Short baseline experiments and sterile neutrinos

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Solvay-Francqui Workshop on Neutrinos

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Research Foundation Flanders
Opening new horizons

foundation of public utility
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Fundamental Interactions .be

Overview

- Tensions with 3 neutrino paradigm by range of experiments $\rightarrow$ sterile neutrinos
- Cosmological bounds
- Mutual tension between experiments
- Prospects for near future
- The SoLid experiment at SCK-CEN

Tensions

- B. Kayser @ Moriond EW 2012:arXiv: 1207.2167
  “Not all of the neutrino data are successfully described by the standard three-neutrino paradigm. …
  …there are hints, coming from a variety of sources, that nature may contain more than three neutrino mass eigenstates, and squared-mass splittings significantly larger than the measured $|\Delta m^2_{21}|$ and $|\Delta m^2_{32}|$. Whether individually or taken together, these hints are not convincing. However, they are interesting enough to call for further, hopefully conclusive, investigation”

Sterile neutrinos

- Experimental observation of short-baseline oscillations suggest at least one extra ν mass eigenstate with relatively large mass splitting $|\Delta m|^2 \gtrsim 0.1\ eV^2$
- If confirmed & combined with Z decay properties this implies the existence of an electroweak singlet ν state which is dubbed ‘sterile’
- Sterile ν’s can couple no non-SM particles and are valid candidates for (warm) dark matter
- Sterile ν’s can be easily incorporated in the SM Lagrangian via introduction of Dirac and/or Majorana mass terms

Bounds from Planck

- CνB decoupled at T=1MeV (~2 second old universe)
- Current temperature of CνB

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \approx 1.945K \rightarrow kT_\nu \approx 1.68 \cdot 10^{-4} eV$$

Number density/flavor
For relativistic plasma

$$n_f = \frac{3}{4}\frac{\varsigma(3)}{\pi^2} g_f T_f^3 \rightarrow n_{\nu_k,\bar{\nu}_k} \approx 0.1827 \cdot T_\nu^3 \approx 112 cm^{-3}$$

Extra radiation component

$$\Omega_\nu h^2 = \frac{7}{4}\left(\frac{4}{11}\right)^{4/3} N_{eff}^\nu \Omega_\gamma h^2$$

Standard Model predicts:

$$N_{eff}^\nu = 3.046$$

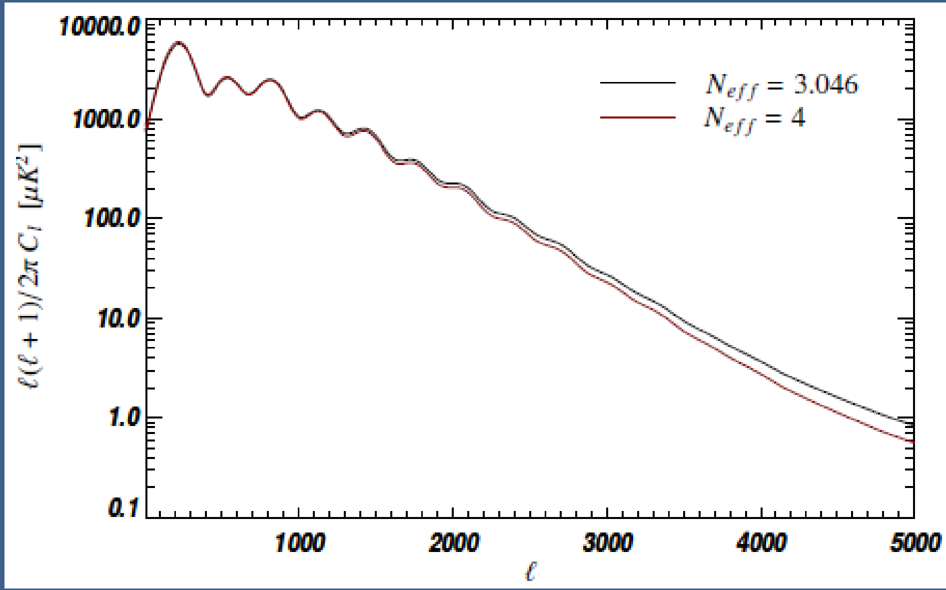
If non-relativistic

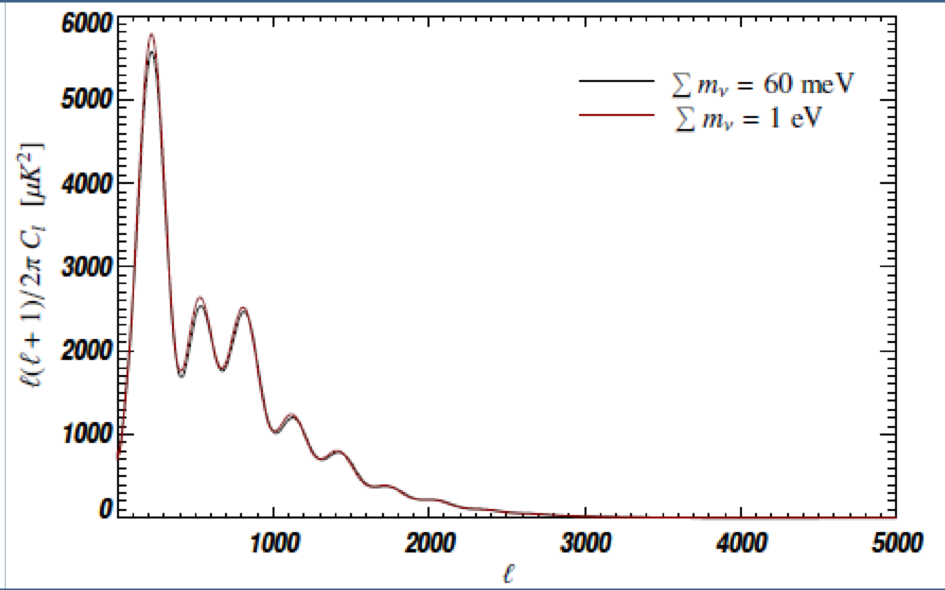
$$\Omega_\nu h^2 = \frac{\sum m_\nu}{94.1 \text{ eV}}$$

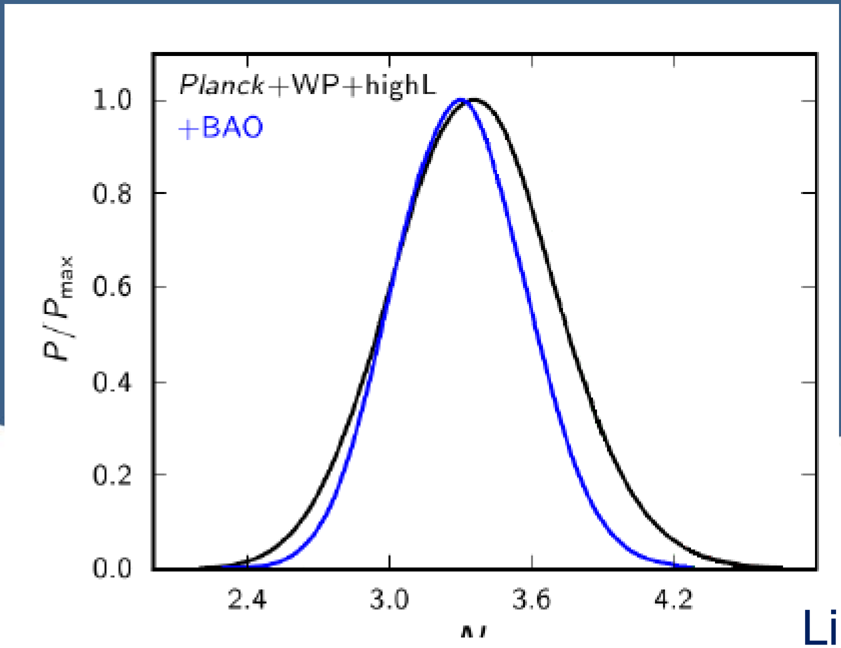
Changing Neff changes expansion rate at recombination
Inversely proportional to small angular scale anisotropy

CMB also slightly sensitive to $\sum m_{\nu i}$

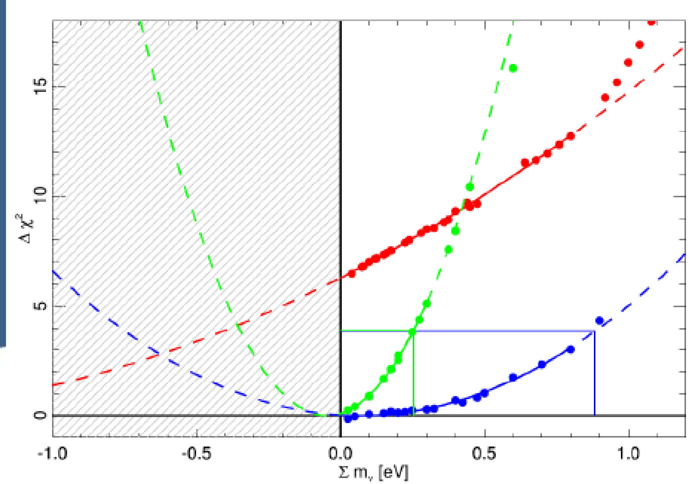
Bounds from Planck[6]







[Planck intermediate results.XVI.]



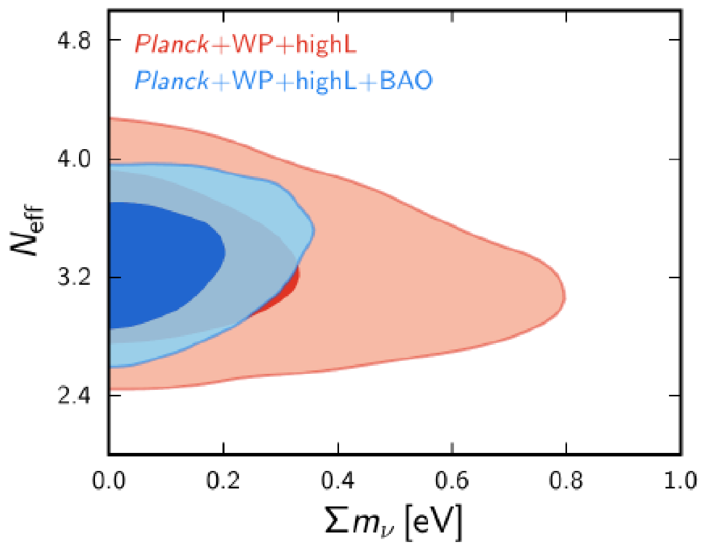
Planck+WP+Highℓ + lensing

+ BAO

Likelihood fit

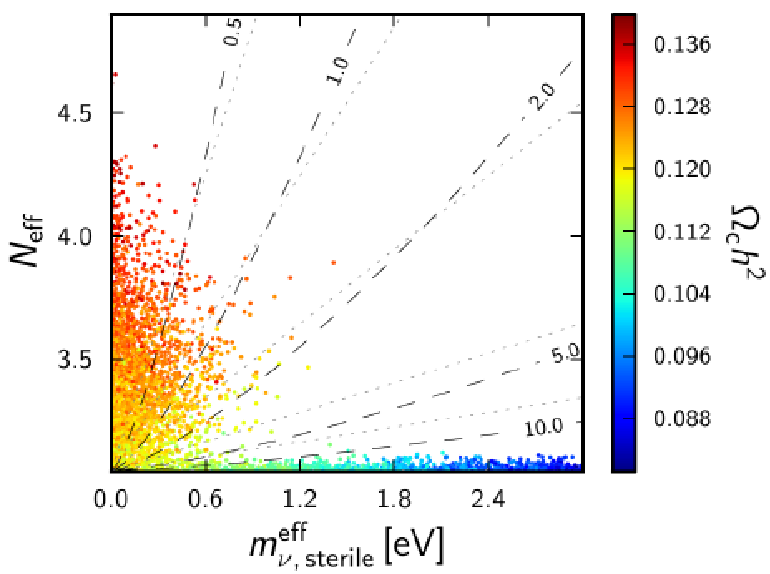
Bounds from Planck[7]

[Planck 2013 results.XVI.]



- assumption: 3 active neutrinos coexisting with extra massless species
- $\sum m_\nu$ and $N_{\rm eff}$ different impact on CMB: **no significant correlation**
- results adding BAO:

$$\begin{cases} N_{\rm eff} = 3.32 \pm 0.27 \ (68\% CL) \\ \sum m_\nu < 0.28 \text{ eV } (95\% CL) \end{cases}$$



$$m^{\rm eff}_{\nu,\rm sterile} = (\Delta N_{\rm eff})^{3/4} m^{\rm thermal}_{\rm sterile}$$

- for low $N_{\rm eff}$ unconstrained within $\Omega_c h^2$
- for $m^{\rm thermal}_{\rm sterile} < 10$ eV
  $N_{\rm eff} < 3.91$
  $m^{\rm eff}_{\nu,\rm sterile} < 0.59$ eV

M. Spinelli, Neutrino 2014

(same results valid for

Bounds from BBN

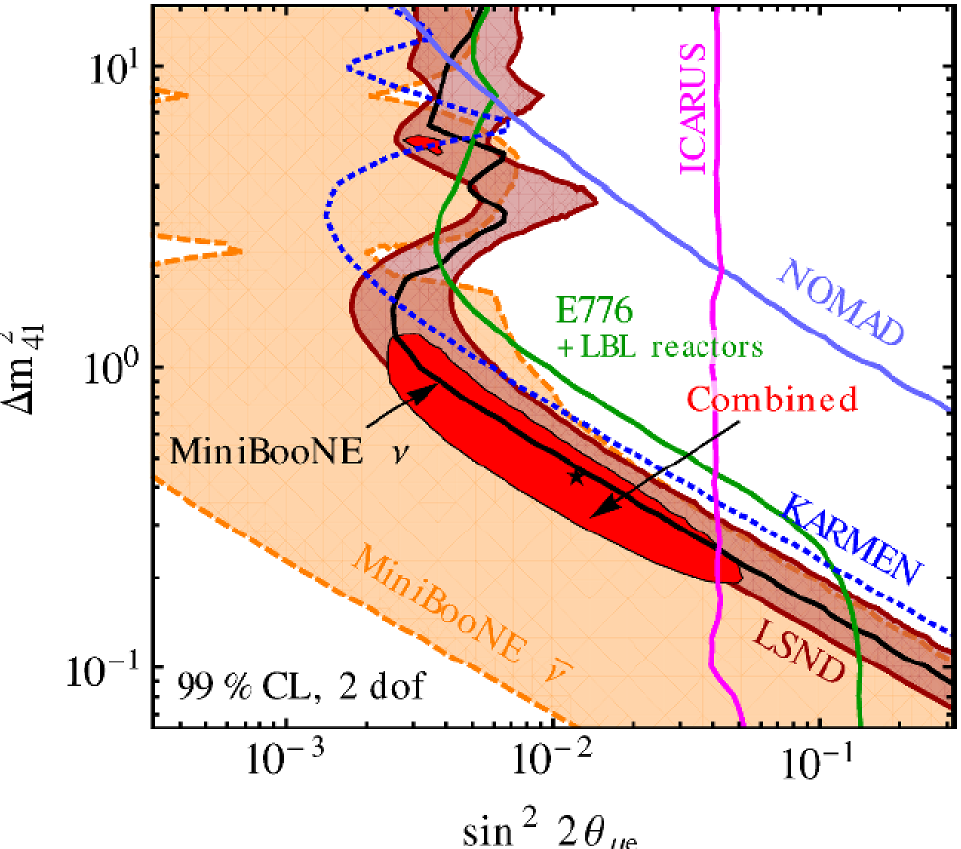
- Abundance of light elements largely driven by total baryon/proton ratio
- But:
  - Electron neutrino's determine proton/neutron ratio
  - Change in expansion rate influences neutron/proton ratio
  - Abundance of helium most sensitive to N_{eff}

Model	Data	N_{eff}	Ref.
$\eta+N_{eff}$	$\eta_{CMB}+Y_p+$D/H	$3.8^{(+0.8)}_{(-0.7)}$	[331]
	$\eta_{CMB}+Y_p+$D/H	$<(4.05)$	[332]
	Y_p+D/H	3.85 ± 0.26	[333]
	Y_p+D/H	3.82 ± 0.35	[333]
	Y_p+D/H	3.13 ± 0.21	[333]
$\eta+N_{eff}$, $(\Delta N_{eff} \equiv N_{eff} - 3.046 \geq 0)$	$\eta_{CMB}+$D/H	3.8 ± 0.6	[122]
	$\eta_{CMB}+Y_p$	$3.90^{+0.21}_{-0.58}$	[122]
	Y_p+D/H	$3.91^{+0.22}_{-0.55}$	[122]

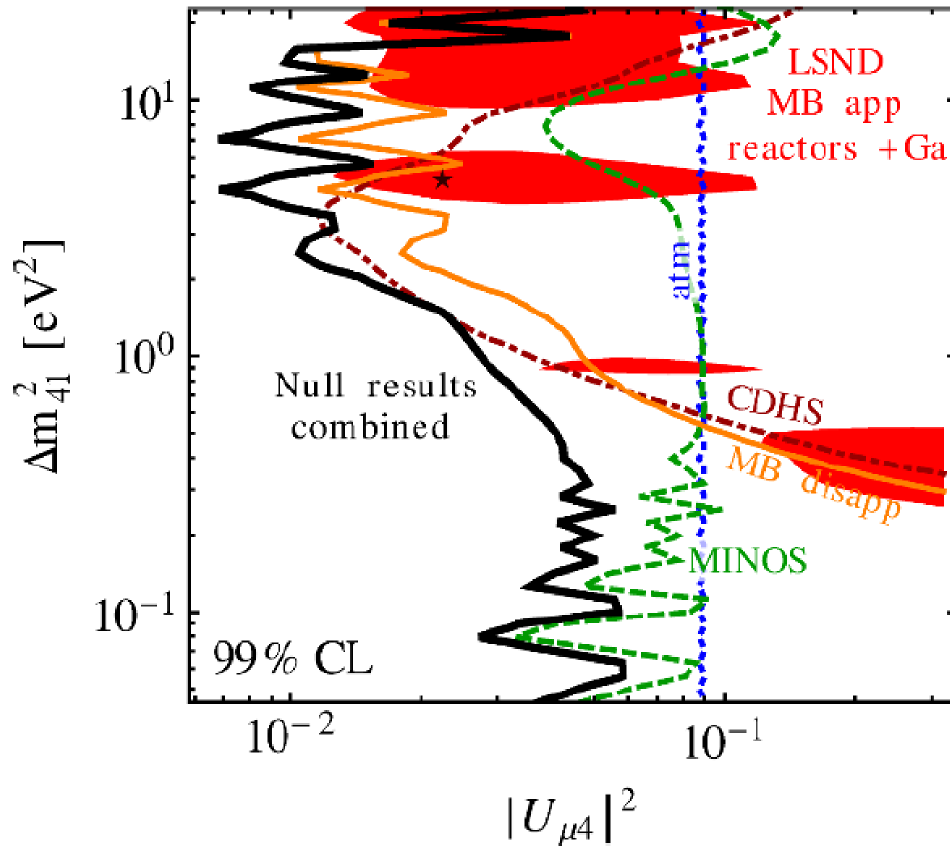
K. N. Abazajian et al. ArXiv:1204.5379v1 [hep-ph] 18 Apr 2012

Global fits to SB Accelerator data

Appearance data



Disappearance data



$$\sin^2 2\theta_{\mu e} \equiv 4|U_{\mu 4}U_{e4}|^2$$

From Kopp, Machado, Maltoni, Schwetz JHEP05(2013)050

Global SBA fits

- Very narrow overlaps in detected signals
- Disappearance probability is quadratically suppressed by (small) appearance amplitudes

$$\sin^2 2\theta_{\mu e} \approx 4 \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$$

- Forementioned tension can be (artificially) relaxed by considering 3+2, 1+3+1 scenarios

$$P^{\mathrm{SBL},3+2}_{\nu_\alpha \to \nu_\beta} = 4\,|U_{\alpha 4}|^2 |U_{\beta 4}|^2 \,\sin^2\phi_{41} + 4\,|U_{\alpha 5}|^2 |U_{\beta 5}|^2 \,\sin^2\phi_{51} + 8\,|U_{\alpha 4} U_{\beta 4} U_{\alpha 5} U_{\beta 5}|\,\sin\phi_{41}\sin\phi_{51}\cos(\phi_{54} - \gamma_{\alpha\beta})$$

