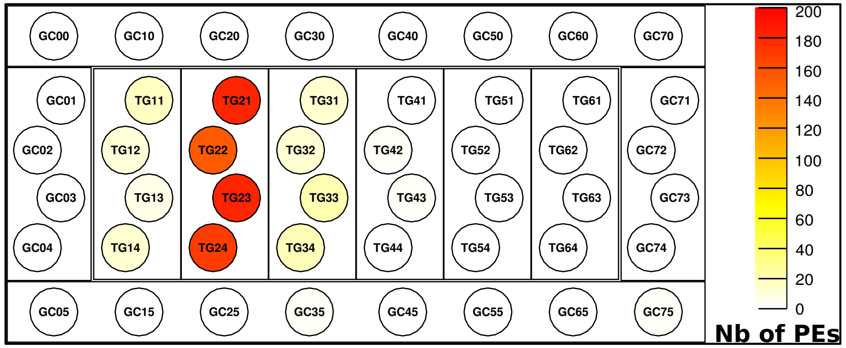
Insertion underneath the ILL water channel



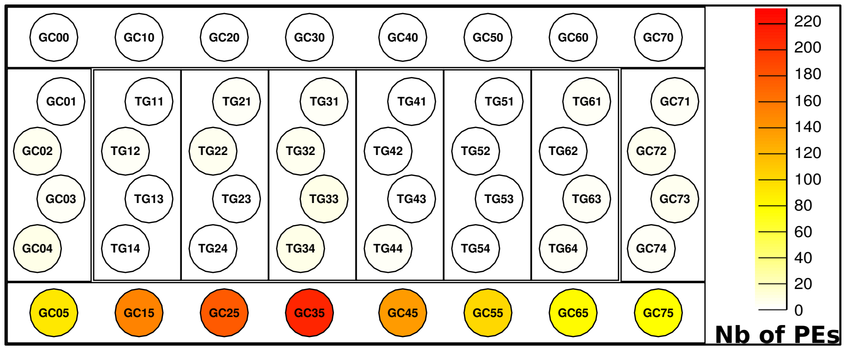
Reactor Background

Event display of PMT charges

Target event (~2.7 MeV)



Crown event tagging the entry point of an external background (~ 3.7 MeV)

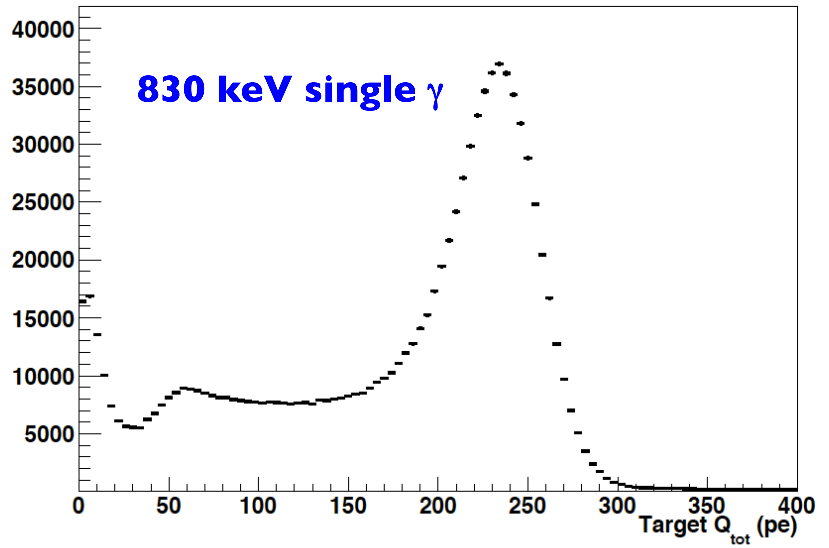


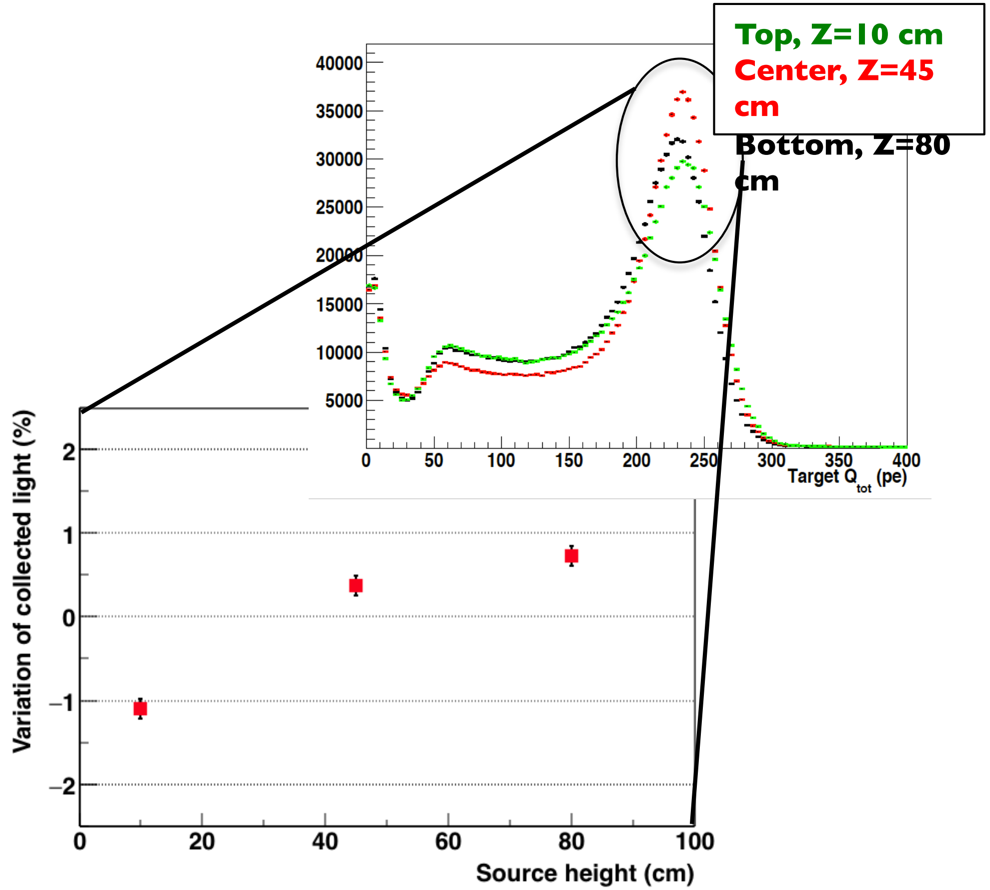
Stereo meets the challenging attenuation of the external gamma and neutron fluxes induced by the reactor and nearby neutron beam experiments.

- The measured single rate in target in the 2-8 MeV window is within specifications: 14 Hz.
- The acquisition threshold is currently set as low as 250 keV with a rate of 79 Hz in the target after applying the muon veto.
- Correlated background under study.

Light collection

Detector response to ^{54}Mn source at the center of one cell





- **Light collection of 280 p.e./MeV as expected**
- **Small (2%) dependence of the full energy deposit on the source position.**
- Caveat: deficient optical coupling of the PMTs in cell4. Related systematics under study for this specific cell.

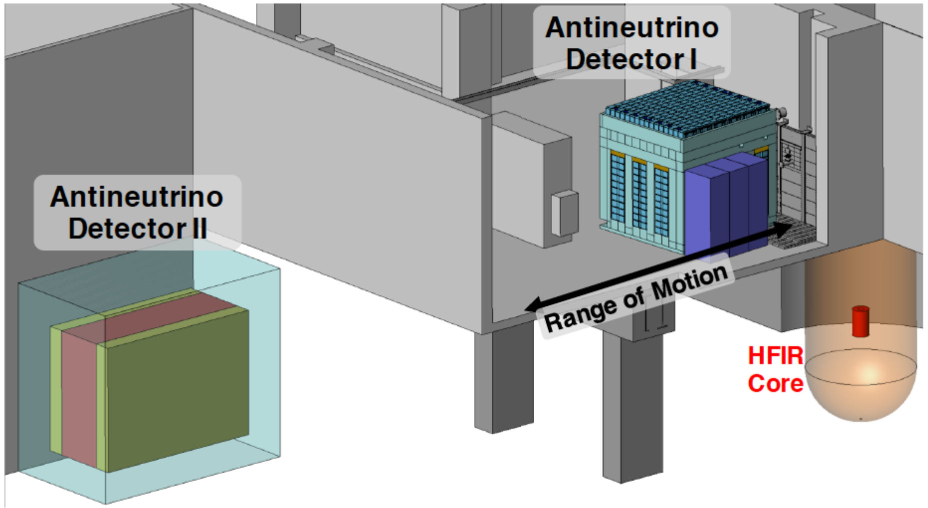
Highly Segmented Liquid Scintillators

+ Li^6-Loaded

Prospect

Search for short-baseline oscillation at distances <10m
Precision measurement of ^{235}U reactor $\bar{\nu}_e$ spectrum

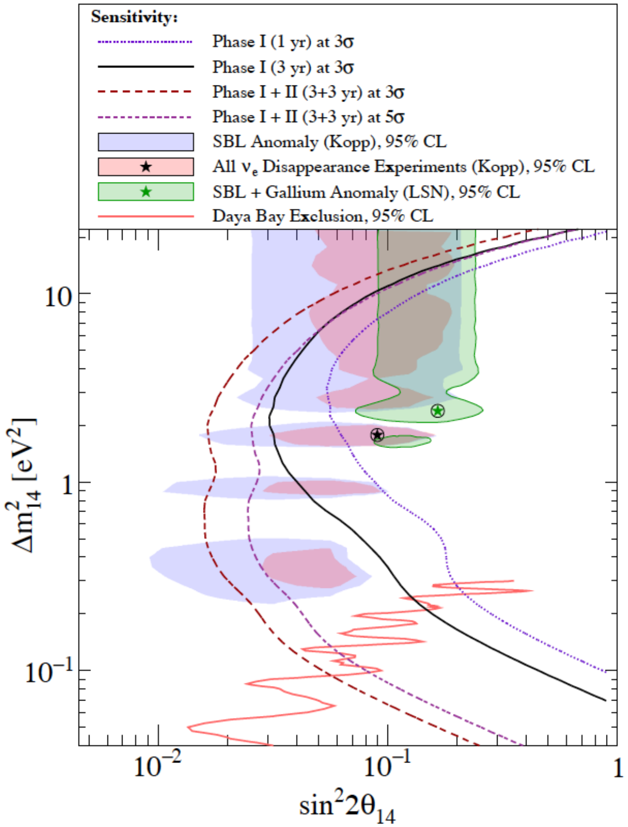
2 detectors, movable baseline, research reactor



power: 85 MW (research)
fuel: highly enriched uranium (^{235}U)

Phase I
one movable detector AD-I, ~7-12 m baseline
(Array of 1.2 m segments filled with L6LS)

Phase II
two detectors,
movable AD-I, ~7-12m baseline
stationary AD-II, ~15-19m baseline



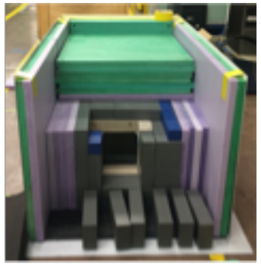
PROSPECT: Detector and Shielding Development

PROSPECT-0.1
Characterize LS
Aug 2014-Spring 2015

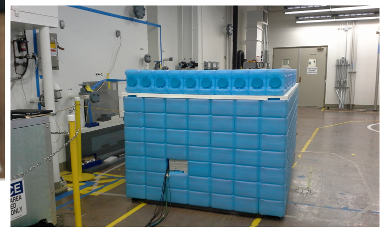
5cm length
0.1 liters
LS, ^{6}LiLS

PROSPECT-2
Background studies
Dec 2014 - Aug 2015

12.5 cm length
1.7 liters
^{6}LiLS

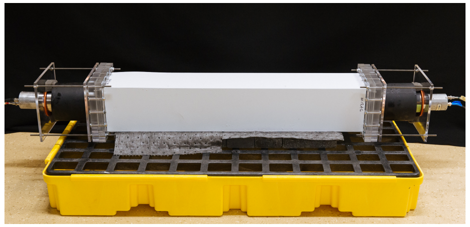


multi-layer shielding



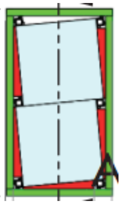
PROSPECT-20
Segment characterization
Scintillator studies
Background studies
Spring/Summer 2015

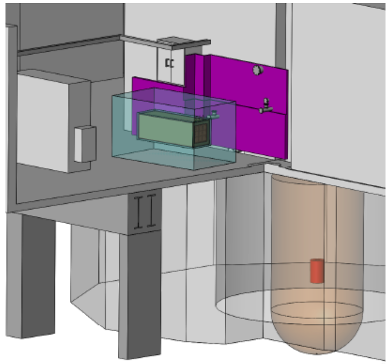
1m length
23 liters
LS, ^{6}LiLS



PROSPECT-50
Baseline design prototype
Winter 2015

1x2 segments
1.2m length
50 liters
^{6}LiLS

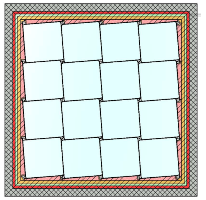




local reactor shielding

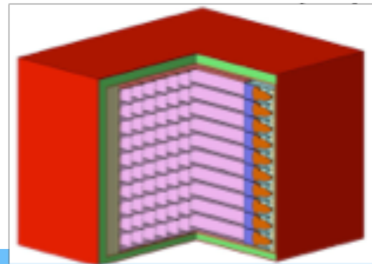
PROSPECT-400*
Fiducialization and background studies
Mid 2016

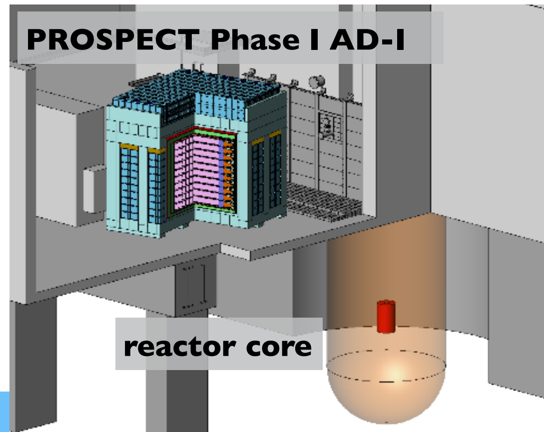
4x4 segments
1.2m length
400 liters
^{6}LiLS



PROSPECT AD-I
Physics measurement
Late 2016

10x12 segments
1.2m length
~3 tons
^{6}LiLS

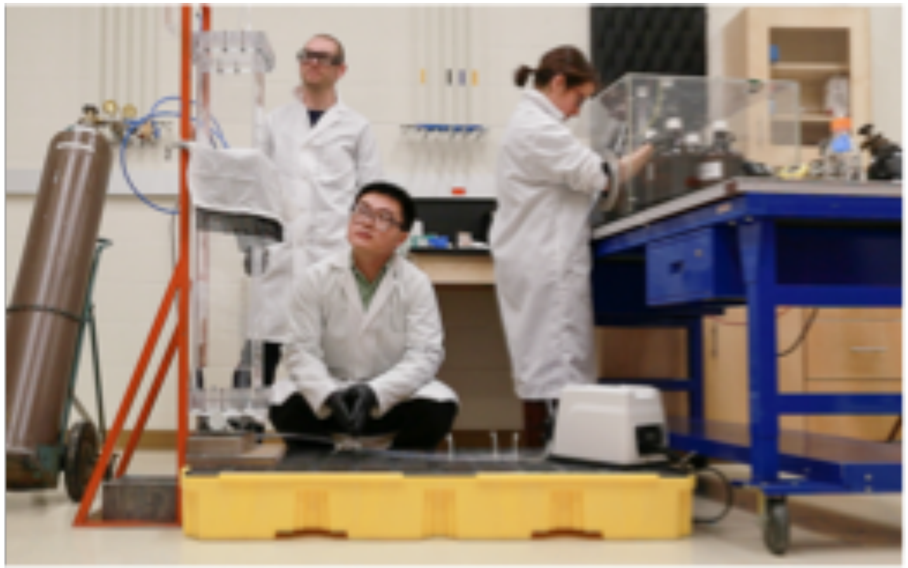


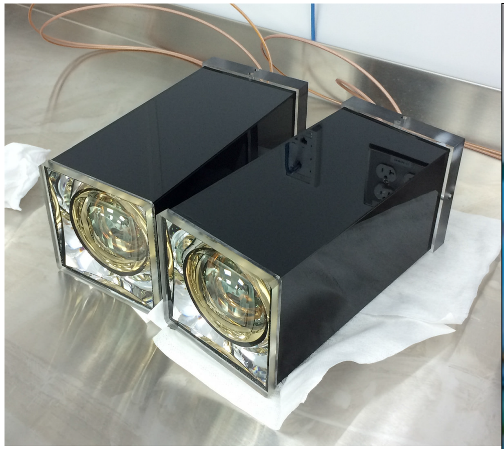


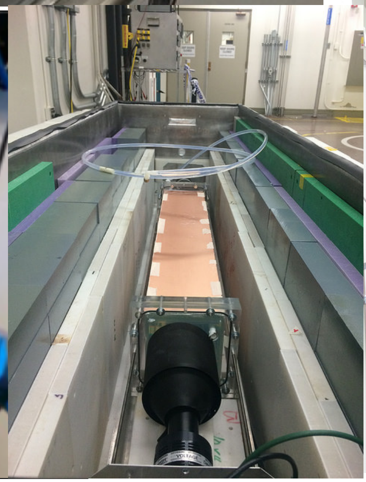
4-5%/√E resolution

**Technically ready to proceed directly to AD-I with available funding*

Prototyping and Detector Assembly





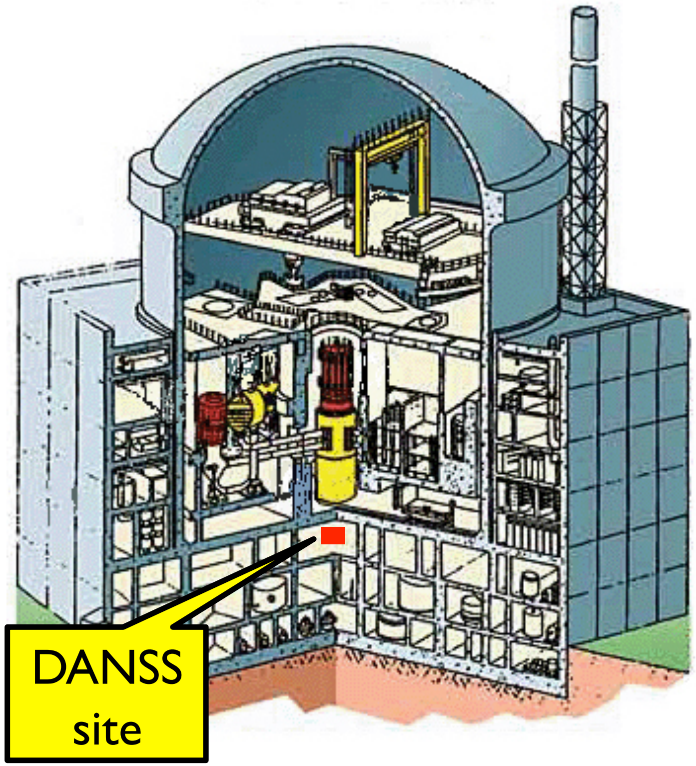


Highly Segmented Plastic Scintillators

+Gd-coating

DANSS/DANSSino

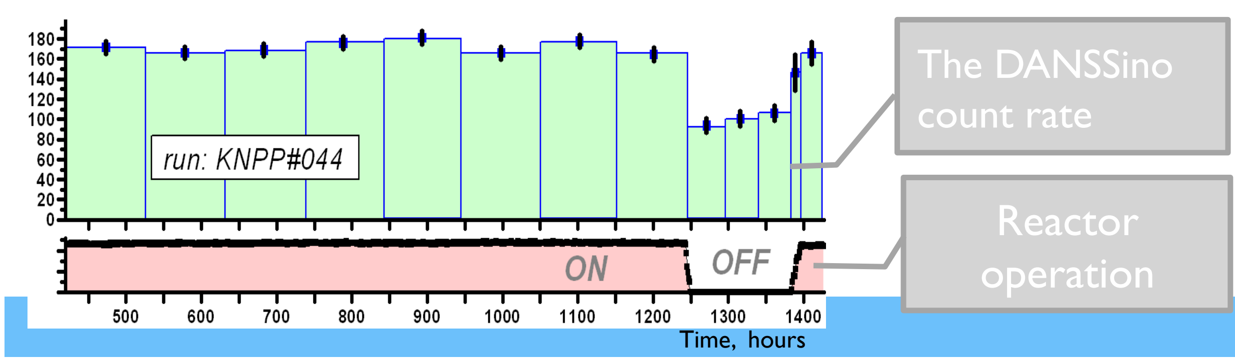
DANSS : Detector of the reactor AntiNeutrino based on Solid state Scintillator *(aim: reactor monitoring and search for sterile neutrino oscillations)*

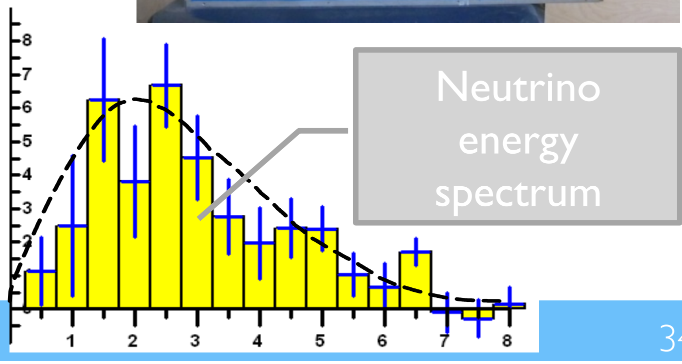


- Segmented "XY" plastic scintillator (1 m^3) close to the core of the Kalinin NPP reactor #4 (3 GW_{th})
- Expected IBD count rate $\sim 10^4\ \overline{\nu}_e$ / day; S/B ≥ 100
- Movable lifting platform => Φ_ν (L=9.7–12.2 m)
- Planned start of operation : 28/12/2015

- Pilot version (**DANSSino**): 40 kg = 1/25th of DANSS
- Agreement with MC
- arXiv:1304.3696
- arXiv:1305.3350

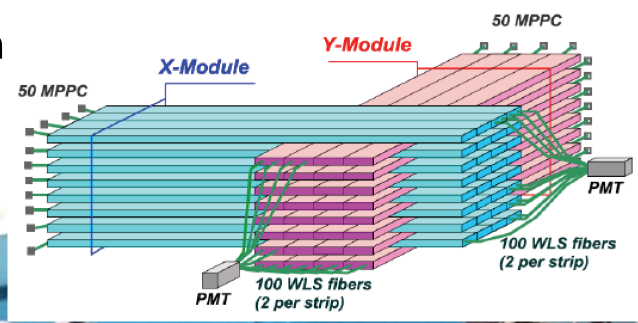
Example of the reactor neutrino monitoring

