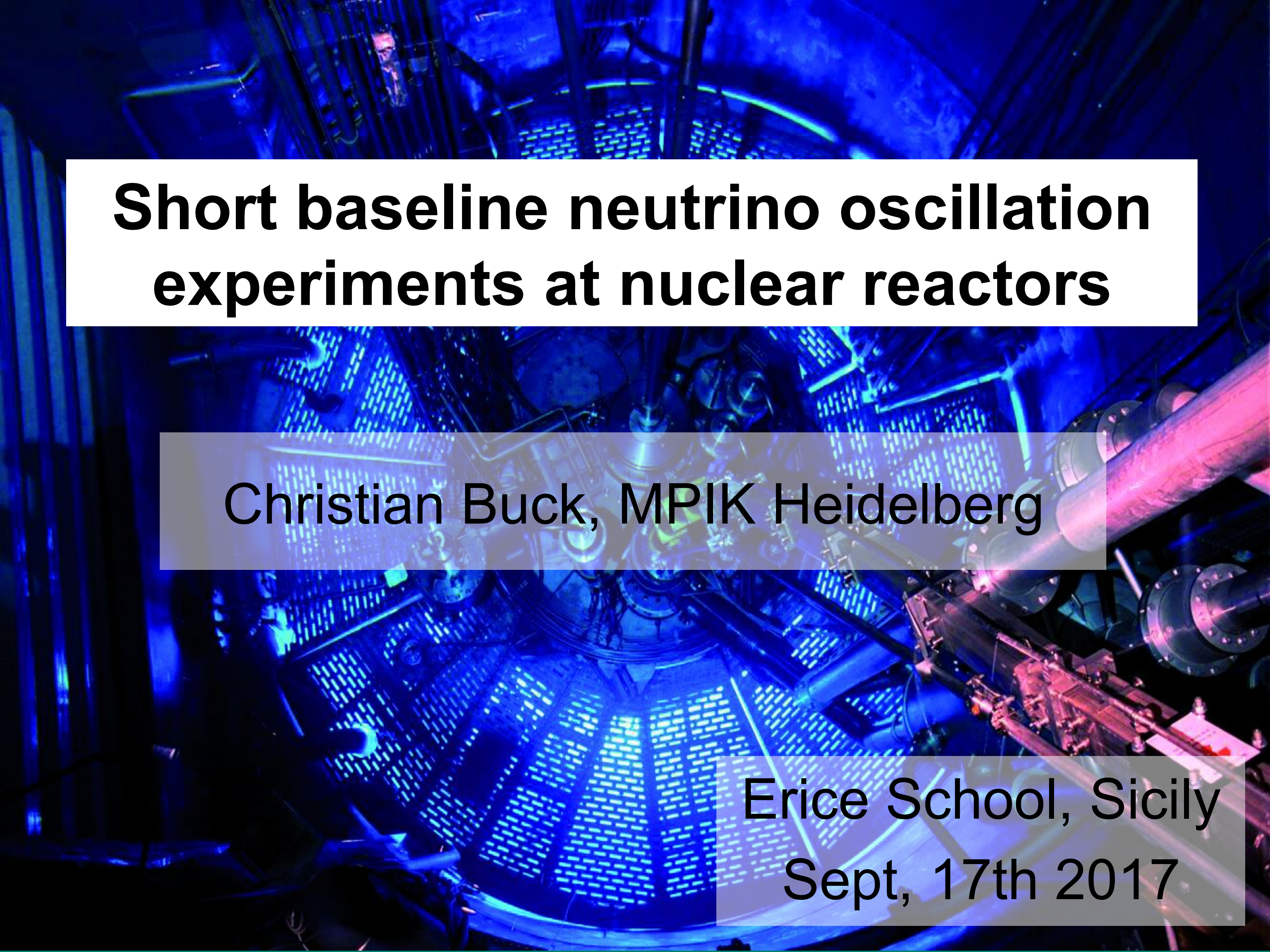


Short baseline neutrino oscillation experiments at nuclear reactors

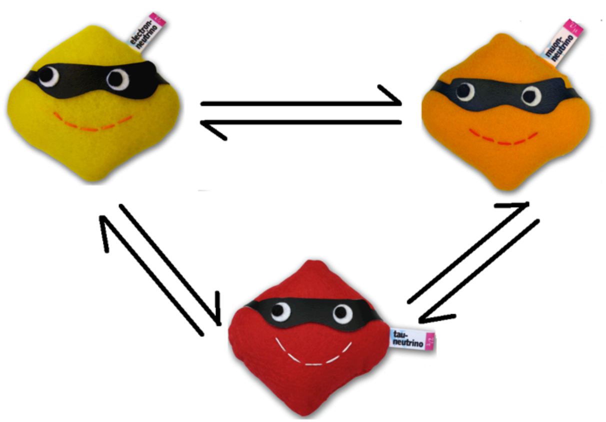
Christian Buck, MPIK Heidelberg

Erice School, Sicily
Sept, 17th 2017

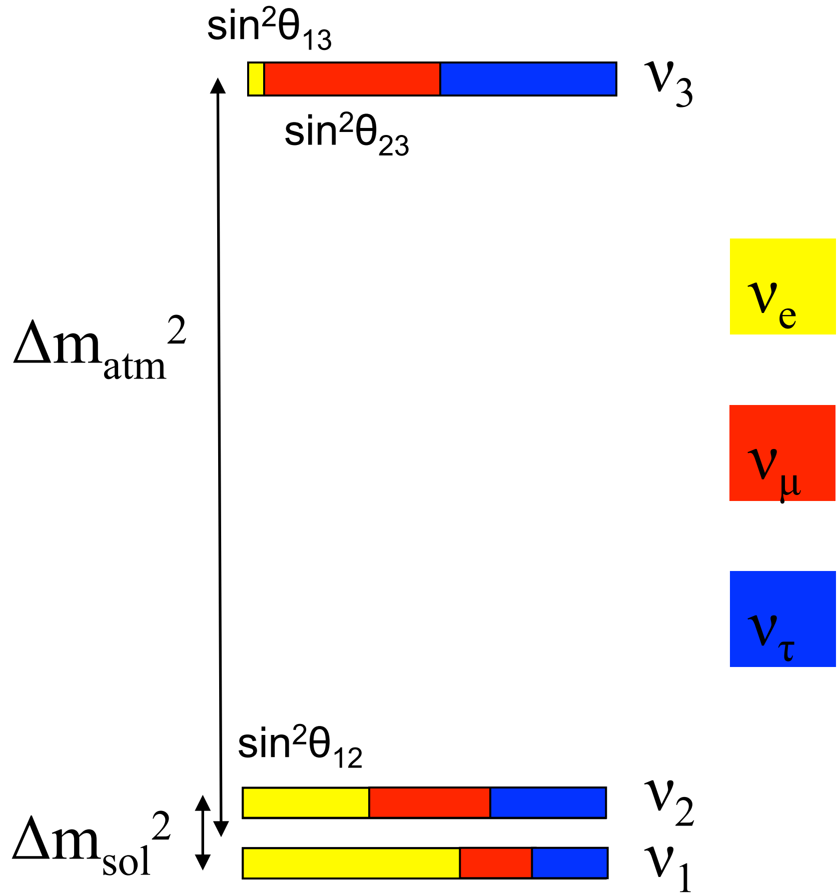
Neutrino oscillations

PMNS matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

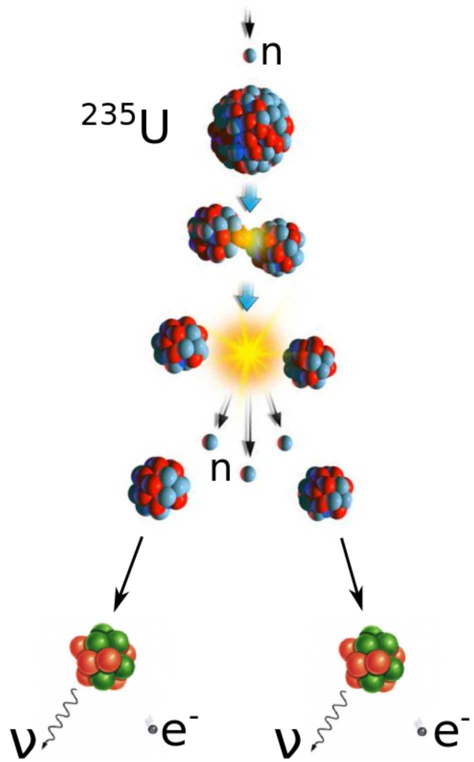


$\Delta m_{atm}^2 \sim 2.5 \cdot 10^{-3}$ eV^2, $\sin^2(2\theta_{23}) \sim 1$
$\Delta m_{sol}^2 \sim 7.5 \cdot 10^{-5}$ eV^2, $\sin^2(2\theta_{12}) \sim 0.85$