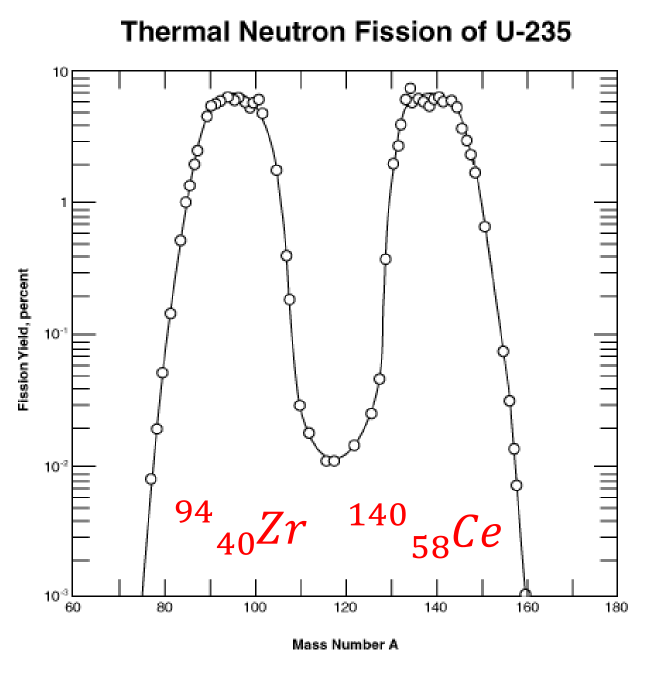
Short Baseline Reactor

- Fission reactors are intense source of $\bar{\nu}_e$:

$$^{235}{}_{92}U + n \rightarrow X_1 + X_2 + 2n \text{ (200MeV)}$$

$\rightarrow$ 6 $\bar{\nu}_e$ per fission $\rightarrow 2.10^{20}$ n/s/GW$_{th}$

  - 2x 3 beta decays distributed over hundreds of possible β-decay branches
  - $\bar{\nu}_e$'s generally detected via inverse β-decay: $\bar{\nu}_e$ +p$\rightarrow e^+ + n$ (1.8 MeV energy treshold)
  - (only) 4 fissile isotopes produce $\bar{\nu}_e$'s above IBD treshold: $^{235}U, {}^{238}U, {}^{239}Pu, {}^{241}Pu$



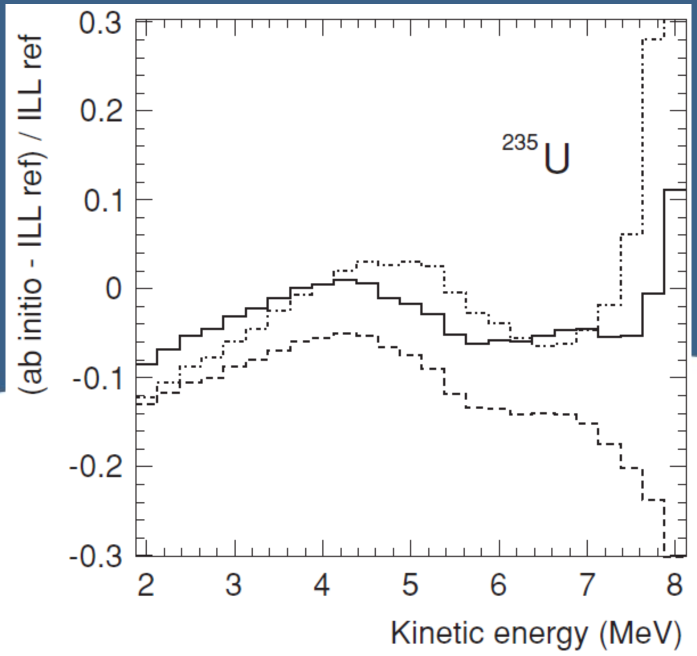
- First direct observation of $\bar{\nu}_e$ by Cowan & Reines at Savannah River power plant: Science 124, 103 (1956).
- Followed by many measurements in 1980's and '90's at Savannah River, Goesgen, Rovno, Bugey, ILL

$\bar{\nu}_e$ flux calculation and reactor anomaly

- Ab initio computing: 1000's of decay branches computed analytically with input on branching fractions from nuclear databases, and using MCNP MC to track burnup and activity of each isotope over time: $\rightarrow$ predicts electron and $\bar{\nu}_e$ spectra in rather model independent way

Th. A. Mueller, et al., Phys. Rev C **83**, 054615 (2011)

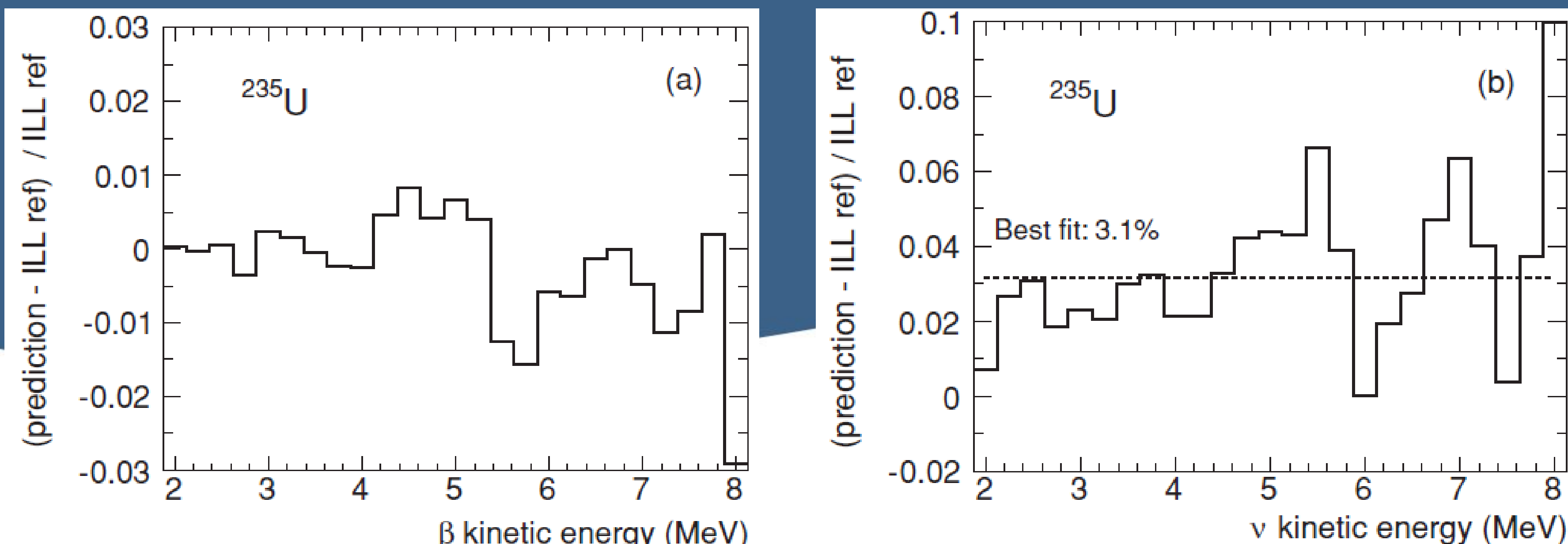
$\bar{\nu}_e$ spectrum predicted with ~10% accuracy, dominated by missing experimental data on exotic nuclei and pandemonium effects



$\bar{\nu_e}$ flux calculation and reactor anomaly

- Lots of high precision electron energy spectra available for pure fissile isotopes → conversion of measured e-spectra into predicted $\bar{\nu_e}$ spectra: Fit ~ 30 slices of endpoints to iteratively extract ~ 30 component $\bar{\nu_e}$ spectra via $E_\nu = E_0 - E_e$
- Combine ab-initio with fitting and inclusion of much more branches to obtain best prediction: uncertainties smaller and 3% systematic shift wrt precision reference data:

  Th. A. Mueller, et al., Improved predictions of reactor antineutrino spectra, Phys. Rev C **83**, 054615 (2011)



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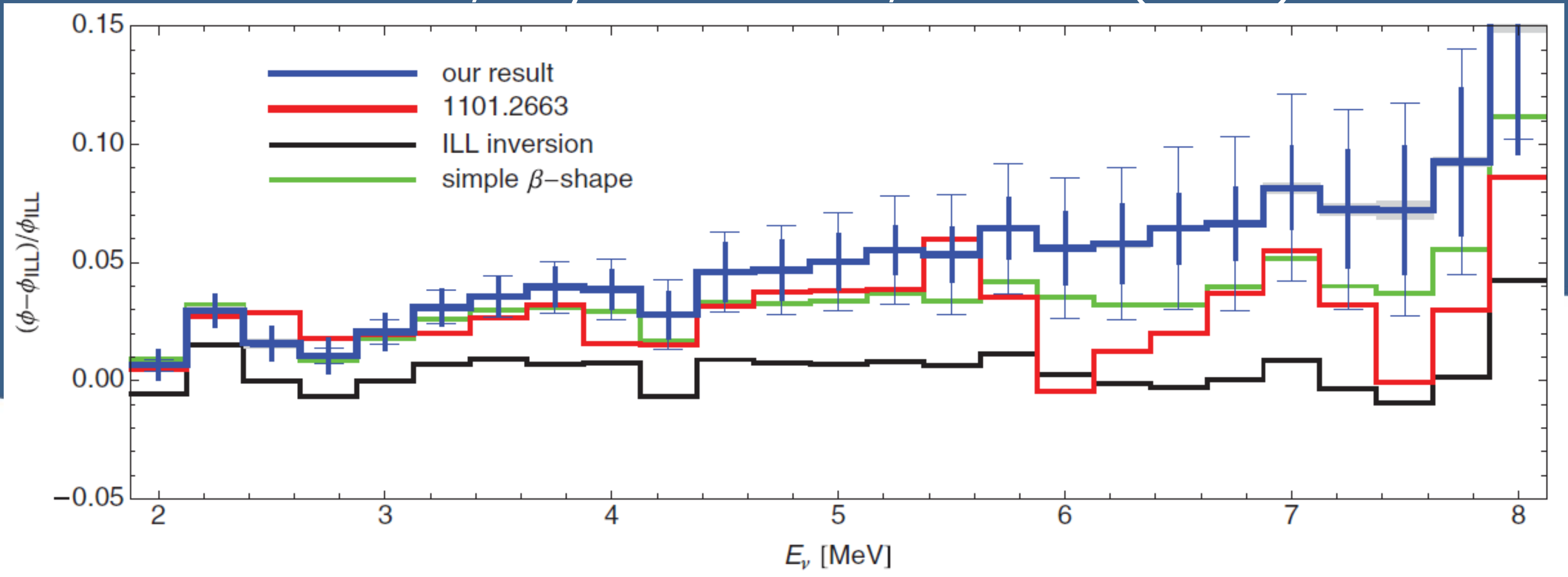
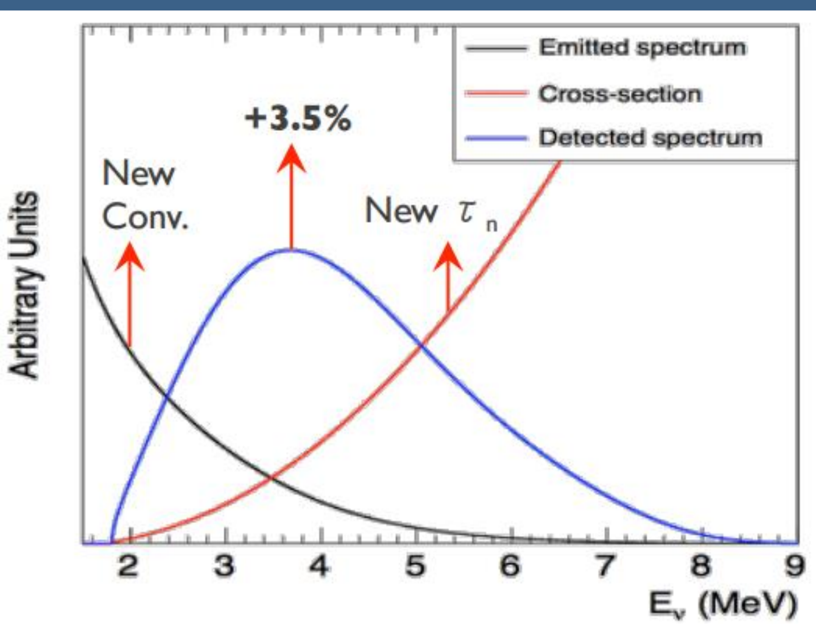
- Combine ab-initio with fitting and inclusion of much more branches to obtain best prediction: uncertainties smaller and 3% systematic shift wrt precision reference data:

P. Huber, Determination of antineutrino spectra from nuclear reactors, Phys. Rev C **84**, 024617 (2011)



Reactor anomaly

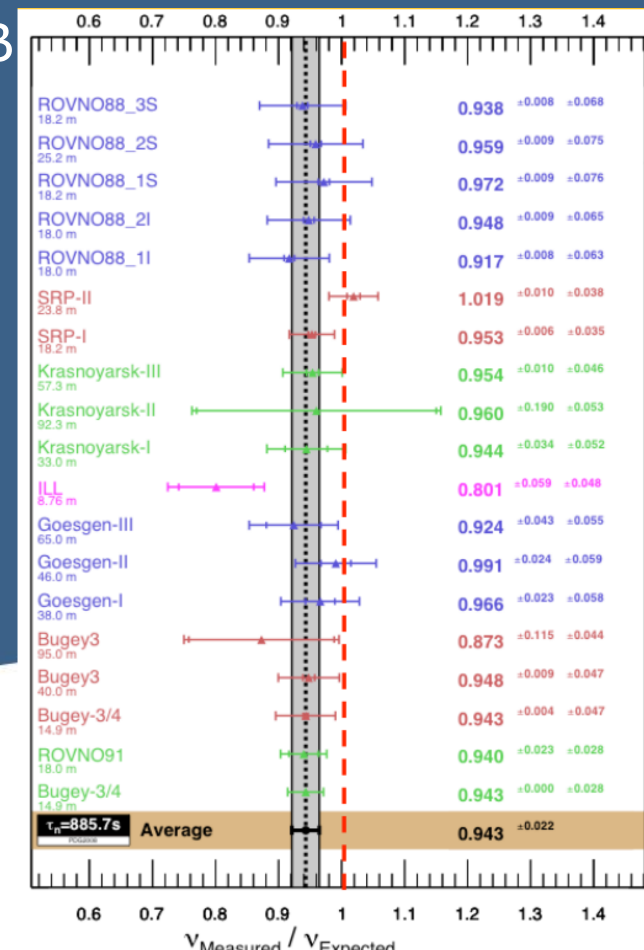
- G. Mention et al., Reactor antineutrino anomaly, Phys.Rev.D 83, 073006 (2011), confirmed by P. Huber Phys.Rev.C 84, 024617 (2011)
- Previous improved $\overline{\nu_e}$ spectra show 3% underestimation of integrated flux
- Improved neutron lifetime increases IB
- Total predicted detectable flux increases by 3.5%