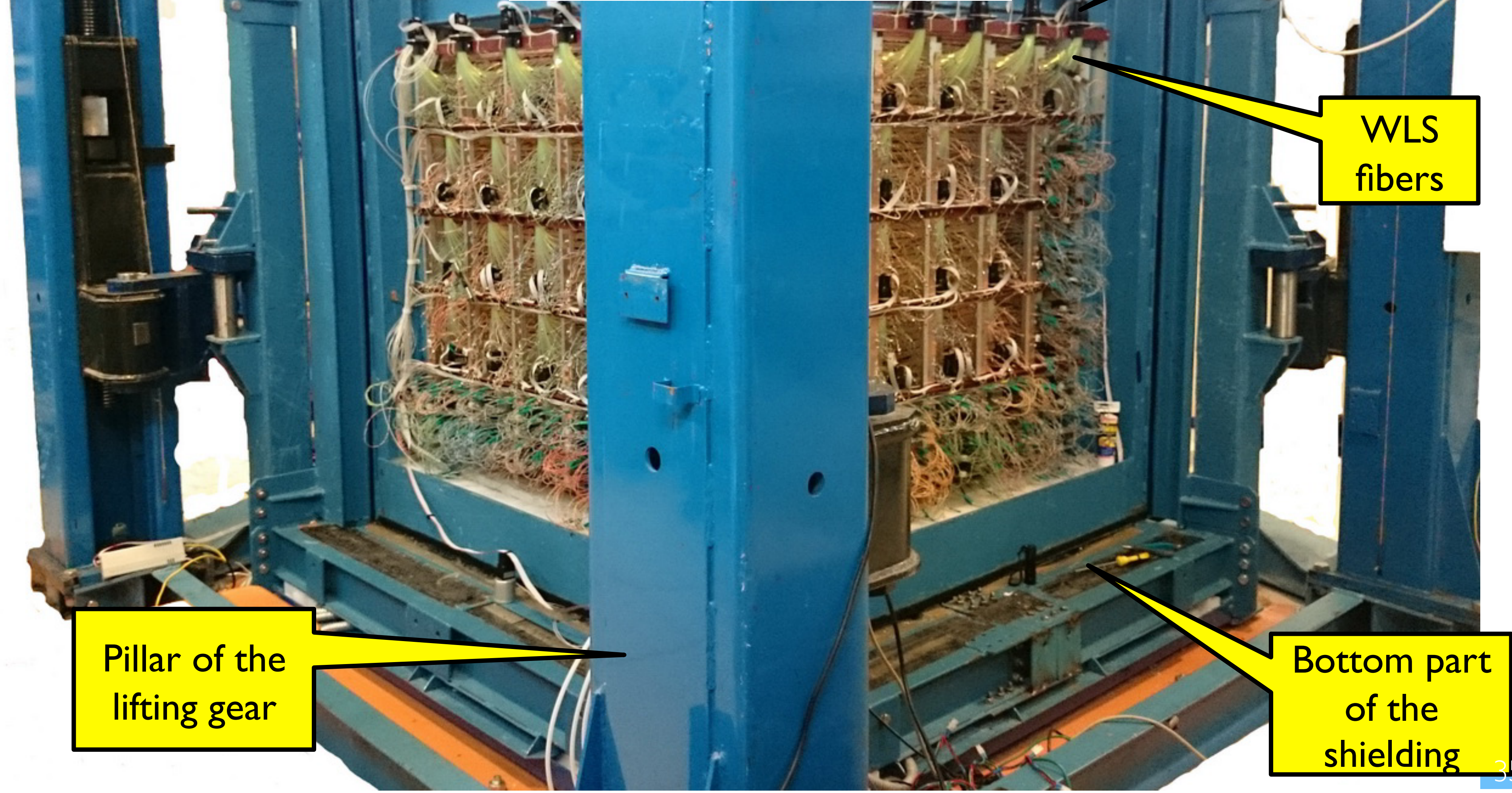




DANSS detector (without external shielding)

installed on the movable platform





SBL Reactor experiments

Highly Segmented Plastics Scintillators

+Li^6 (loading or with Li^6-ZnS scintillator)

NuLat

SoLi∂ (Mars and Chandler technology)

NuLat – Neutrino Lattice

A Novel Detector for probing RAA, reactor monitoring and fast neutron directionality

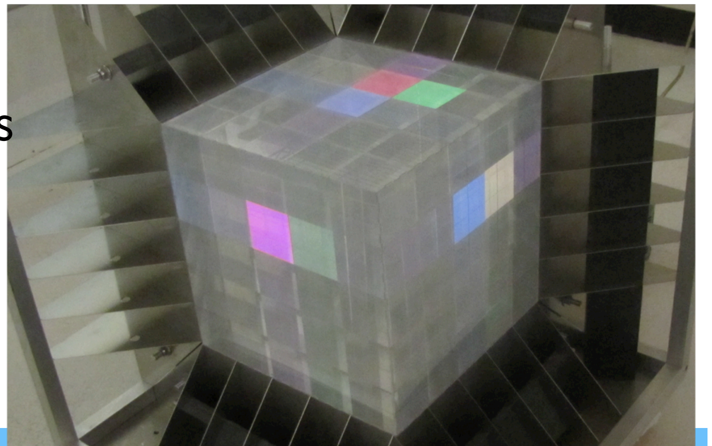
- NuLat – finely, 3D segmented detector
- 10x10x10 ^{6}Li loaded plastic scintillator cubes (2.5"), spaced by thin air gaps.
- Utilizes total internal reflection (n = 1 and n = 1.54) to totally guide and focus light in just 6 PMTs along the three principal axis
- Easily scalable, zero mass wall (air)
- LY > 600 pe/MeV over just 6 PMTs! (En. Res: 4%/ sqrt(E))
- NuLat is a joint

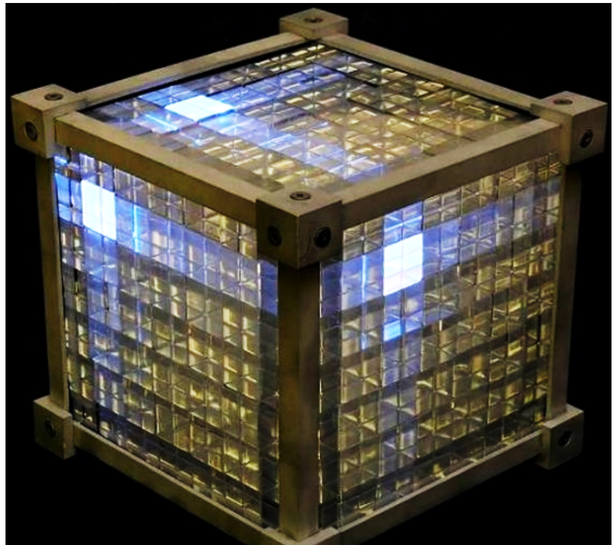
  endeavor of 20+ scientists

  (Drexel, Johns Hopkins*, LSU, NIST,*

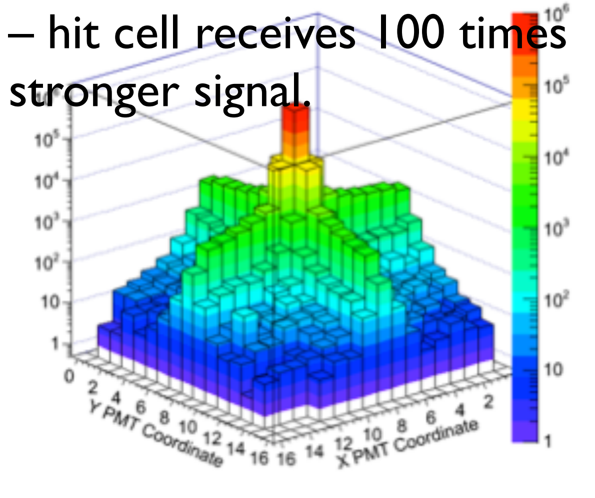
  NCCU, Ultralytics LLC,

  University of Hawaii, Virginia Tech)





Signal strength on a cube side – hit cell receives 100 times stronger signal.



NuLat Highlights

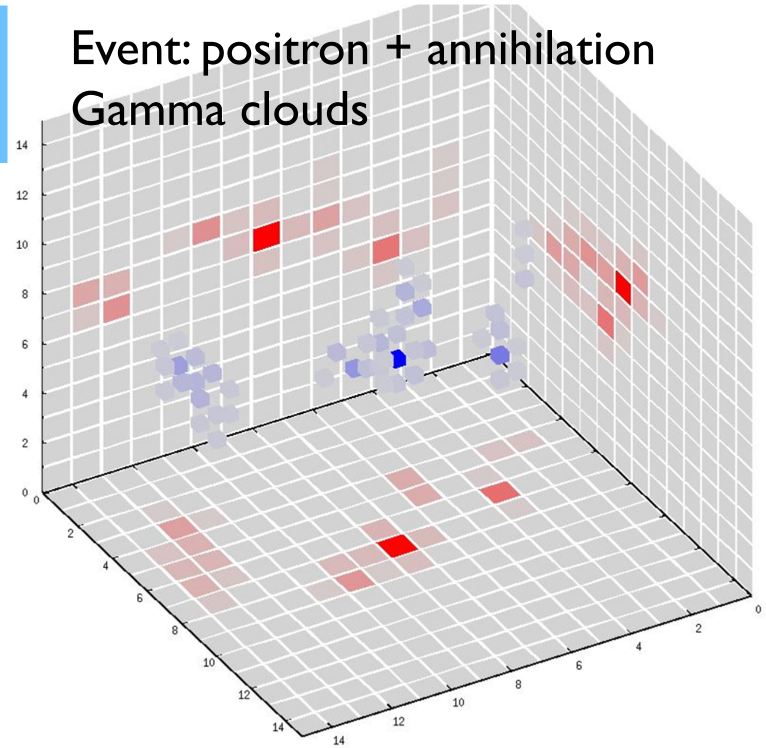
- Inverse beta decay with neutron capture

  on ^{6}Li

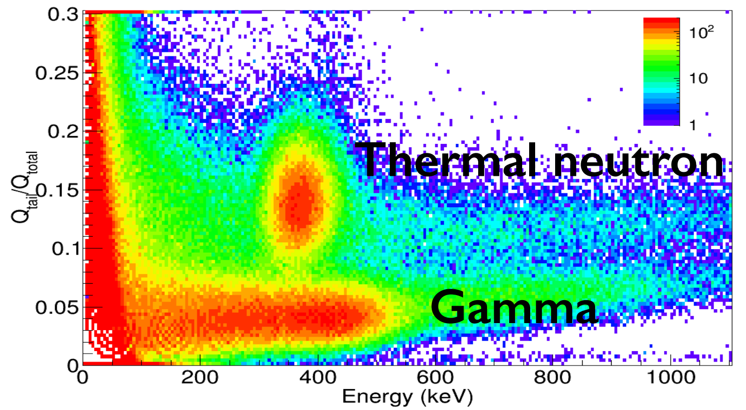
  $^6Li + n \rightarrow 3H + \alpha + 4.8$ MeV

- Localized 400 keV_{ee}
- Excellent localization and background rejection
- Prompt signal: positron + annihilation gammas, clearly distinguishable by complete event topology

Event: positron + annihilation Gamma clouds



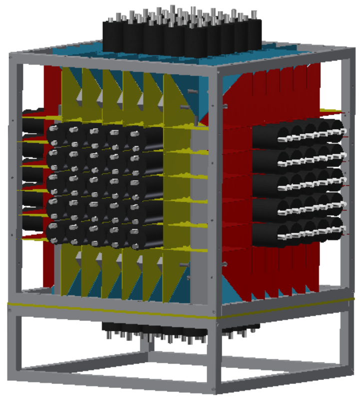
Eljen LLNL based EJ-200 ^{6}Li PSD

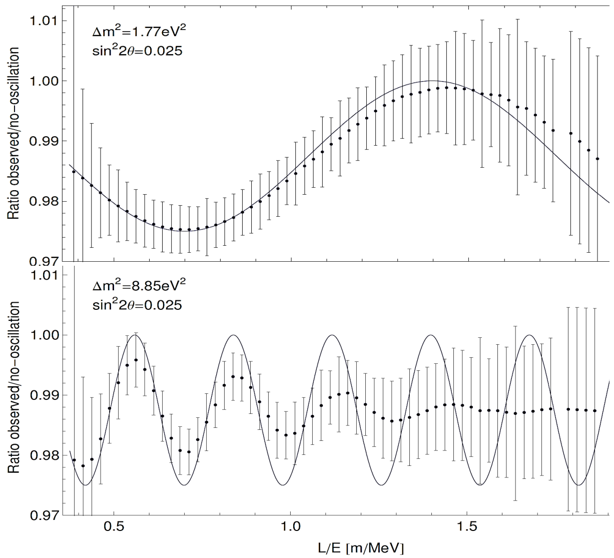


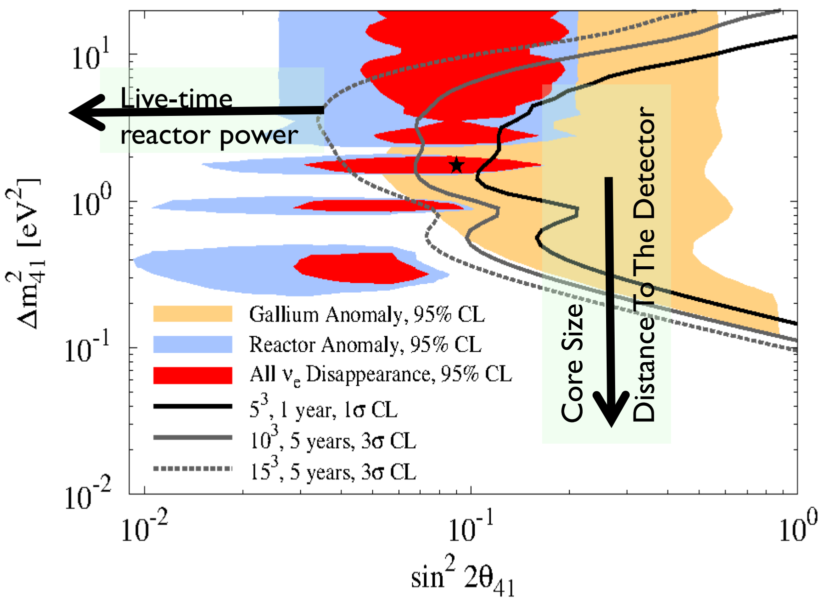
- Short capture time – 7 μs
- Distinguishable delayed signal thanks to pulse shape discrimination

NuLat – Sensitivity and timeline

- 5x5x5 demonstrator under construction
- Design finalized and major parts ordered months ago
- Final assembly in March 2016
- Deployment at 2 reactors: NIST (Maryland) and North Ana (Virginia)
- Decent sensitivity with the demonstrator
- Proposal under review for 10x10x10 detector



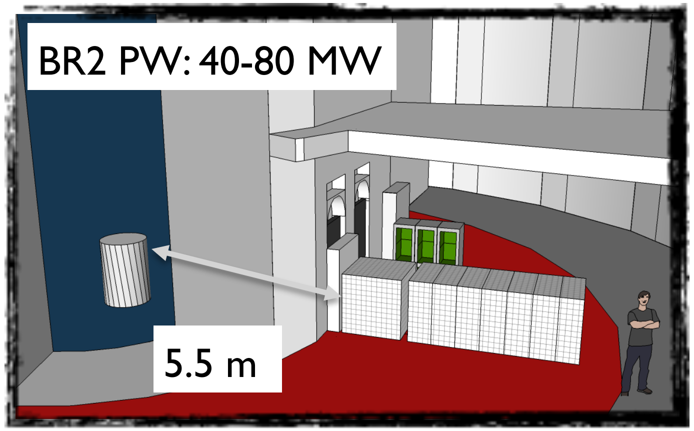




SoLid: General Principle

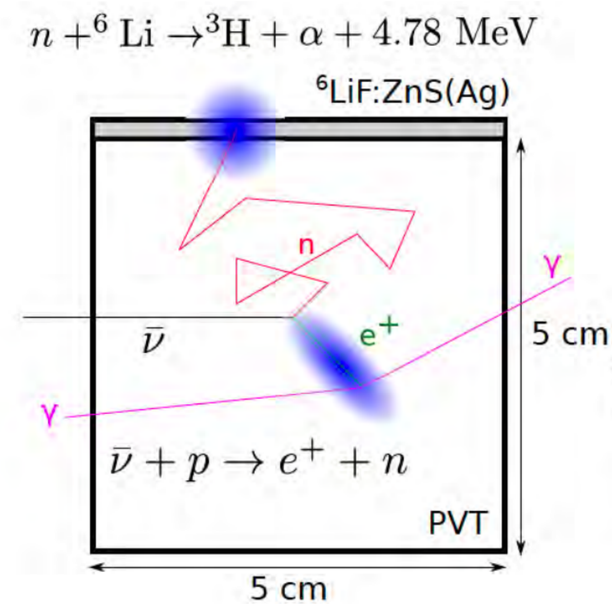
✓Search for sterile neutrinos ($\Delta m^2 \sim eV^2$) via very short baseline oscillations at BR2 HEU reactor at SCK•CEN, Mol, Belgium

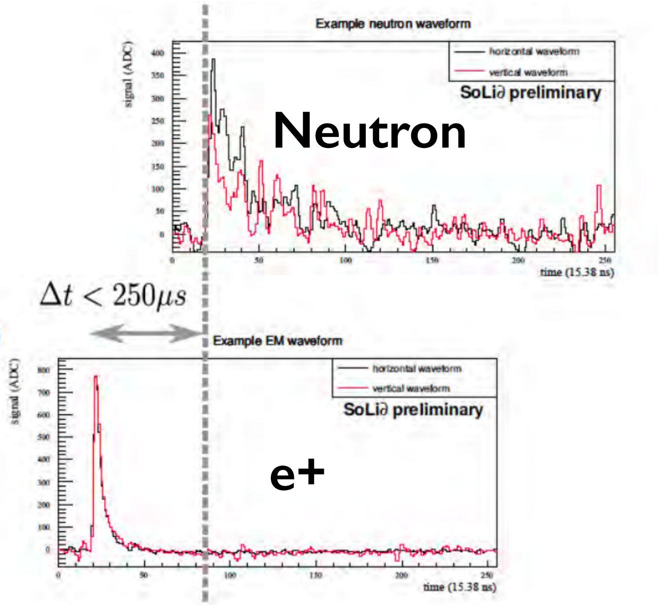
✓Precision measurement of the anti- e energy spectrum of a U235 reactor



→ **High segmentation via innovative technology:**

Planes made of 16*16 5.5 cm PVT cubes + ^{6}Li layers for efficient neutron capture.

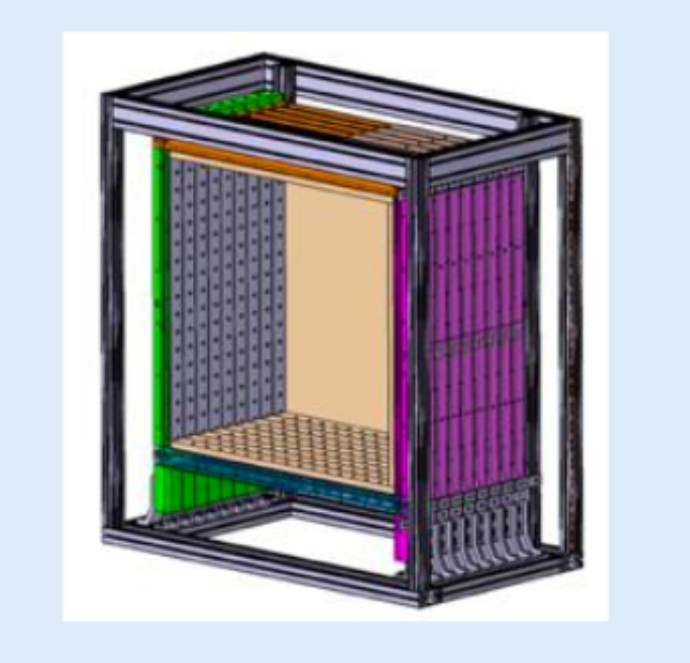




IBD=2 very different waveforms in time coincidence.

Spring 2015: SM1

- ✓ Validation of detector's concept;
- ✓ Performance study (ex: ε neutron)
  => a guide for phase1 trigger design;
- ✓ Development of calibration methods;
- ✓ Proof of the bkg reduction capabilities;
- ✓ First IBD candidates.



- 16*16*9 cubes, 288 channels;
- 50h reactor-on;
- 430h reactor-off.

Spring 2015: SM1

- ✓ Validation of detector's concept;
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- ✓ Development of calibration methods;
- ✓ Proof of the bkg reduction capabilities;
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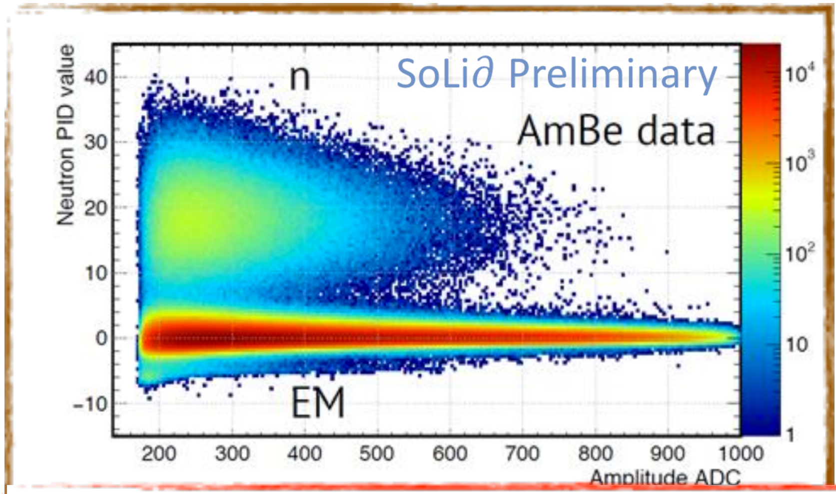
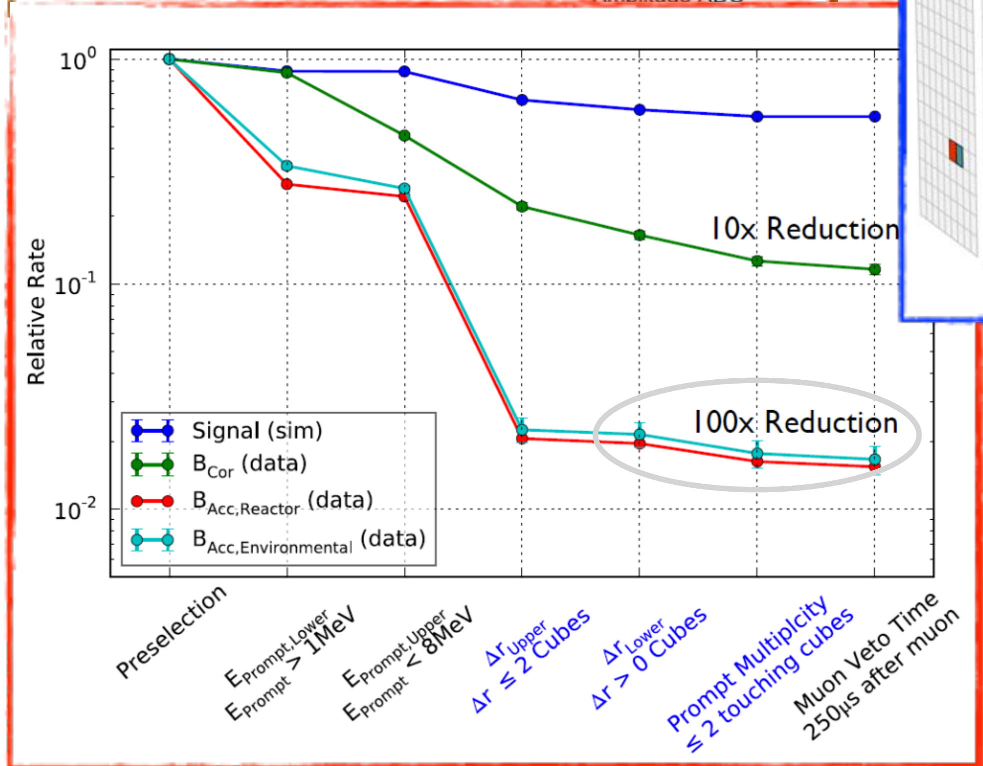
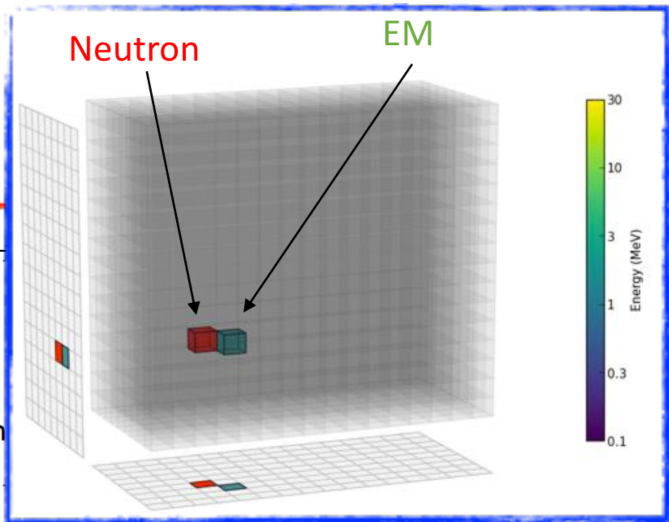
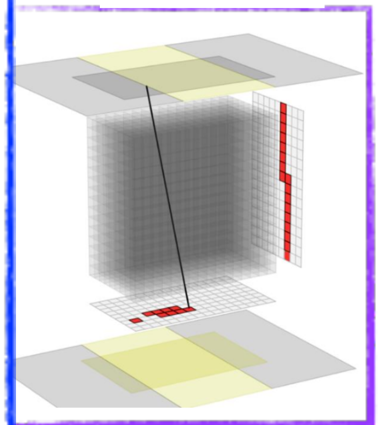
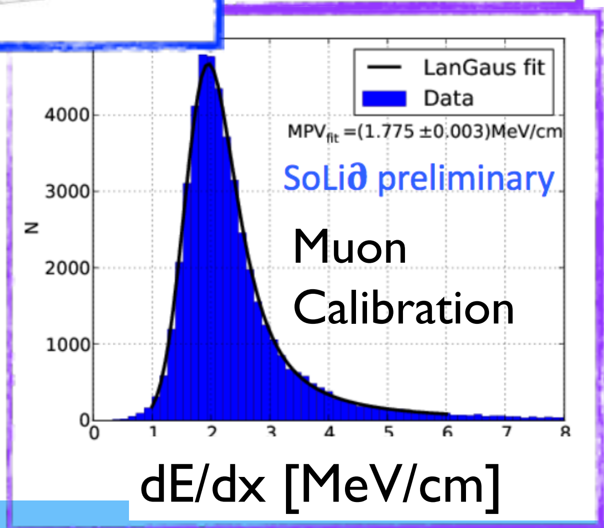






Muon





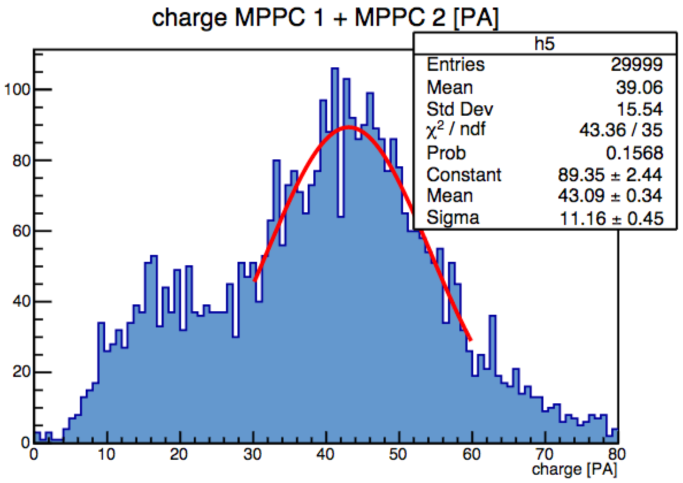
2016: toward the full scale experiment

✓Caracterisation of the cubes chosen for phase 1.
Test bench: cubes exposed to 1 MeV e- (^{207}Bi).
=> σE~15%

✓ Electronics design;

✓ Full simulation well advanced;

✓ Design and construction of the off- and on-site calibration systems;



Light yield (PA)

Early 2017: Phase 1 !