$\sin^2(2\theta_{13}) \sim 0.1$



Normal or inverted hierarchy?
Absolute scale?

Reactor neutrinos



Thermal power

$$N_\nu^{\exp}(E,t) \propto \frac{1}{L^2} \times \frac{P_{th}(t)}{\langle E_f \rangle} \times \langle \sigma_f \rangle$$

distance

Energy per fission

Cross section per fission

Fractional fission rate of isotope k

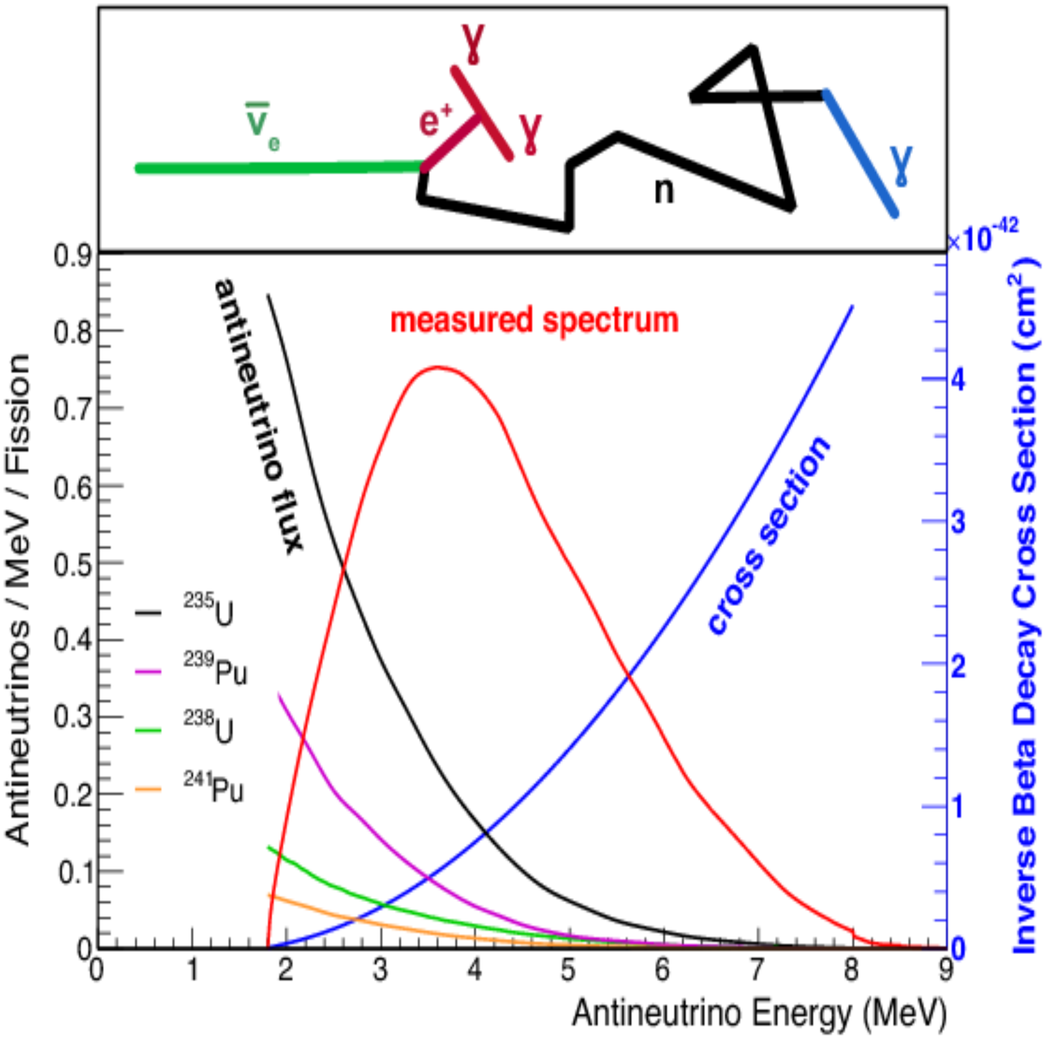
$$\langle \sigma_f \rangle = \sum_k \alpha_k \int_0^\infty S_k(E) \times \sigma_{\det}(E)\, dE$$