$R_{old} = 0.976 \pm 0.024$

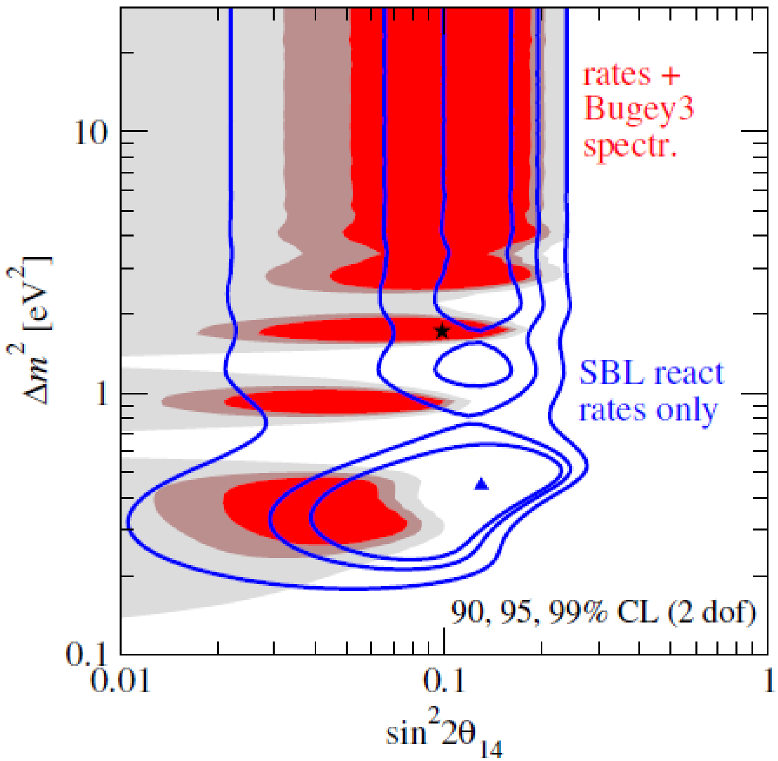
$R_{new} = 0.943 \pm 0.023$

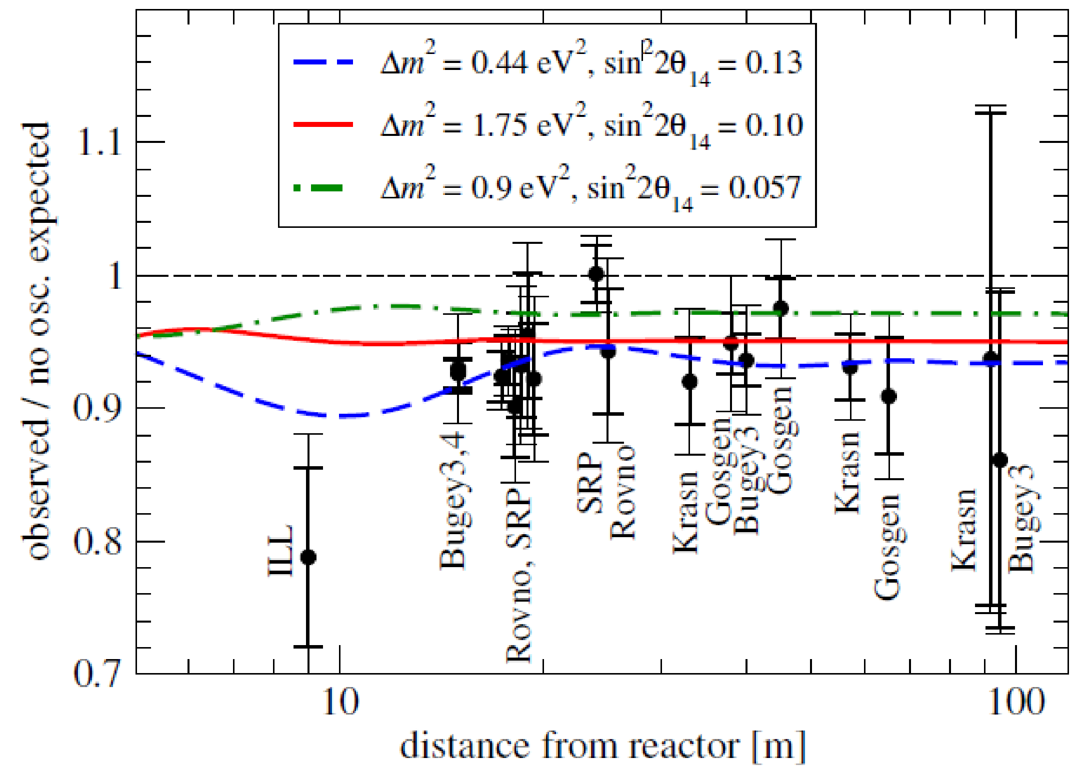
R=1 excluded at 98.6% CL



G. Mention, Rencontres IPhT-SPP, 2012

Reactor anomaly



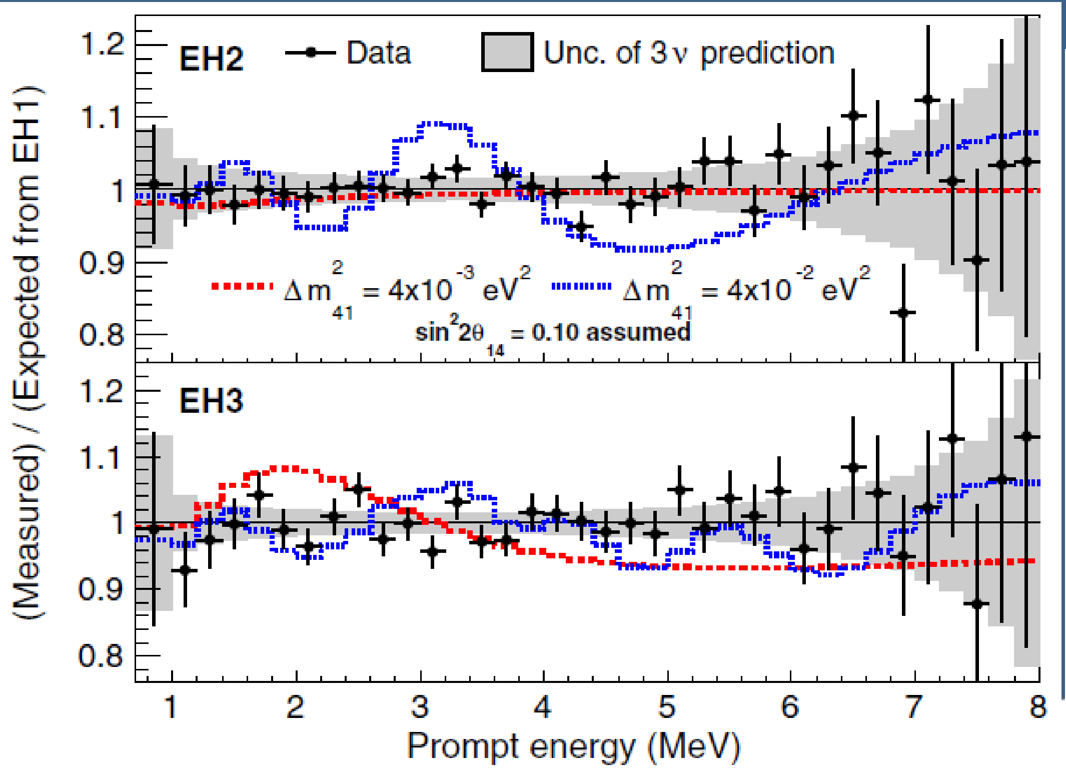


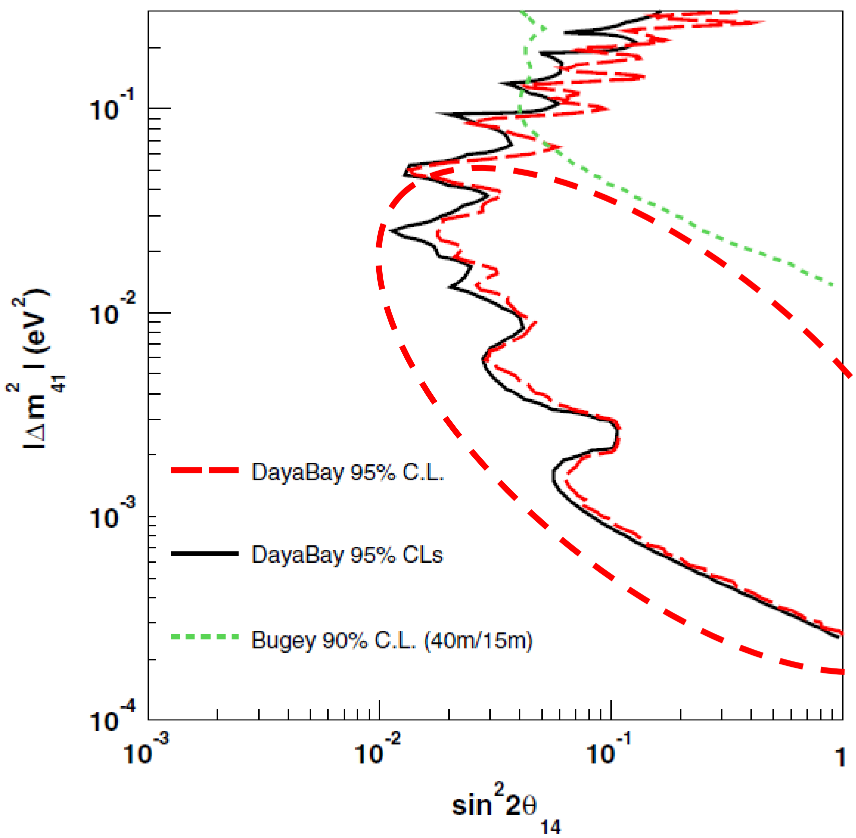
$$P_{ee}^{\mathrm{SBL},3+1} = 1 - 4|U_{e4}|^2(1-|U_{e4}|^2)\sin^2\frac{\Delta m_{41}^2 L}{4E} = 1 - \sin^2 2\theta_{ee}\sin^2\frac{\Delta m_{41}^2 L}{4E}$$

$\boldsymbol{\theta_{ee} = \theta_{14}}$

Constraints from LBR[17]

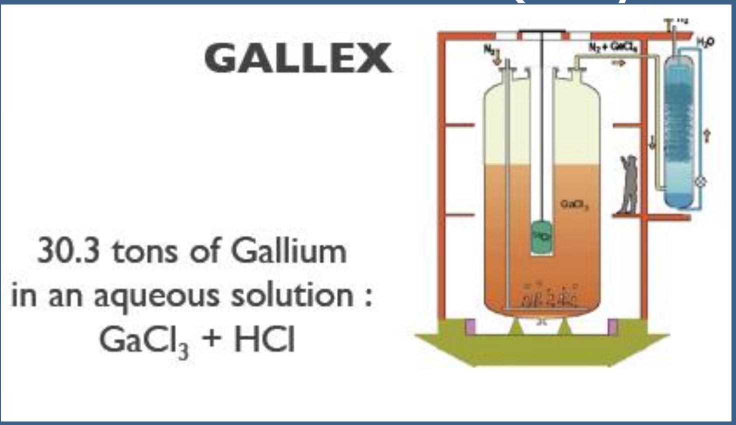
- Daya Bay coll, "Search for a Light Sterile Neutrino at Daya Bay", PRL 113, 141802 (2014)

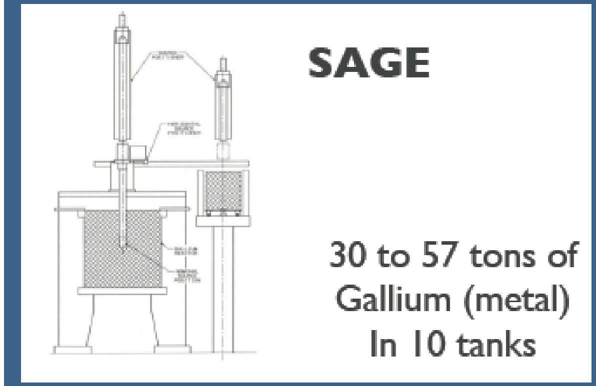




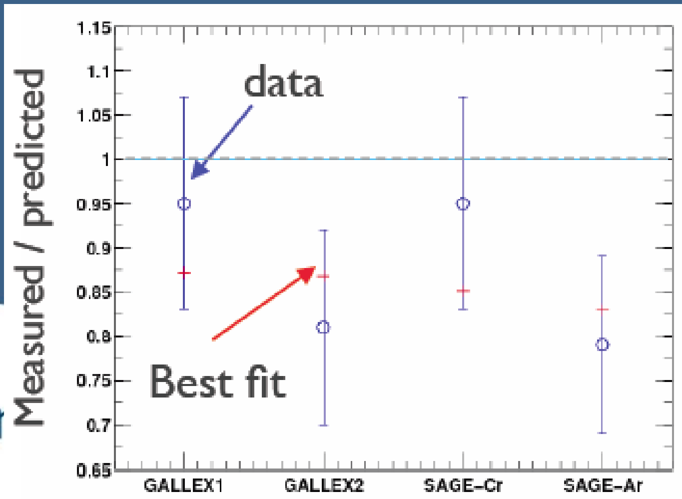
Gallium Anomaly

- Radiochemical experiments GALLEX (Phys. Lett. B 420 (1998) 114, Phys. Lett. B 685 (2010) 47) & SAGE (Phys. Rev. C 59 (1999) 2246)





- Calibrated with β-sources ($^{51}Cr, ^{37}Ar$)

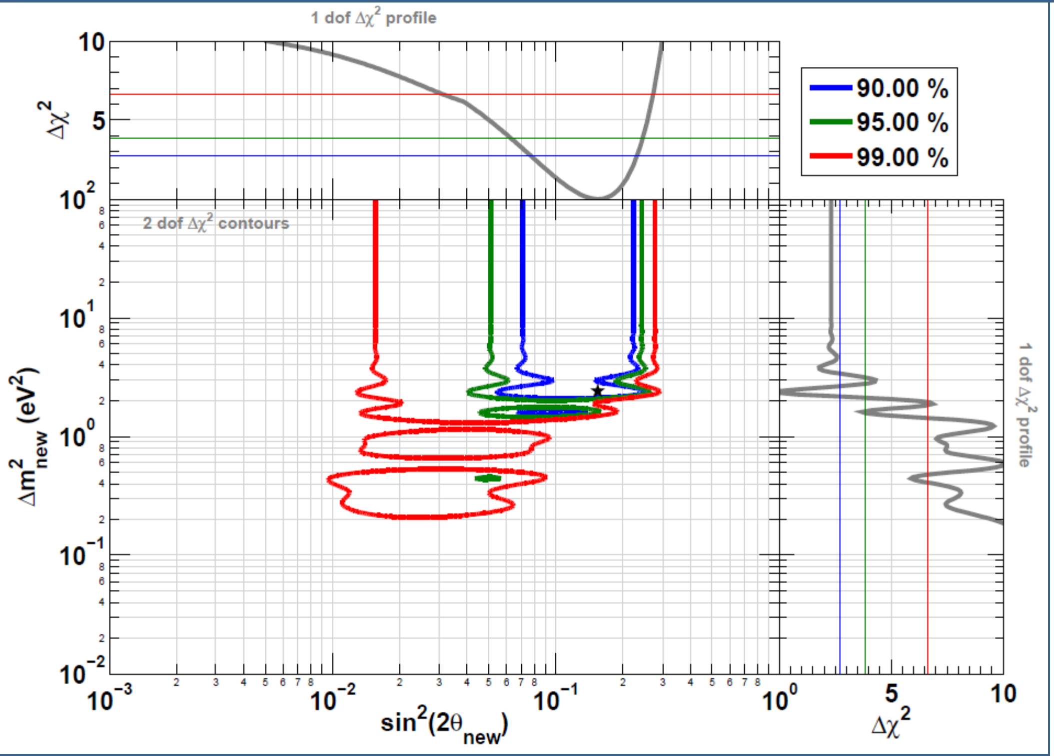


All observed a **deficit** of neutrino interactions **compared** to the **expected activity:**

R = meas./pred. rates = 0.86 ± 0.06(1 σ)

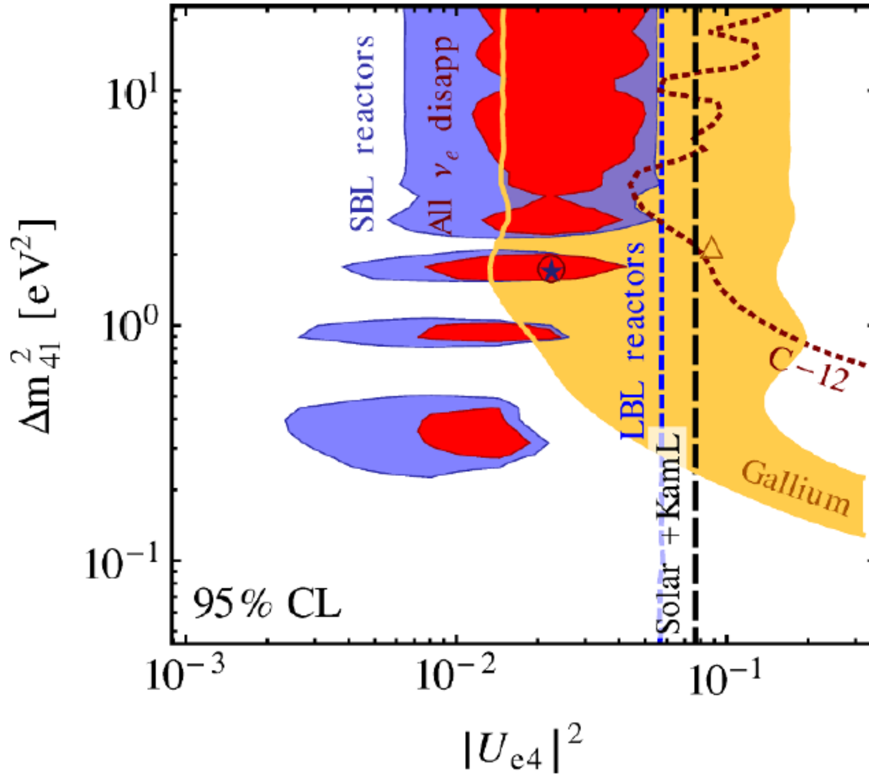
Combined fits

Reactor data only



K. N. Abazajian et al. ArXiv:1204.5379v1 (2012)

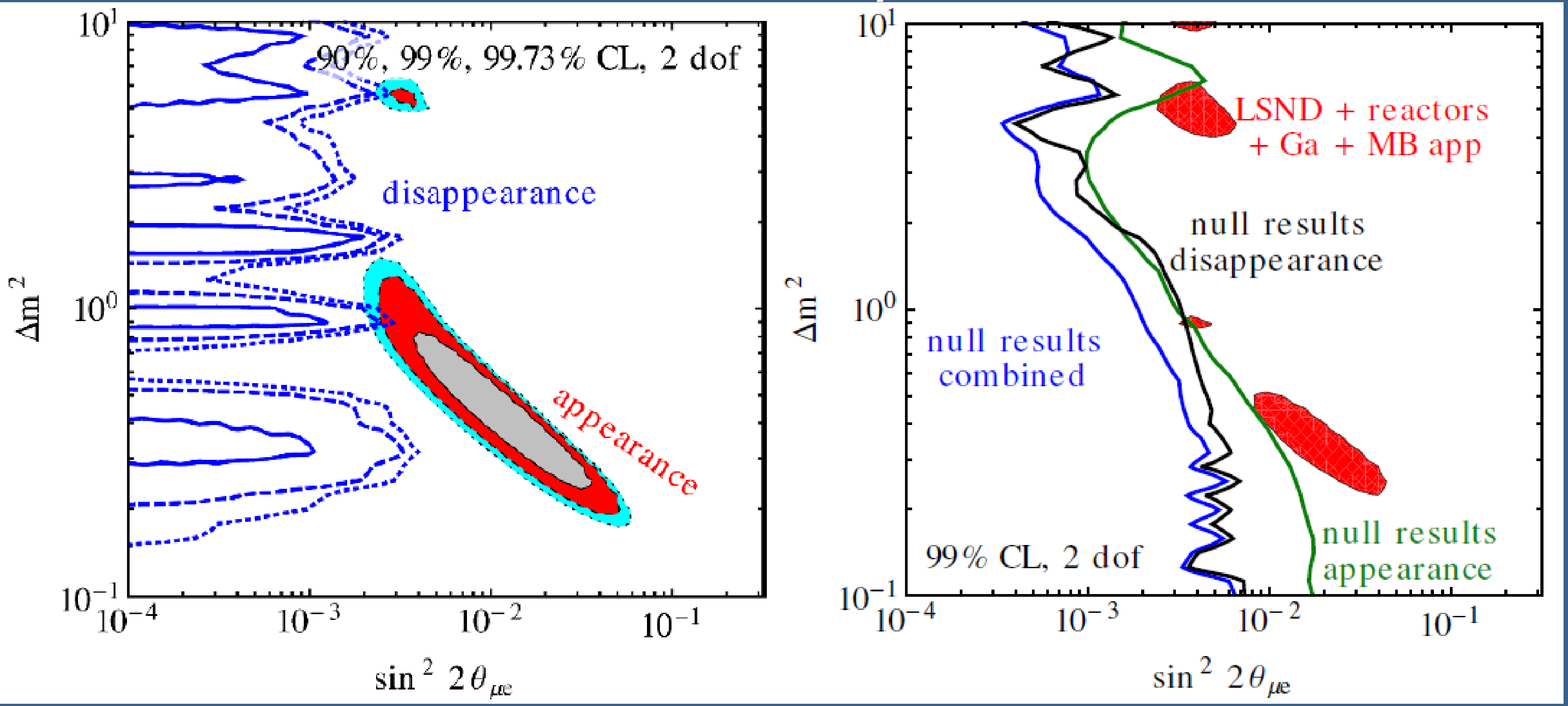
Reactor + Gallium



J. Kopp et al., JHEP05(2013)050

- Combined no oscillation disfavored at more than 99.9% C.L.
- Significance of best fit ~ 3.3 σ

GLOBAL fits of SBA, reactor&Gallium



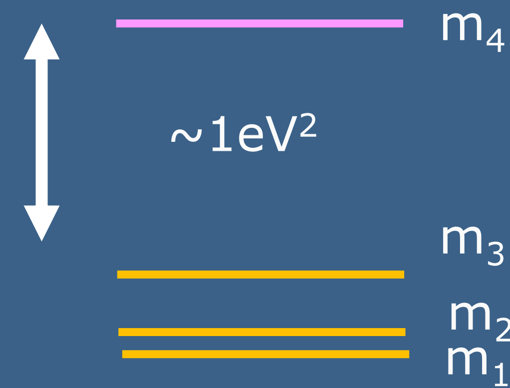
- Severe tensions between disappearance & appearance data, between null results and signals
- Only 2 $|\Delta m_4|^2$ values around 0.9 and 6 eV^2 preferred

Probing $0.1\,eV^2 < |\Delta m_4|^2 < 10\,eV^2$

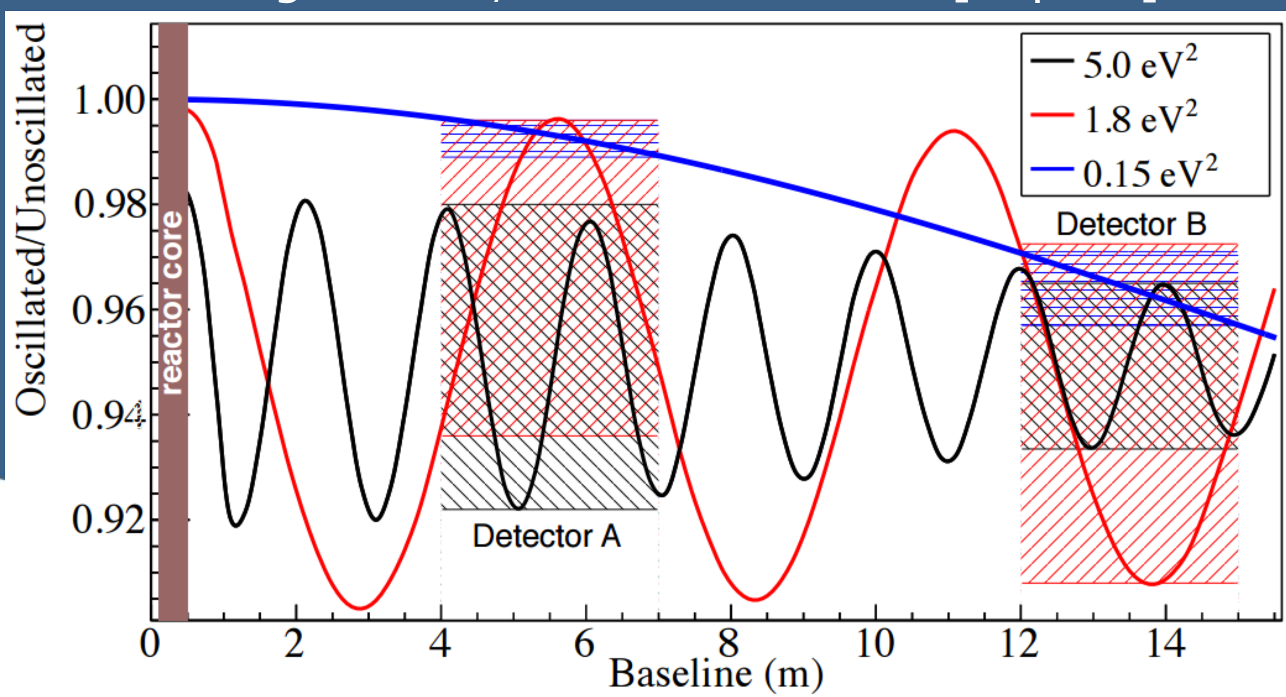
$$P_{ee} = 1 - 4|U_{e4}|^2(1-|U_{e4}|^2)\sin^2\frac{\Delta m^2 L}{4E} = 1 - \sin^2 2\theta_{ee}\sin^2\frac{\Delta m^2 L}{4E},$$

$$\lambda_{ij}(m) = 2.47\,\frac{E(MeV)}{\Delta m^2{}_{ij}(eV^2)}$$

$\lambda_{12} = 30\,km$ $\lambda_{23} = 0.8\,km$ $\boxed{\lambda_{14} = 5 - 10m}$