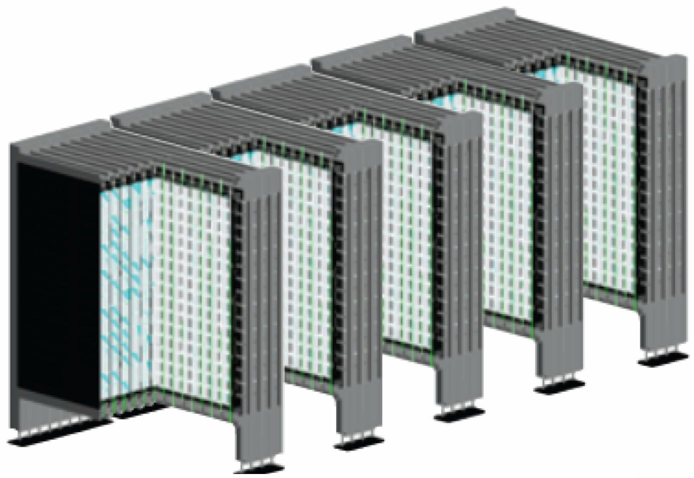
Winter/Spring

-Construct, commission, calibrate;
-Refine analysis methods and bkg understanding.

Then 300 days reactor-on

-1st indication of an oscillation;
- U5 spectrum measurement.

2017



5 modules, 1.6 tons

2016: toward the full scale experiment

✓Caracterisation of the cubes chosen for phase 1.
Test bench: cubes exposed to 1 MeV e- (^{207}Bi).
=> σE~15%

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✓ Full simulation well advanced;

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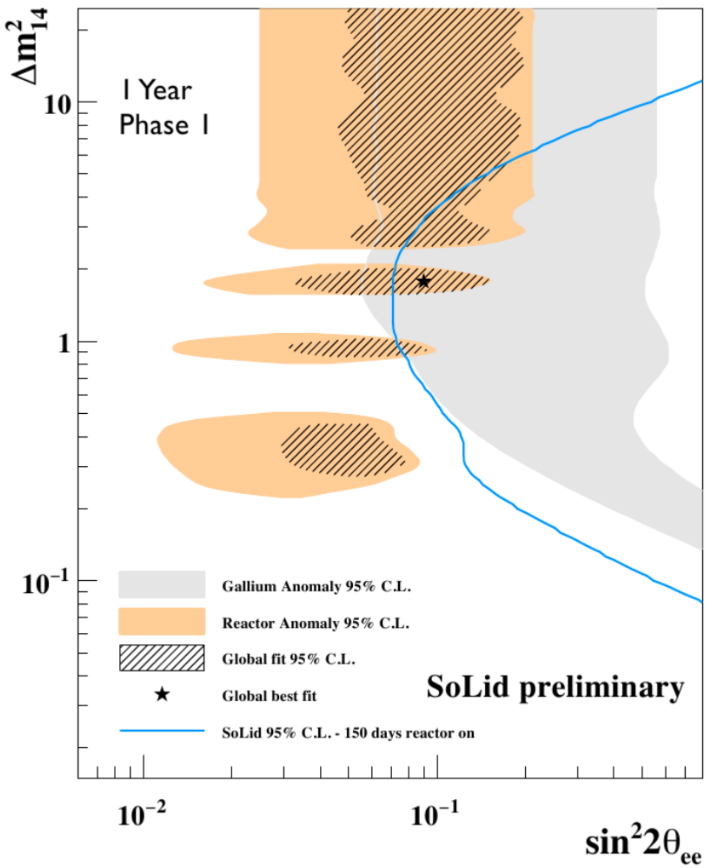
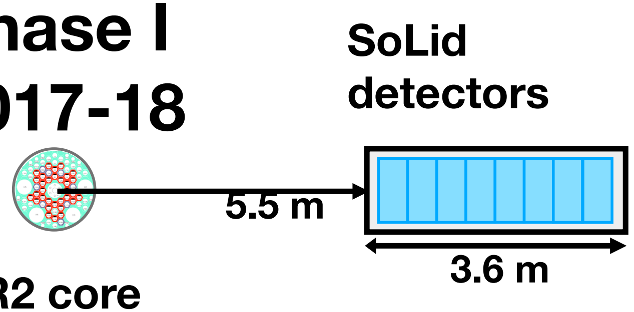
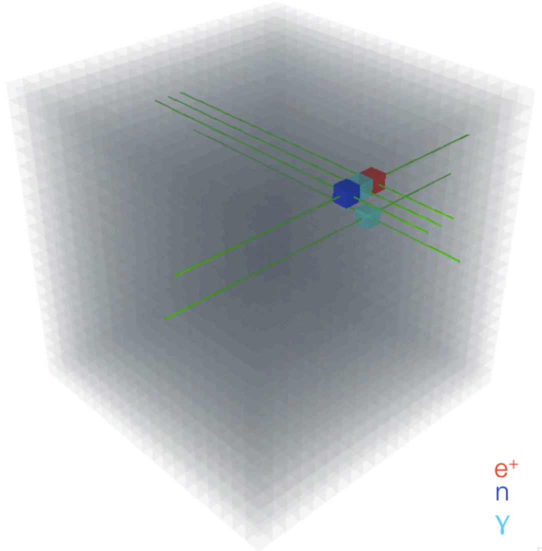


SoLi∂ : Experiment phases

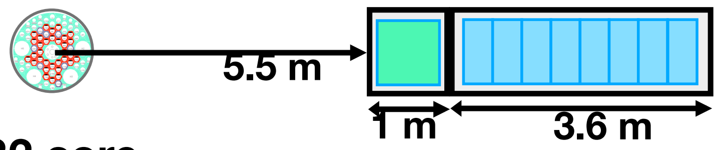
Phase I 2017-18



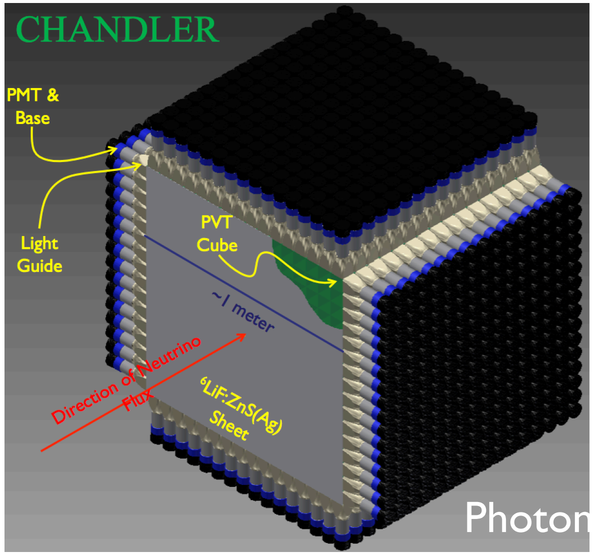
8x MARS modules
PVT cubes + WLS fibres
2 tonnes fiducial



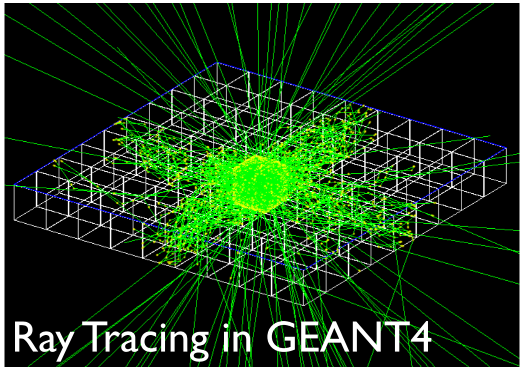
Phase II ~ 2019



HiRes module
WLS PVT cubes + PMTs
1 tonne fiducial



Light is transported by total-internal-reflection

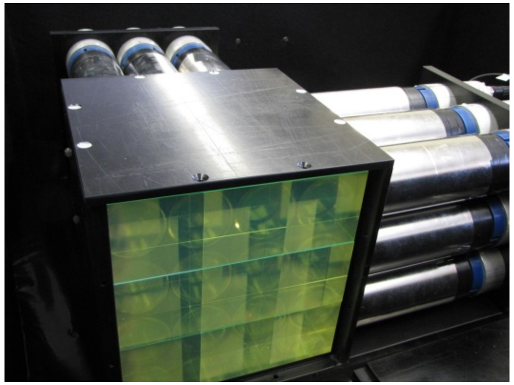


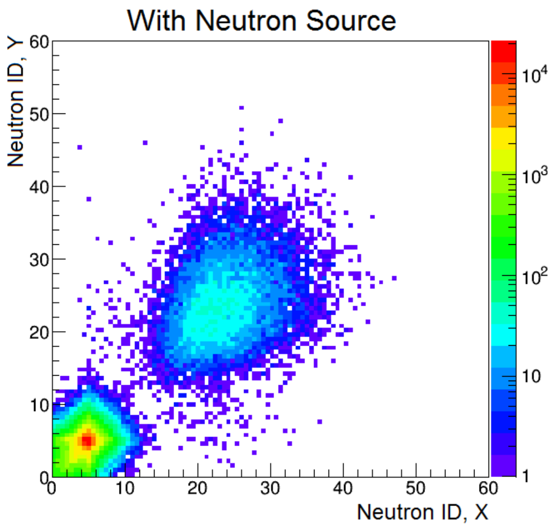
Photon Ray Tracing in GEANT4

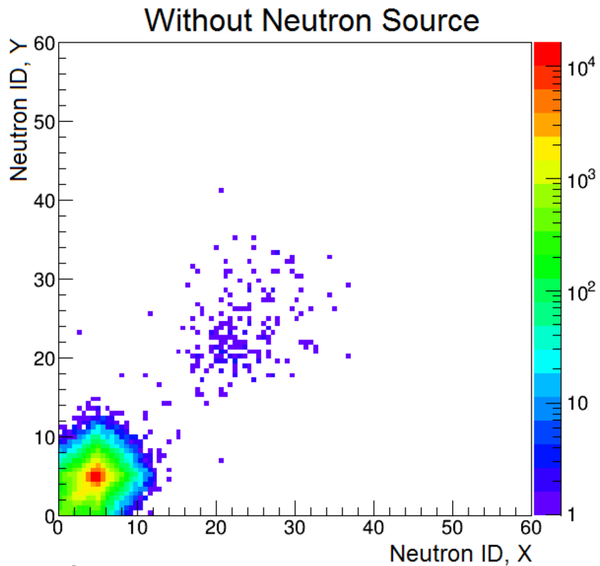
Neutron Capture in MicroCHANDLER

The 18-channel MicroCHANDLER prototype is idea for testing neutron tagging.

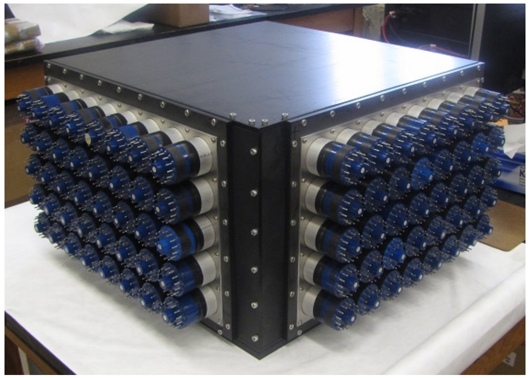
For each hit cell, we compute the neutron ID variable as the ratio of the integral of the pulse to the pulse peak value.





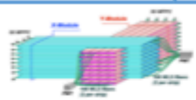
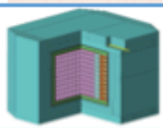
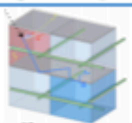
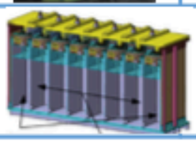


- Very good discrimination Neutron / gamma-ray by pulse shape



MiniCHANDLER is a **fully funded** system test (8×8×5) which is now being commissioned and will be deployed at North Anna Nuclear Power Plant, Virginia.

SBL reactor experiments

Experiment	Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia) 	3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only
NEOS (South Korea) 	2800 MW LEU fuel	~20	Homogeneous Gd-doped LS	none	Direct double ended PMT	recoil PSD only
nuLat (USA) 	40 MW ^{235}U fuel	few	Homogeneous ^{6}Li doped PS	Quasi-3D, 5cm, 3-axis Opt. Latt	Direct PMT	Topology, recoil & capture PSD
Neutrino4 (Russia) 	100 MW ^{235}U fuel	~10	Homogeneous Gd-doped LS	2D, ~10cm	Direct single ended PMT	Topology only
PROSPECT (USA) 	85 MW ^{235}U fuel	few	Homogeneous ^{6}Li-doped LS	2D, 15cm	Direct double ended PMT	Topology, recoil & capture PSD
SoLid (UK Fr Bel US) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm multiplex	WLS fibers	topology, capture PSD
Chandler (USA) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm, 2-axis Opt. Latt	Direct PMT/ WLS Scint.	topology, capture PSD
Stereo (France) 	57 MW ^{235}U fuel	~15	Homogeneous Gd-doped LS	1D, 25cm	Direct single ended PMT	recoil PSD

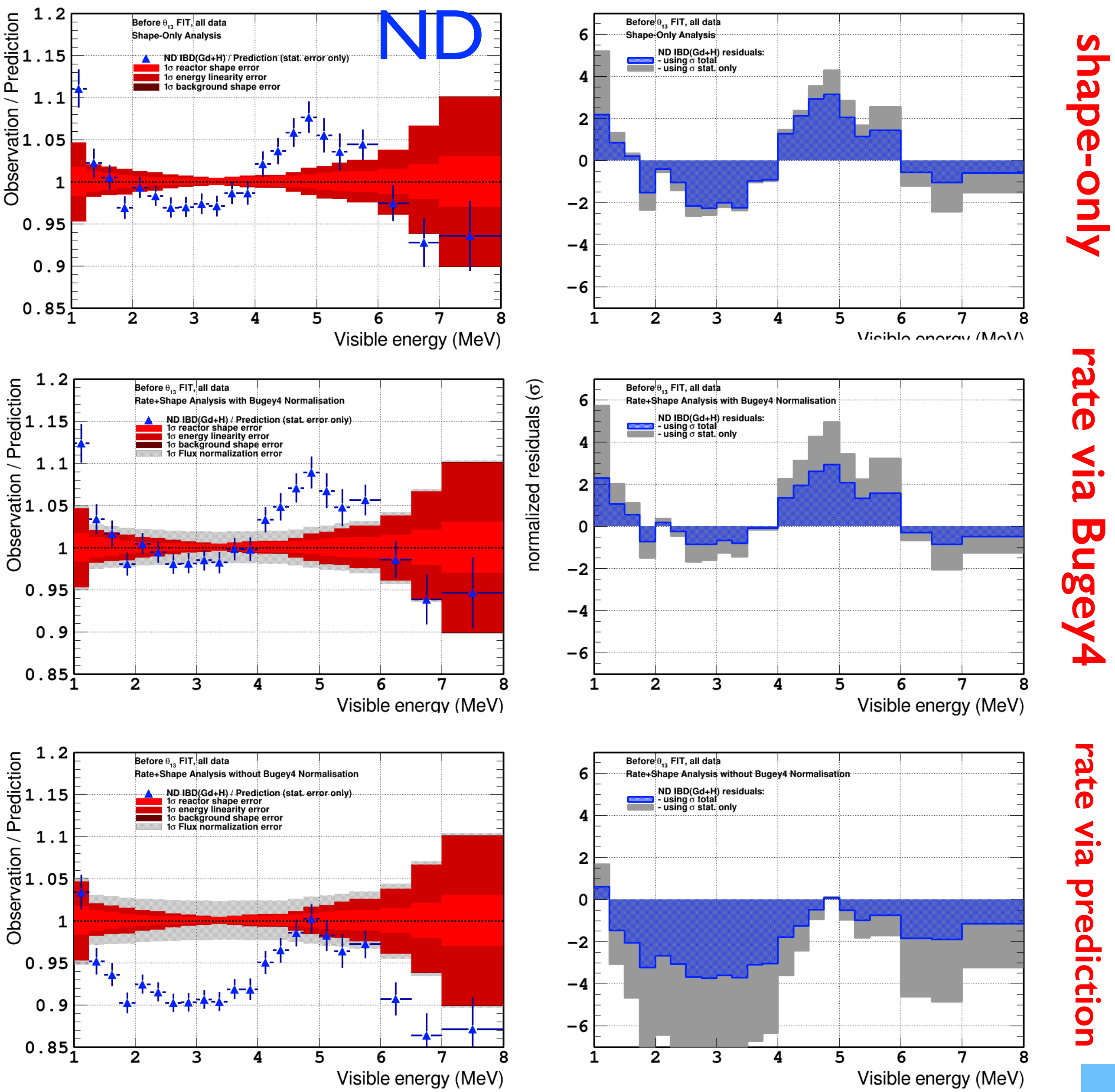
Different technolgies, sites, features…

Summary

- Detection at very short distance and low overbudern:
  - Challenging background conditions to handle
  - Large panels of detection technologies: Liquid vs plastic, segmented, size of the segmentation, neutron capture, many R&Ds provided to enhance discrimination of IBD
- Most of the experiments focus on both L (baseline) and E (energy) information to provide a clear L/E unambiguous oscillation pattern if any
- Reactor experiments offer direct test of the reactor anomaly and the sterile neutrino hypothesis
- Antineutrino Spectra at HEU reactors for a better understanding of the 5MeV distortion

Thanks to D. Lhuilier, V. Egorov, D. Franco, J. Maricic, C. Mariani, K. Heeger, Y. Ho, A. Serebrov, et al. for slides and material

Distortion analysis with ND rate+shape (A. Cabrera CERN seminar 09/16)



Test the existence of features not biased by shape-only assumption (i.e. smaller errors)

shape-only≈Bugey4 (consistency of Bugey4?)

non-statical features
- which is deficit?
- which excess?
- which is OK?

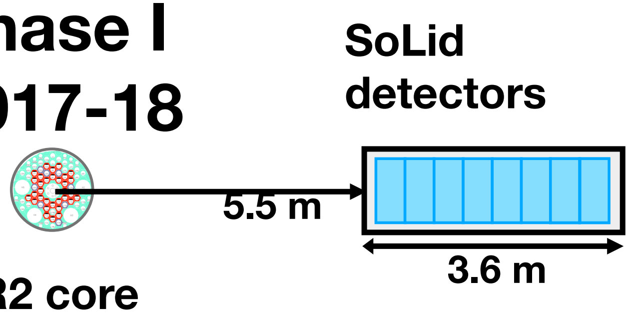
⇒ less evident!!

careful analysis before stating the "trouble region" is bump problem really? (maybe no bump whatsoever)

(bias question → bias answer)