ν spectrum

Detection cross section

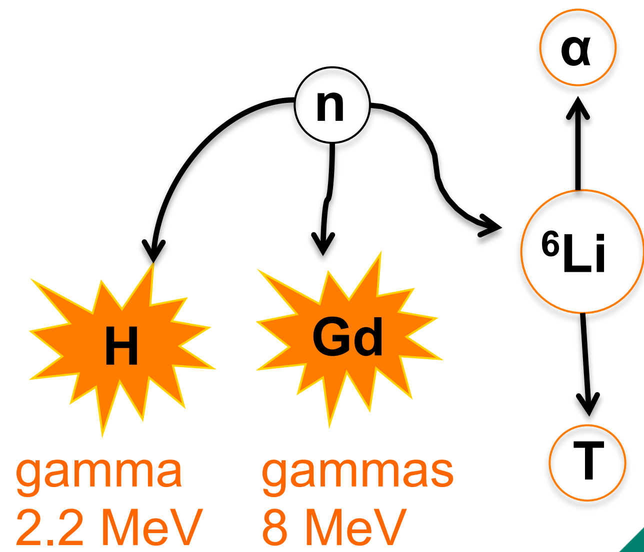
- Pure $\overline{\nu}_e$ source (6 / fission)
- High rate: 10^{20} ν / (GW s)
- Energy: 1-10 MeV