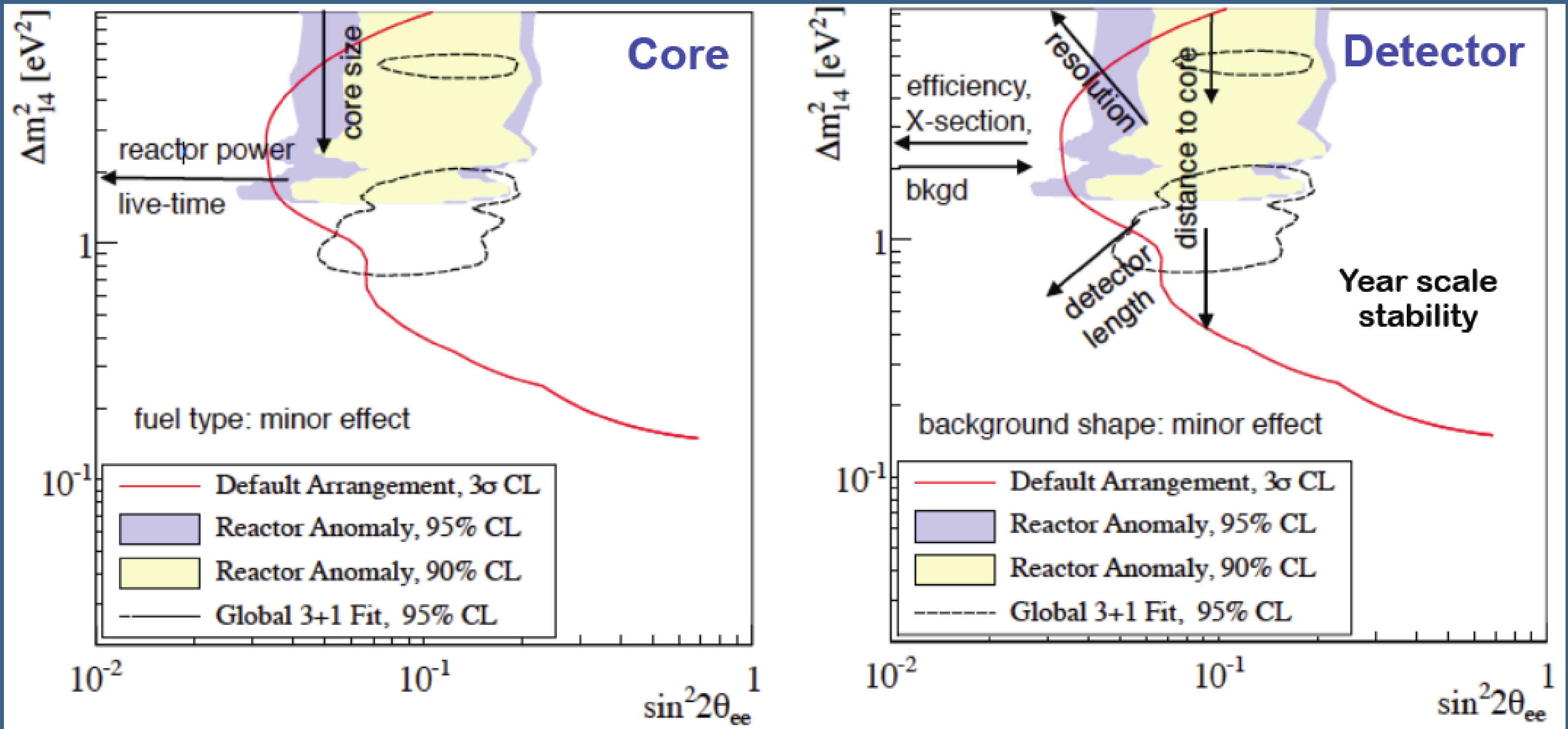
K.M. Heeger at al., arXiv:1212.2182 [hep-ex]



Reactor experiment requirements

- High flux $\rightarrow$ High Thermal power
- Compact core: diam < 1 m
- Small flux model uncertainties: pure & enriched fuel
- Approachable to d<10m
- Low backgrounds
- Fine detector segmentation and good energy resolution to allow E/L measurements
- High CC detection efficiency

Impact of key exp. parameters



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

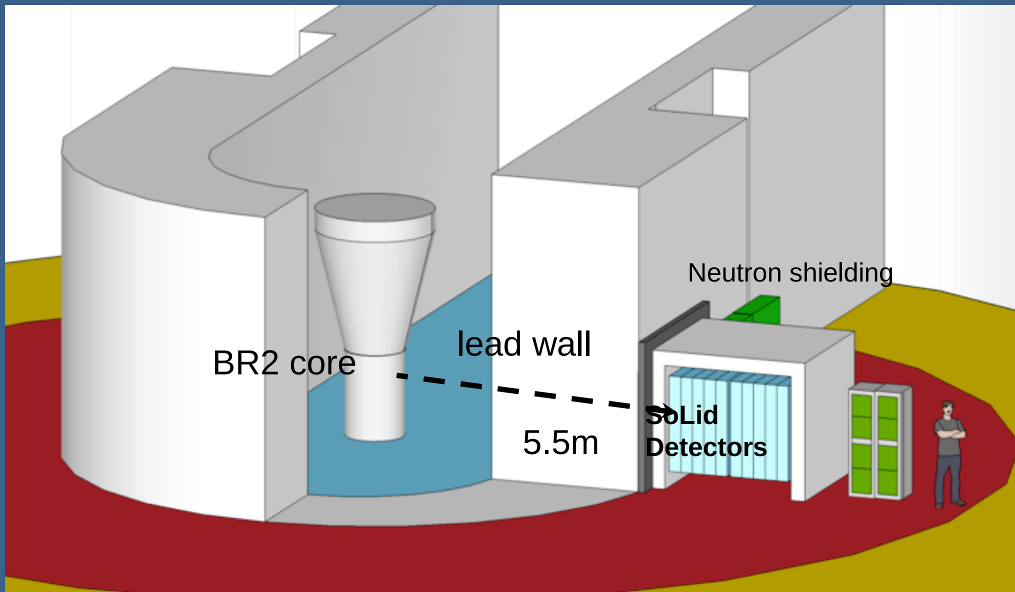
New reactor experiments

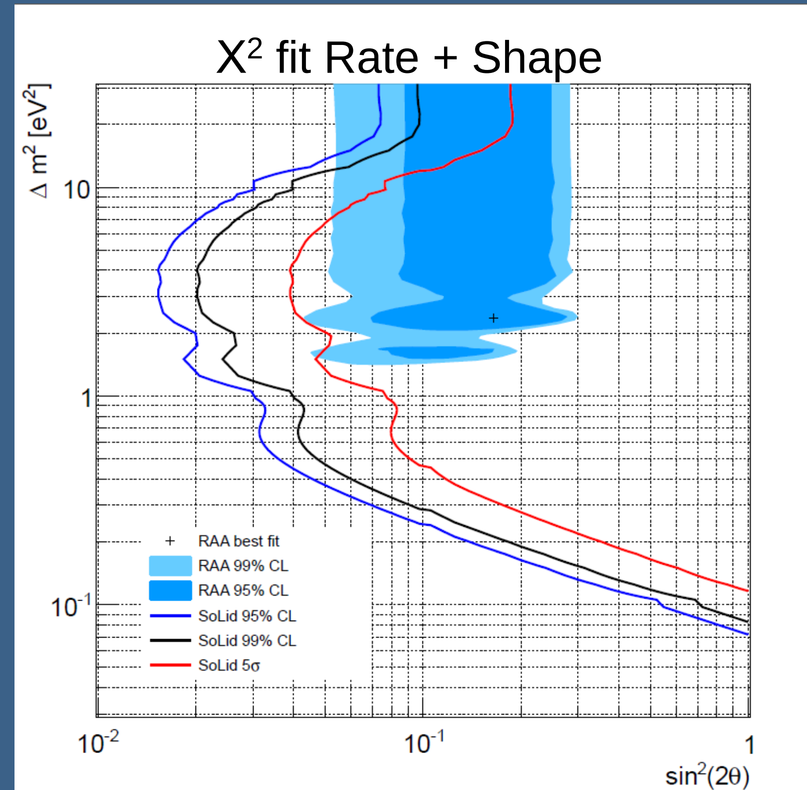
Name	Det	Size [# × l]	ΔE @MeV	BL [m]	Rate [1/d]	Effi [%]
SBL Korea	Gd-LS	1×700	6%	27	900	40
Neutrino-4	Gd-LS	2×800	100 pe/PM	6-13		
STEREO	Gd-LS	6×300	400 pe	8.8…11.2 10…12.4	410_{det}	60
Prospect	LS Li	140×20	10%	7.9		30
		10k		17.9		
DANSS	PS Gd	2.5k×0.4	24%	9.7↔12.2	10k	
SoLid	PS Li	23k×0.125	17%	5.5…11	416_{det}/t @6.8m	41

Universiteit Antwerpen
LPC Caen
Universiteit Gent
Merton College Oxford
University of Oxford
SCK•CEN
Subatech
Vrije Universiteit Brussel
Laboratoire de l'Accélérateur Linéaire
Virginia Tech 1872

SoLi∂

SoLid experiment overview





- Source: **SCK-CEN BR2 MTR** reactor
  - **45-70 MWth** power, 150 days/year
  - Relatively low level of reactor background
- Baseline L = **6.8**m (center detector)
- **2.88 tonnes** fiducial mass
- Modest passive shielding
- 416 reconstructed evts/day
- E resolution = 17%
- Data taking in early **2016**

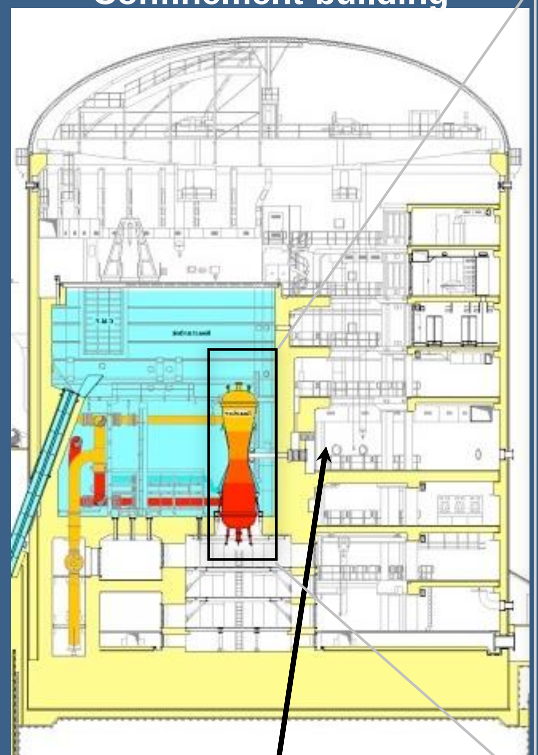
- IBD efficiency 41% at 600keV treshold
- 300 days running at 6.8m baseline
- flux normalisation (4.1%), detector efficiency (2%) systematics and backgrounds (S:B ~ 5-6)
- large bins to account for energy smearing effects

SoLid collaboration formed sept 2014

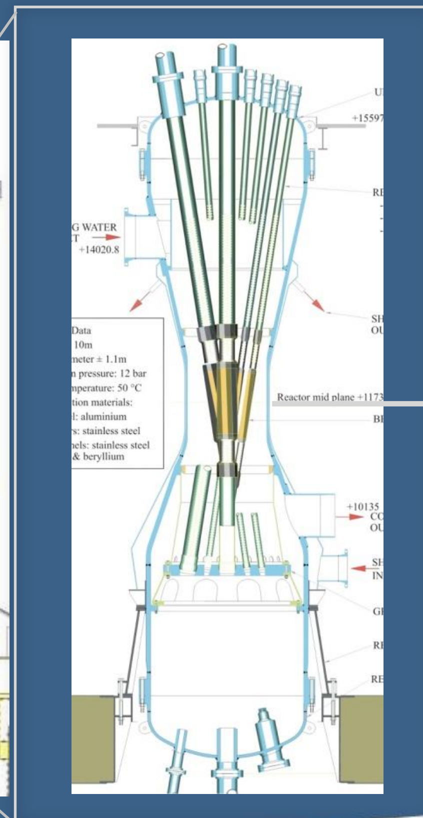
SCK•CEN BR2

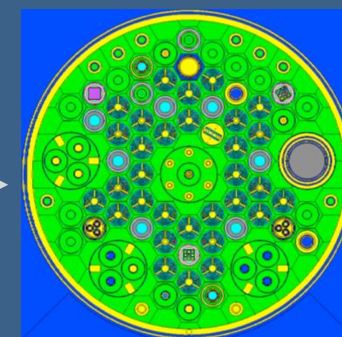
- Tank in Pool MTR research reactor
- Licensed to run at power up to 100 MW
  - variable operating power
  - 5/6 cycles per year
  - low reactor backgrounds

Confinement building



Level 10m67
on axis with reactor





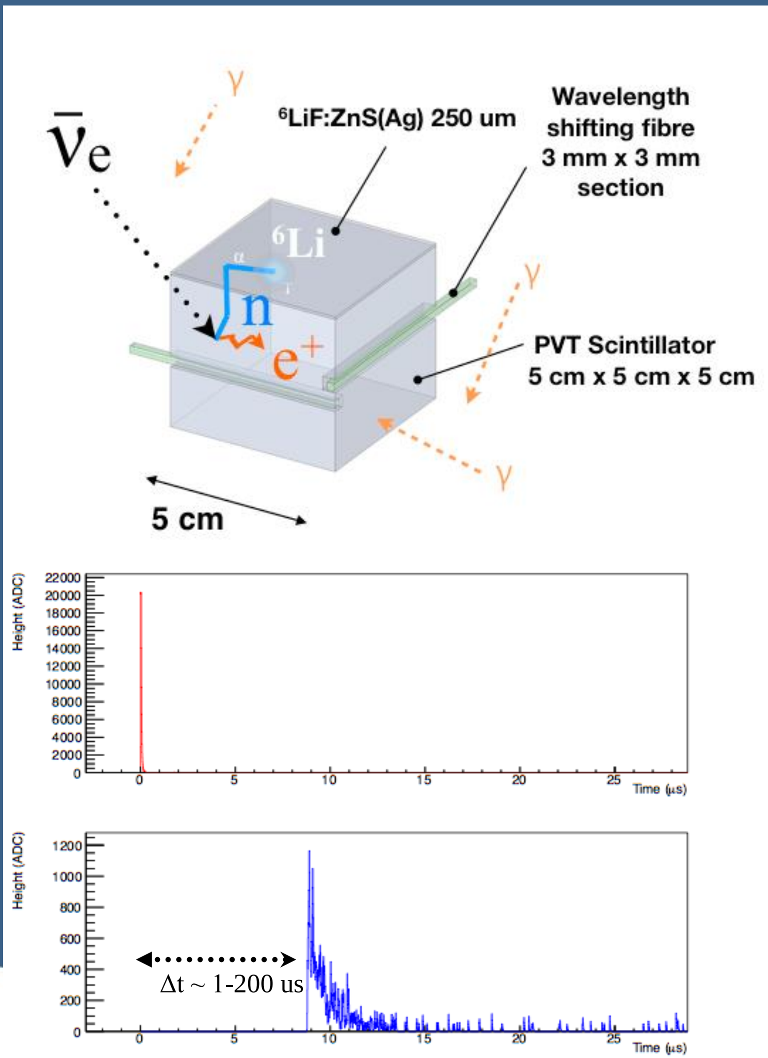
1.0 m

Beryllium matrix and assemblies

Aluminum pressure Vessel
Twisted core

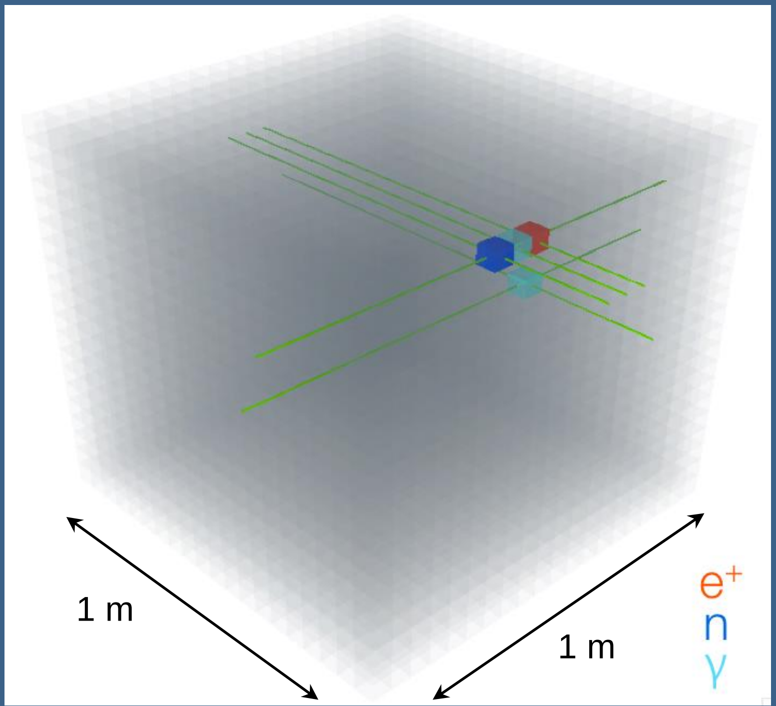
Detector principle[29]

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



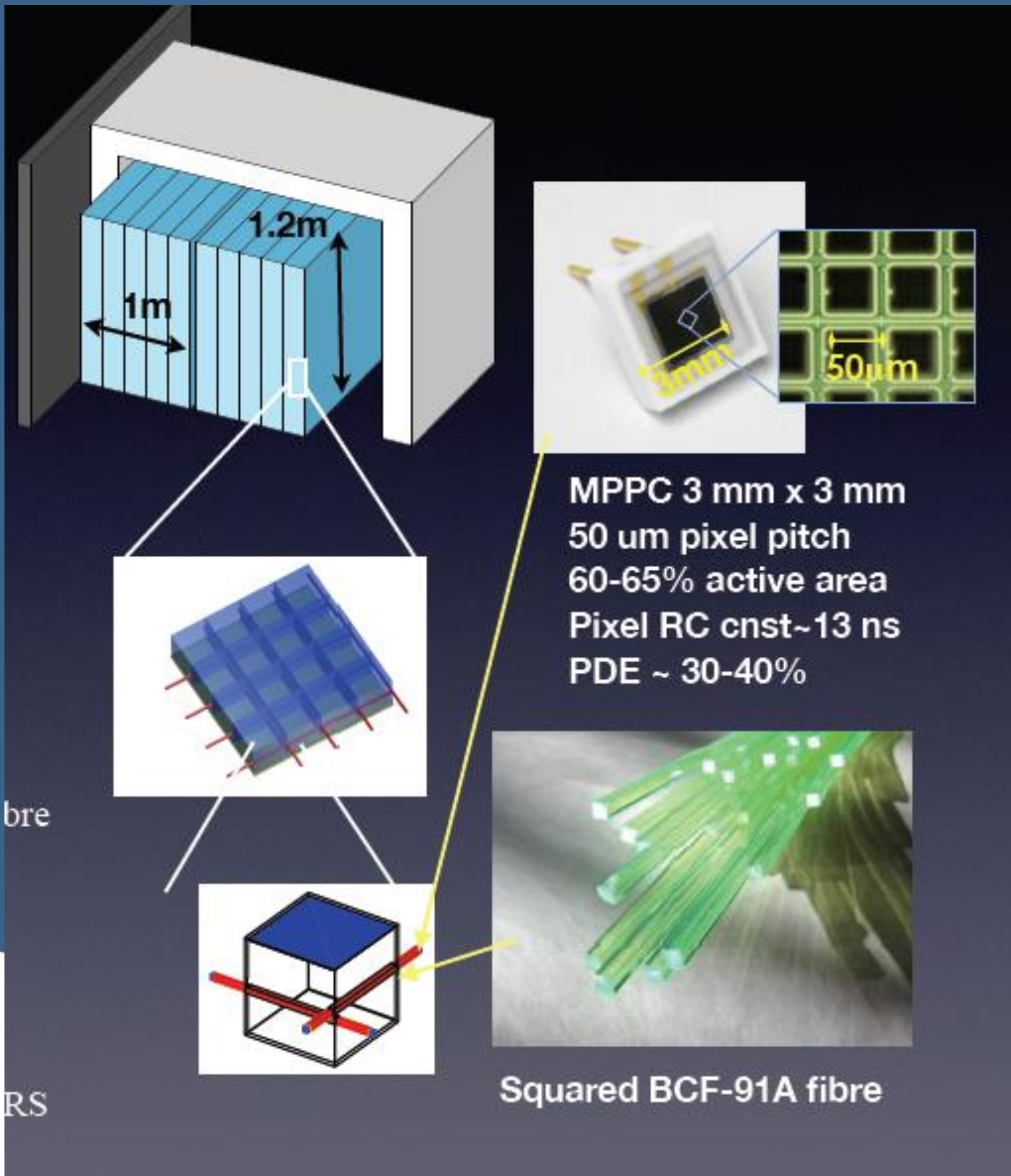
Un

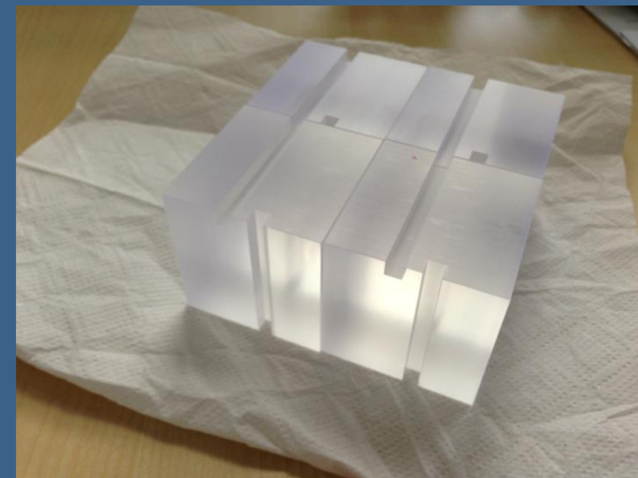
$${}^6_3\mathrm{Li} + \mathrm{n} \rightarrow^2_4 \mathrm{He}\ (2.05\ \mathrm{MeV}) +^1_3 \mathrm{T}\ (2.75\ \mathrm{MeV})$$