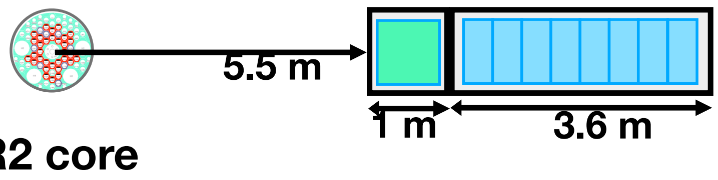
SoLi∂ : Sensibility

Phase I 2017-18

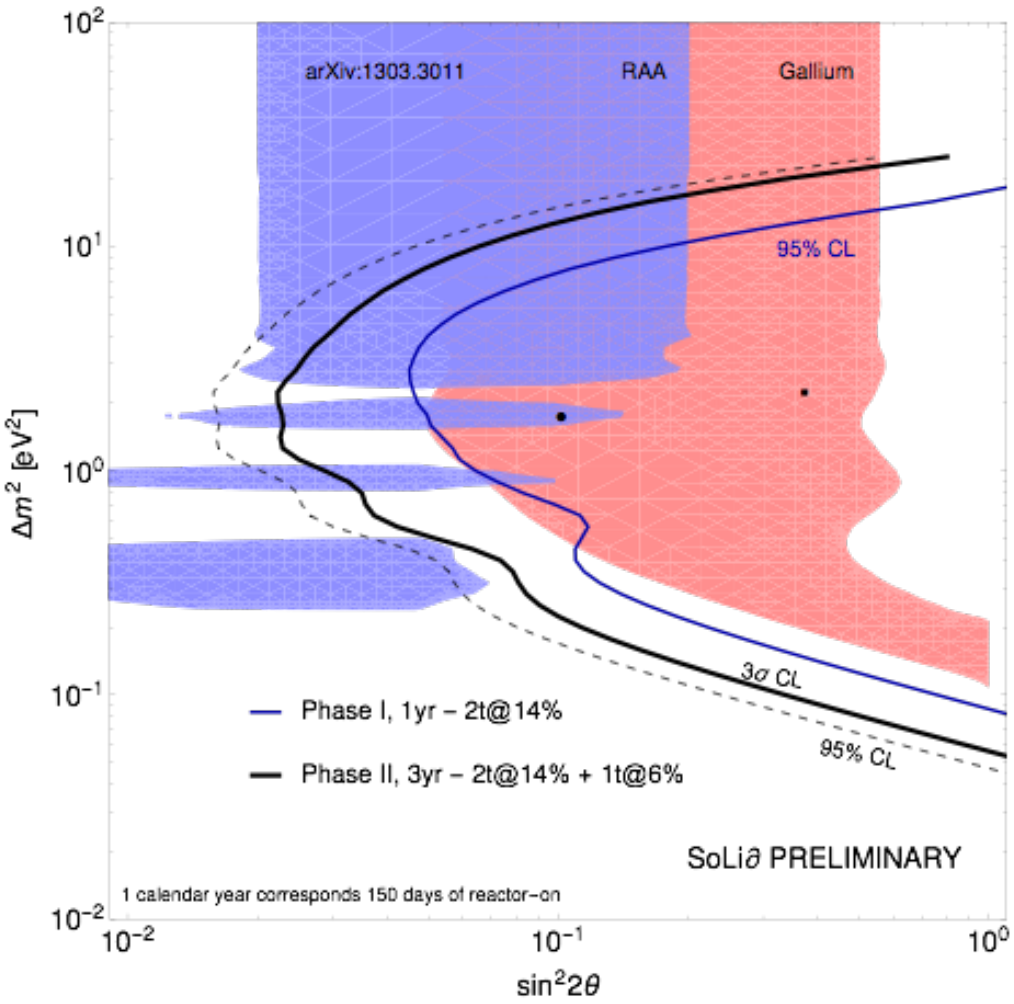


8x MARS modules
PVT cubes + WLS fibres
2 tonnes fiducial

Phase II ~ 2019



HiRes module
WLS PVT cubes + PMTs
1 tonne fiducial



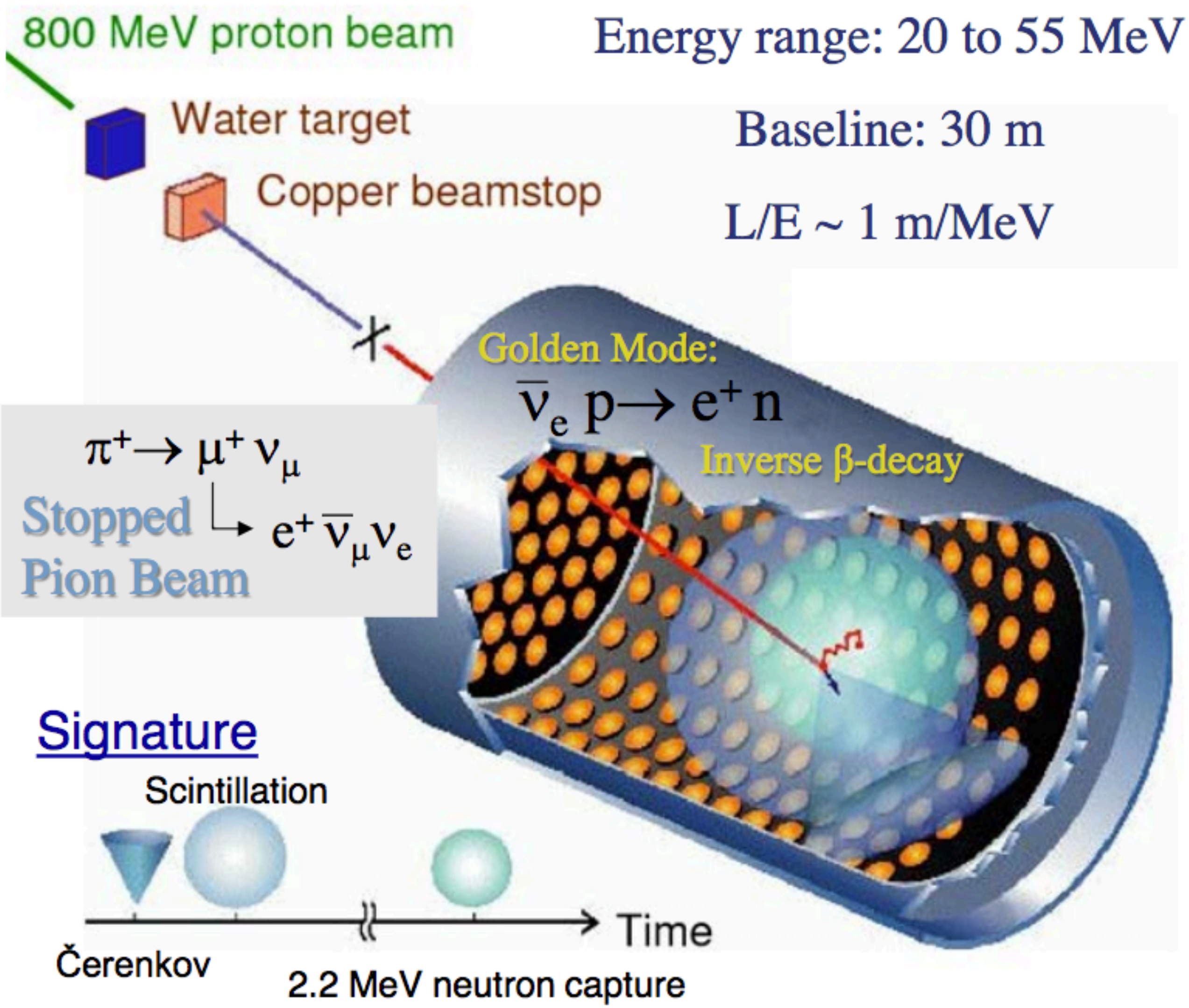
Backup

LSND $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ Appearance

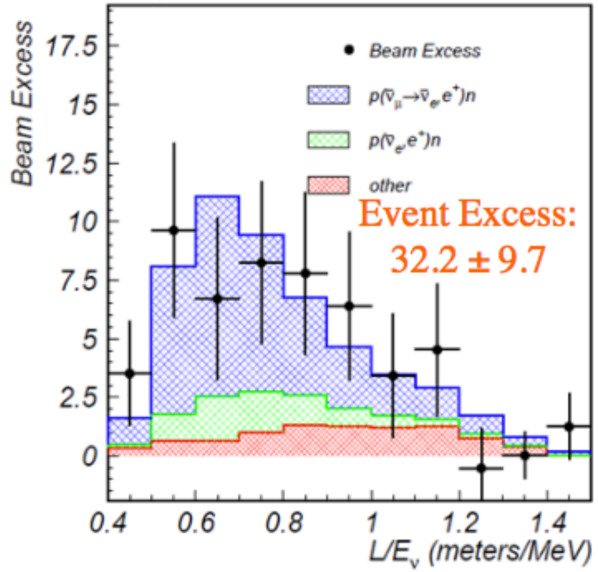
Energy range: 20 to 55 MeV

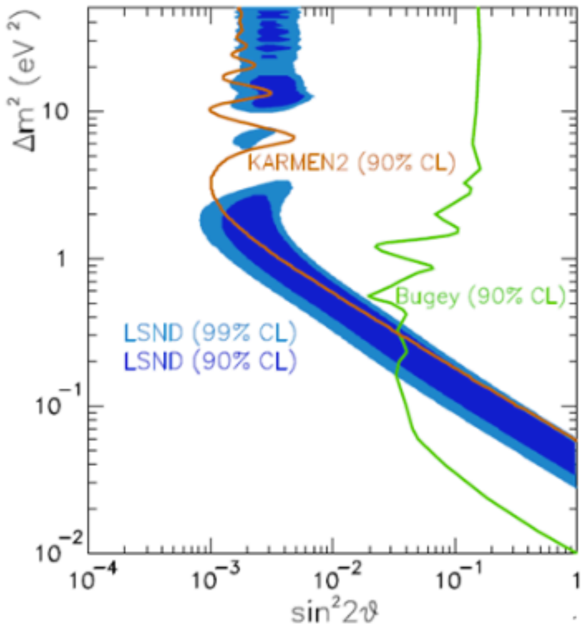
Baseline: 30 m

L/E ~ 1 m/MeV



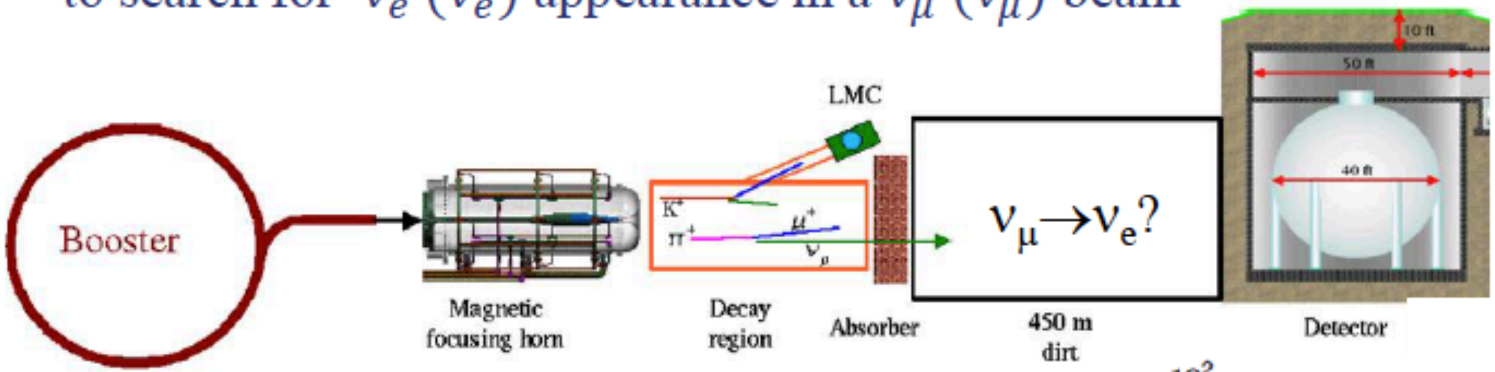
Phys.Rev.D64, 112007 (2001)





MiniBooNE $\nu_\mu \rightarrow \nu_e$ Appearance Search

MiniBooNE used a π^+ (π^-) decay in flight beam and a liquid Cherenkov detector to search for ν_e ($\bar{\nu}_e$) appearance in a ν_μ ($\bar{\nu}_\mu$) beam

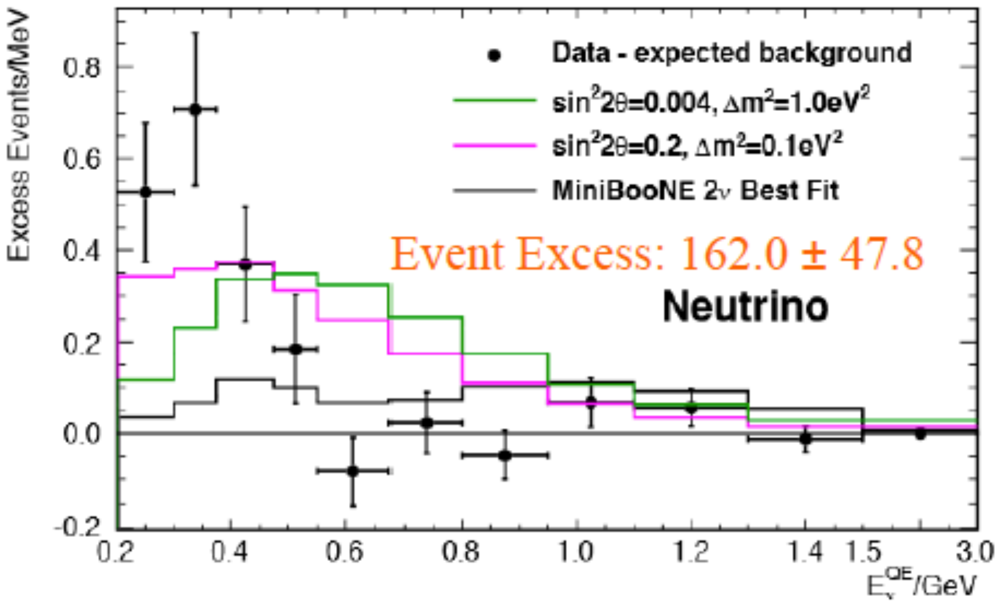


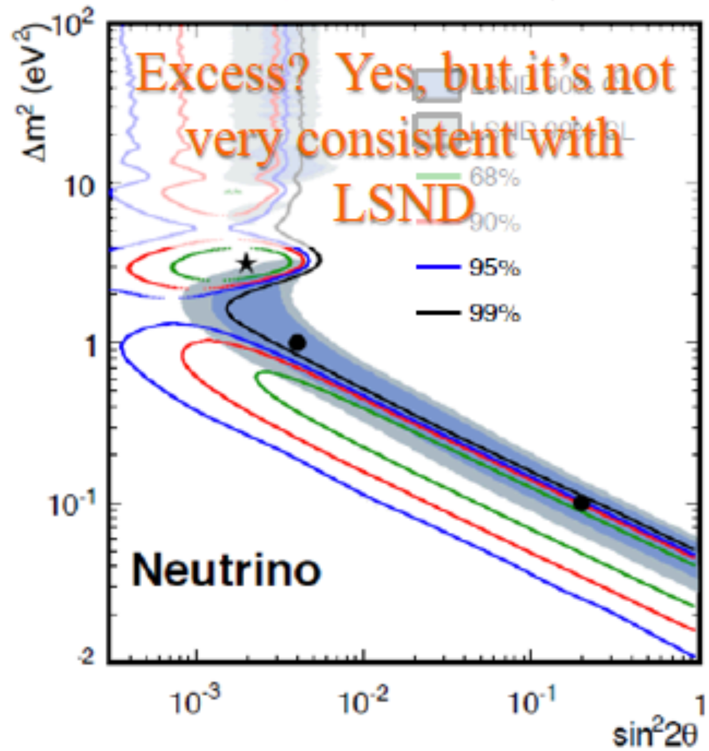
Baseline ~ 500 m

$\langle E_\nu \rangle$ ~ 500 MeV

L/E ~ 1 m/MeV

Phys.Rev.Lett. 110, 161801 (2013)

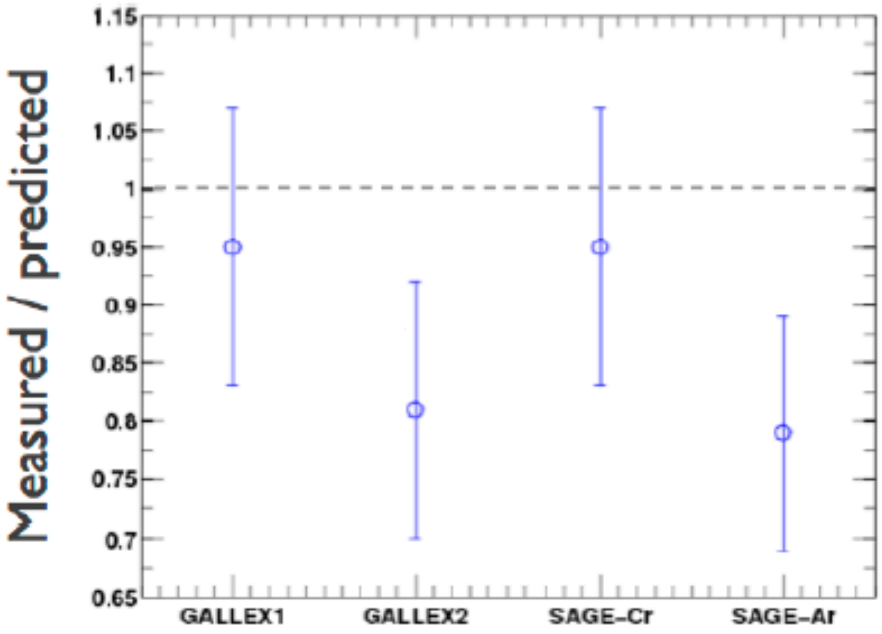




Gallium Anomaly (ν_e Disappearance)

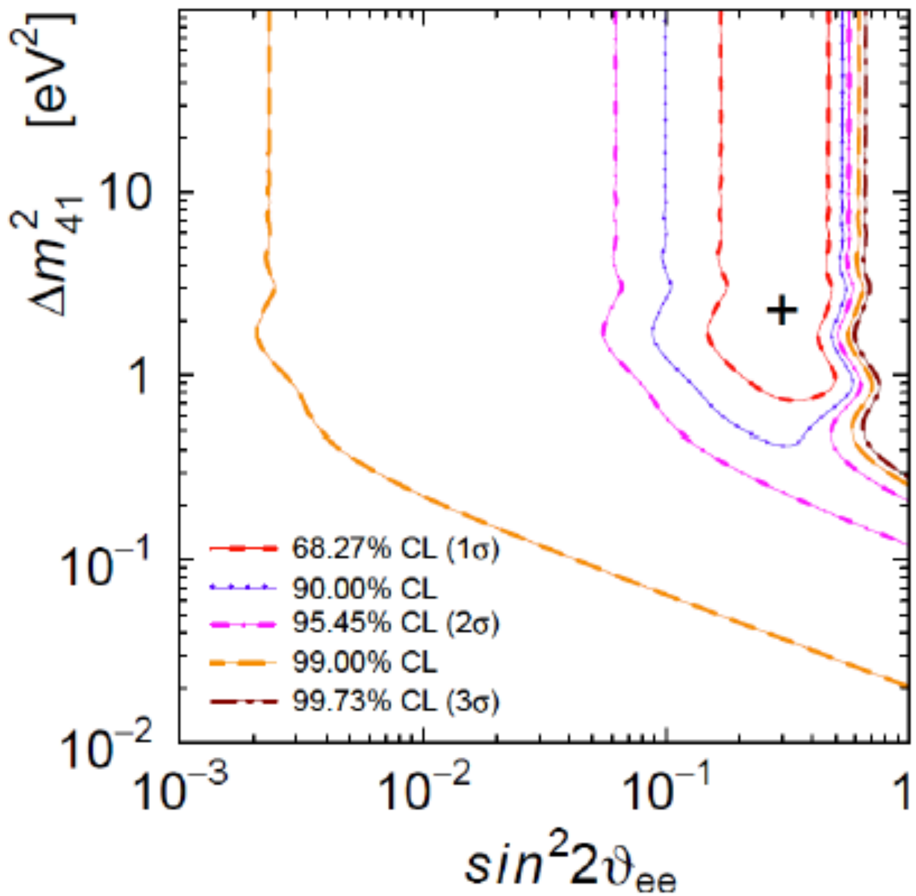
The solar radiochemical detectors GALLEX and SAGE used intense electron capture sources (^{51}Cr and ^{37}Ar) to "calibrate" the $\nu_e{}^{71}Ga$ interaction/detection rate.

A reanalysis, based on new cross section calculations, suggests that were too few events.



Giunti & Laveder, Phys.Rev.C83, 065504 (2011)

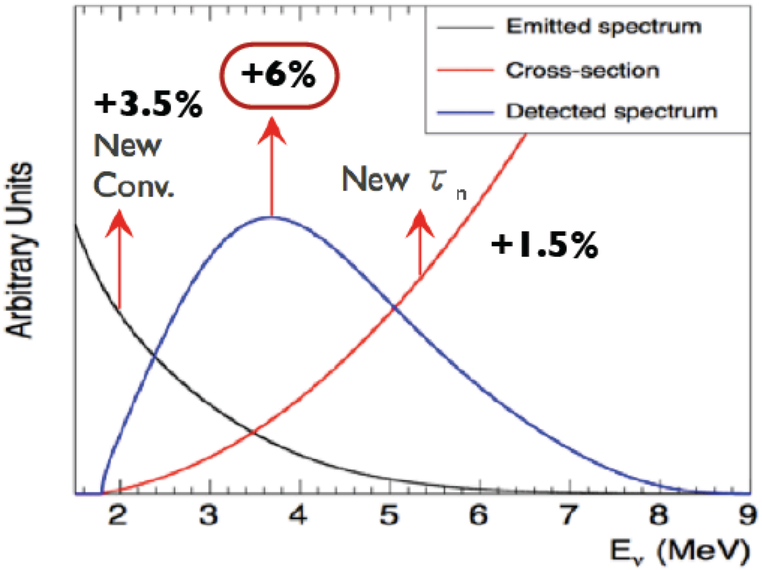
Giunti *et al.*, Phys.Rev.D86, 113014 (2012)



Revised reactor neutrino spectra (ν_e Disappearance)

2011 re-evalatation of reactor antineutrino flux and update on cross-section parameters
(Mueller et al. PhysRevC83054615)

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

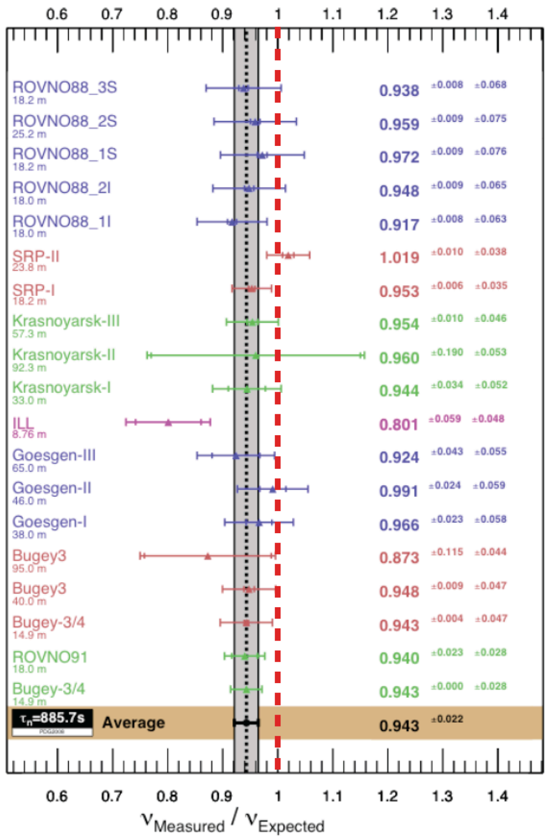


- 3.5% new conversion of ILL beta spectra
- 1.5% off-equilibrium
- 1.5% neutron lifetime τn

➔ Significant increase of the prediction by 6.5%

↔ **Rate deficit 6.5%**

Reanalysis of reactor SBL experiments
G. Mention et al., Phys. Rev. D83, 073006 (2011)

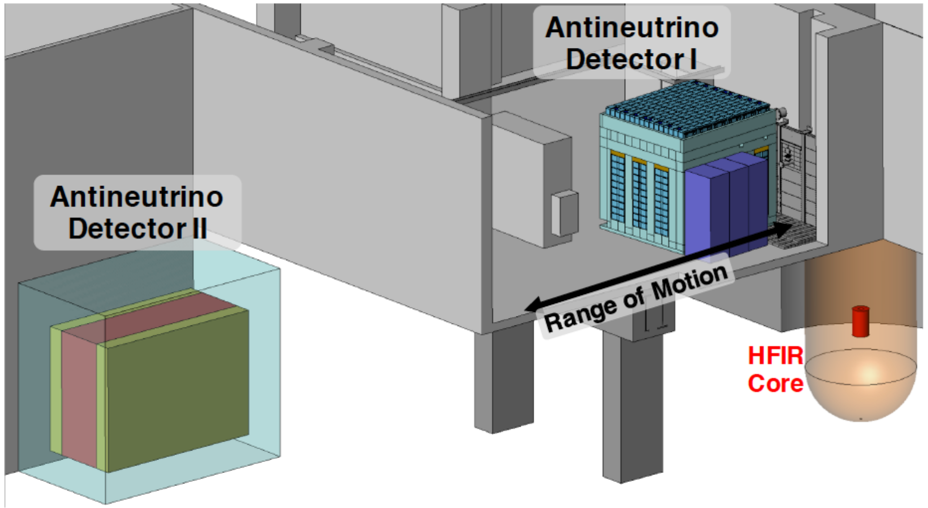


μ = 0.927 ± 0.023,
(updated in White Paper on sterile neutrinos:
[2012 result]
[hep-ph:1204.5379]

PROSPECT: Precision Oscillation and Spectrum Experiment

Search for short-baseline oscillation at distances <10m
Precision measurement of ^{235}U reactor $\bar{\nu}_e$ spectrum

2 detectors, movable baseline, research reactor



Phase I
one movable detector AD-I, ~7-12 m baseline
(Array of 1.2 m segments filled with L6LS)

power: 85 MW (research)
fuel: highly enriched uranium (^{235}U)
core shape: cylindrical, compact
duty-cycle: 41%