IBD reaction

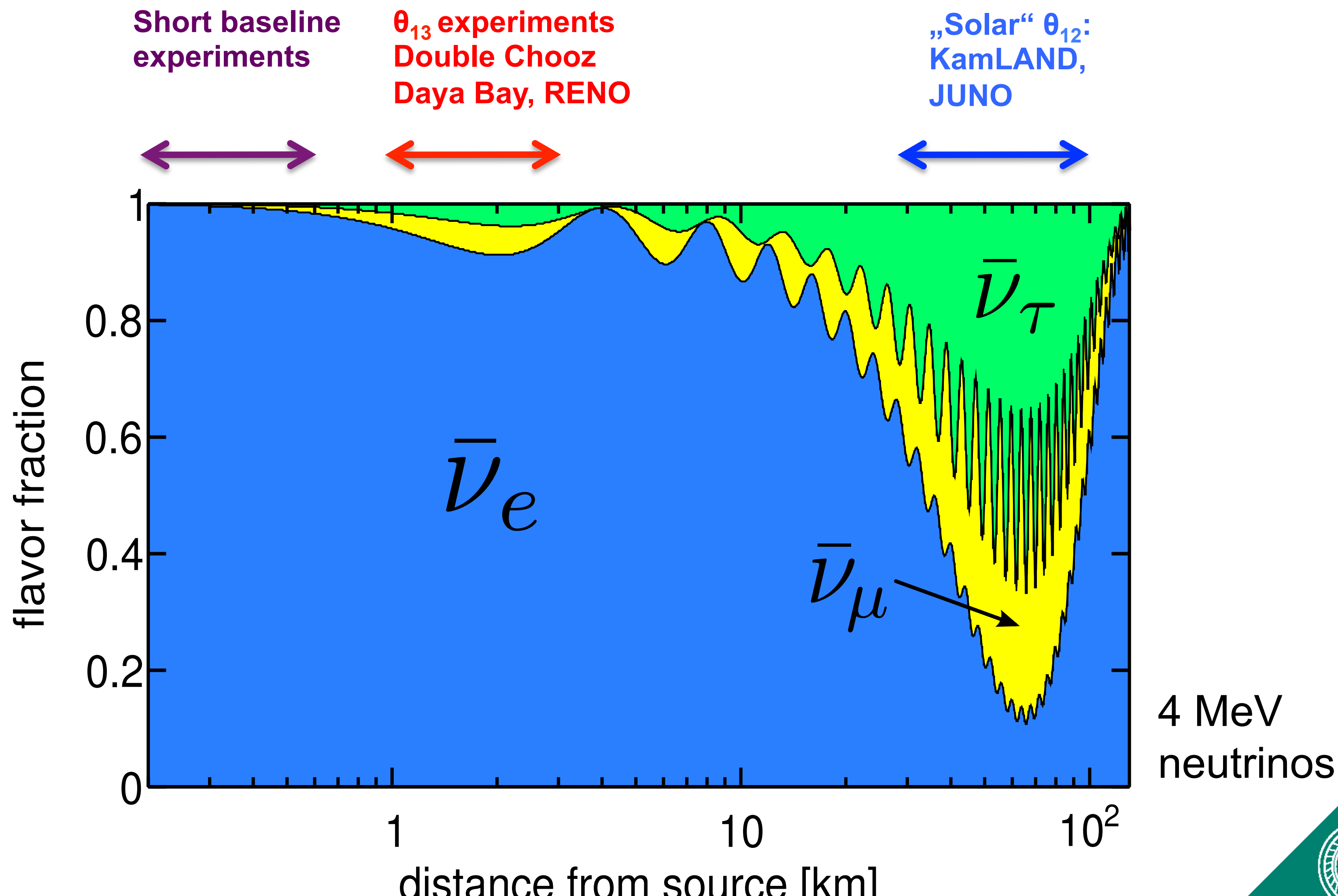


$$\bar{\nu}_e + p \rightarrow e^+ + n$$

E_{th} = 1.8 MeV
$E_{vis} = E_\nu$ – 0.8 MeV

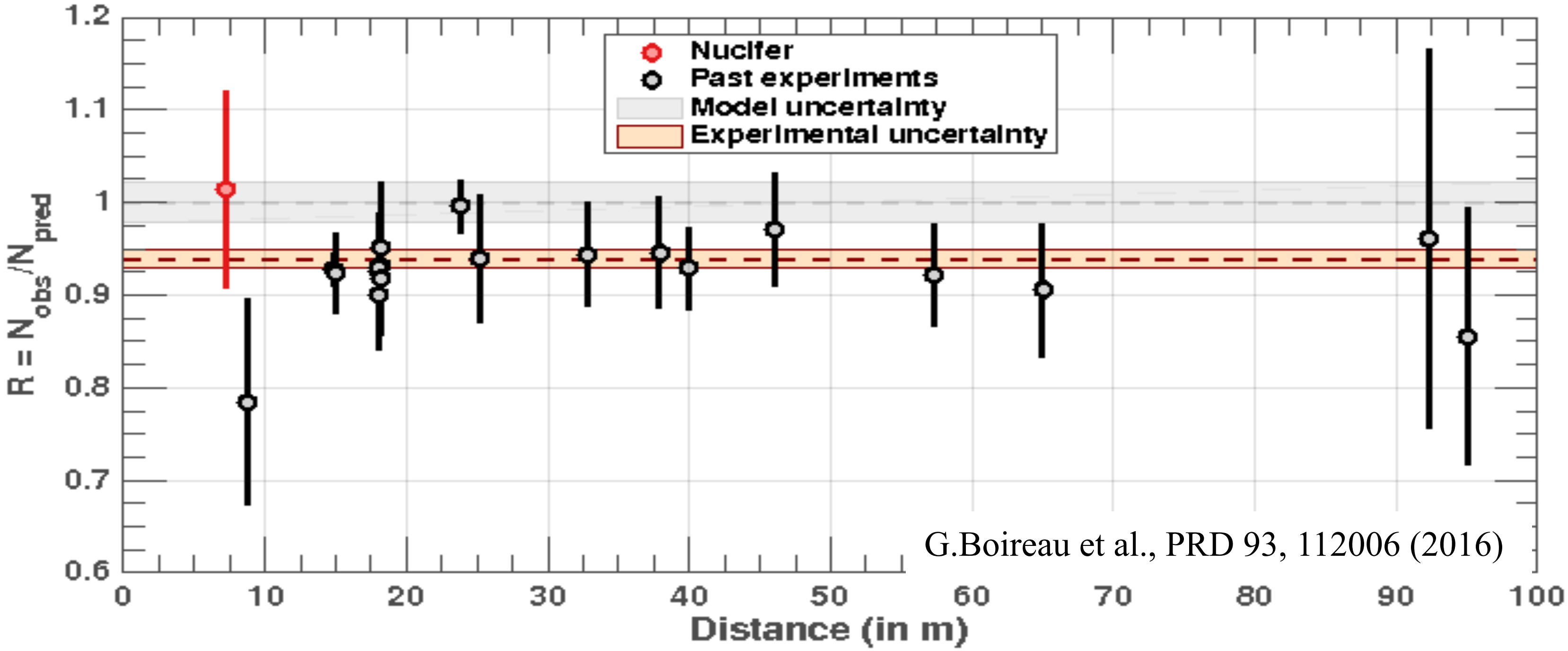


Oscillation at reactors



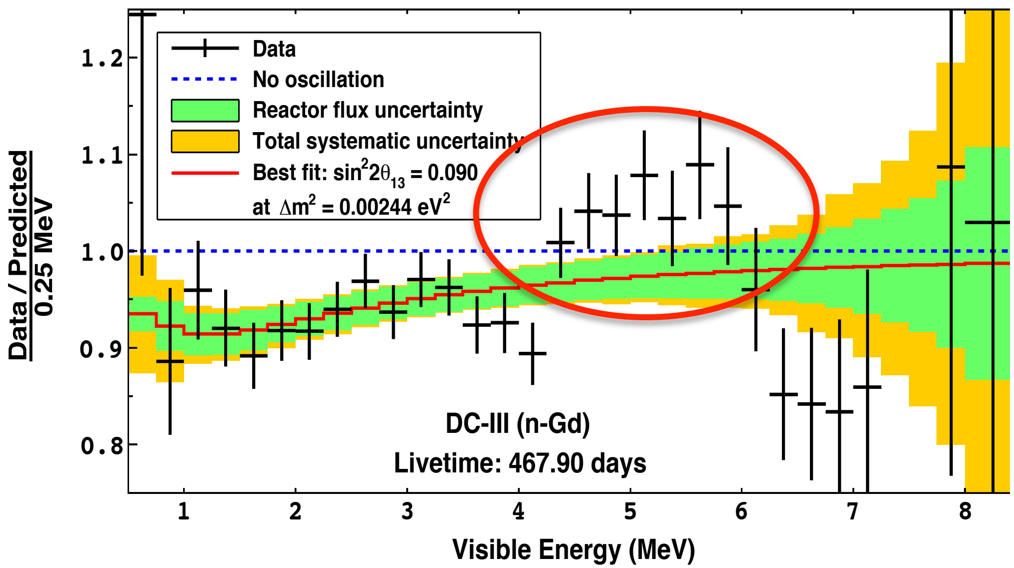
Reactor neutrino anomaly

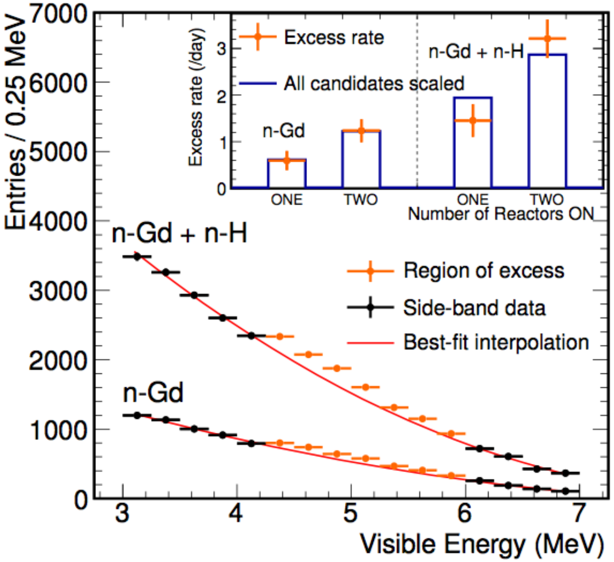
- New flux prediction in context of θ_{13} experiments
- Updates on conversion from measured beta spectra at ILL (Müller et al., Huber)



R = 0.940 ± 0.024 (2.5σ deviation from unity)