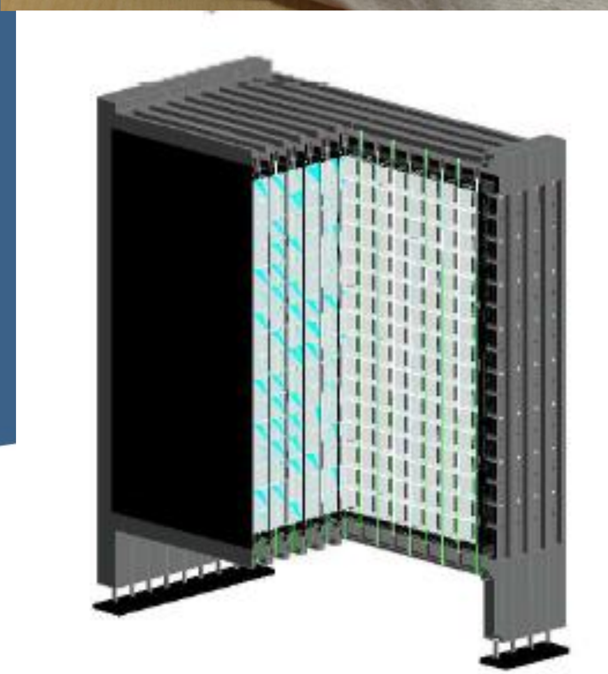


- **Neutron / gamma-ray discrimination from pulse**
  - **distinctive response for prompt and delayed signal**
  - **neutron used to trigger event read out**
- **Voxelisation of target volume**
  - **neutron captured in neighboring cube increasing localisation of IBD event**

Technology& Design







Advantages

- Very compact and highly efficient detector:
  - Spatial resolution of 5 cm!
  - energy resolution: 10-17%
  - Movable over distance to core between 6-15m
  - Extendable by adding more planes
  - Very high background rejection due to
    - Time and topological signature of true $\overline{\nu_e}$ signals
    - Additional shielding
    - Already operating in low background environment

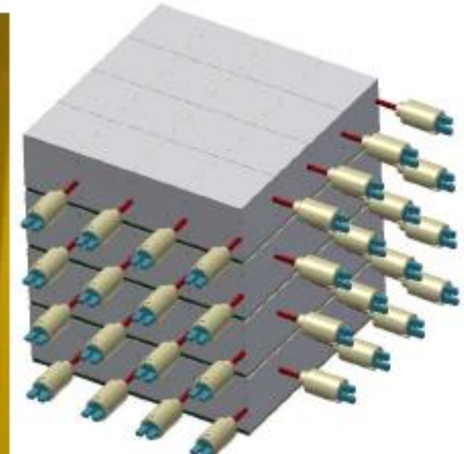
Staged design

- Started with 8 kg prototype in dec 2013
- Finished construction of 288 kg full scale module in Nov 2014
- Planned (and funded) construction of a 1.4 T detector by summer 2016
- If more funding secured: Extension with 2nd station of 1.4 T

NEMENIX 8kg prototype

Purposes:

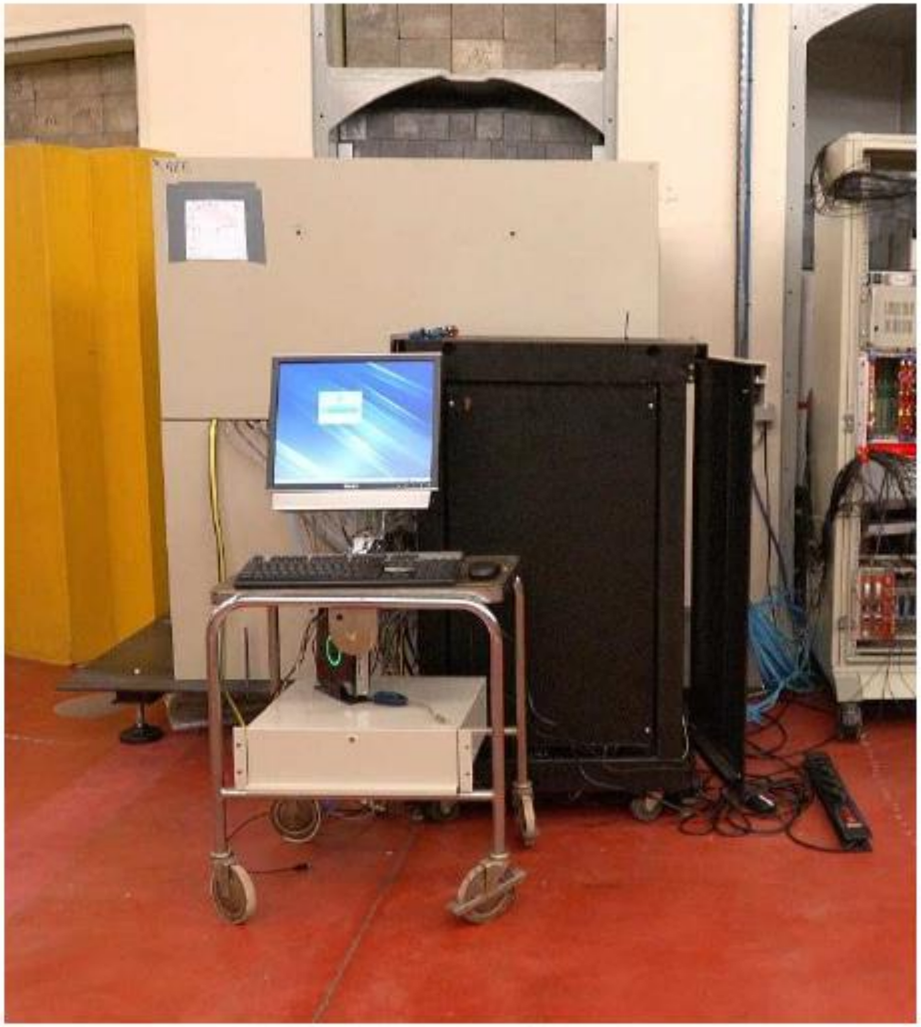
- Proof of composite scintillator concept
- Develop reconstruction techniques
- Measure backgrounds at experimental location
- TRL 2 - 3



SM1 288 kg module

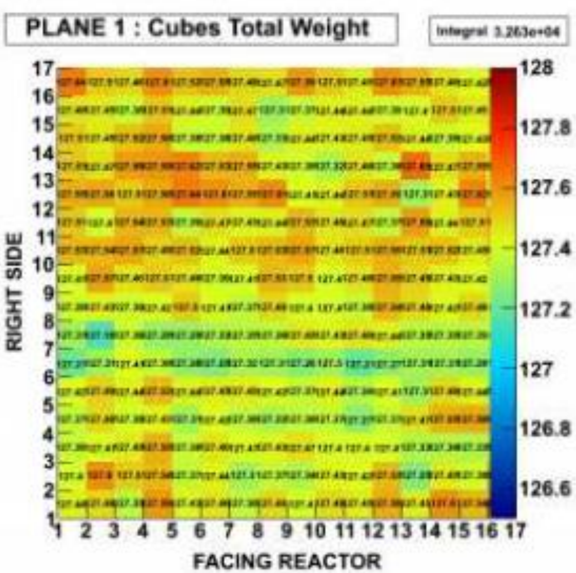
Purposes:

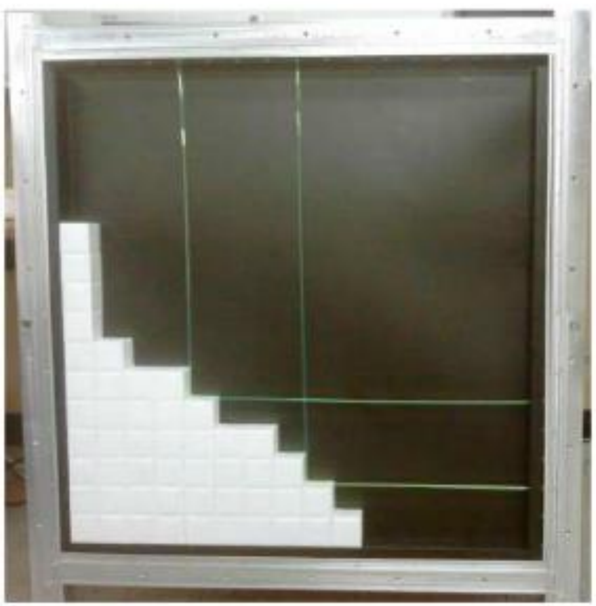
- $80 \times 80 \times 45$ cm^3
- Proof of event topology concept
- Measure $\bar{\nu}_e$ energy spectrum
- Compare measured and calculated flux and spectrum
- Demonstrate reactor monitoring
- Scale up production, DAQ, etc.
- Improve reconstruction, analysis
- TRL 3 - 5



Construction of SM1

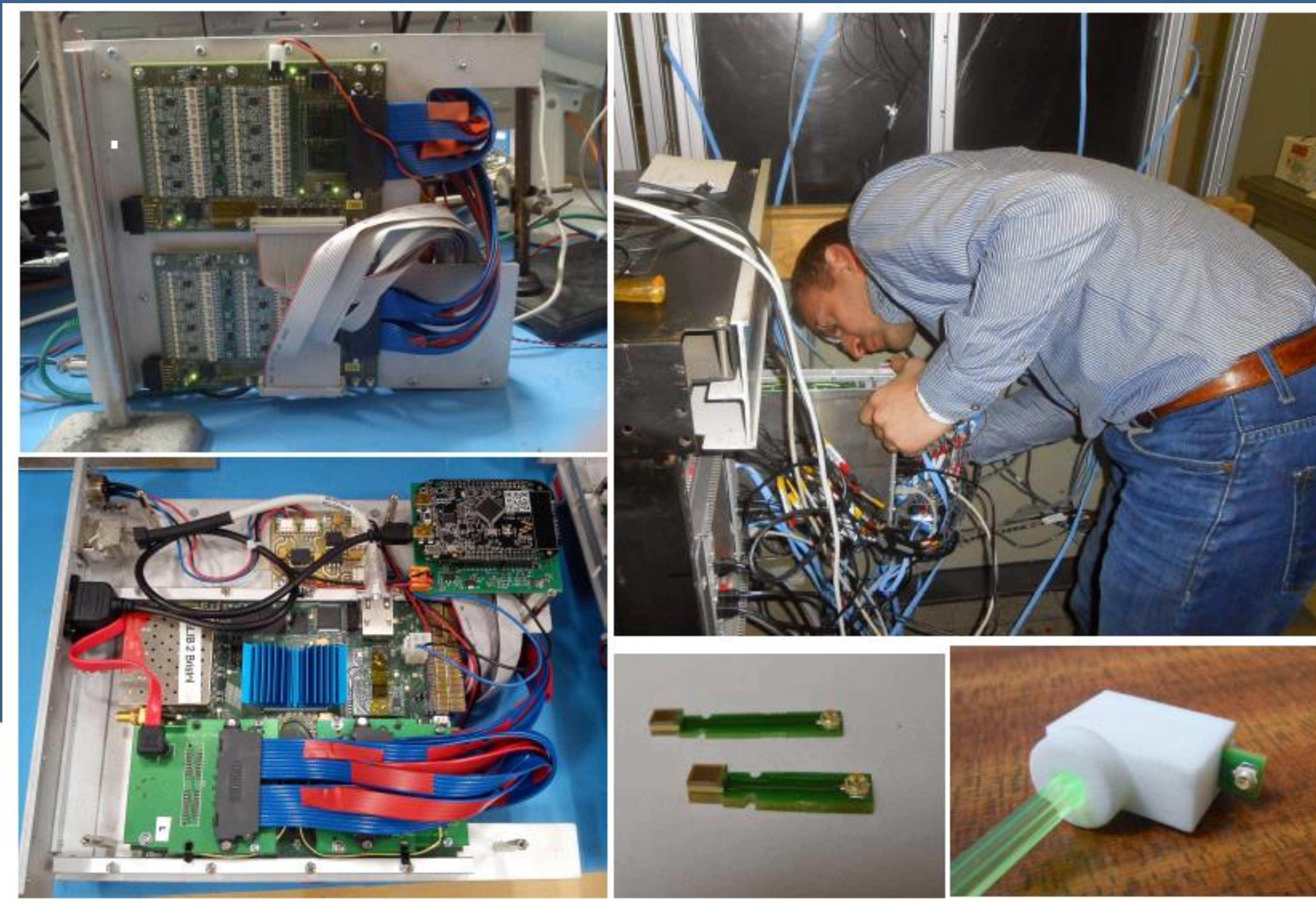
- UAntwerpen, UGent & VUB :
- 3000 cubes machined & assembled in 3,5 months time
- Cosmic Muon veto system built & tested
- Mechanical design + financing materials: SUBATECH Nantes



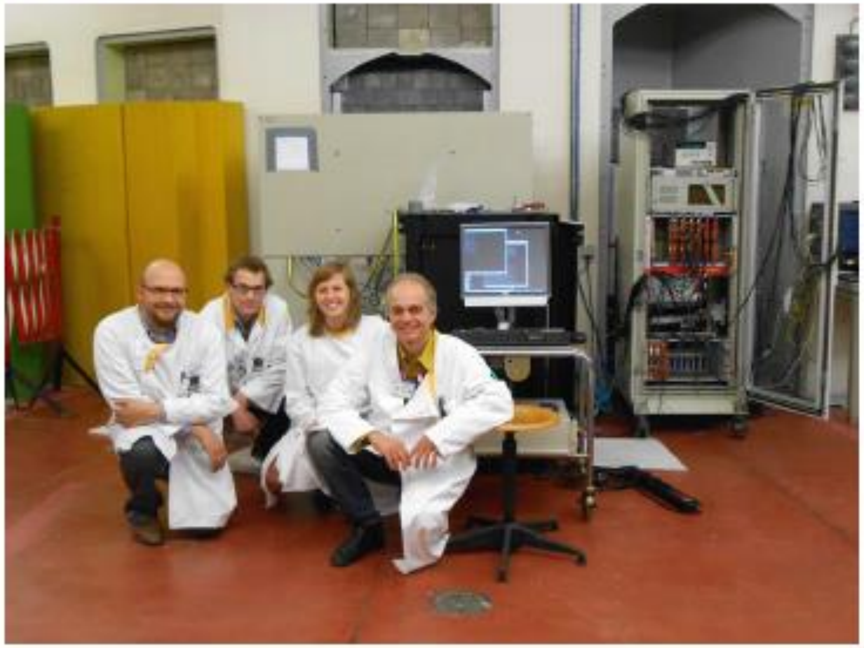


Construction of SM1

- Electronics: Oxford & Bristol
  - 300 MPPC sensors coupled to 300 optical fibers
  - 10 amplifier&digitizer boards, 5 DAQ modulel

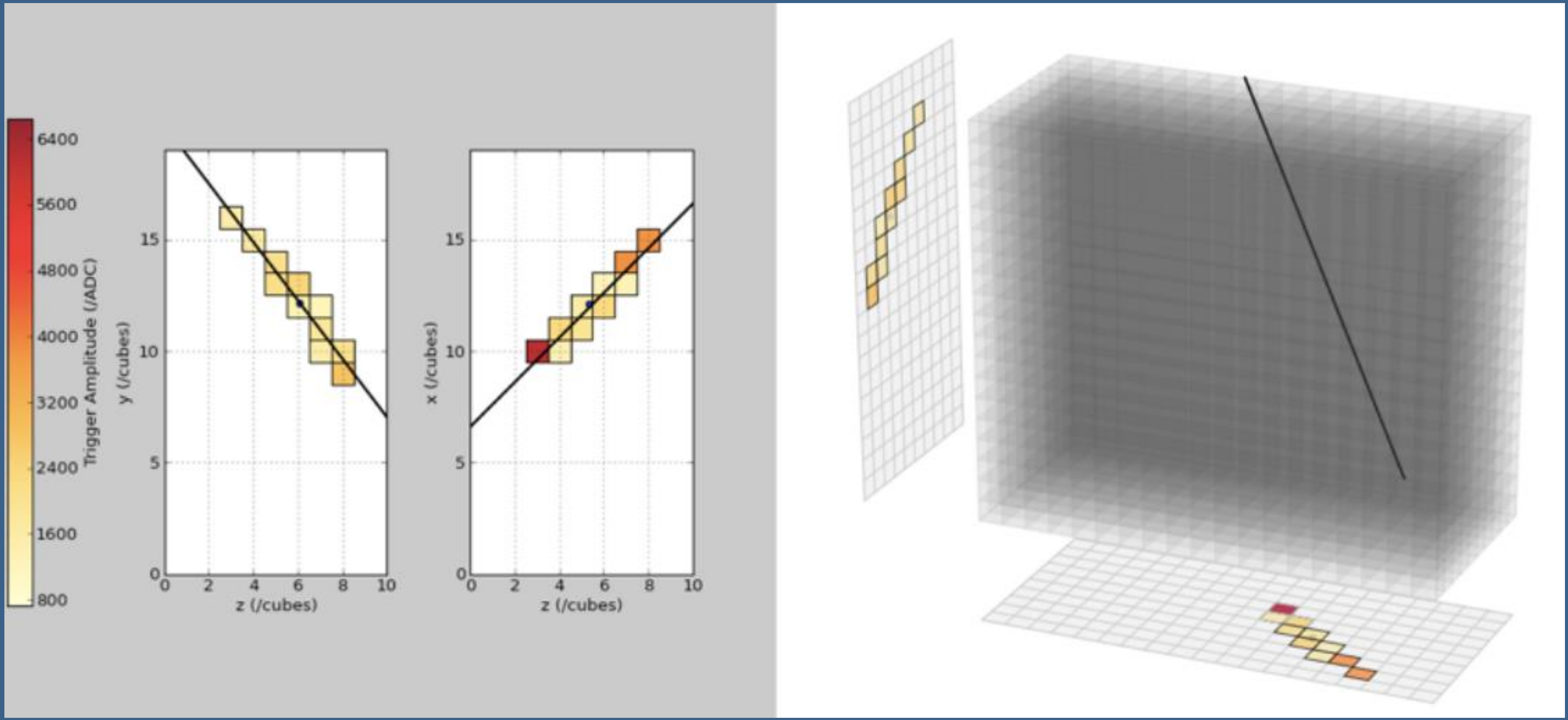


Deployment at SCK



First results

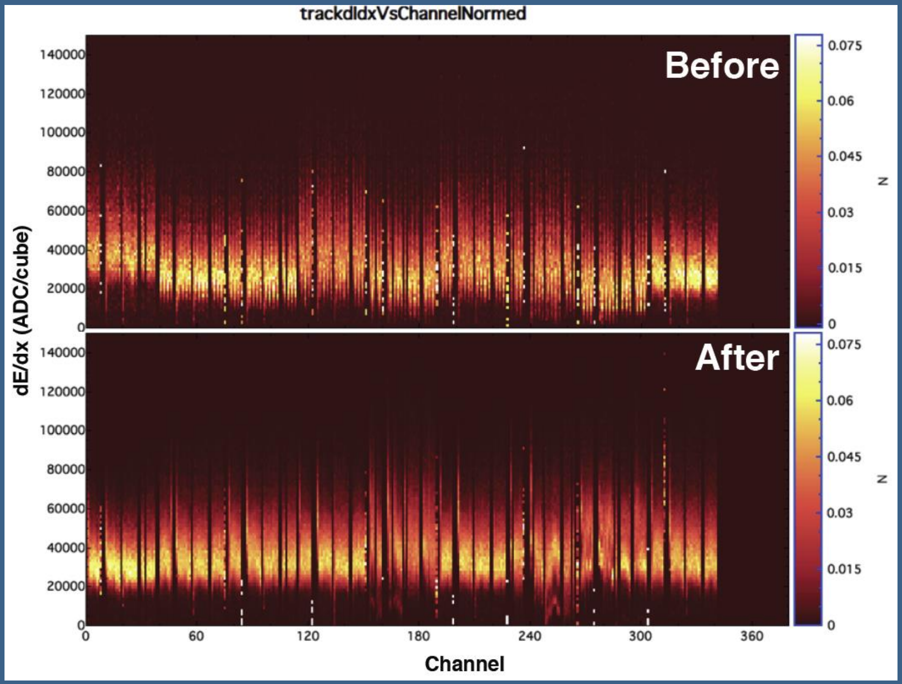
- Cosmic muon tracks and dE/dx

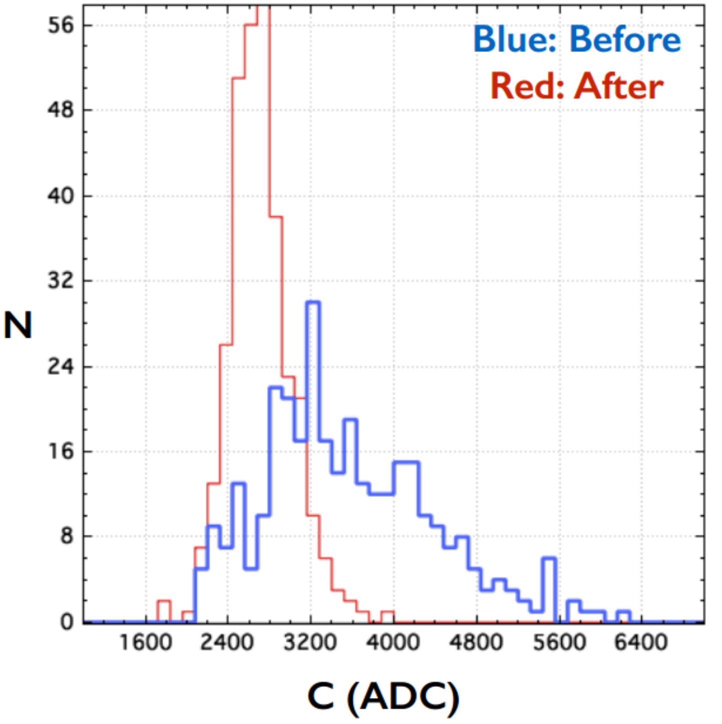


- Allow to calibrate uniformity of gains in channels
- Estimate energy scale and resolution