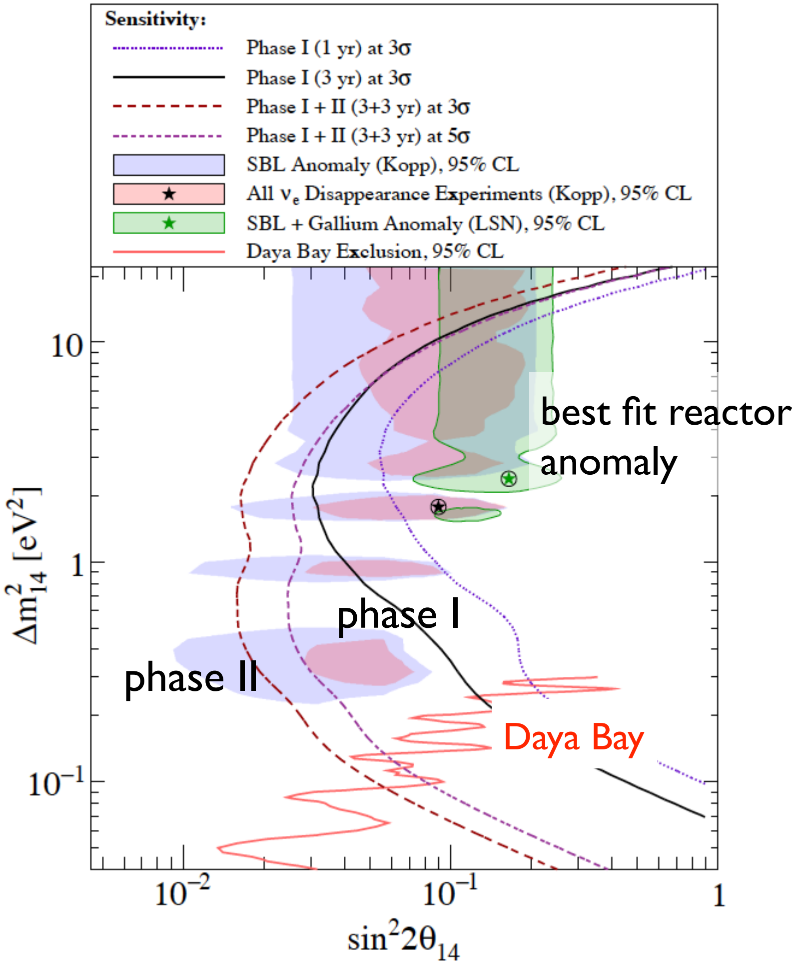
Phase II
two detectors,
movable AD-I, ~7-12m baseline
stationary AD-II, ~15-19m baseline

physics program, arXiv: 1512.02202
test detector studies, JINST 10 P11004 (2015)
background measurements, NIM A806 (2016) 401
whitepaper, arXiv: 1309.7647

prospect.yale.edu

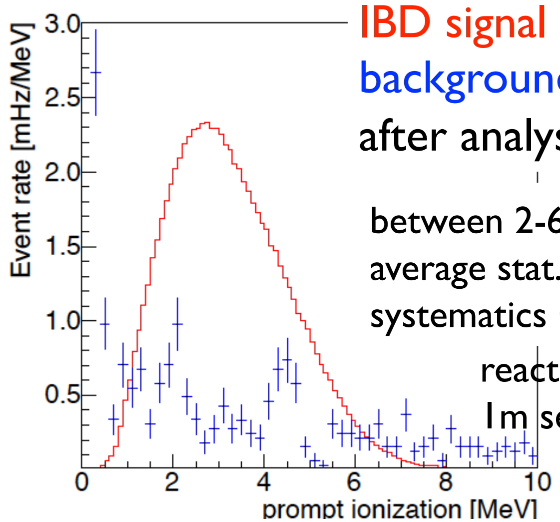
A Precision Oscillation Experiment

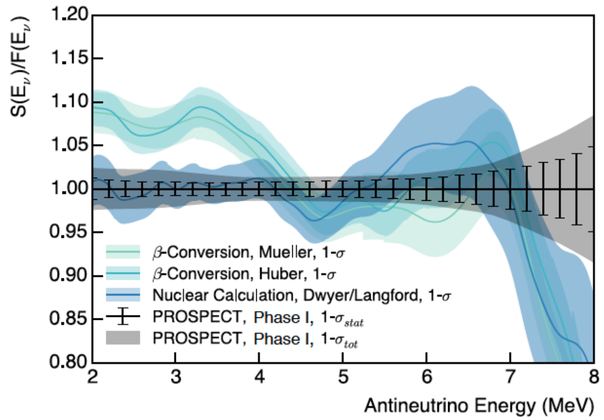
4 σ test of best fit after 1 year
>3 σ test of favored region after 3 years
5 σ test of allowed region after 3+3 years



A Precision Spectrum Experiment

Measurement of ^{235}U spectrum
Compare different reactor models
Opportunity to compare different reactor cores





SBL Reactor experiments

Highly Segmented Plastic Scintillators

+Li^6-loaded

NuLat

NuLat – Neutrino Lattice

A Novel Detector for probing RAA, reactor monitoring and fast neutron directionality

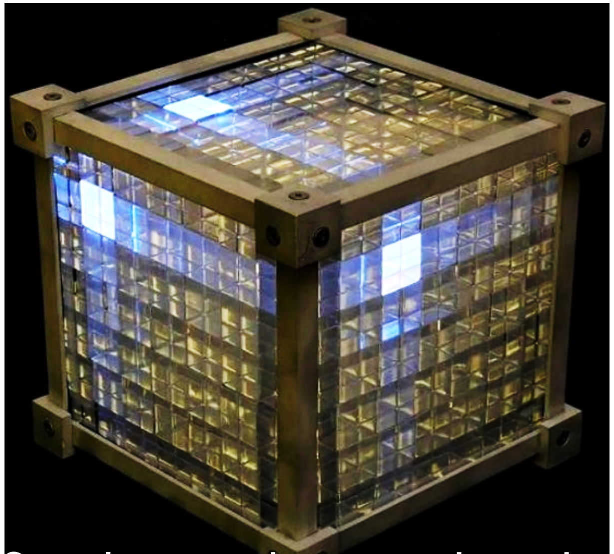
- NuLat – finely, 3D segmented detector
- 10x10x10 ^{6}Li loaded plastic scintillator cubes (2.5"), spaced by thin air gaps.
- Utilizes total internal reflection (n = 1 and n = 1.54) to totally guide and focus light in just 6 PMTs along the three principal axis
- Easily scalable, zero mass wall (air)
- LY > 600 pe/MeV over just 6 PMTs! (En. Res: 4%/sqrt(E))
- NuLat is a joint

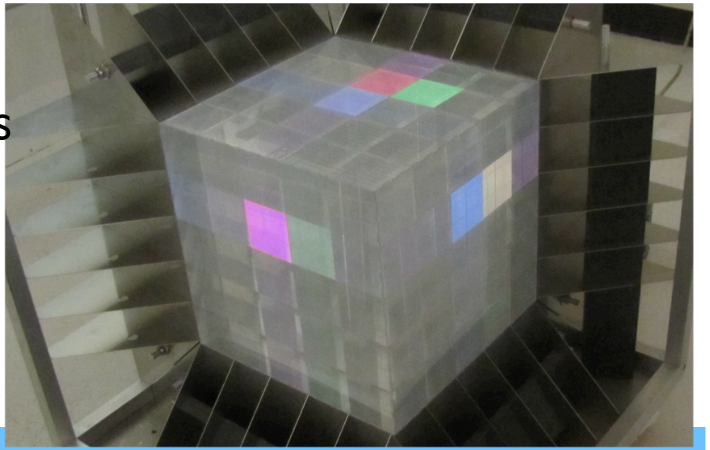
  endeavor of 20+ scientists

  (Drexel, Johns Hopkins, LSU, NIST,

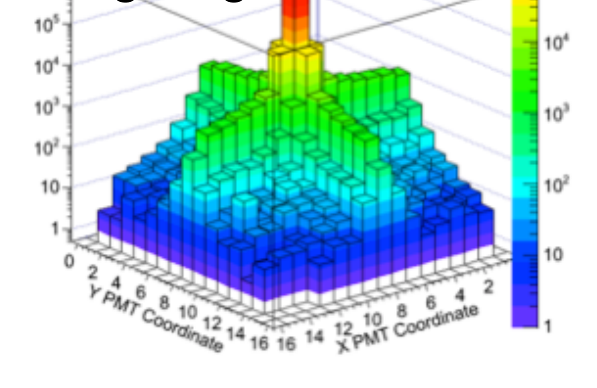
  NCCU, Ultralytics LLC,

  University of Hawaii, Virginia Tech)





Signal strength on a cube side – hit cell receives 100 times stronger signal.

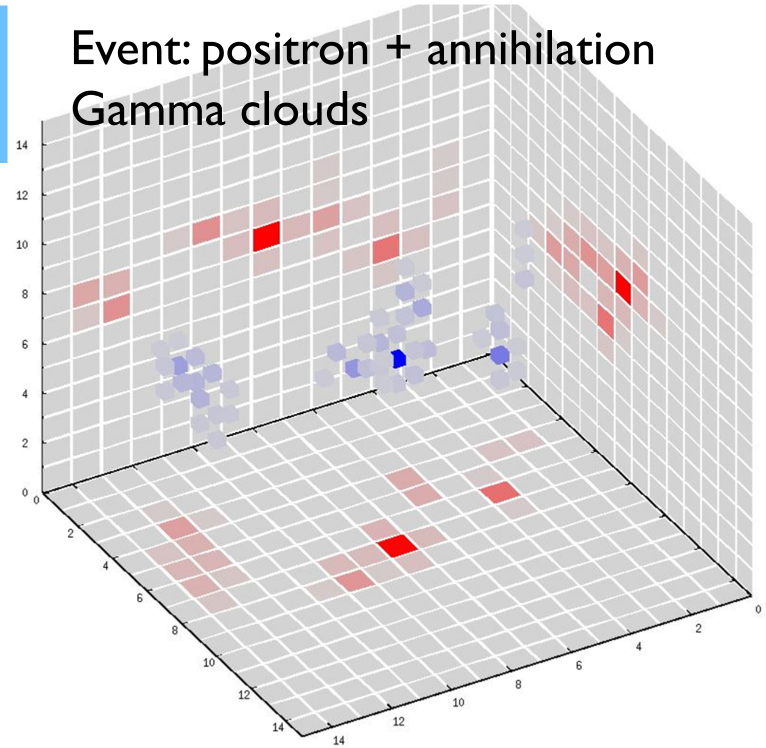


NuLat Highlights

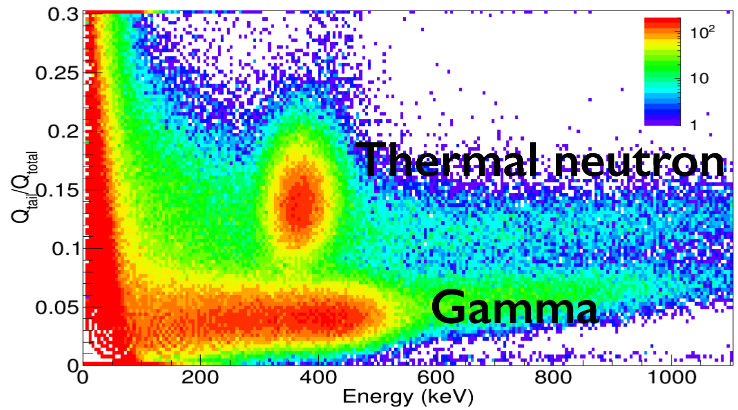
- Inverse beta decay with neutron capture on ^{6}Li

  $^{6}Li + n \rightarrow 3H + \alpha + 4.8$ MeV

- Localized 400 keV_{ee}
- Excellent localization and background rejection
- Prompt signal: positron + annihilation gammas, clearly distinguishable by complete event topology



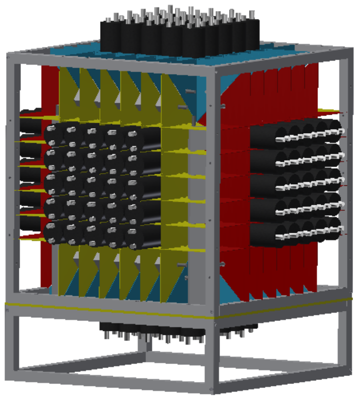
Eljen LLNL based EJ-200 ^{6}Li PSD

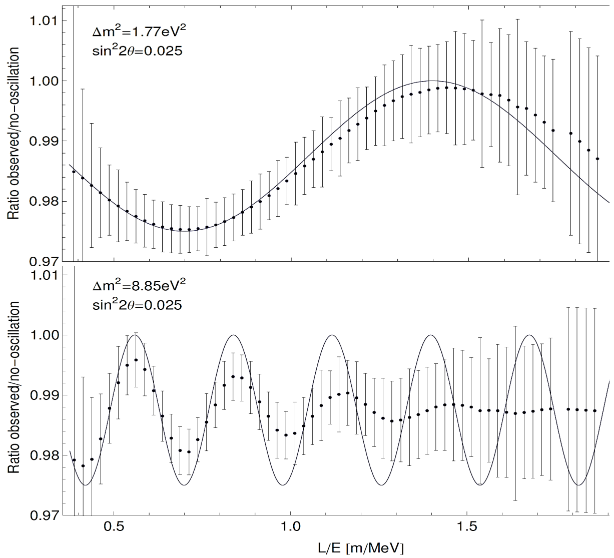


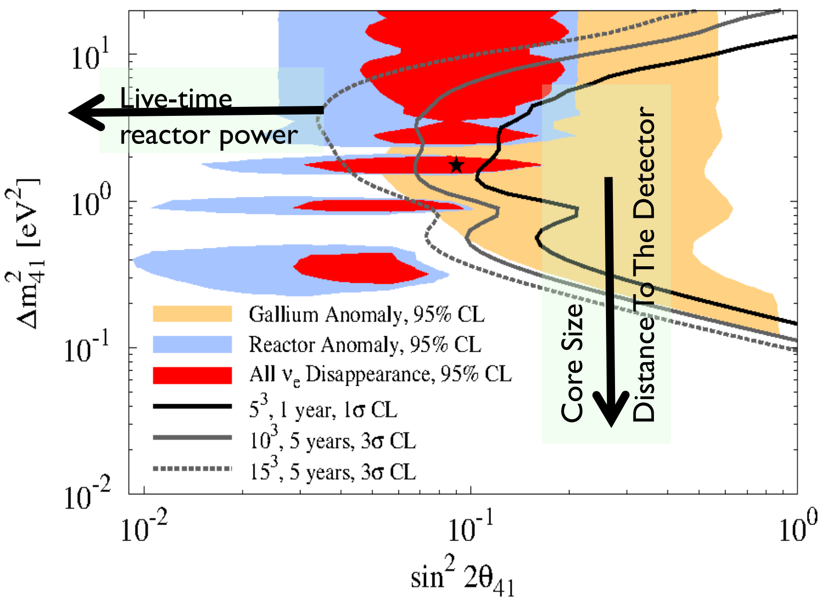
- Short capture time – 7 μs
- Distinguishable delayed signal thanks to pulse shape discrimination

NuLat – Sensitivity and timeline

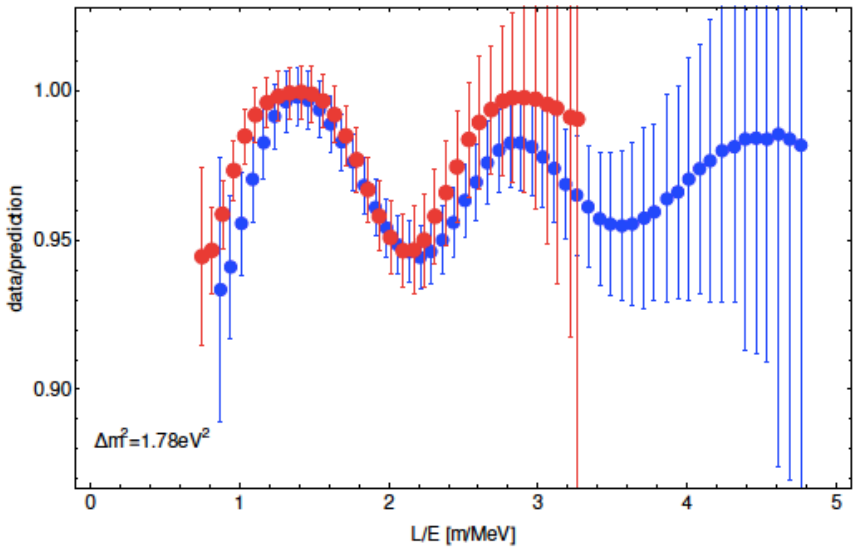
- 5x5x5 demonstrator under construction
- Design finalized and major parts ordered months ago
- Final assembly in March 2016
- Deployment at 2 reactors: NIST (Maryland) and North Ana (Virginia)
- Decent sensitivity with the demonstrator
- Proposal under review for 10x10x10 detector



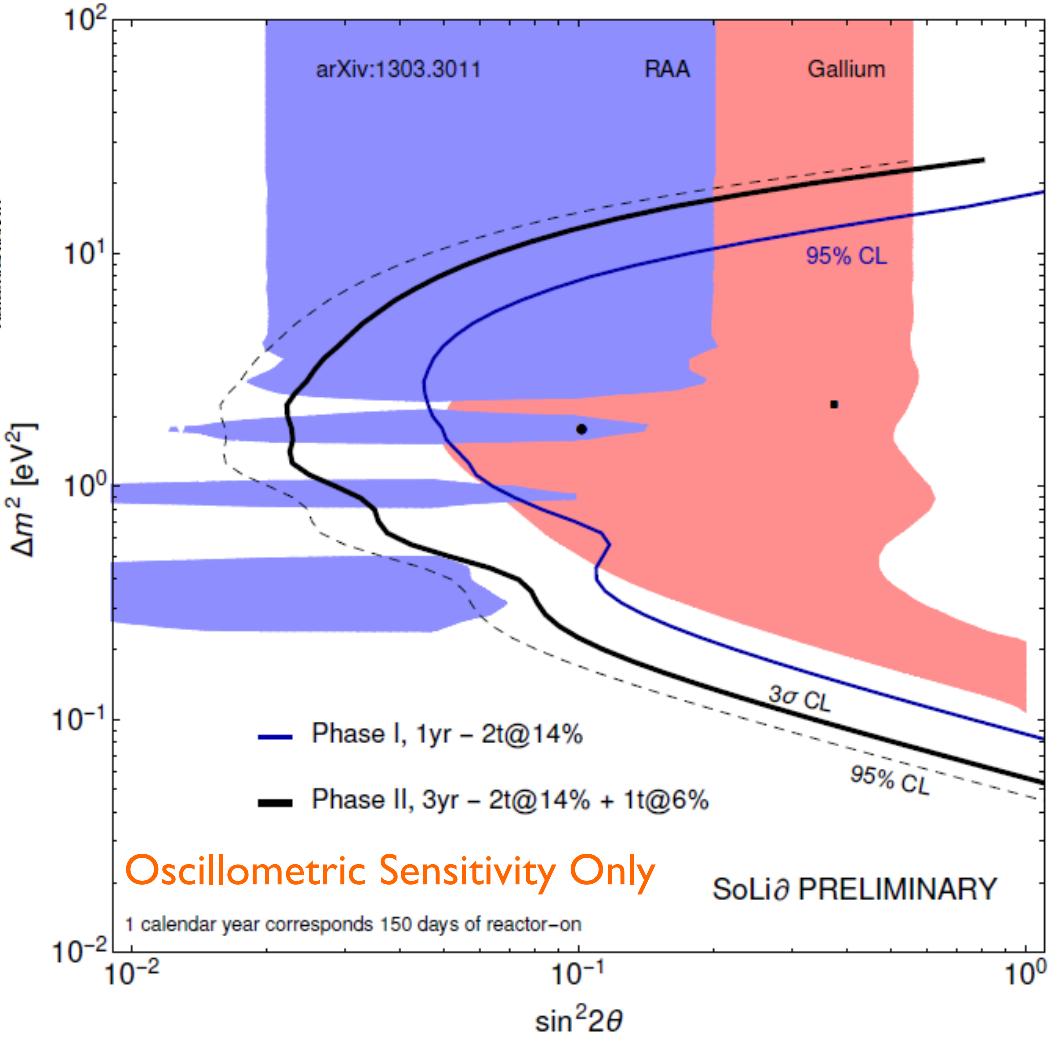




SoLid Sensitivity with CHANDLER



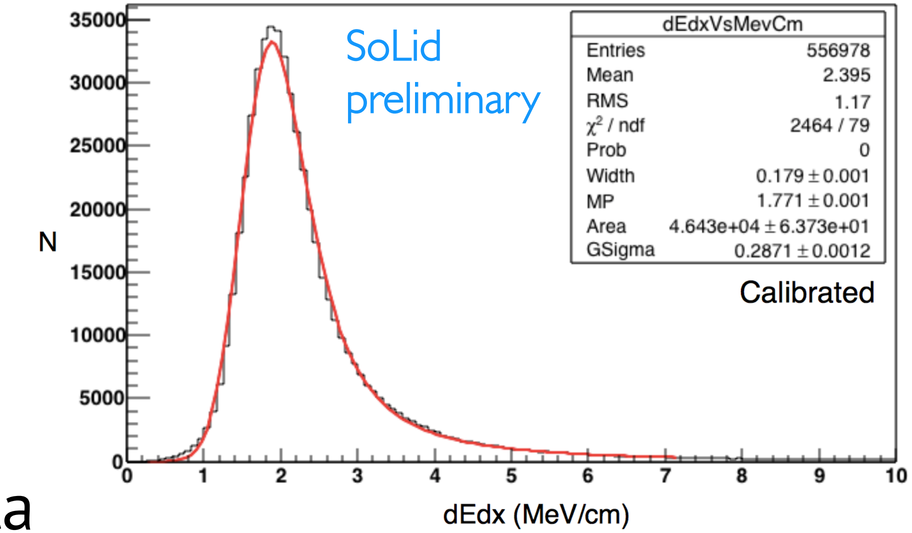
Distribution of events as a function of L/E for Δm^2**=1.78eV^2** .
The red data points are for CHANDLER and the blue data points are for SoLid. Resolutions are fully included and the error bars represent the statistical errors after background subtraction.



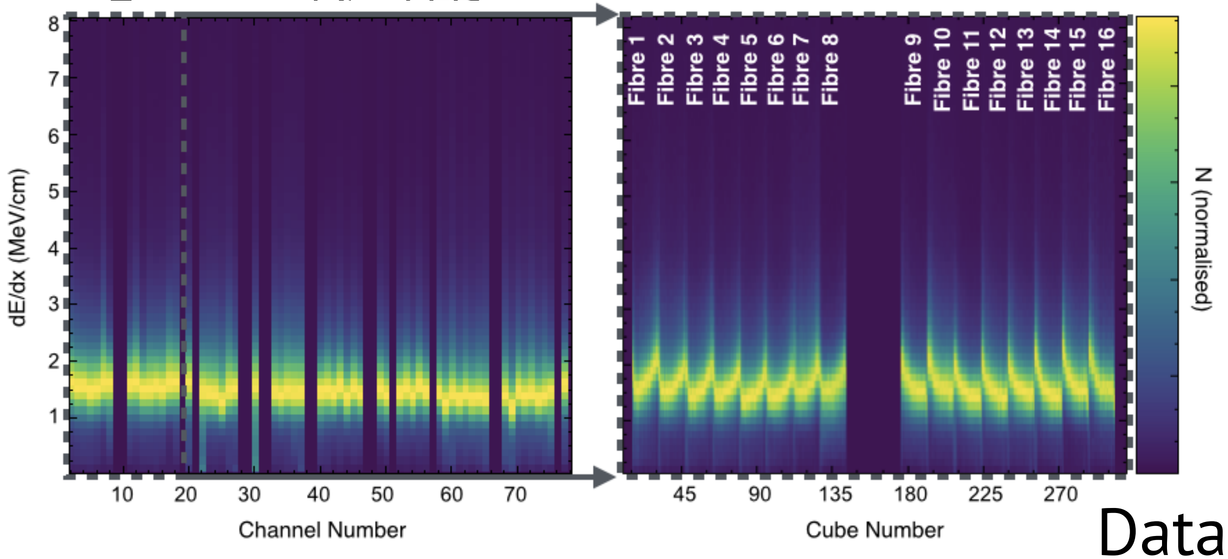
Adding CHANDLER to the three-year Phase II extends the coverage to higher Δm^2 and pushes the reach well into the Reactor Anomaly. These sensitivities are purely oscillometric, based on energy spectrum and baseline information alone.