Spectral distortion

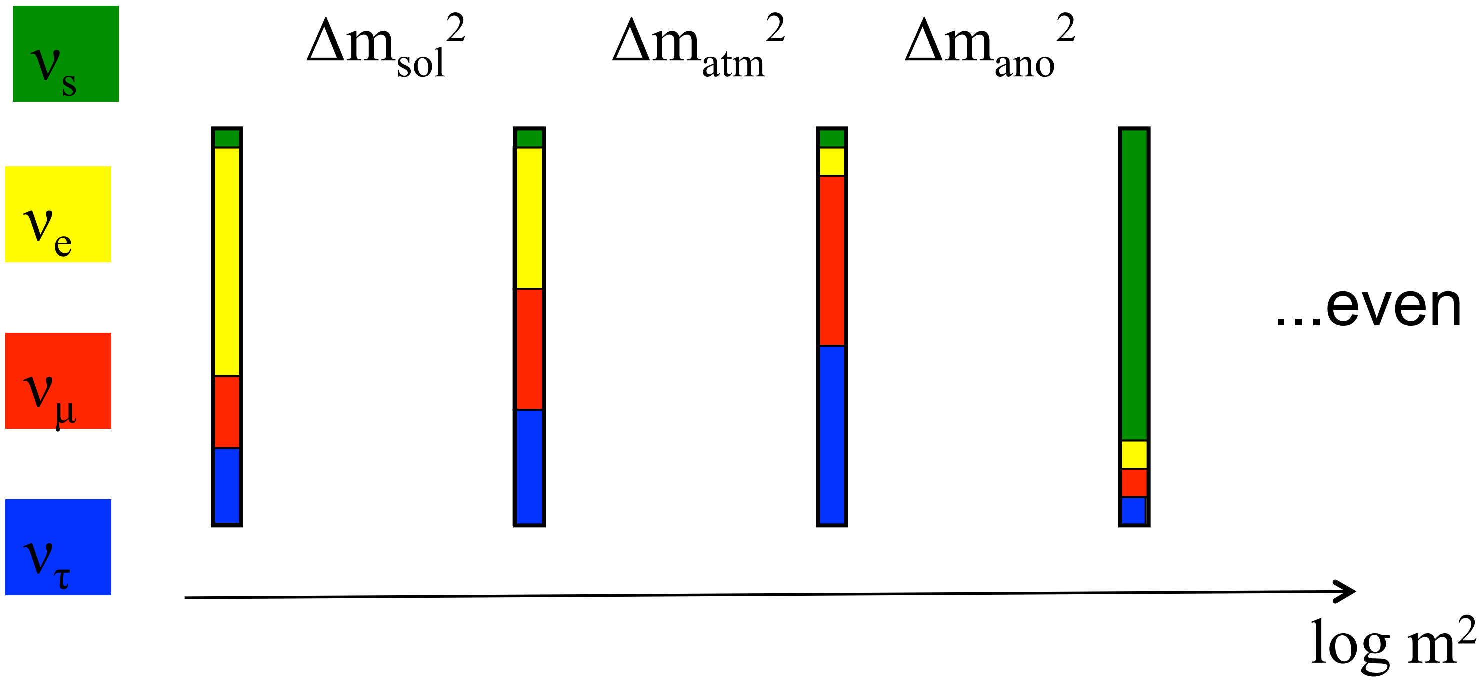




Y.Abe et al., JHEP10 (2014)

- Excess events in 4 – 6 MeV region
- Similar behavior seen in Daya Bay, RENO and NEOS
- Background and energy scale disfavored
- Neutrino prediction?!

Nuclear or neutrino physics?

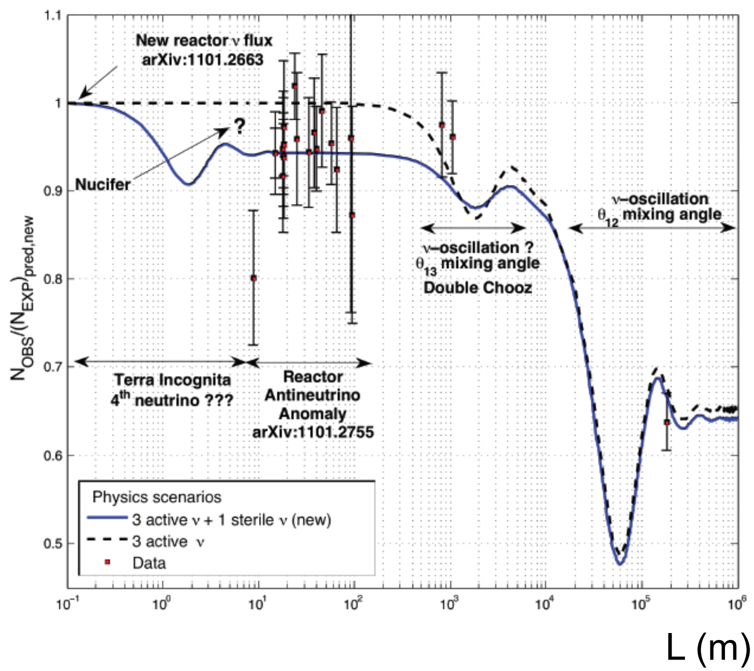


...even more?

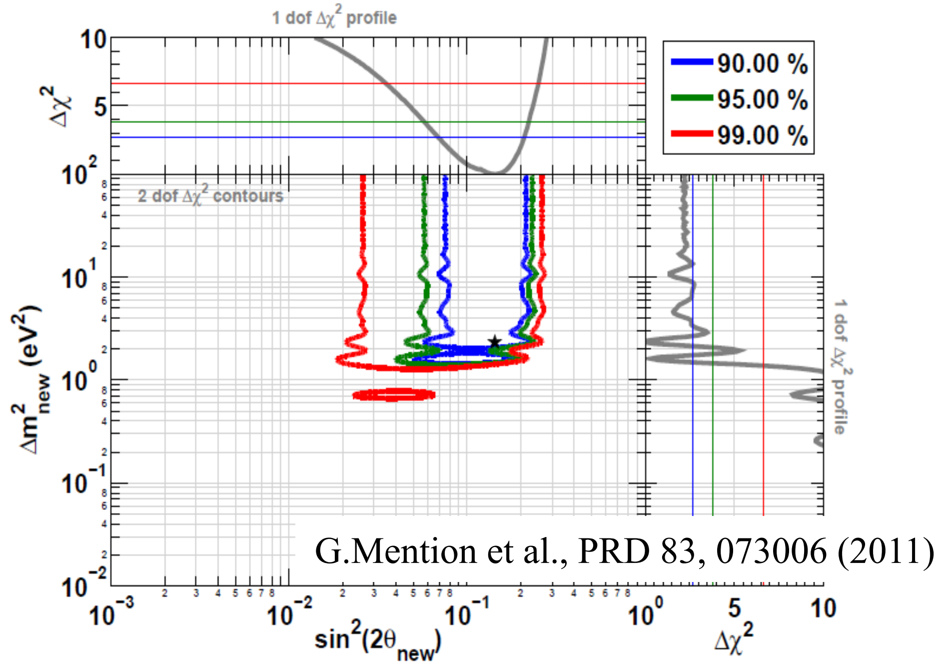
Sterile neutrino could explain rate anomaly, not spectral distortion

Sterile neutrino solution

$\Delta m^2 \approx 1$ eV^2, $\sin^2(2\theta) \approx 0.1$



Data and expectation with (blue) and without (black dashed) sterile neutrino



Allowed region from combination of reactor, Ga source, MiniBooNE

Oscillation length: $L \propto \frac{E}{\Delta m^2}$

End of sterile neutrino option?