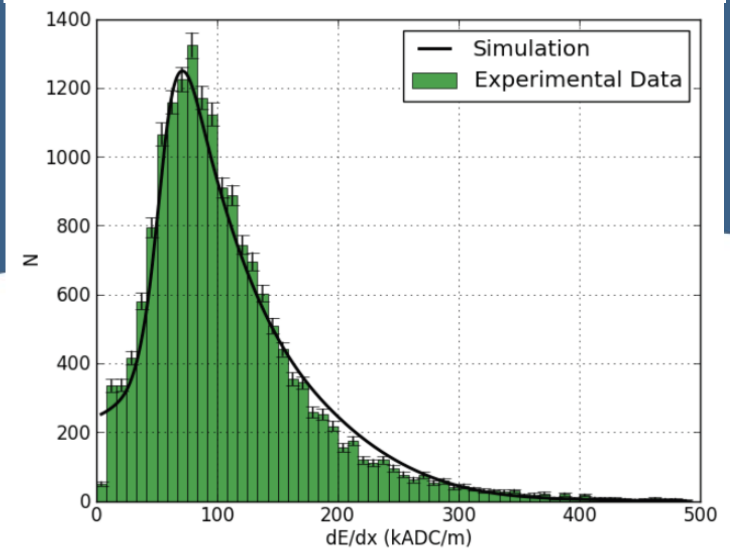
First results

- Channel gain calibration



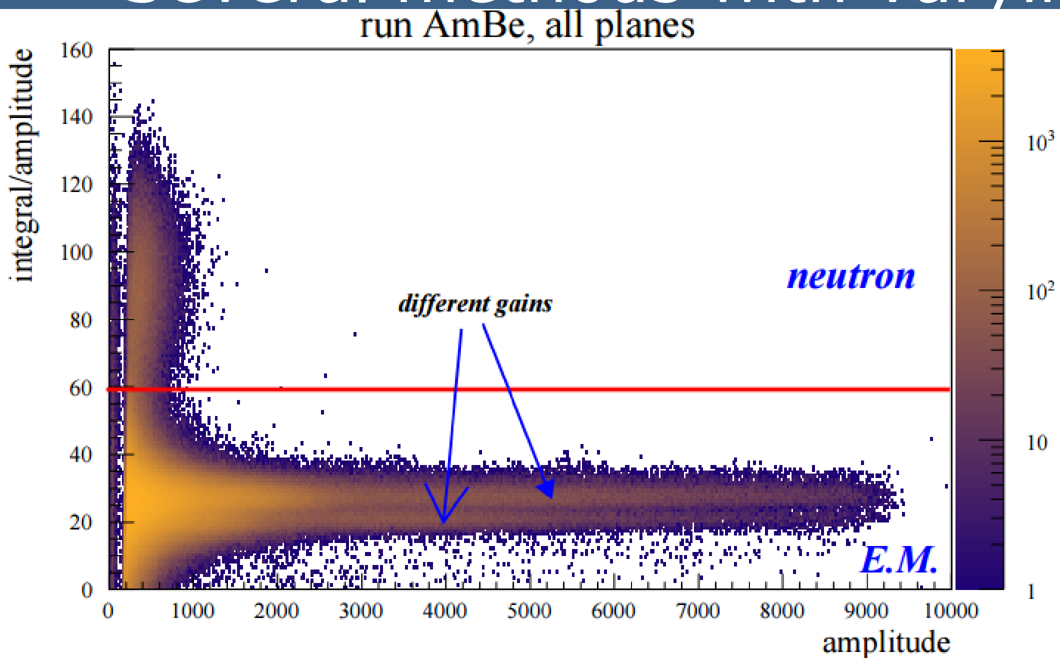


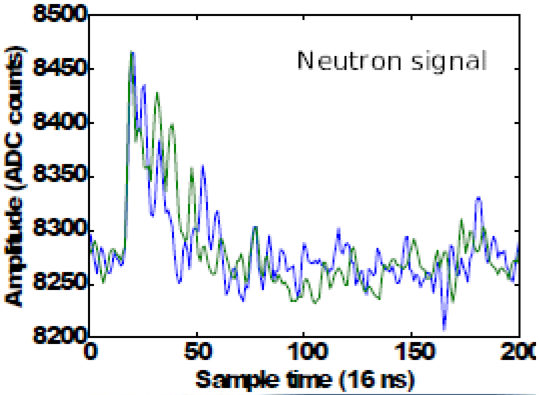
- Energy scale

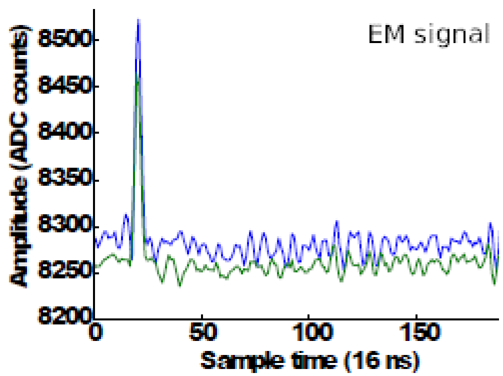


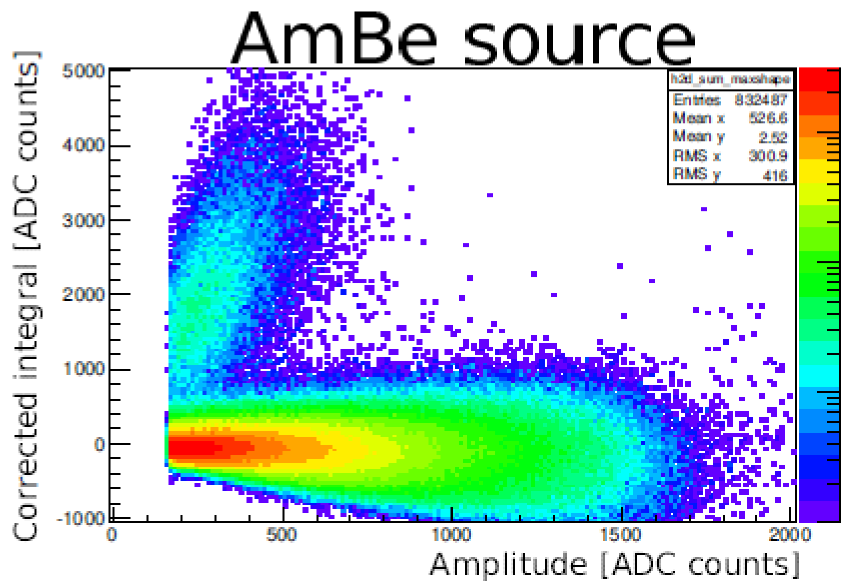
Neutron ID

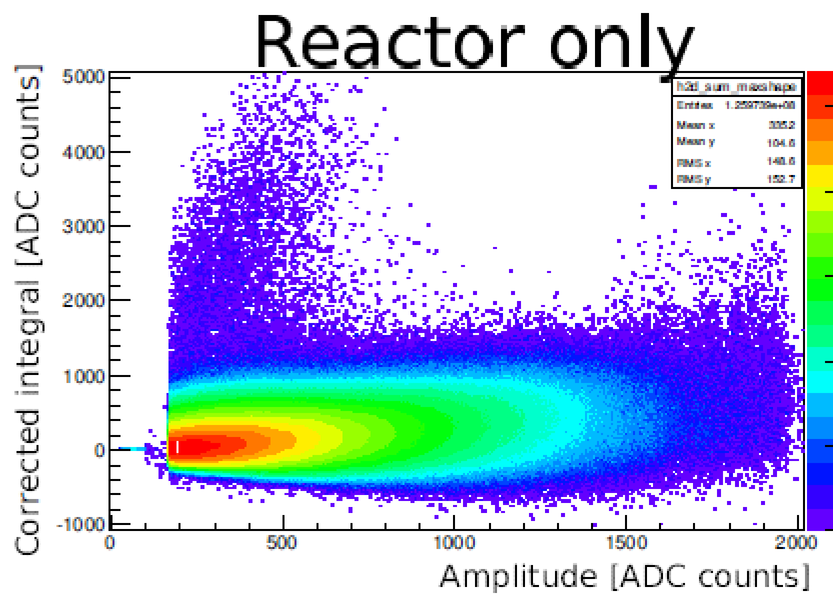
- Several methods with varying complexity





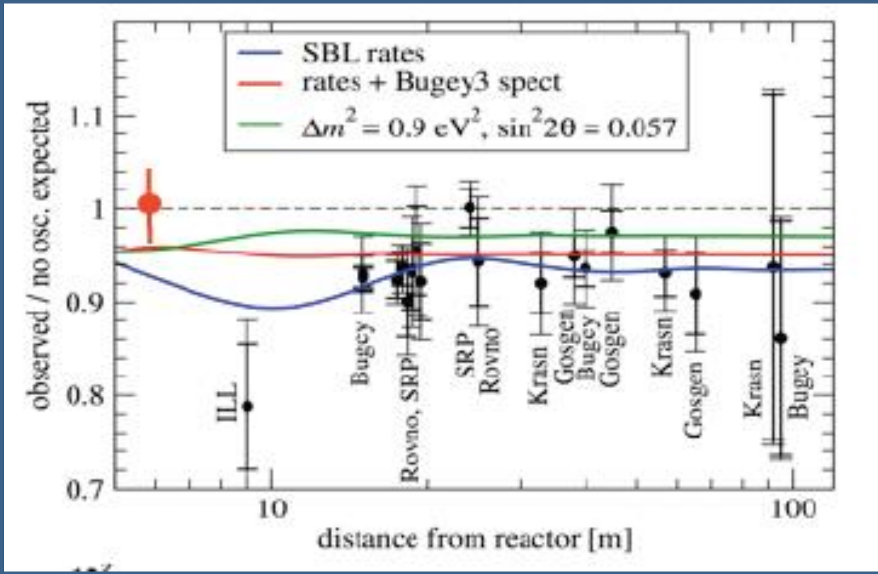






Physics potential of Phase 1

- Opportunity for precision measurement of flux at <d>=5.8m with 1-2 cycles
- Dominated by systematics
- Before most (or all) other experiments
- Measure rate difference at two values of d (5.5-6m)
- Measure E difference at two values of d
- Reactor flux calculation:
  - Will determine spectrum



Current status

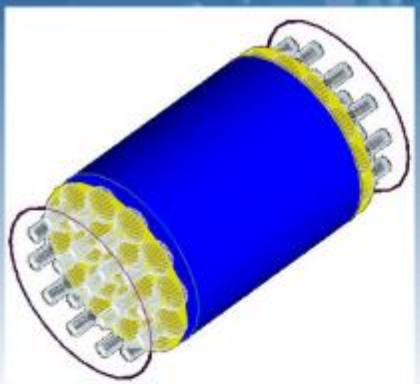
- 8kg prototype: ~60 days of reactor ON data under analysis: hints of significant excess of $\bar{\nu}_e$ candidates $\rightarrow$ to be published soon
- 288 kg demonstrator:
  - ~10 days of good quality reactor ON data should allow first flux measurement at ~5.5 m distance (uncovered terrain), perhaps first energy spectrum
  - Currently calibrated with cosmics, γ and n sources
- 1.4 T station under construction, to be finished by summer 2016
- Next BR2 cycle expected for Aug 2016

Conclusion

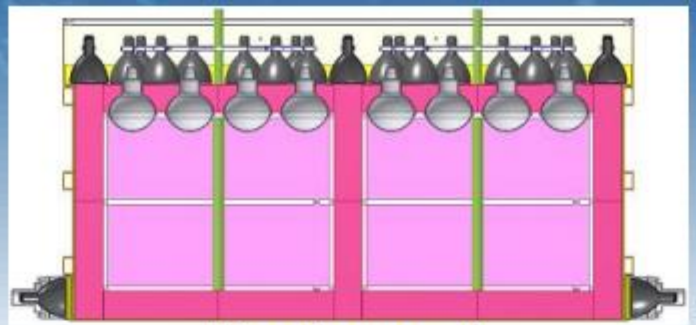
- Lots of conflicting data in search for short baseline oscillations
- Sterile neutrinos still viable portal for new physics
- New generation of improved SB accelerator and reactor experiments being staged
- Belgian BR2 reactor and SoLid experiment seem to be at front line for reactor based sterile neutrino searches