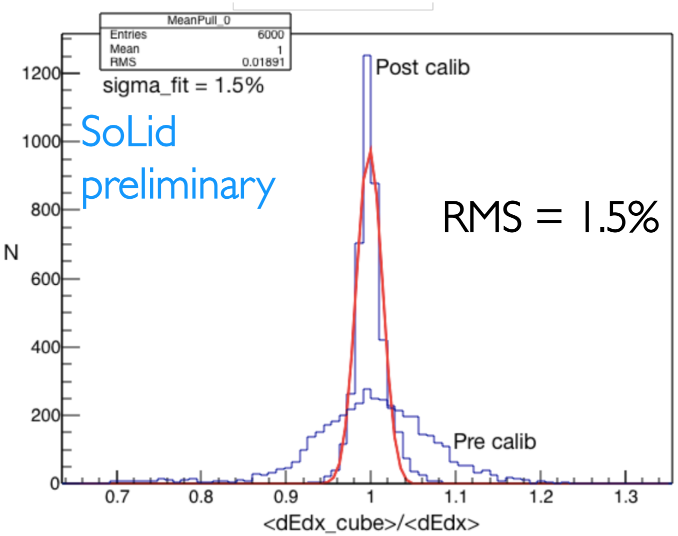
SoLiə : In situ calibration with muons

- in-situ energy calibration using dEdx
  - channels intercalibration
  - cube response equalisation
- Light yield measured : 25 PA/cube
- MPPC gain measured with dark count rate



Data

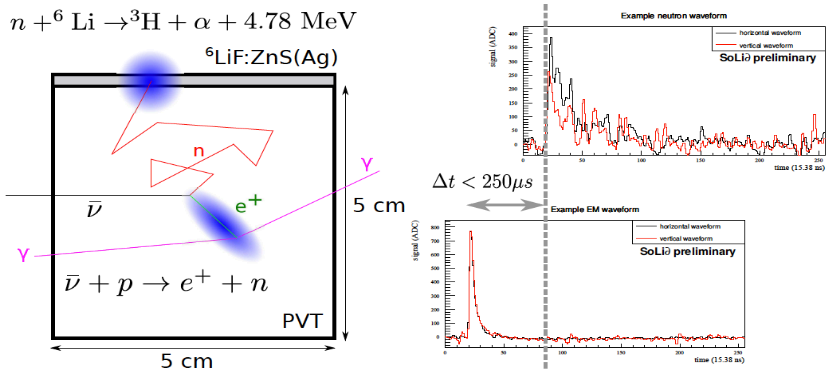


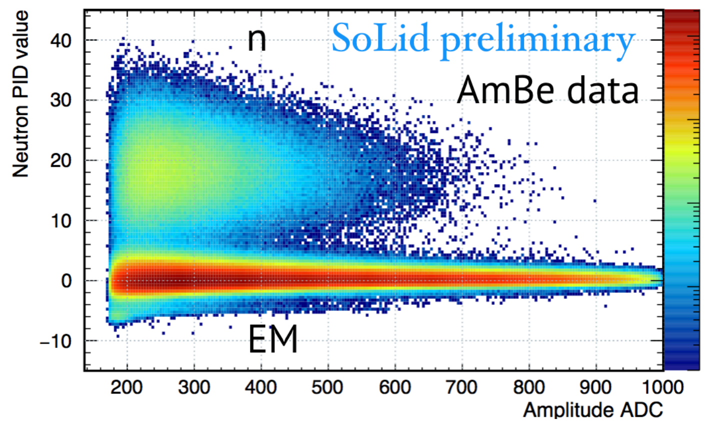


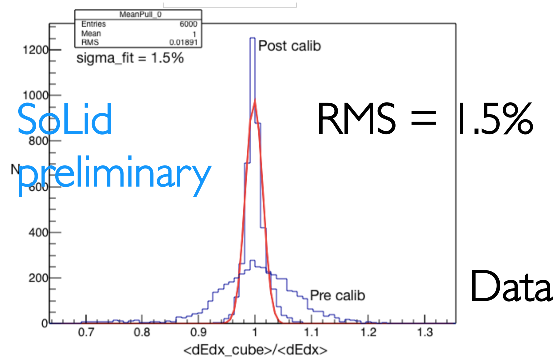
Data

SoLi∂ : Detector

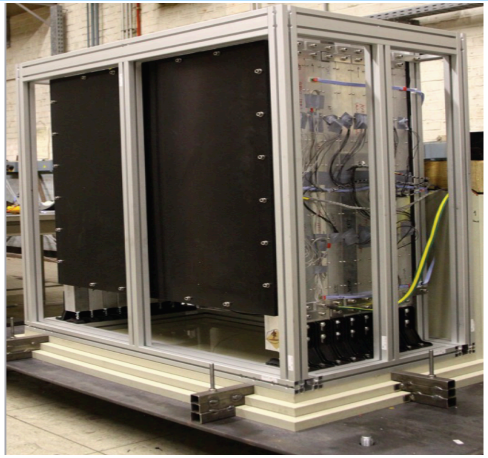
- High segmentation of target volume
  - Precise localisation of IBD event (< 5cm)
  - limit the need for large passive shielding
- Discrimination Neutron / gamma-ray by pulse shape
  - distinctive response for prompt and delayed signal
  - Identification based on neutron pulse (shape proportional to integral)
  - neutron can be used to trigger event read out
- Calibration with SM1
  - in-situ energy calibration using Muon dEdx + Light yield measured : 25 PA/cube (SM1)
  - Very good stability of energy scale observed (few %)

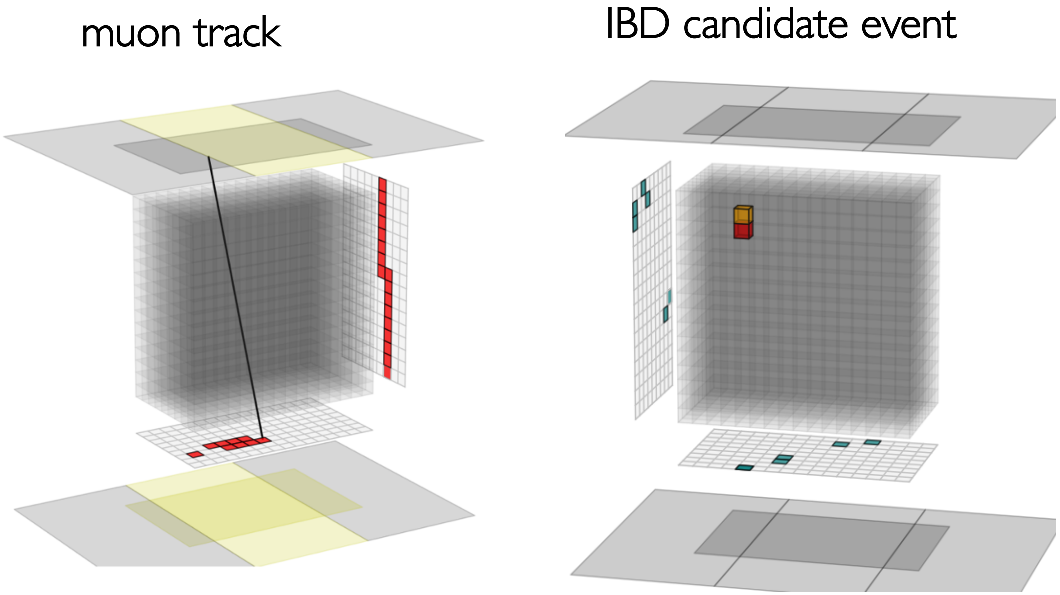




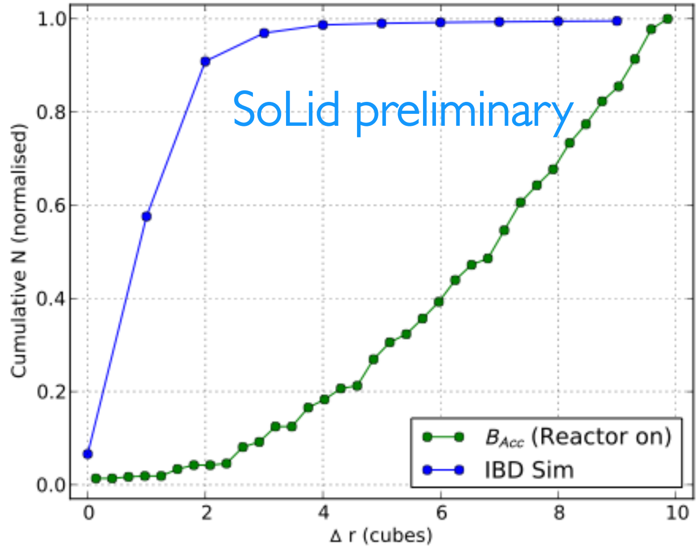


SoLid : IBD analysis



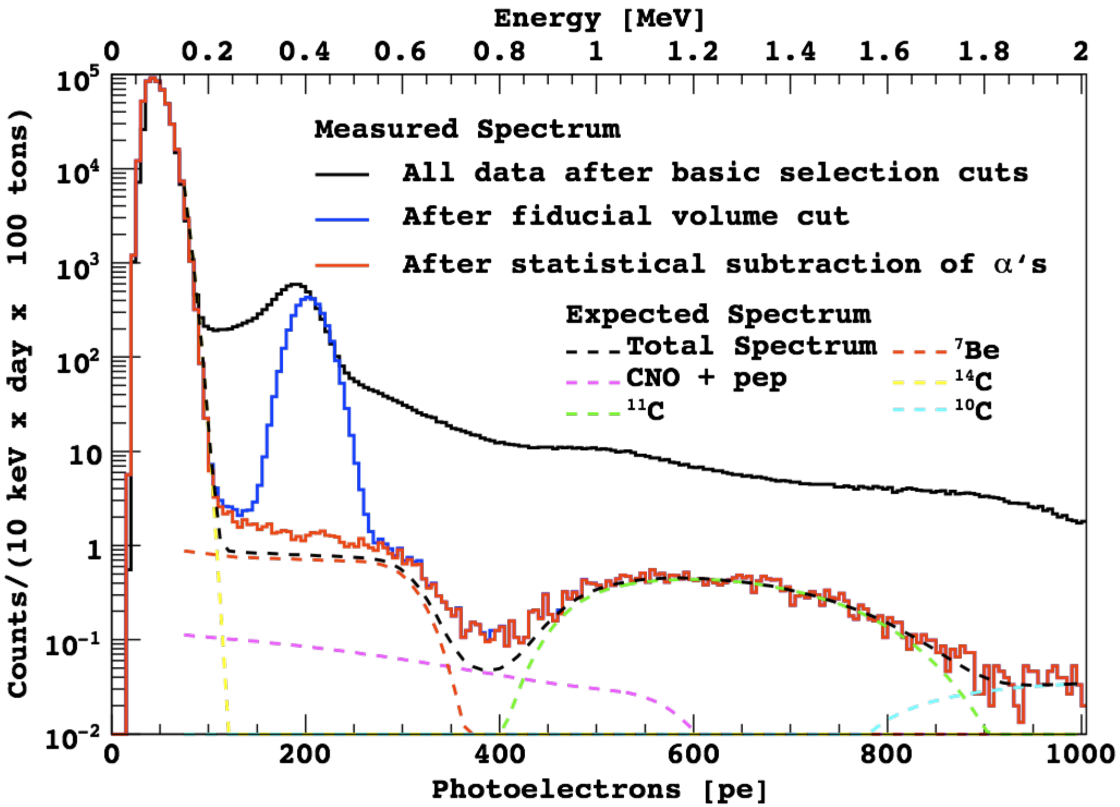


- First data processing completed
- Study of background events and selection cuts started
  - Expect S:Bacc ~2:1 using cube segmentation
- aim for result early next year



Radio-purity

Expected and measured spectra, before and after the cuts

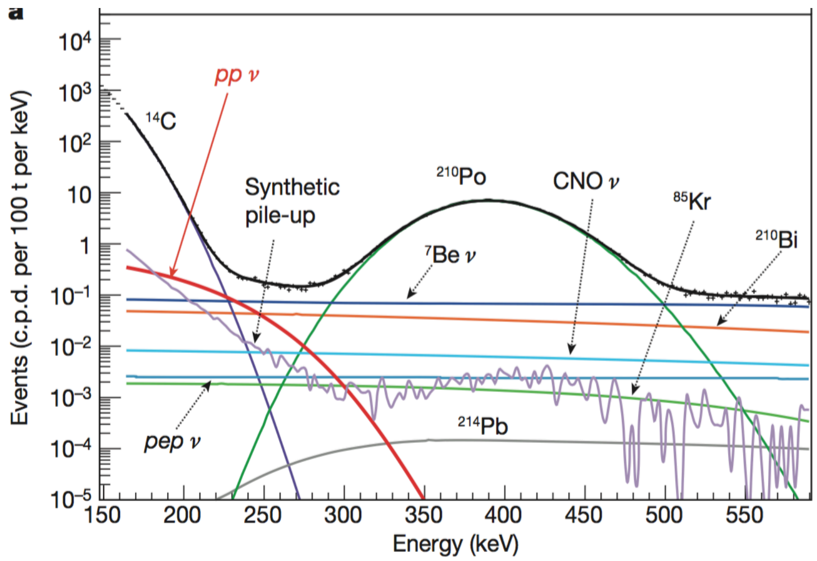


- Alpha's from **^{210}Po** are subtracted via pulse shape discrimination
- Most of the rejected events are **external background** and cosmic **muon induced** events
- Contamination intrinsic to the scintillator is the **lowest ever reached** in organic scintillators:
  - ^{238}U and ^{232}Th at ~10^{-19} g/g of scintillator
  - ^{14}C/^{12}C ~ 10^{-18}

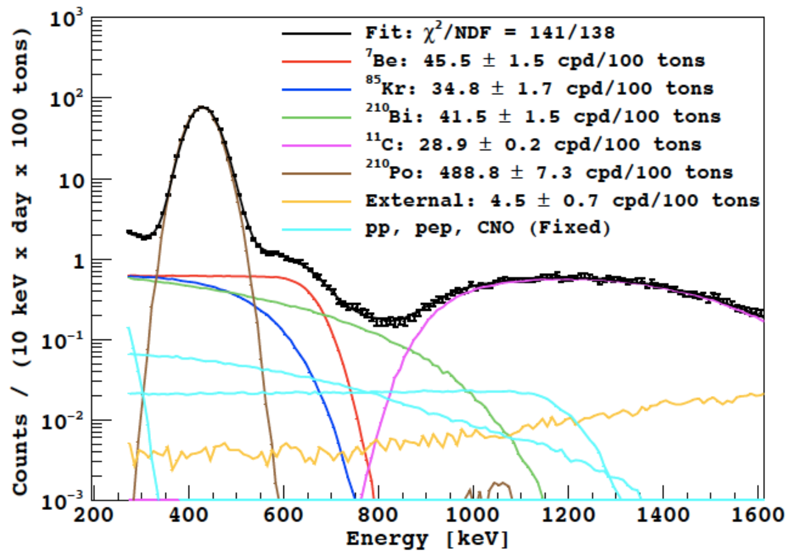
The extremely low background extended the physics potential of Borexino in the solar neutrino physics, geo-neutrinos, and fundamental particle physics

Solar Neutrinos

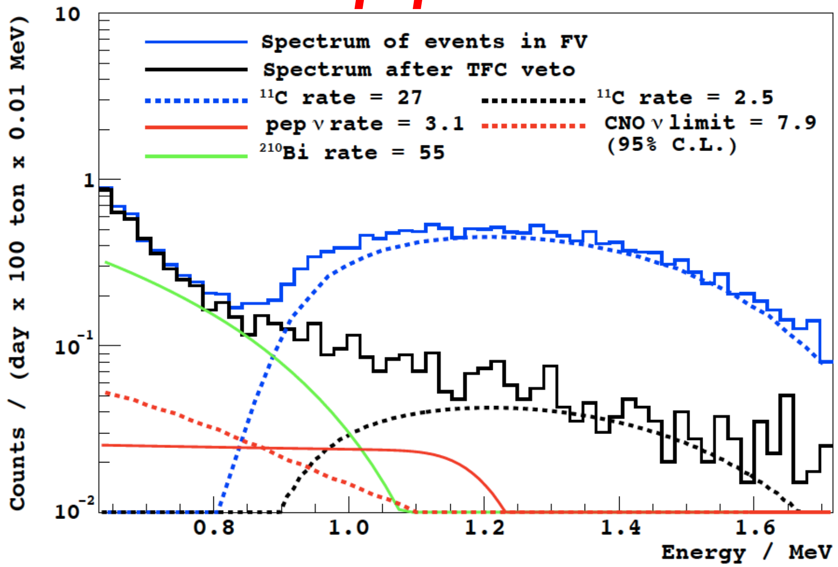
pp



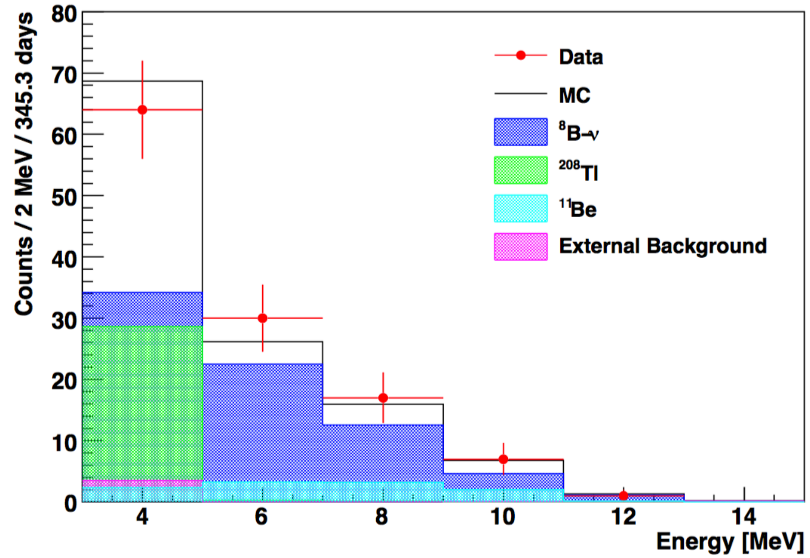
7Be



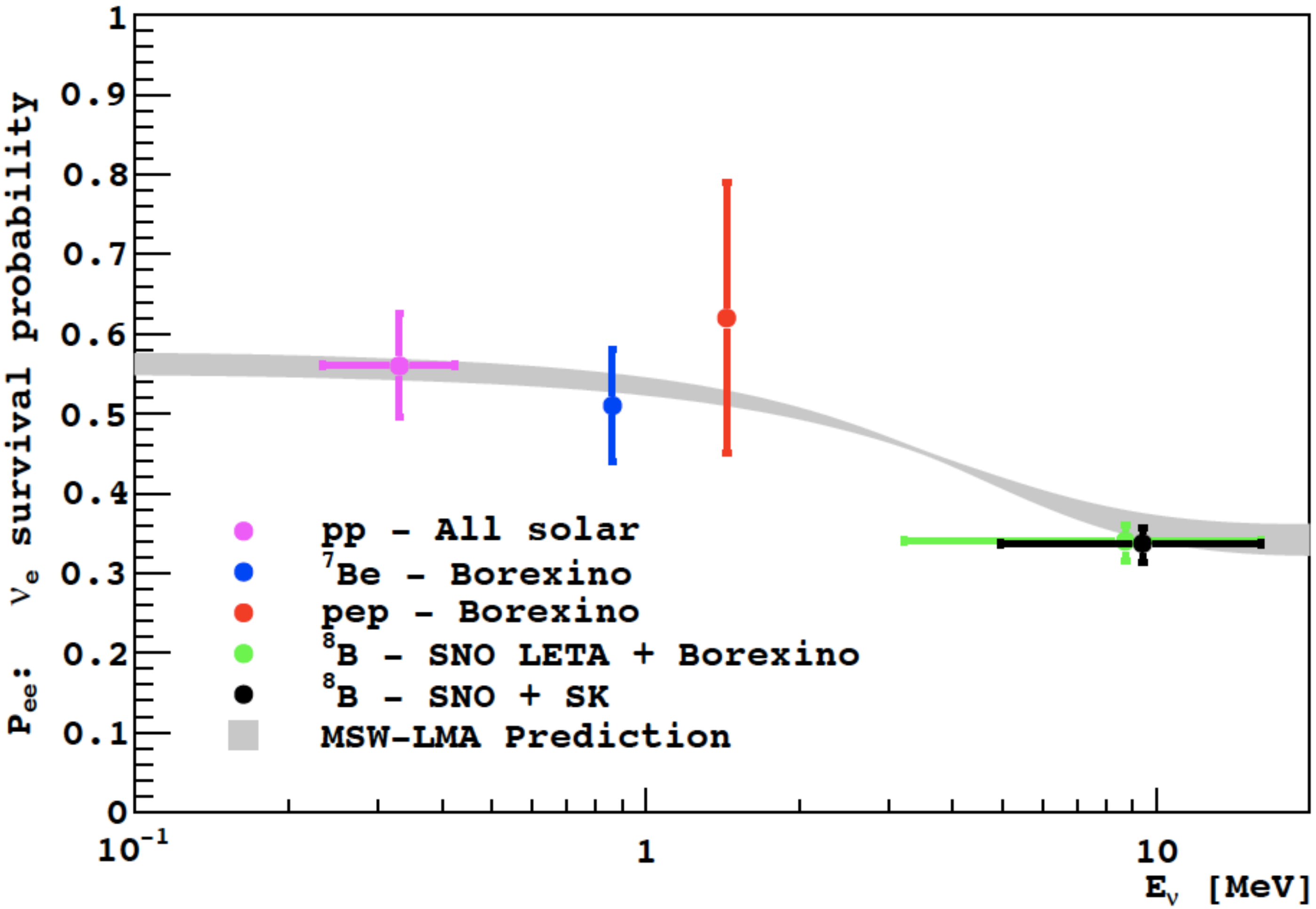
pep



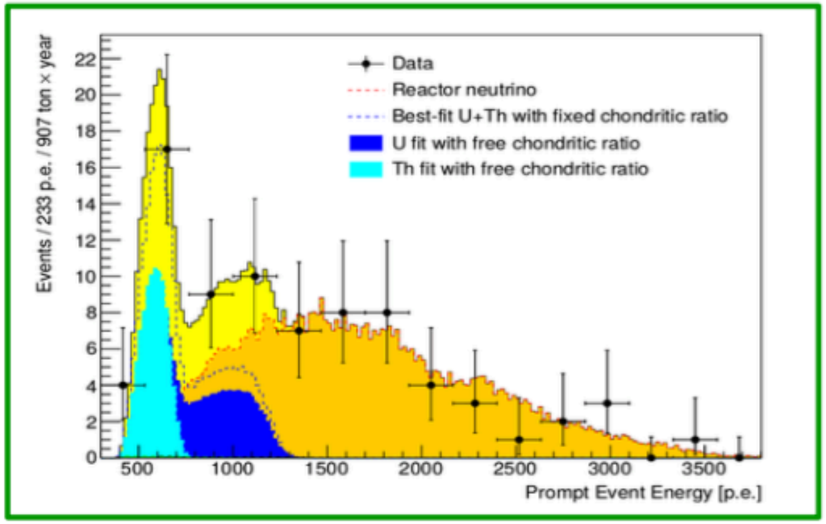
8B



Solar Neutrinos



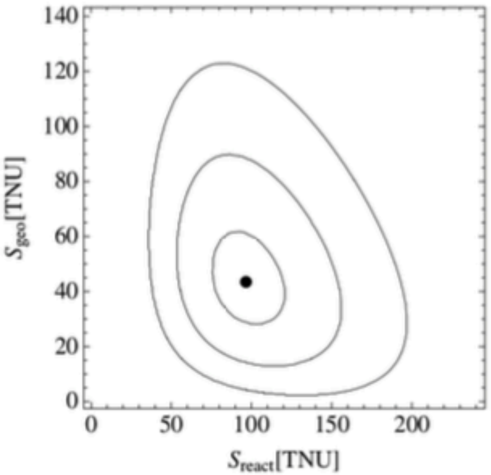
Geo-neutrinos



Detection trough inverse beta dacay

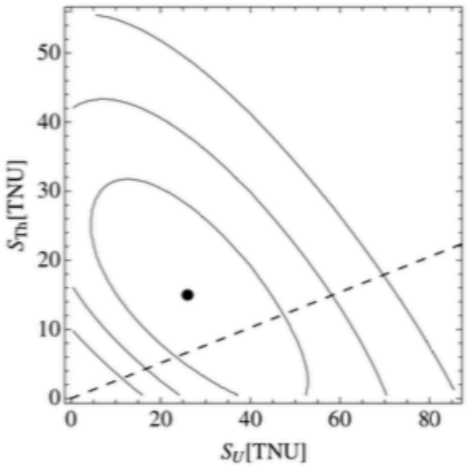
$$\bar{\nu}_e + p \rightarrow n + e^+$$
$$n + H \rightarrow D + \gamma(2.2\text{MeV})$$

Last update: ~ 2000 days exposure



> 5 σ evidence out of null observation

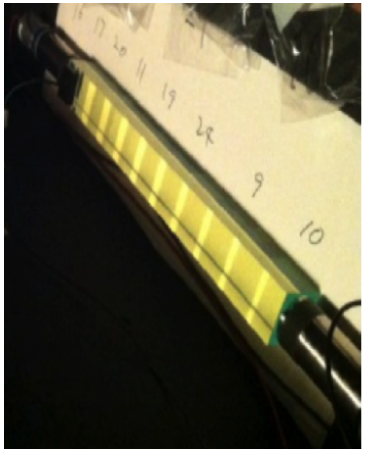
Geo- vs. reactor neutrinos



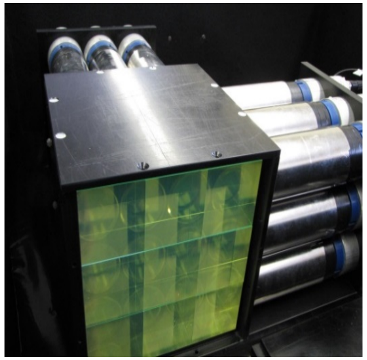
Possibility to distinguish between different geological models

Free chondritic ratio

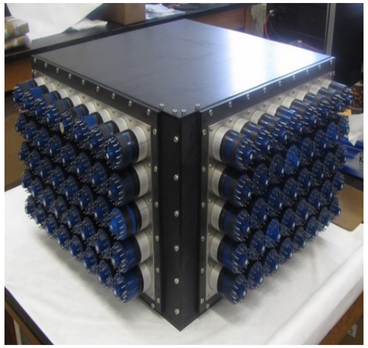
Research and Development Effort



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

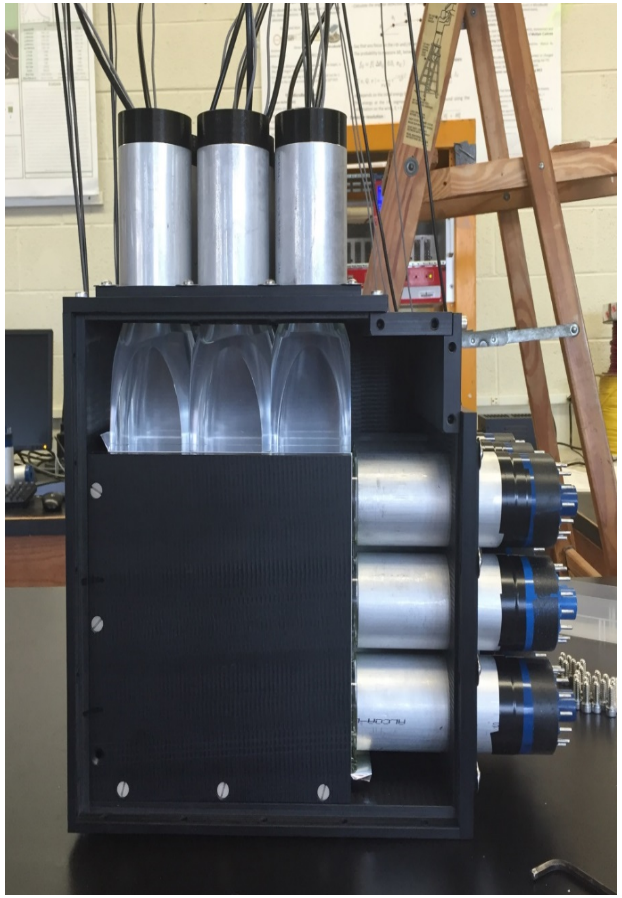


MicroCHANDLER is a 3×3×3 prototype which we are using to test our full electronics chain, develop the data acquisition system, study neutron capture identification and measure background rates.