Daya Bay, PRL118, 251801 (2017):

- Rate vs fuel evolution
- Combined fit for ^{235}U and ^{239}Pu
- ^{239}Pu consistent with model
- ^{235}U almost 8% lower
- Disfavor equal deficit at 2.6σ

Hayes et al. (arXiv 1707.07728)

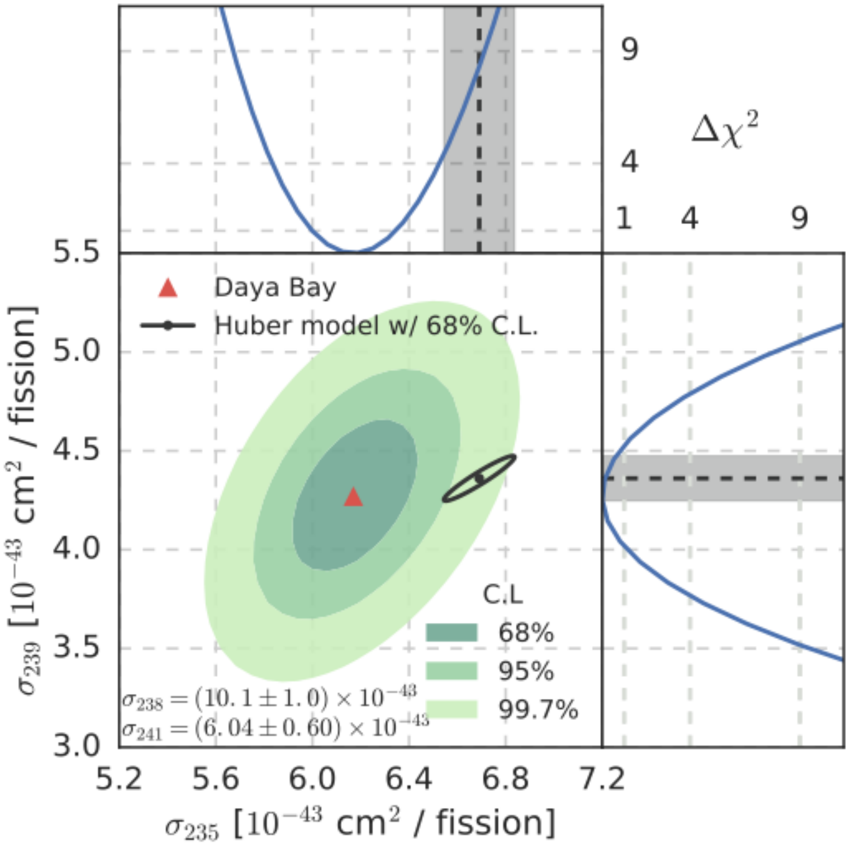
"…conclude that there is currently not enough information…to rule out … sterile neutrinos."

Giunti et al. (arXiv 1708.01133)

Combined analysis of DB evolution data and global rate data favors oscillation over ^{235}U/^{239}Pu

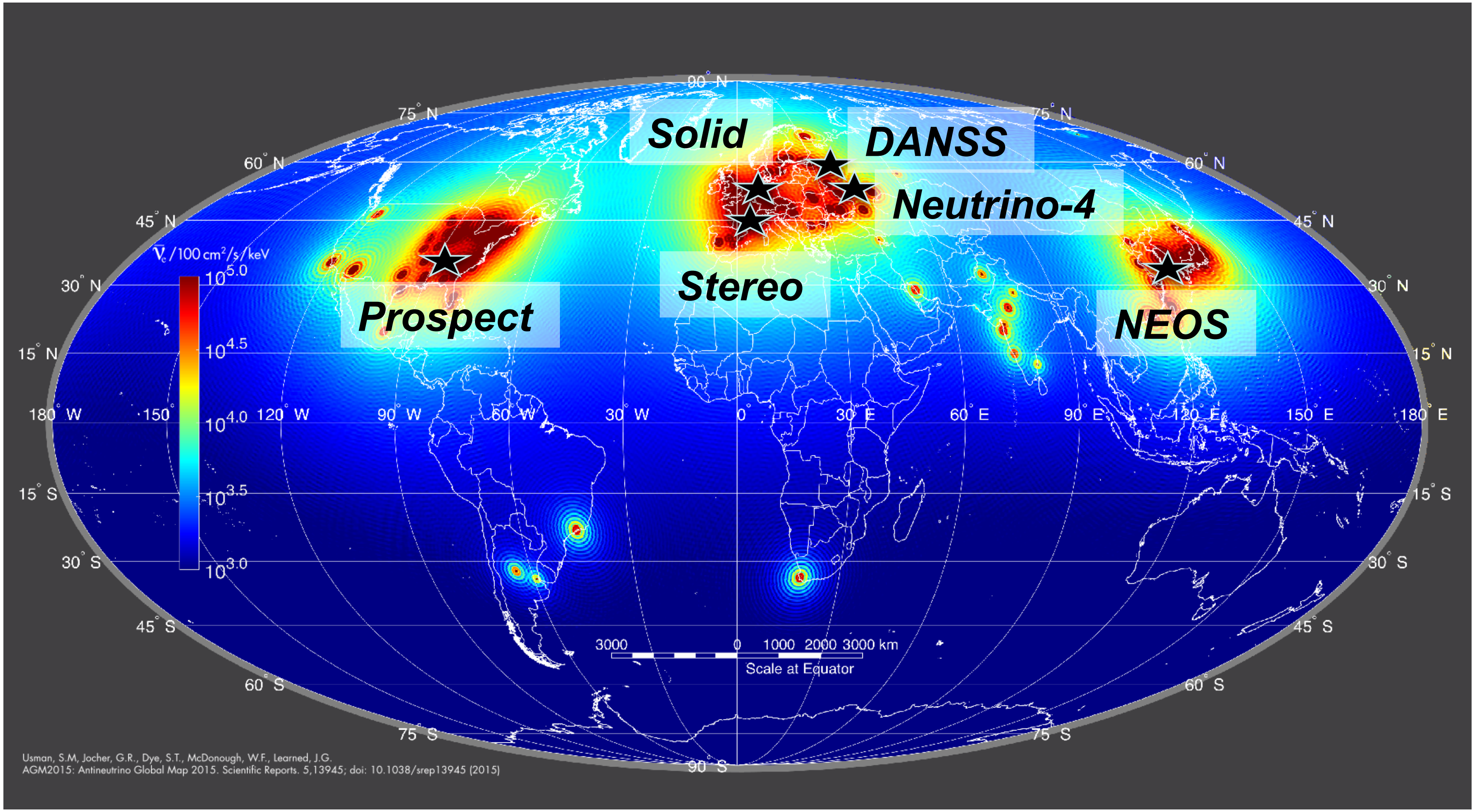
Dentler et al. (arXiv 1709.0429)

„…sterile neutrino hypothesis cannot be rejected based on global data…"