Backup

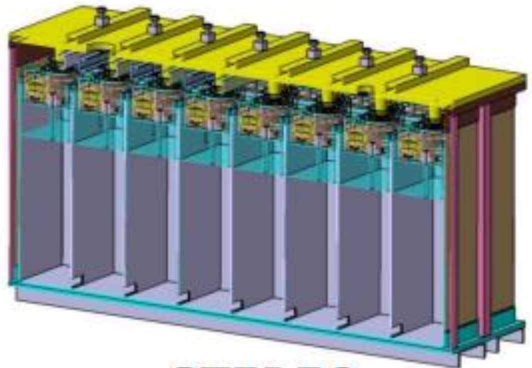
Other SB Reactor experiments



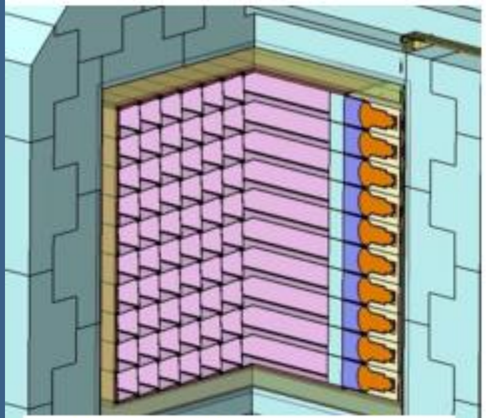
SBL Korea
0.7 m³ Gd-LS



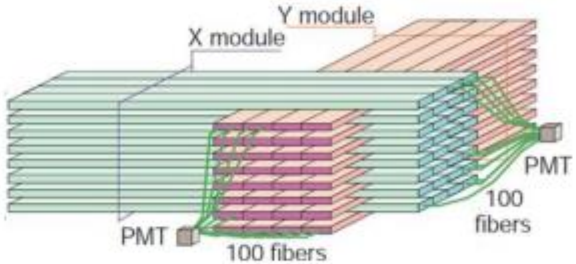
Neutrono-4
2×0.8 m³ Gd-LS



STEREO
6×0.3 m³ Gd-LS



PROSPECT near
140×20 l Li-LS



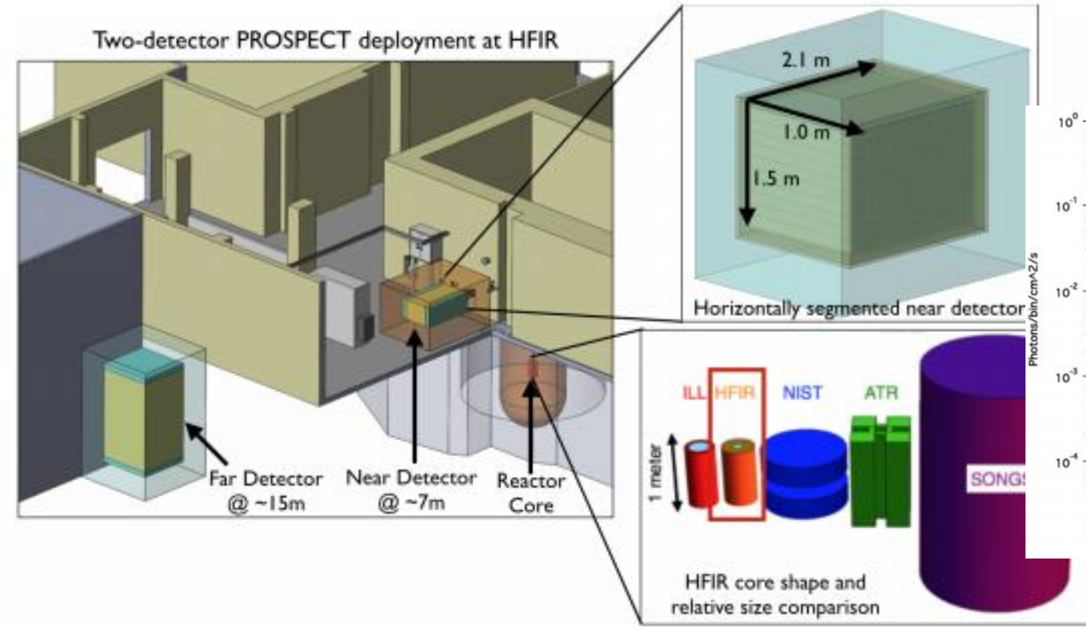
DANSS
2500×0.4 l PS Gd

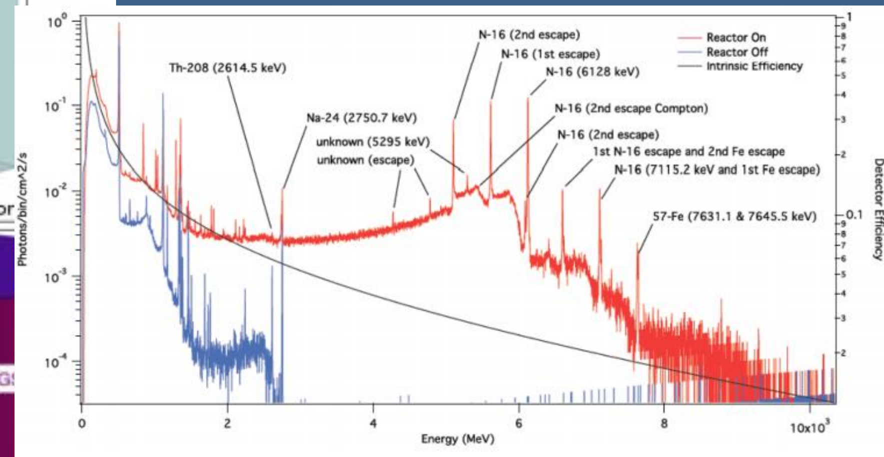
SOLID
23k×0.125 l PS Li

NuPhys2014: Sterile Neutrinos @ Reactors 14

From: T. Soldner at nuPhys 2014, London

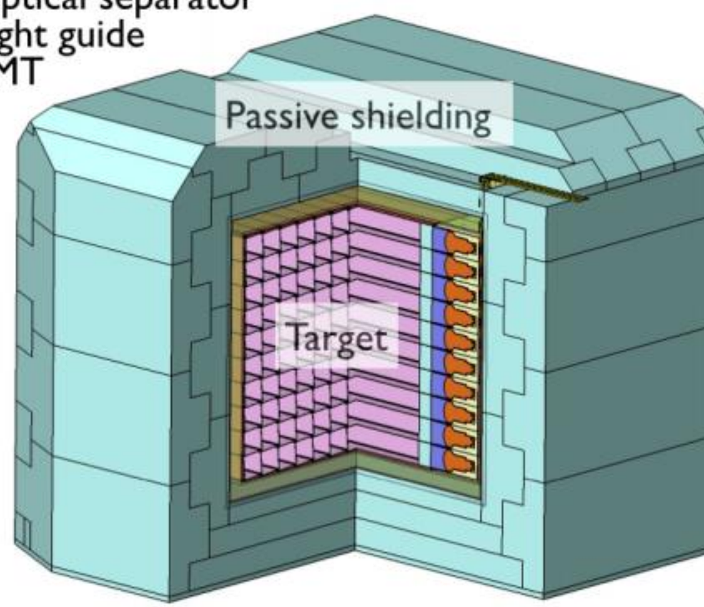
PROSPECT





γ background at NIST

To-scale mockup at HFIR near location



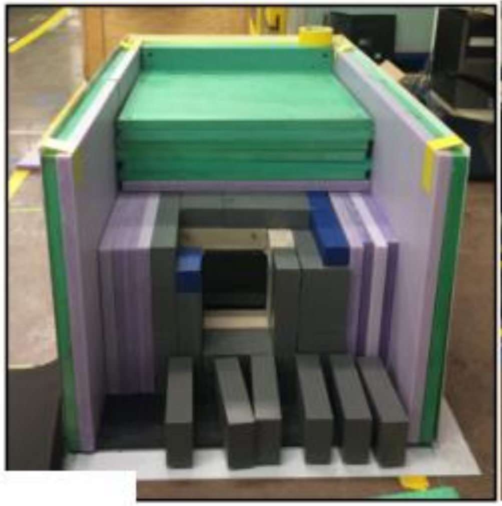
Detector conceptual design drawing

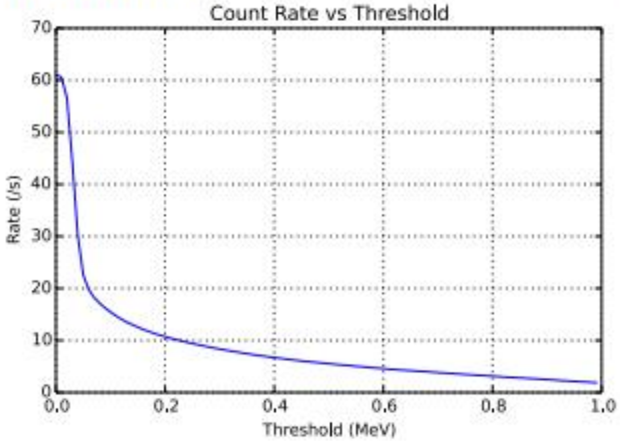
PROSPECT Coll, arXiv:1309.7647v3

Hot off the press: PROSPECT2 operating @ HFIR

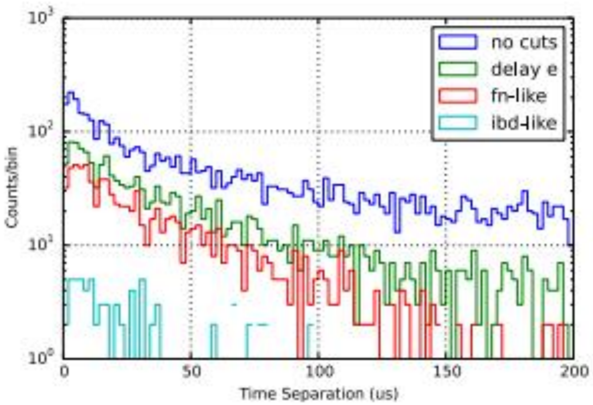
~2 liter Li-LS detector in small B-poly/ lead shield

- not representative of final shield design but useful for MC validation





10Hz Rx On singles rate > 200keV
-several orders of magnitude reduction with more to come



^{6}Li and fast neutron PSD strongly suppress backgrounds

Studies Underway:

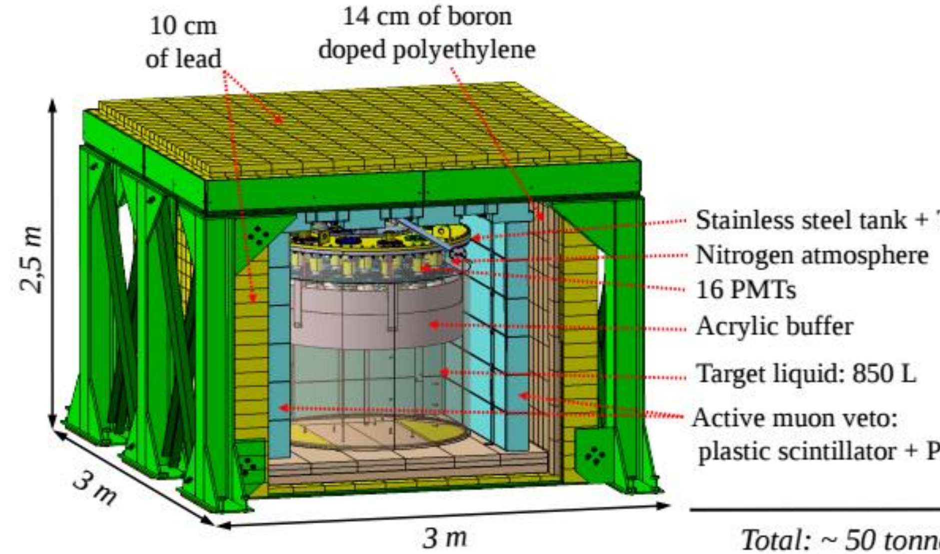
- Muon correlations
- Detailed simulation comparison
- Internal background contribution (Rx off)
- …

From N. Bowden at AAP workshop, Paris 2014

NUCIFER @ OSIRIS and STEREO @ ILL

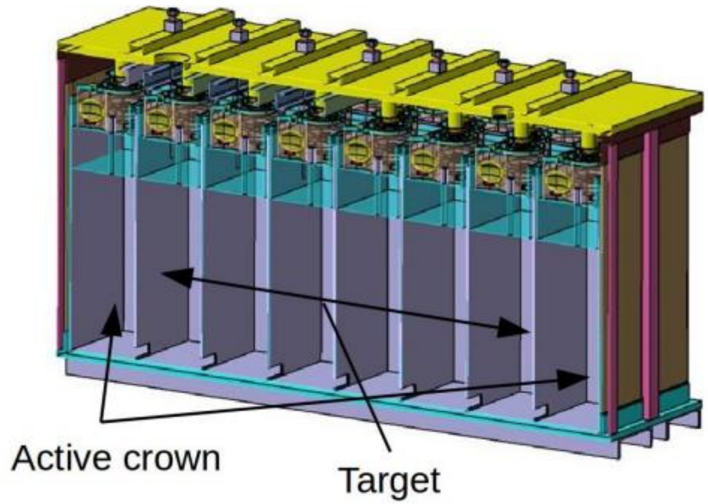
Main caracteristics of NUCIFER :

- 850 L of Gd-loaded (0.2%) liquid scintillator (MPIK scintillator),
- 16 PMTs fixed on an acrylic buffer,
- central calibration tube,
- $\sim$7 m from a 70 MW$_{th}$ "pool type" research reactor.

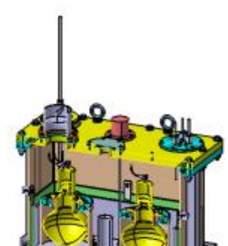


STEREO

- Six cells (40x90x90) cm^3 filled with Gd-loaded liquid scintillator.
- Surrounding crown filled with unloaded liquid scintillator.
  - Containment of energy leakage
  - Active veto of external background

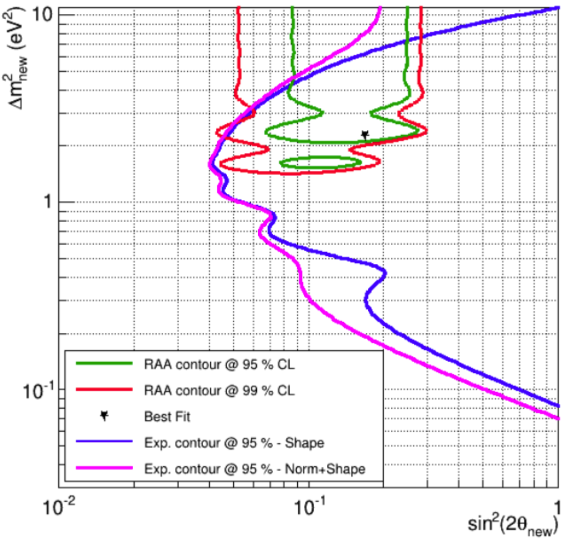


- Light collection :
  - Four PMTs per cell and acrylic buffer.
  - Acrylic walls and optical segmentations with VM200.



Sensitivities

STEREO Sensitivity



- 300 days, L_0 = 10 m
- E_{prompt}>2 MeV, $E_{delayed}$>5 MeV
- ~410ν_e/day
- δE_{scale} = 2%
- All syst. of predicted spectra
- S/B = 1.5, 1/E+flat model
- Norm 4%
- Start data taking in 2015

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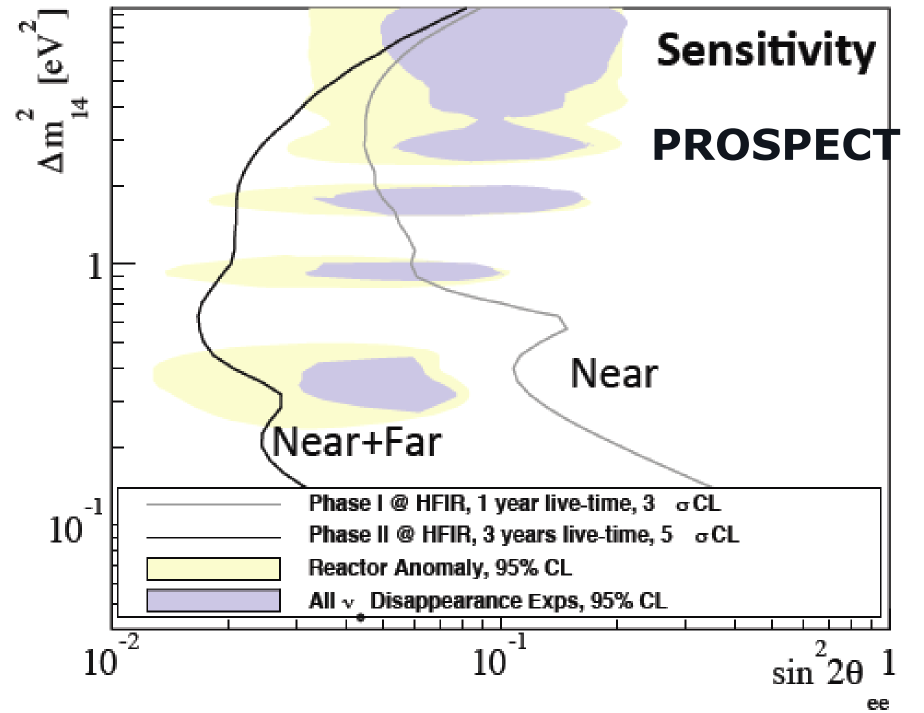
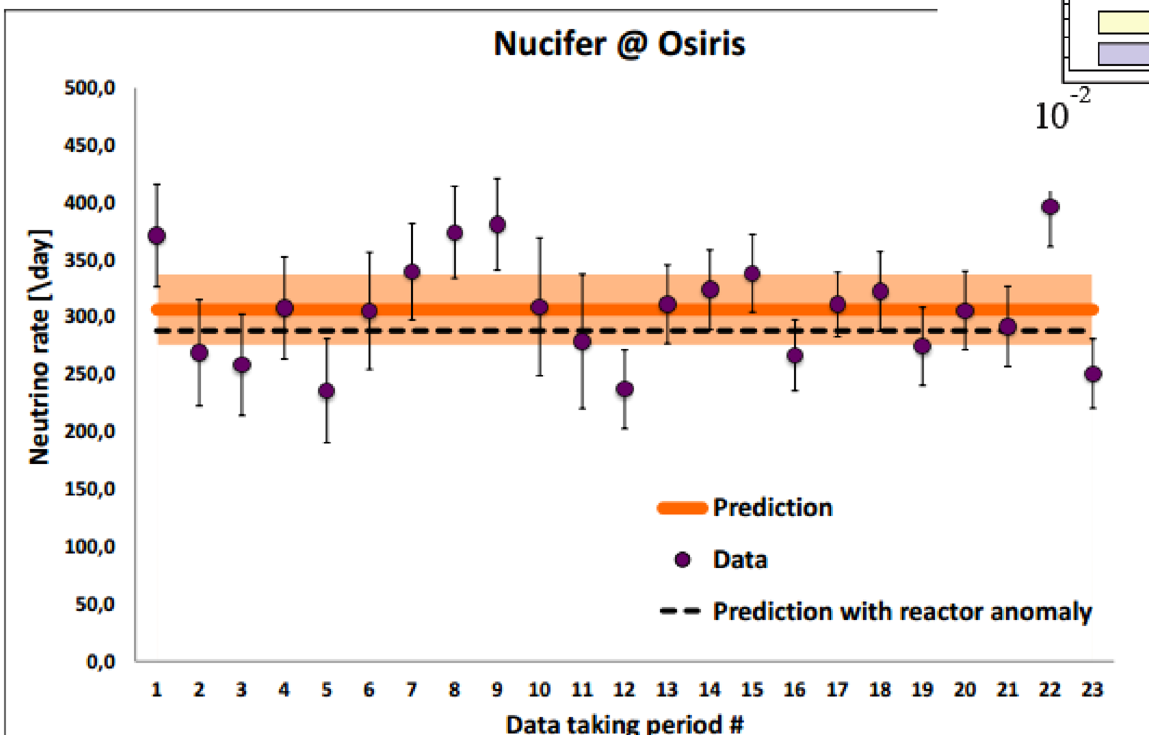
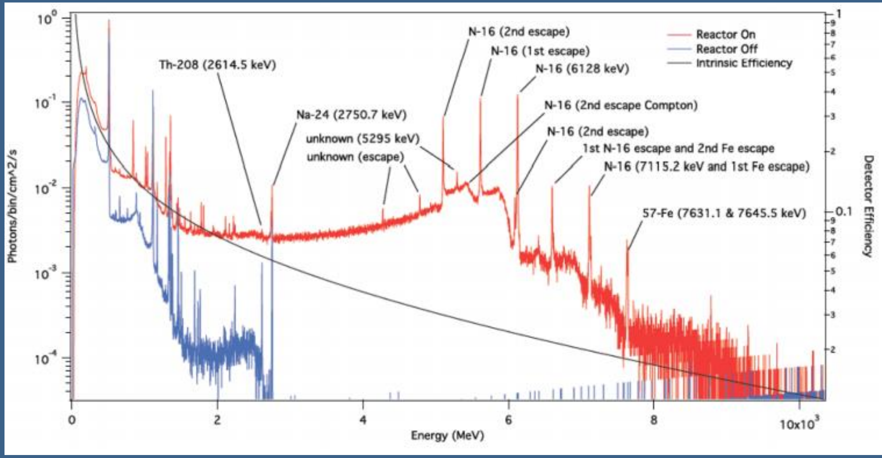


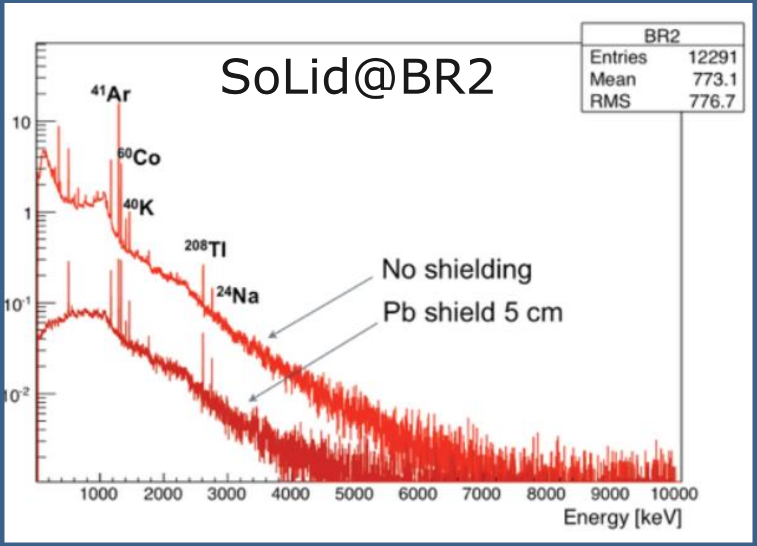


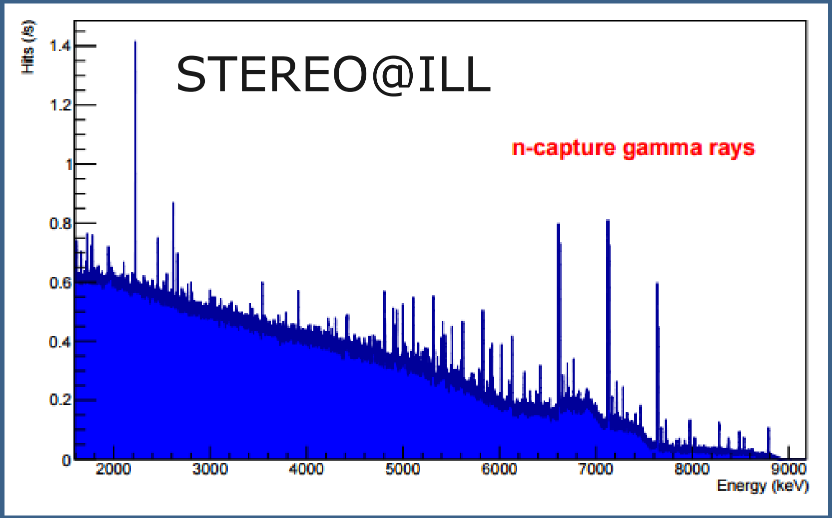
- Mean value = **306 ± 9 ν/day.**
- Predicted value = 307 ± 32 ν/day.