MiniCHANDLER is a **fully funded** system test (8×8×5) which is now being commissioned and will be deployed at North Anna Nuclear Power Plant, Virginia.

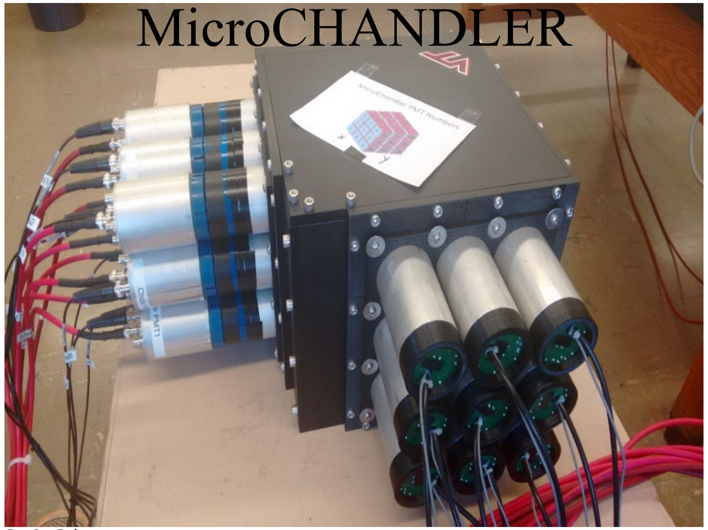
MicroCHANDLER R&D



Light tight mechanical set up of the MicroCHANDLER

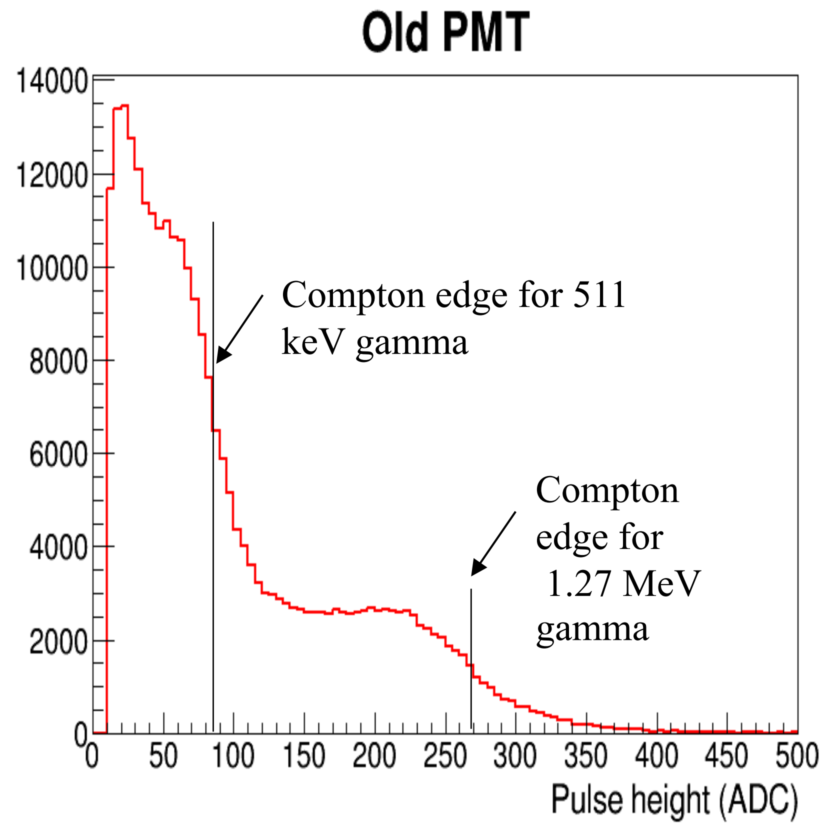
Light guide used with HAMAMATSU PMTs

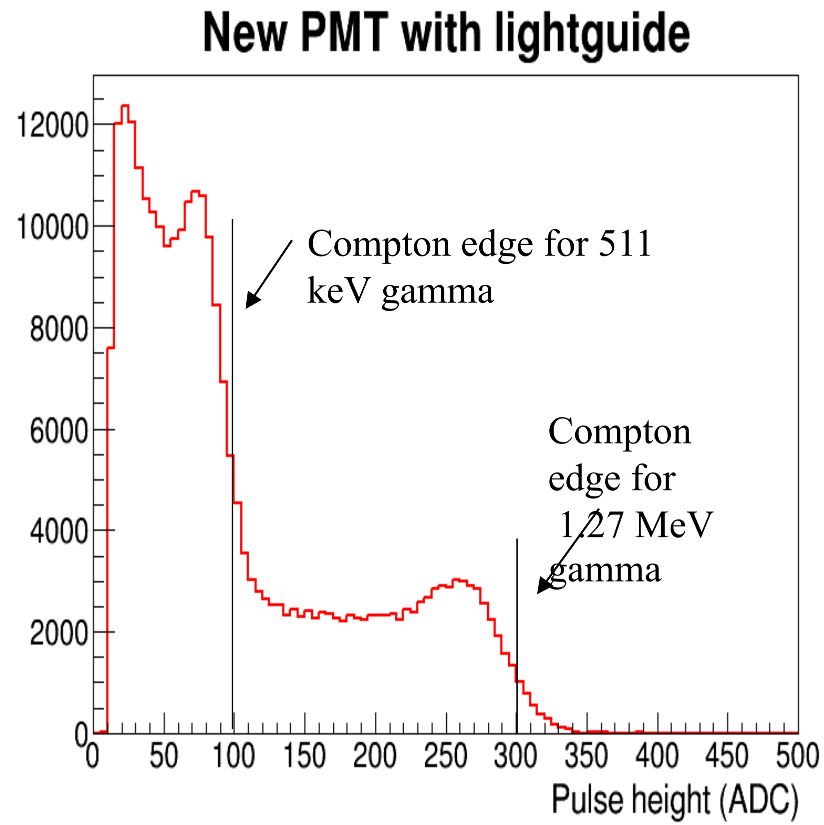
Fully functioning MicroCHANDLER



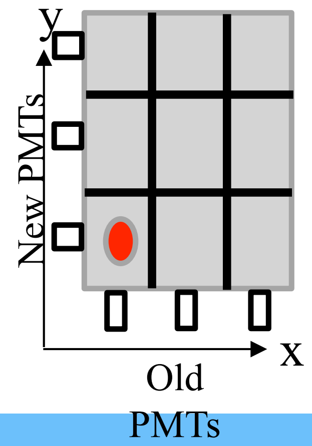
- Old : 2 inch PMT (xp2202)
- New : Hamamatsu (R6231-100), 2 inch diameter, high Q.E. and linearity over large dynamic range.
- Readout resolution of two types of PMTs are being tested in this set up.
- Easy access to PMTs. No possibility of over heating the PMT bases.
- No hassle to put the radioactive source on top of the box.
- **No light leakage** observed.

MicroCHANDLER : Compton edge study





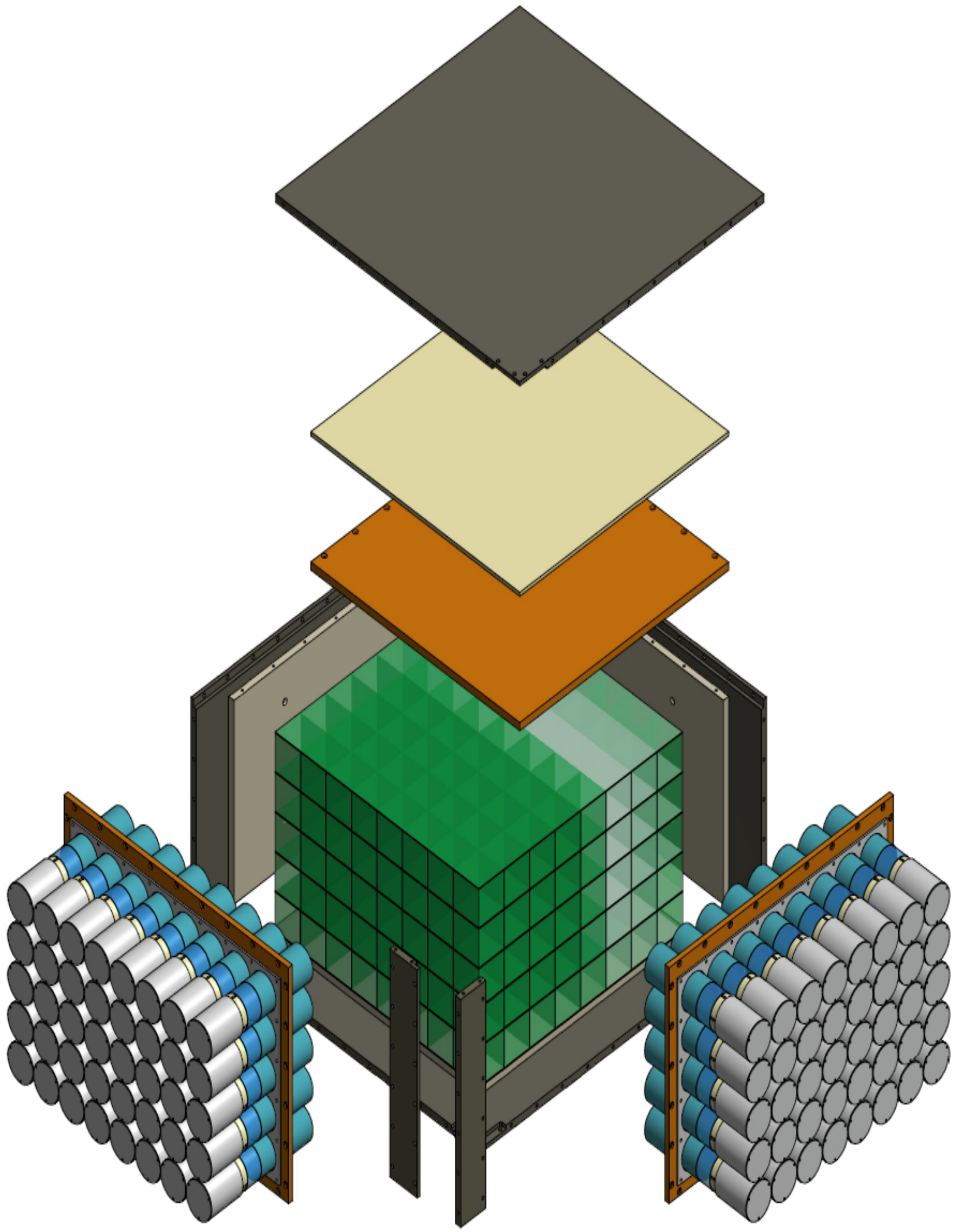
- ^{22}Na gamma source : 0.511 MeV and 1.275 MeV gamma lines.
- Collimated source was placed approximately at the center of each cube on the top layer.
- The spectrum shows : $1\,ADC \approx 5-8\,keV$.
- Threshold used for neutron runs : ~ 10 ADC.
- New PMTs show better resolution.



Mechanical design of MiniCHANDLER

Goal of the MicroCHANDLER mechanical set up was to test the light tightness of the box.

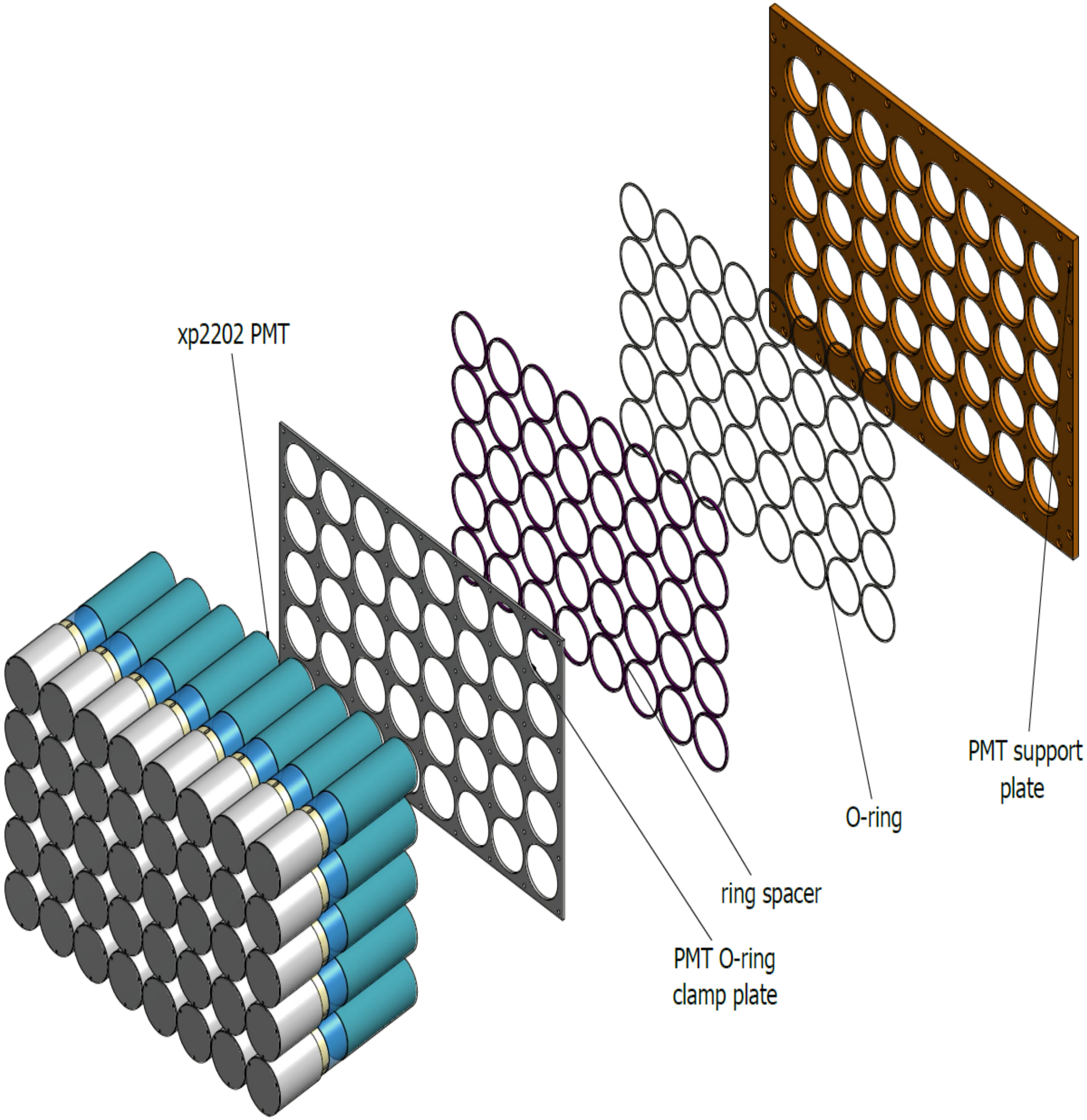
After successful operation of the MicroCHANDLER, same mechanical set up has been prepared for the MiniCHANDLER.



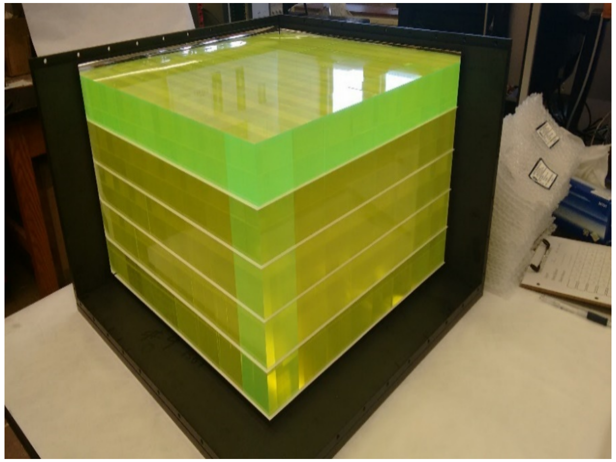
Mechanical design of MiniCHANDLER

Use of O-ring, ring spacer and PMT O-ring clamp plate is to make the box light tight.

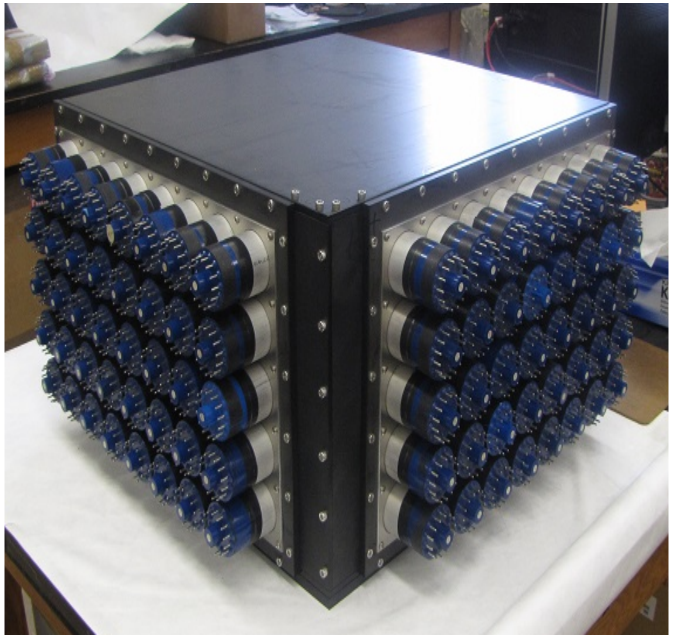
Easy access to any PMT channels as before.

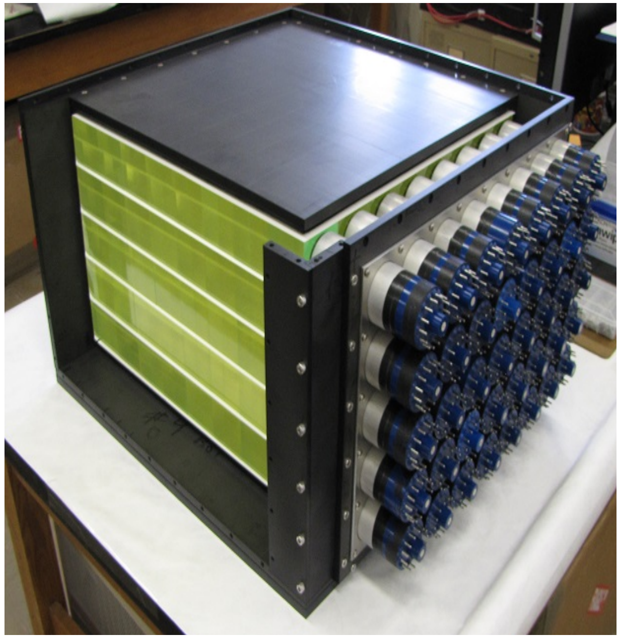


Commissioning of MiniCHANDLER



Assembling WLS scintillator cubes





Assembling PMTs

Li sheets (white) are also visible between layers.

Goal: scale up the technology of the MicroCHANDLER towards CHANDLER.

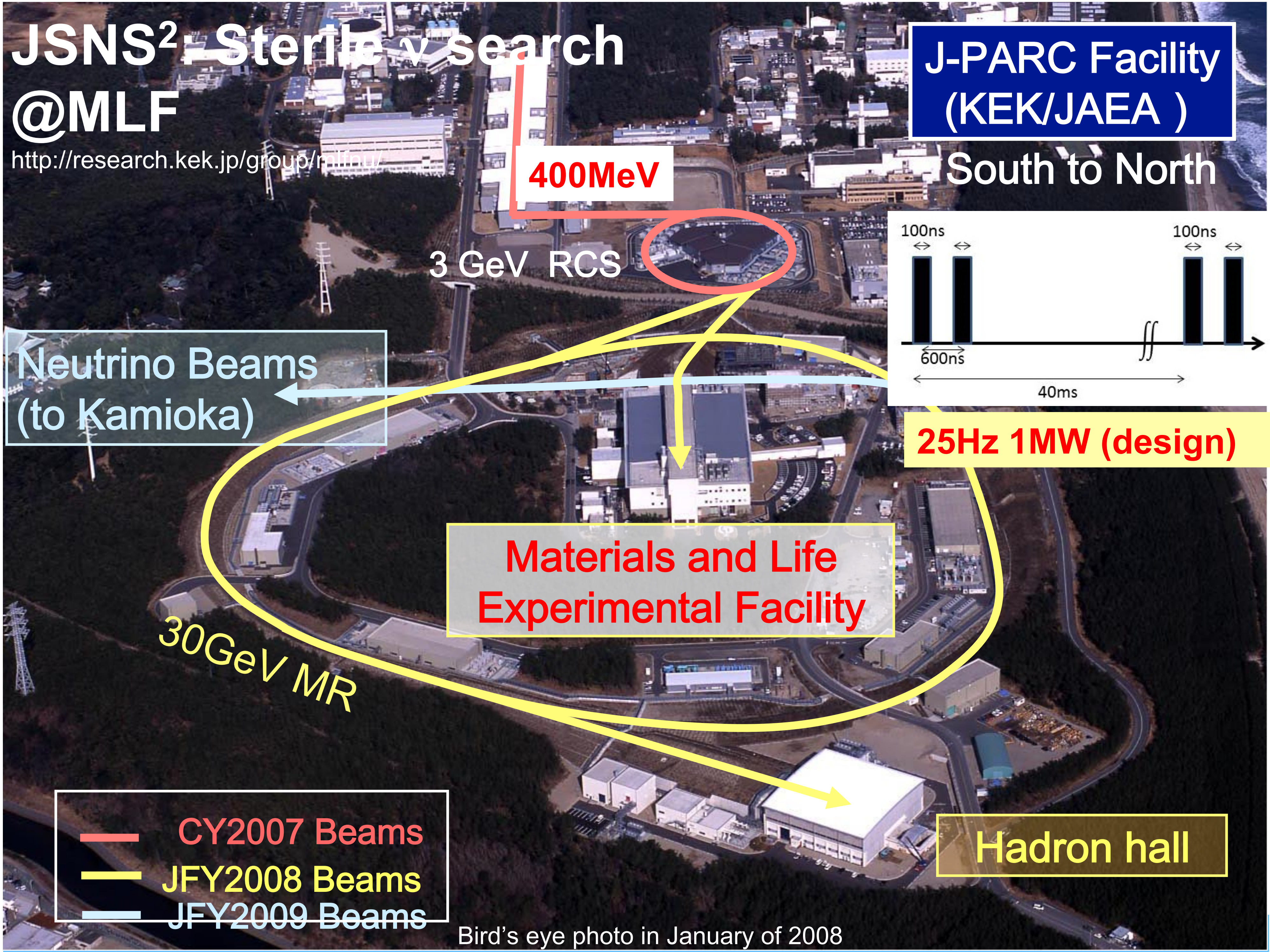
Future plan : Deployment at the reactor site

North Anna Nuclear Power Plant, Virginia

Around 4 hours drive from the Virginia Tech.