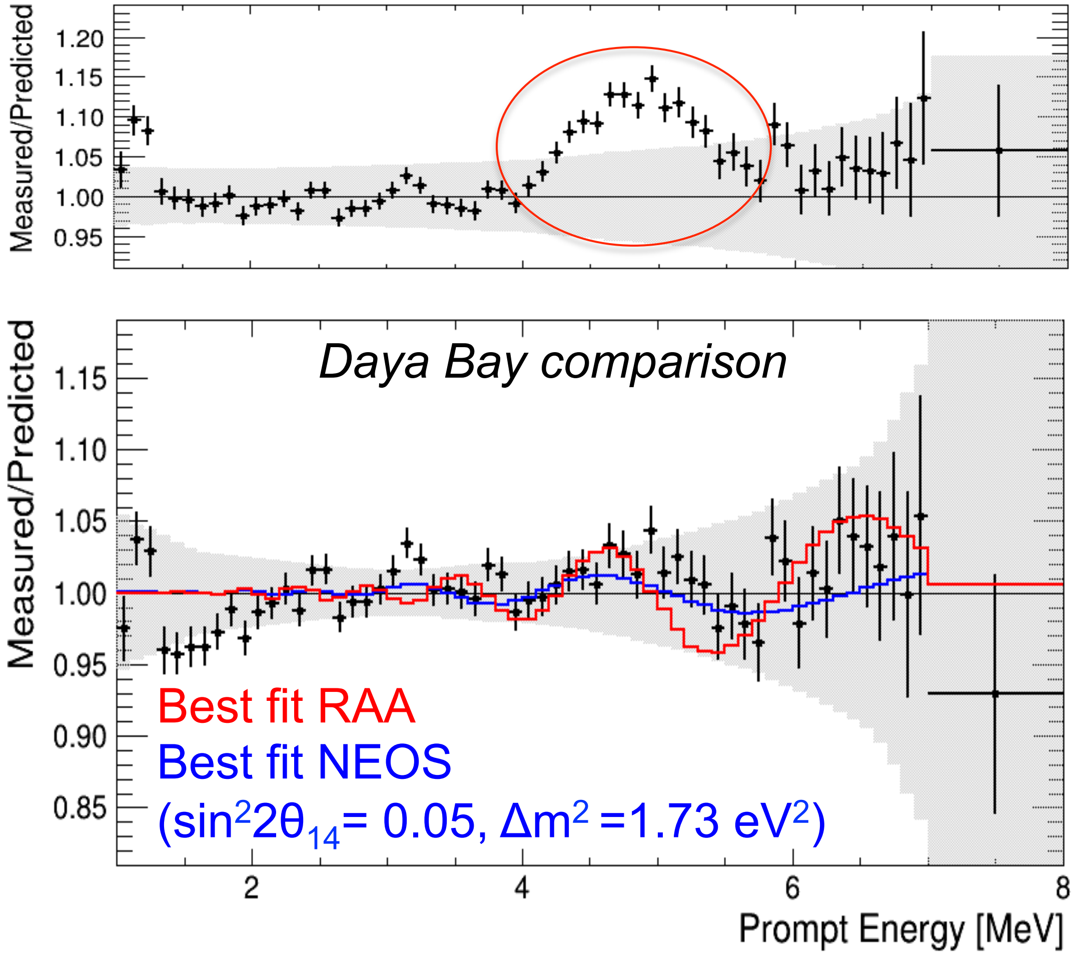
Normalization of flux predictions fully correlated?

Reactor experiments worldwide

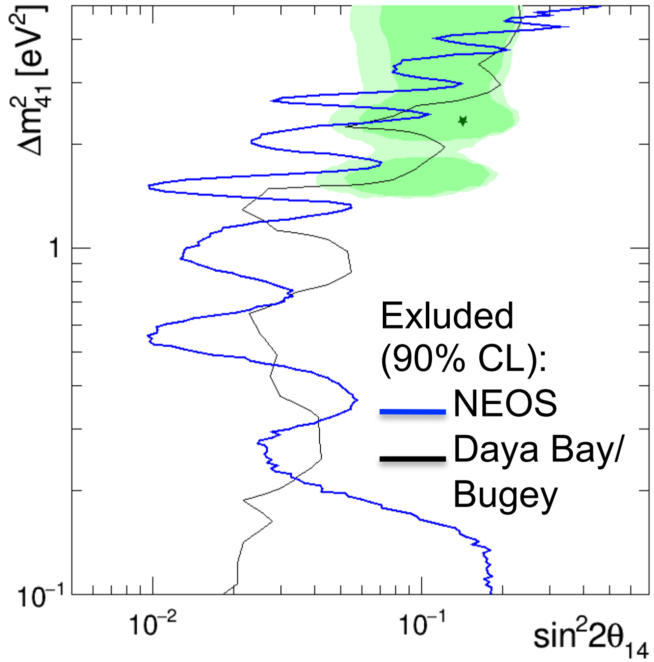


Antineutrino Global Map 2015, Sci.Rep.5 (2015) 13945

NEOS



- LEU reactor, d=25 m
- Unsegmented, 1t Gd-LS
- Running 2015/2016
- 2000 neutrinos/day

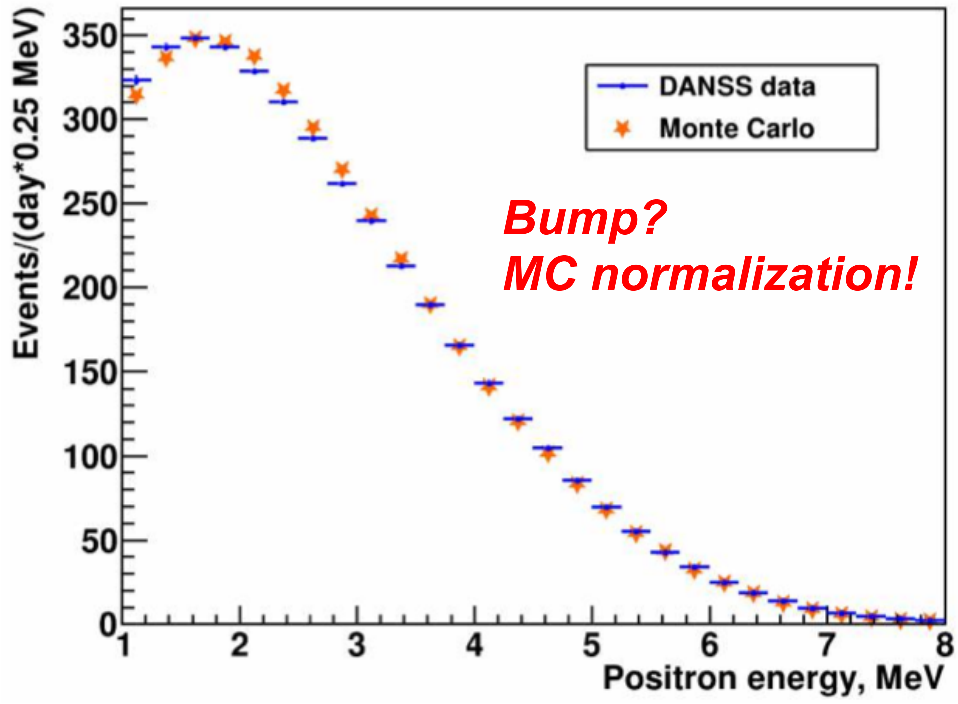


Y.Ko, AAP 2016

Details on Thursday by Y.Oh !