Backgrounds at various facilities

PROSPECT @ NIST

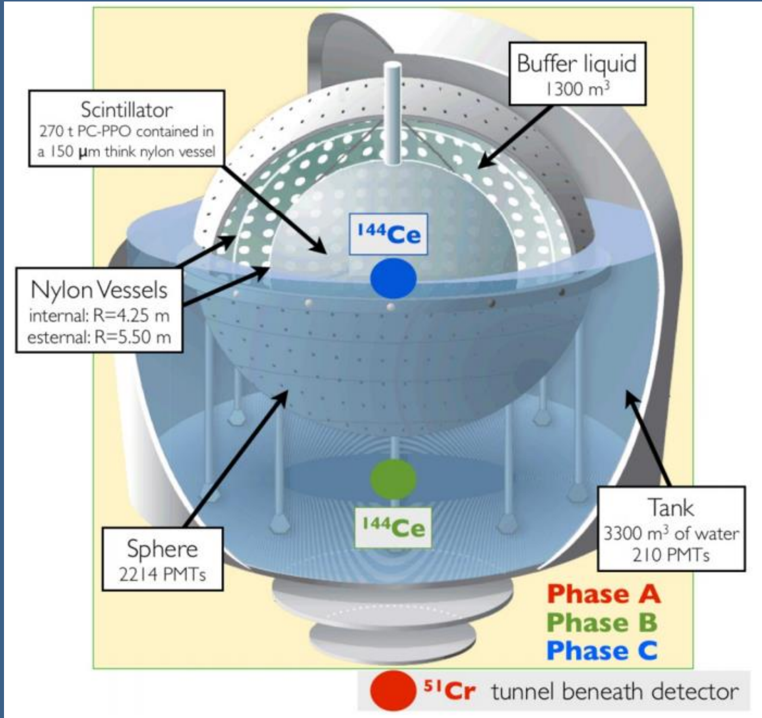






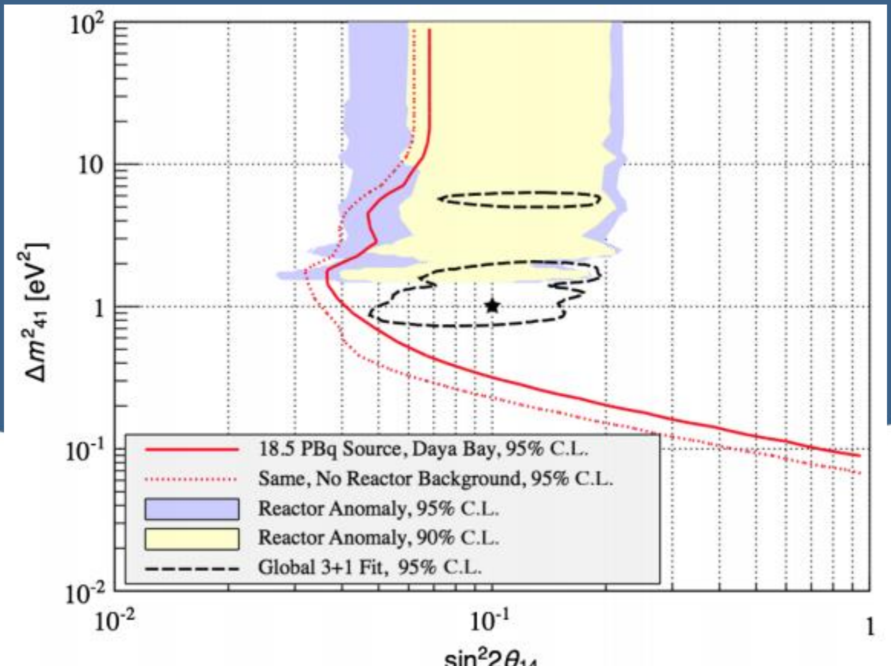
Radioactive sources

- Plans to place MCi sources inside or near existing ν detectors



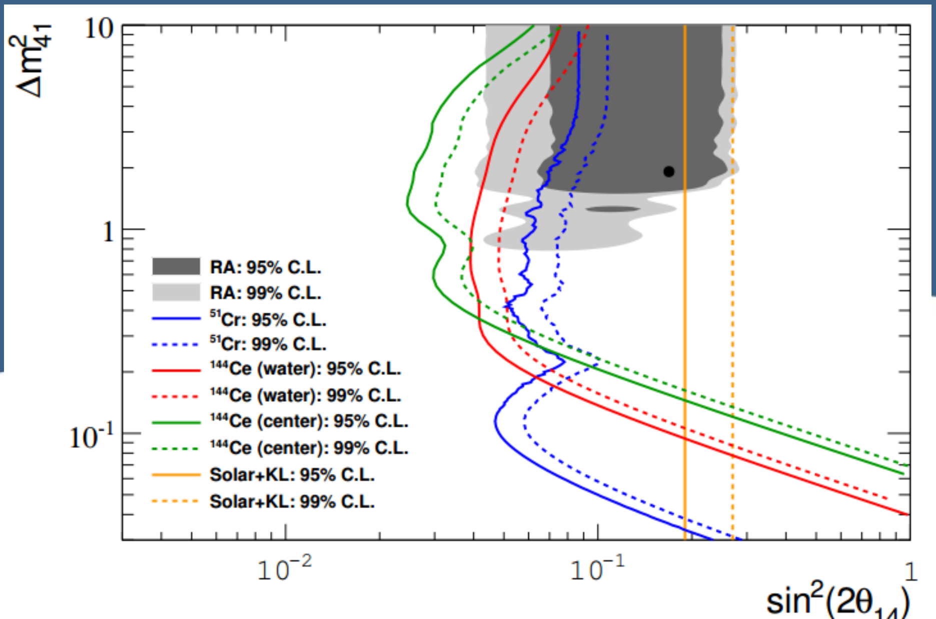
^{144}Ce at Daya Bay

D.A. Dwyer et al.,PHYSICAL REVIEW D 87, 093002 (2013)



^{144}Ce, ^{51}Cr SOX at Borexino

G. Bellini et al., JHEP08(2013)038



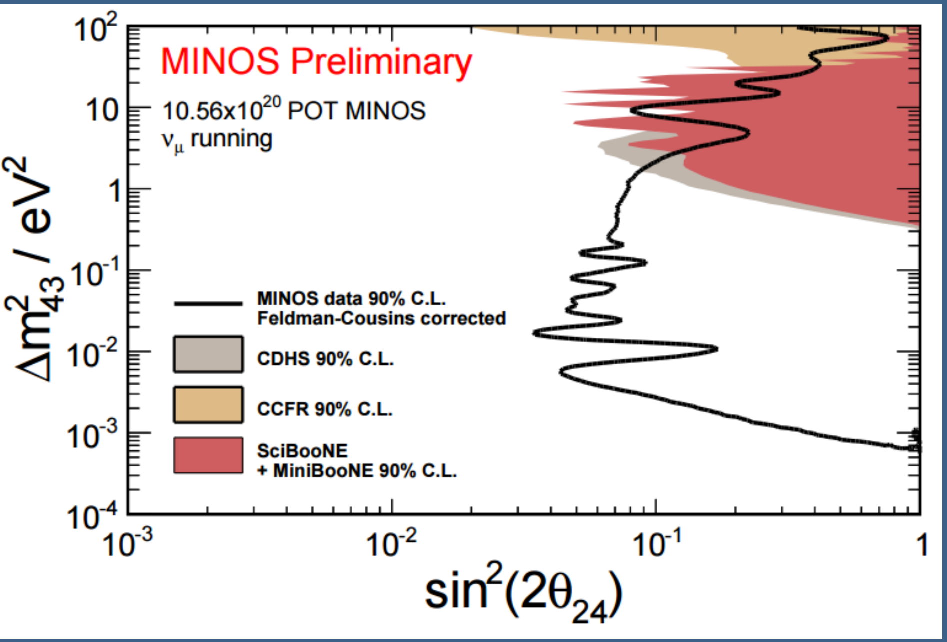
Short Baseline Accelerator

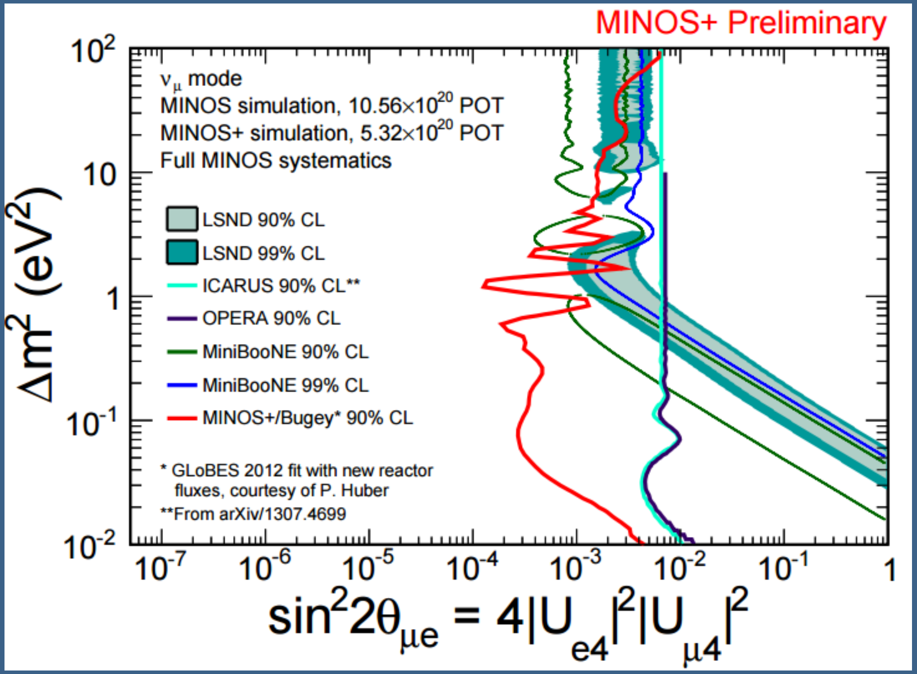
- First ν anomalies appear in short baseline $\overline{\nu_\mu}$ (ν_μ) beam experiments:
  - 2001 LSND Collab.: Evidence for neutrino oscillations from the observation of $\overline{\nu_e}$appearance in a $\overline{\nu_\mu}$ beam, Phys. Rev. D64, 112007 (2001).
    $P(\overline{\nu_\mu} \to \overline{\nu_e})$=(0.264±0.067±0.045)%
    implying $|\Delta m_4|^2 > 0.1eV^2$
  - 2002 KARMEN Collab.: Upper limits for neutrino oscillations $\overline{\nu_\mu} \to \overline{\nu_e}$ from muon decay at rest, Phys. Rev. D65, 112001 (2002)
    Exclude large part (but not all) of parameter space favored by LSND

Short Baseline Accelerator

- First ν anomalies appear in short baseline $\overline{\nu_\mu}$ (ν_μ) beam experiments:
  - MINIBOONE: Initially no conformation (2007), but more data and re-analysis show excess both in $\overline{\nu_\mu} \rightarrow \bar{\nu}_e$ and $\nu_\mu \rightarrow \nu_e$ modes Improved Search for $\overline{\nu_\mu} \rightarrow \bar{\nu}_e$ Oscillations in the MiniBooNE Experiment, PRL 110, 161801 (2013)
  - MINOS (2005-2012): Long baseline with near (1km) and far (735 km) station, high energy ν_μ and $\overline{\nu_\mu}$ beam: no evidence of distorted ν energy spectrum, using CC+NC events: exclude most of the favored region by LSND+MINIBOONE for $|\Delta m_4|^2 < 1eV^2$
- Overall severe tension between signals in appearance and disappearance data
- Large mixing $sin^2\theta_{\mu e4} > 10^{-3}$ excluded for $|\Delta m_4|^2 < 1eV^2$

Update from MINOS





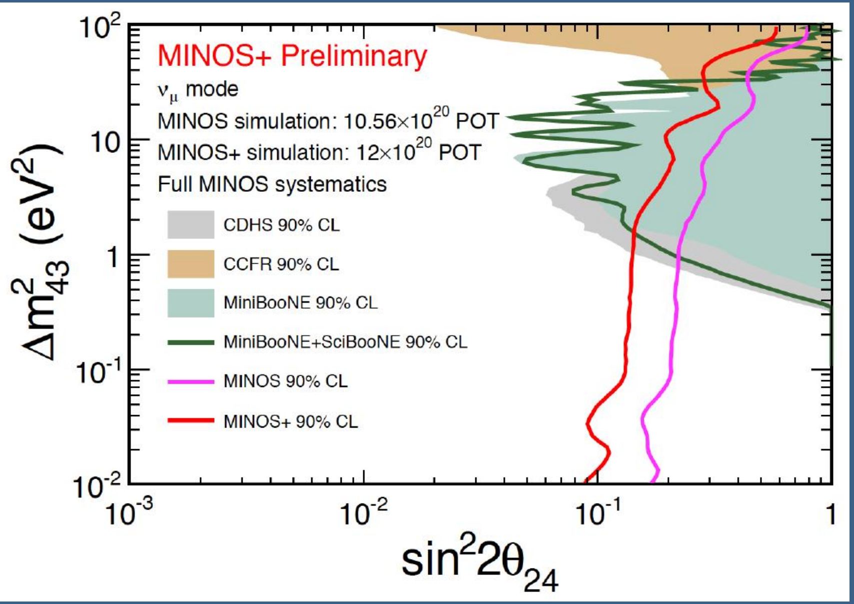
2014 ν_μ dissappearance limits, presented by A. Sousa, neutrino 2014, Boston
arXiv:1502.07715 [hep-ex]

Follow-up experiments

- MINOS+: same Near+far detectors
- Extended beam intensity&energy, since 2013

Expected limits by 2016

Improve mixing angle sensitivity with factor 2



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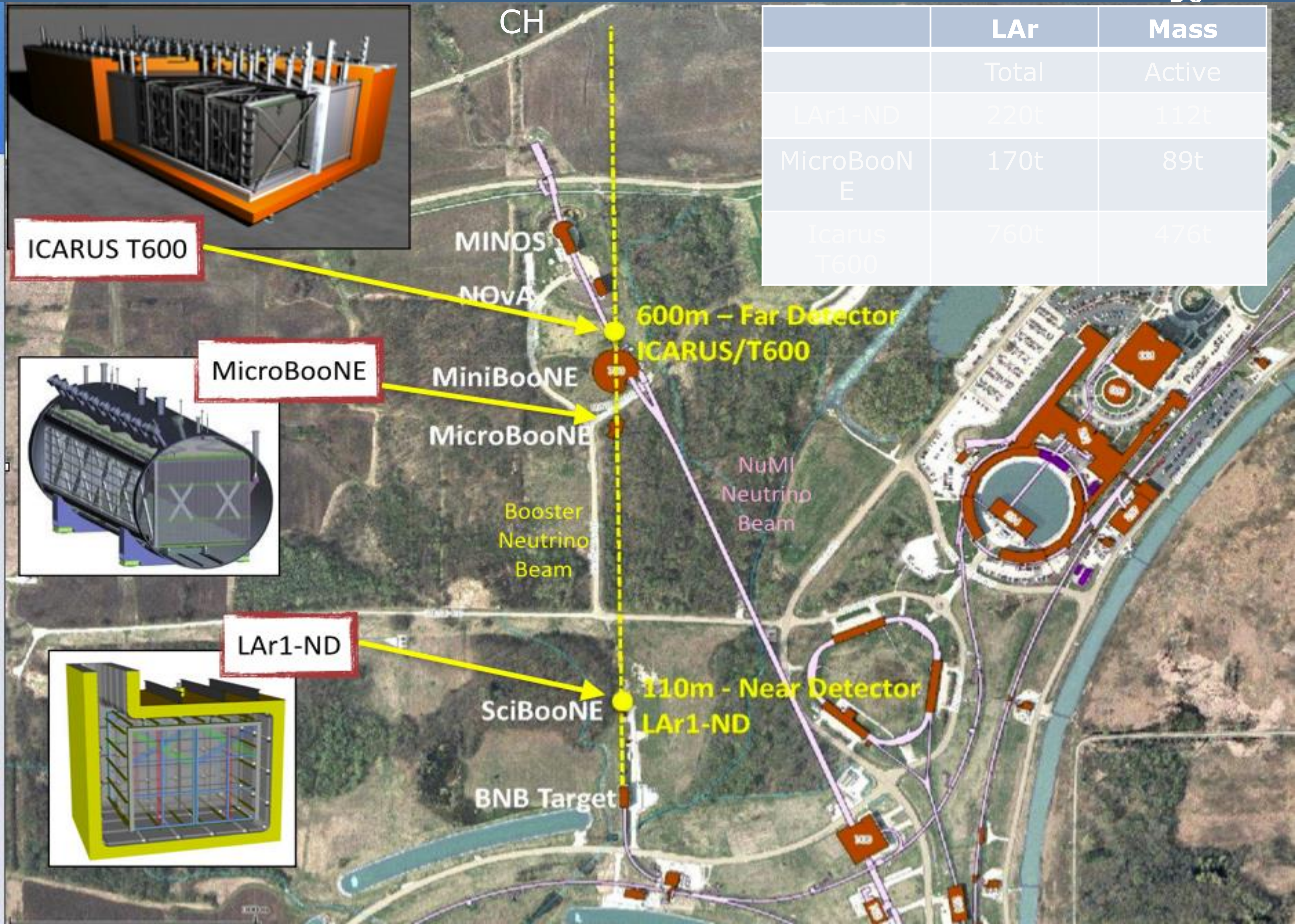
	LAr	Mass
	Total	Active
LAr1-ND	220t	112t
MicroBooNE	170t	89t
Icarus T600	760t	476t



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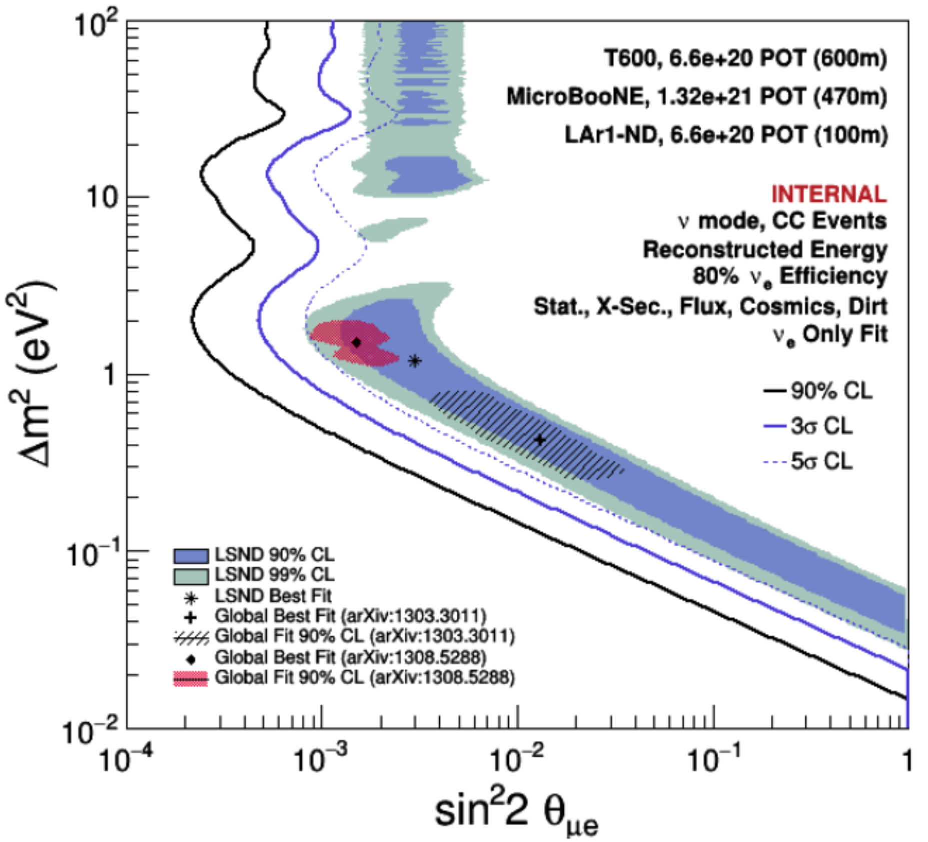
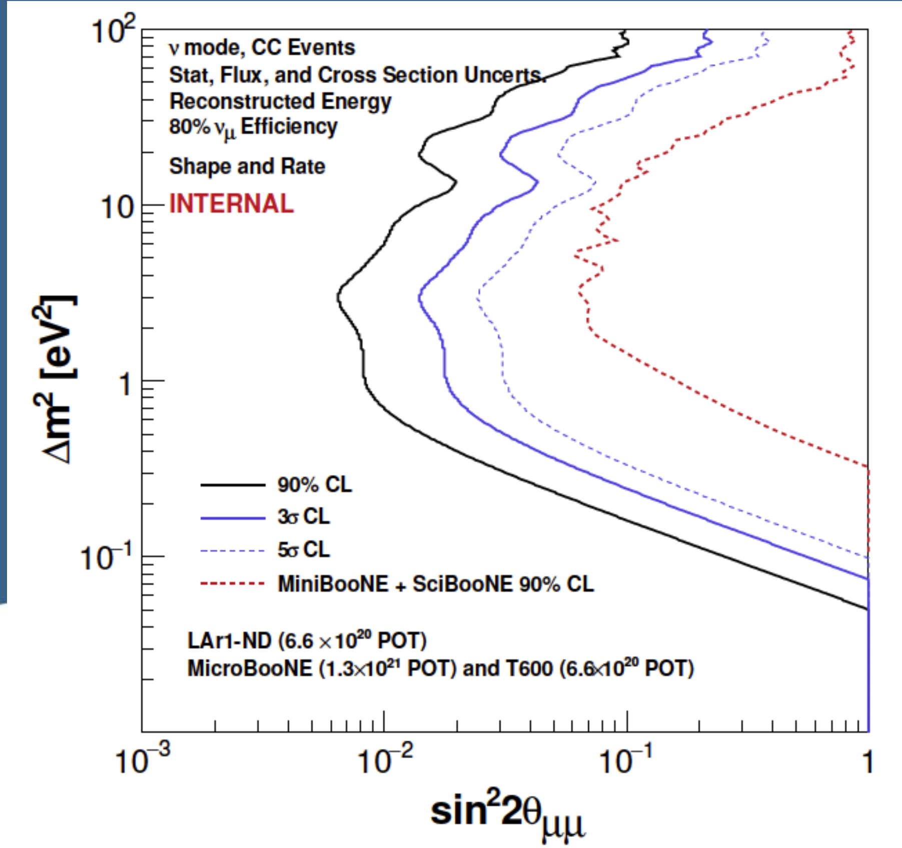
Oscillation Physics

ν_μ to ν_e oscillation
ν_e Appearance

ν_μ to ν_x oscillation
ν_μ Disappearance





nuSTORM

- nuSTORM: proposal for a ν factory via stored μ beam, arXiv:1308.6822v1, arXiv:1402.5250v1