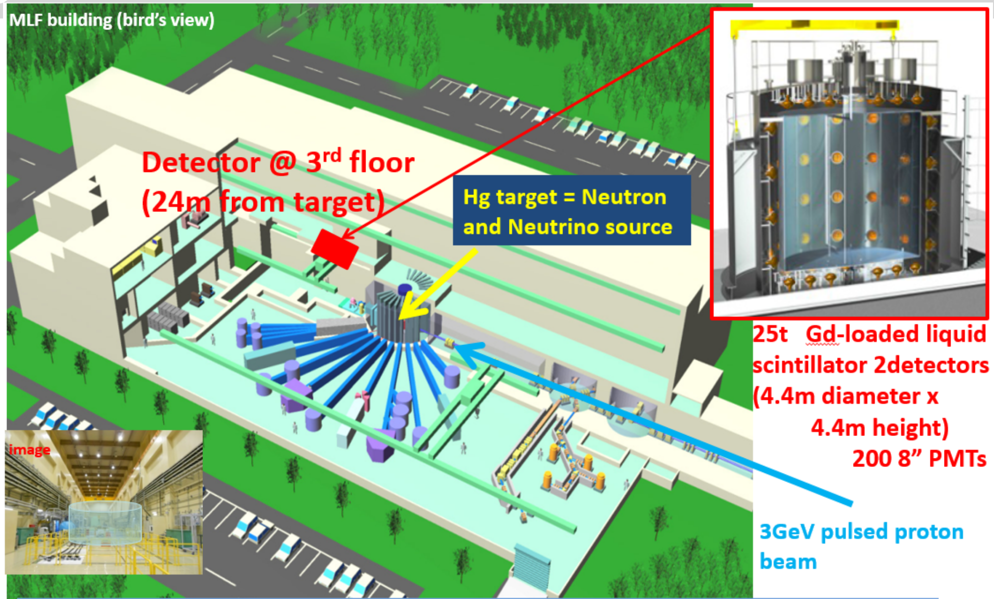
MiniCHANDLER will be placed inside this trailer at the power plant.

JSNS^2: Sterile ν search @MLF

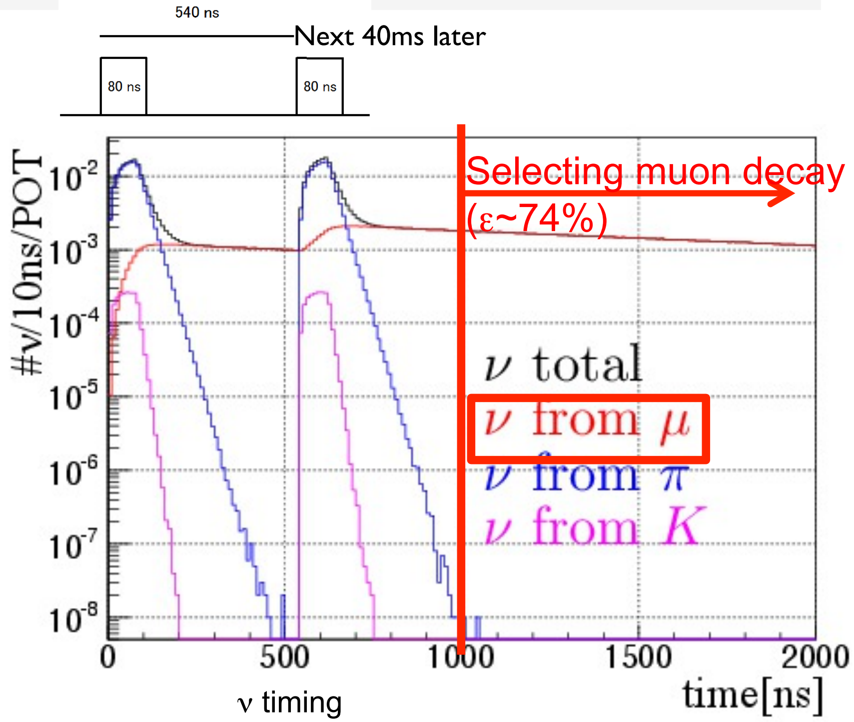


JSNS^2 (direct and ultimate test of LSND)

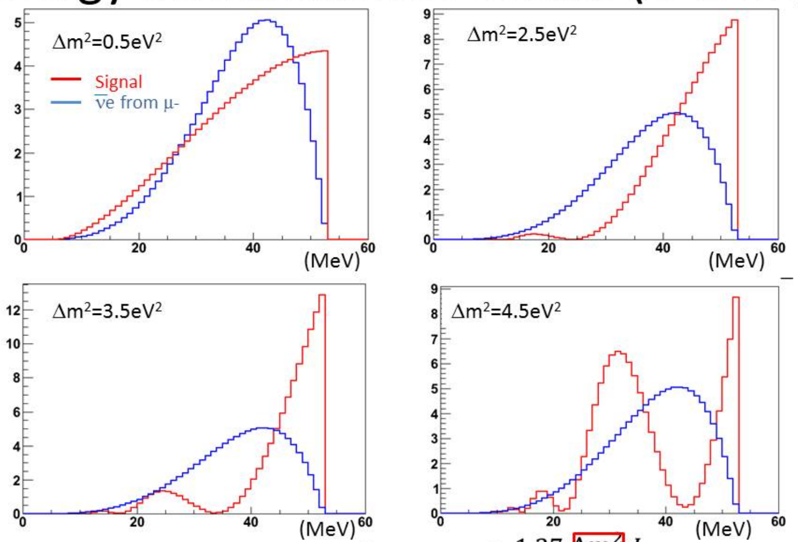
http://research.kek.jp/group/mlfnu/eng



Searching for neutrino oscillation : $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$ with baseline of 24m.
no new beamline, no new buildings are needed → quick start-up

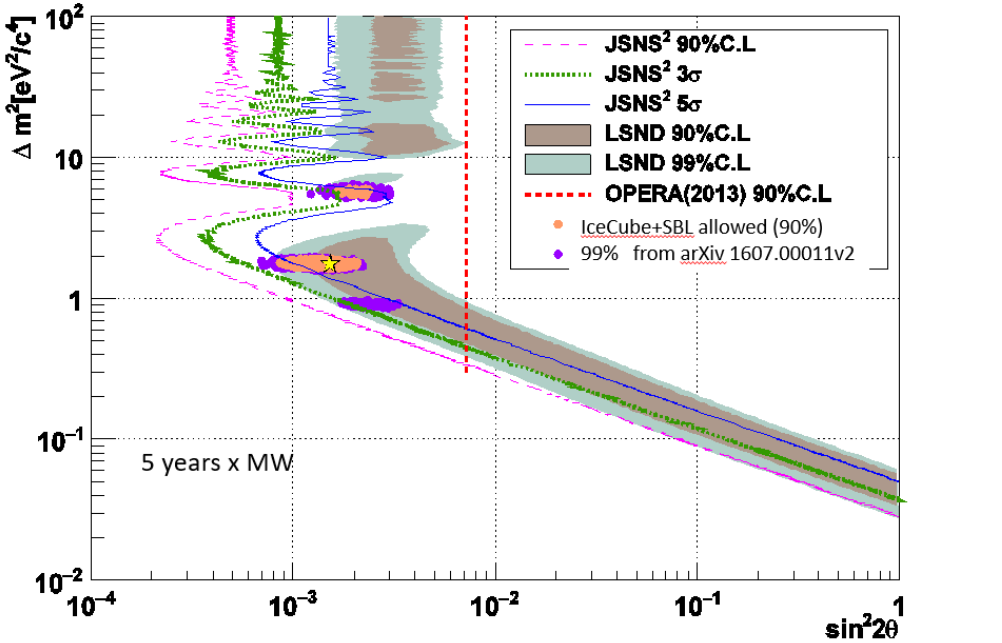


Energy distribution of events (L=24m)



$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \cdot \sin^2\left(\frac{1.27 \cdot \Delta m^2 \cdot L}{E_\nu}\right)$$

- Energy is smeared by 15%/sqrt(E) (detector E resolution)

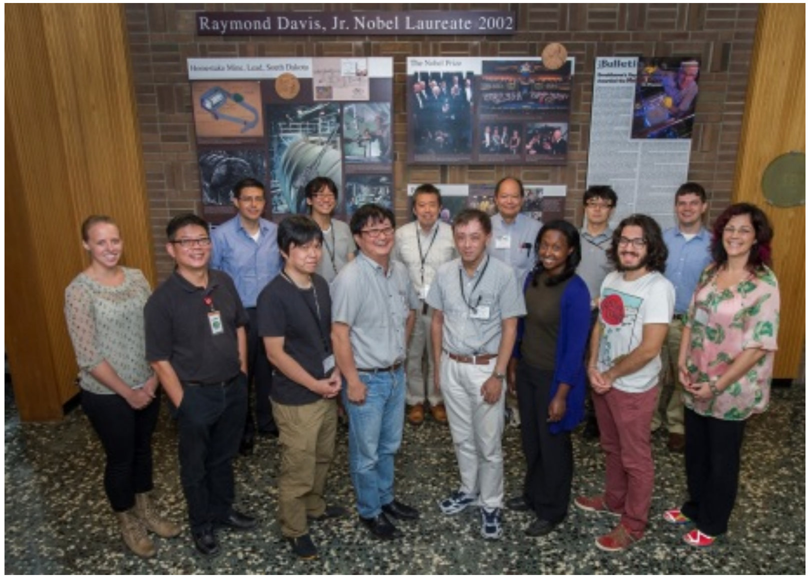


If we could see the hints ~ 3σ, we consider the phase2 experiment (w/ a bigger detector)

Status and Schedule

- JSNS² received the Stage-1 status (out of 2 stages) from KEK and J-PARC in 2015.
- We just received 140Myen to build the first (of two) detector modules from Japan grant-in-aid.
- The JSNS² aims to start the experiment from JFY2018-2019.

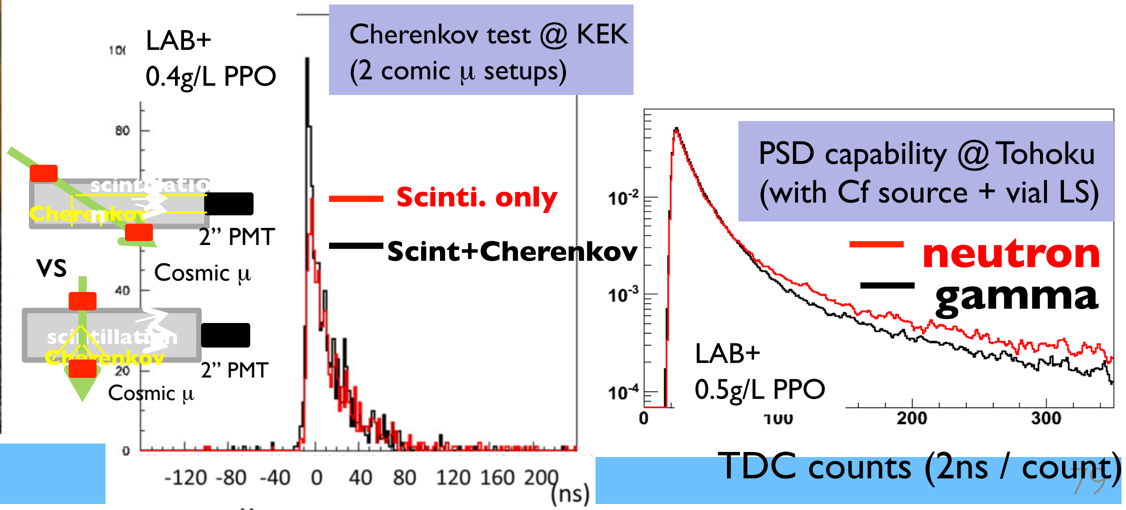
- Lots of R&D and design works have been done.
  - arXiv:1507.07076 (liquid scintillator R&D)
  - arXiv:1601.01046 (R&D for LS and PMT, discussion for safety issues, additional physics: KDAR, supernova)
  - arXiv:1610.08186 (LS R&D, veto system design, software works)
- Technical Design Report will be submitted soon.



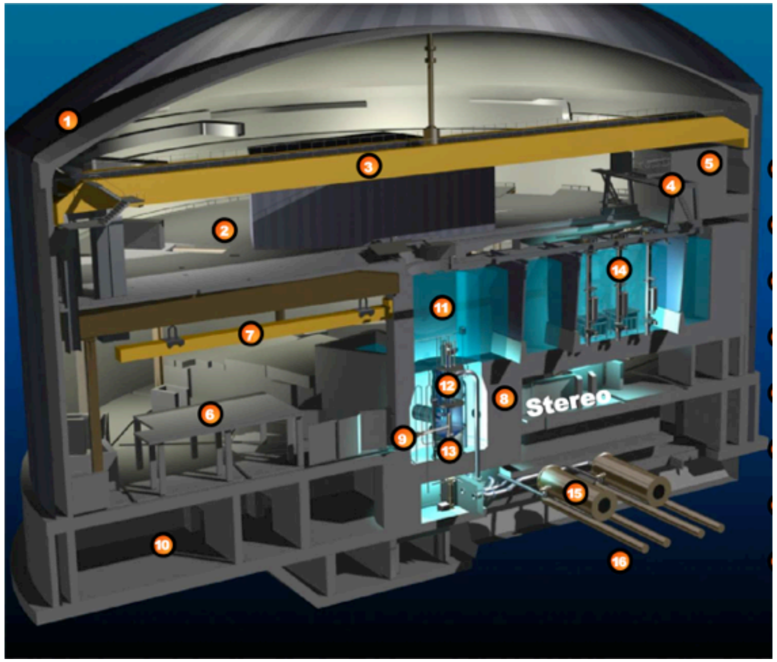
Collaboration meeting on 9/10-Sep-2015@BNL

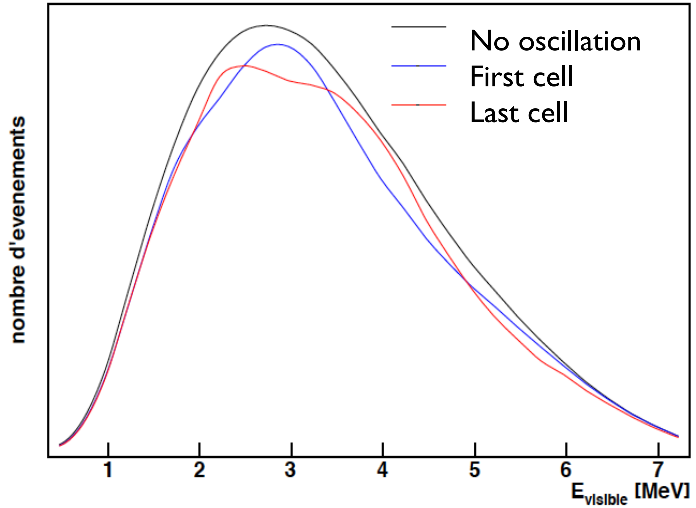
An R&D example for liquid scintillator

(PSD and Cherenkov at the same time to reject neutron BKG efficiently)

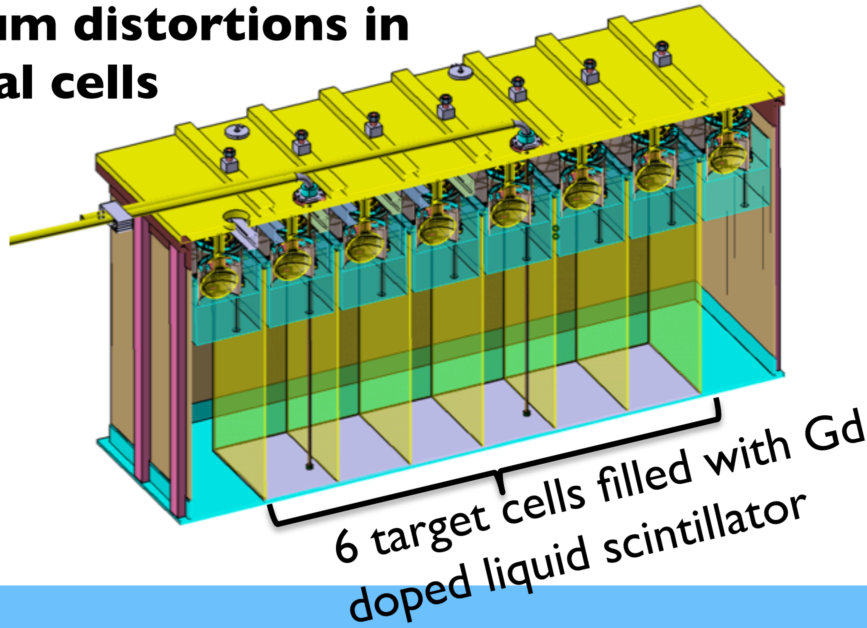


STEREO : $2m^3$ in 6 target cells + GC





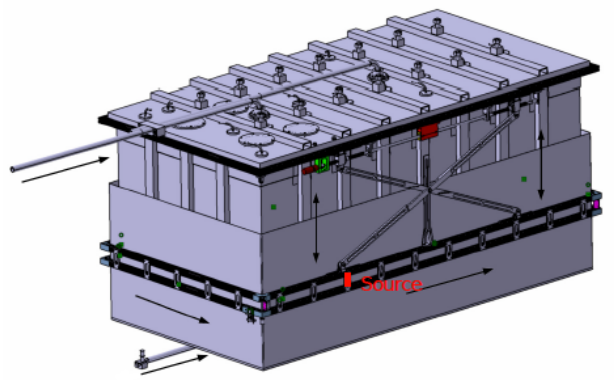
Goal: look for relative spectrum distortions in identical cells

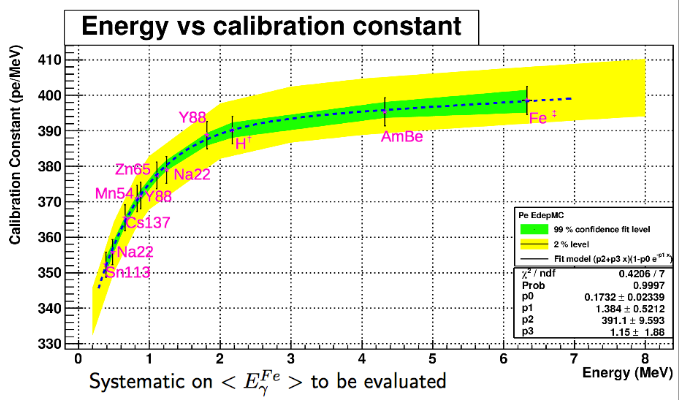


ILL site, Grenoble - France:

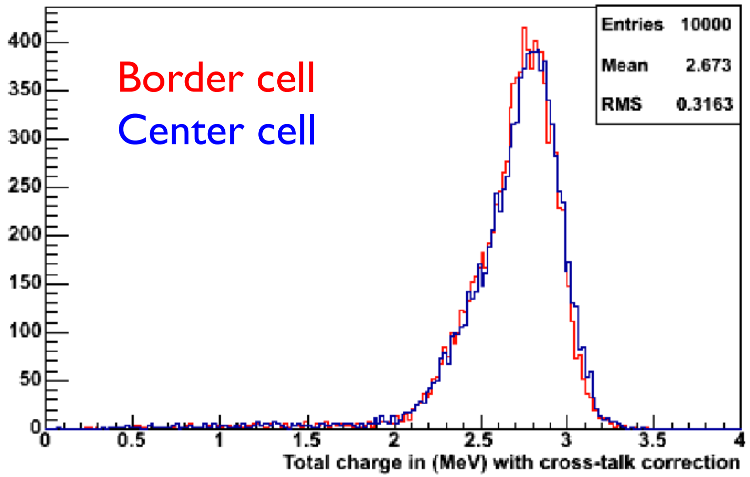
- 57 MW, compact core < 1m
- [8.9–11.1] m from core, possible extension to 12.3 m.
- High level of reactor background
- 15 mwe overburden

STEREO: Accurate Detector Response



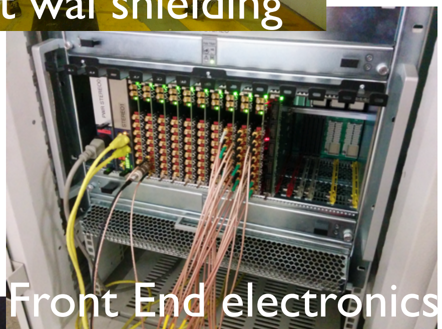


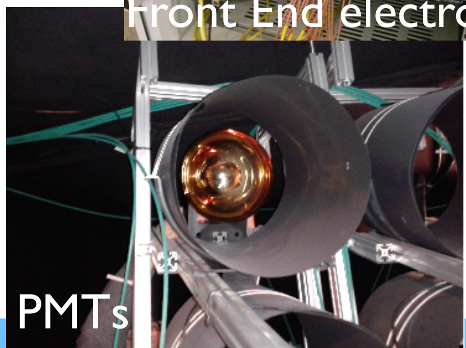
Response to 2 MeV positrons

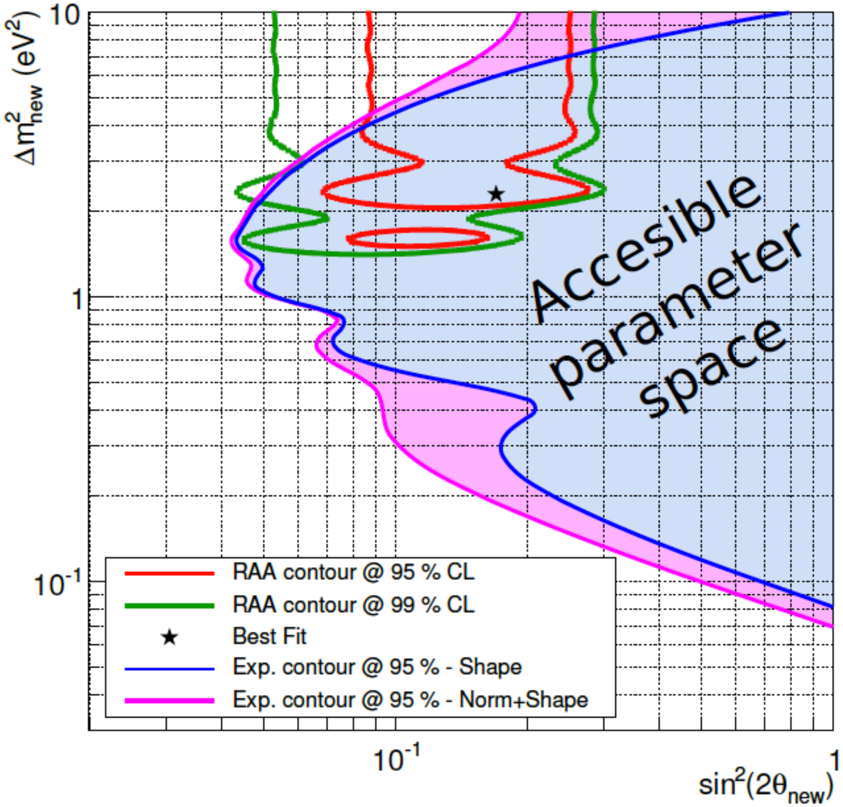


- Uniform response validated with a prototype cell
- Circulation of radioactive sources inside and around the detector
- Complete simulation of light emission and collection
- 11.5% resolution for 2 MeV e^+, including edge effects.

STEREO: Toward Data Taking







- Most detector parts under fabrication
- Installation on the ILL site in winter-spring 2016
- First data expected in summer 2016