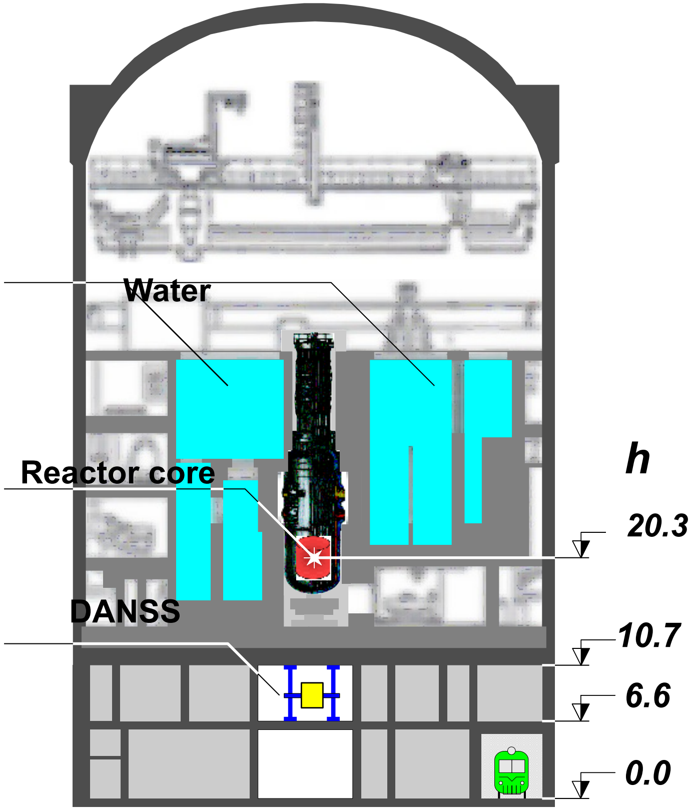
DANSS

- 3 GW LEU reactor (h = 3.5 m)
- 10.7 – 12.7 m baseline (moveable)
- 1 m^3 plastic scintillator strips (2500!) covered by Gd („safe detector design“)
- Low background site (cosmics: 5%)



Bump?
MC normalization!

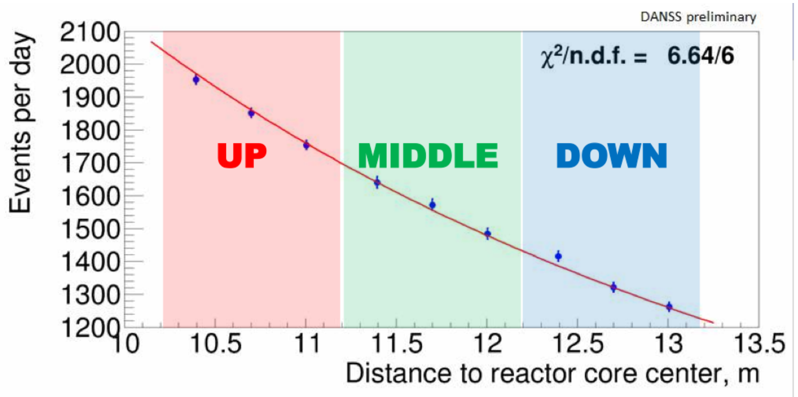
Overburden: 50 mw.e.

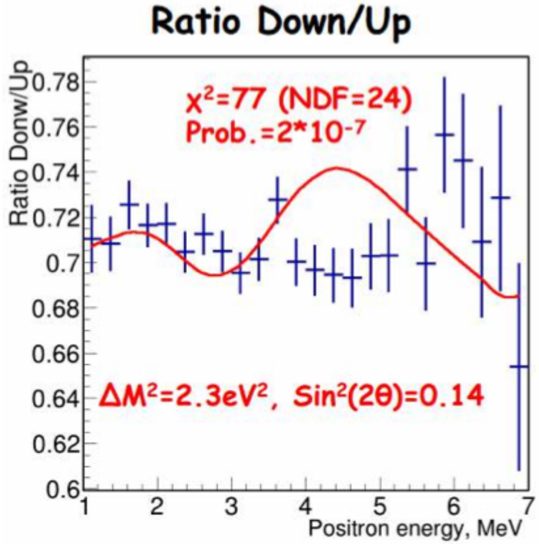


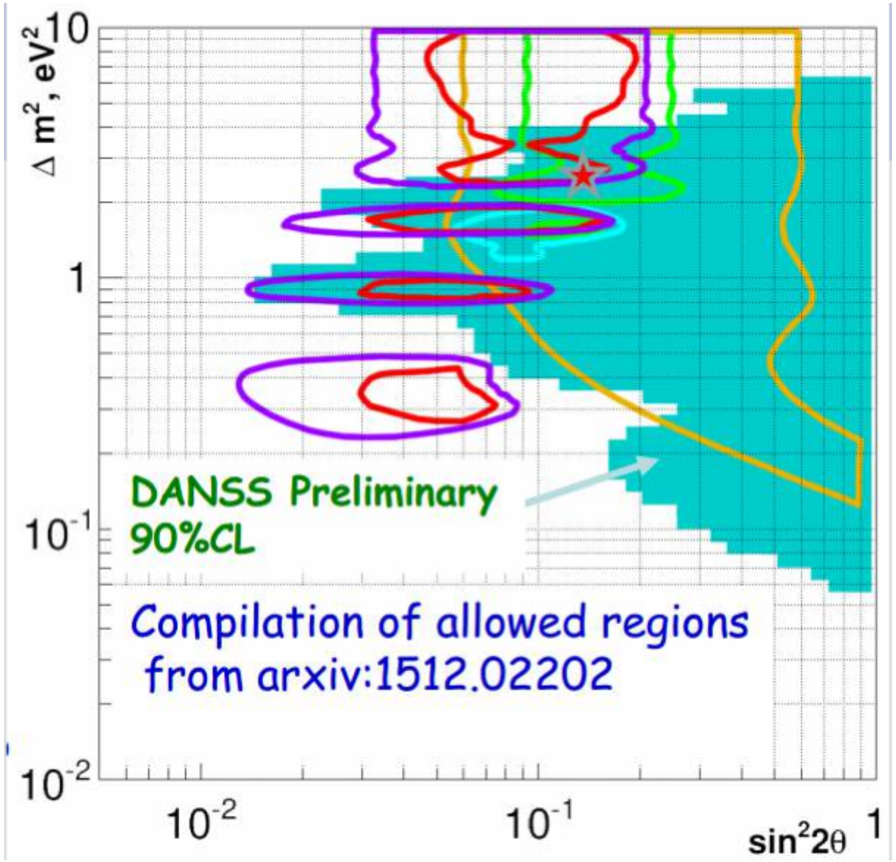
I.Alekseev et al., JINST 11 (2016) P11011

DANSS premilinary results

About 5000 neutrino events/day (data taking since April 2016)



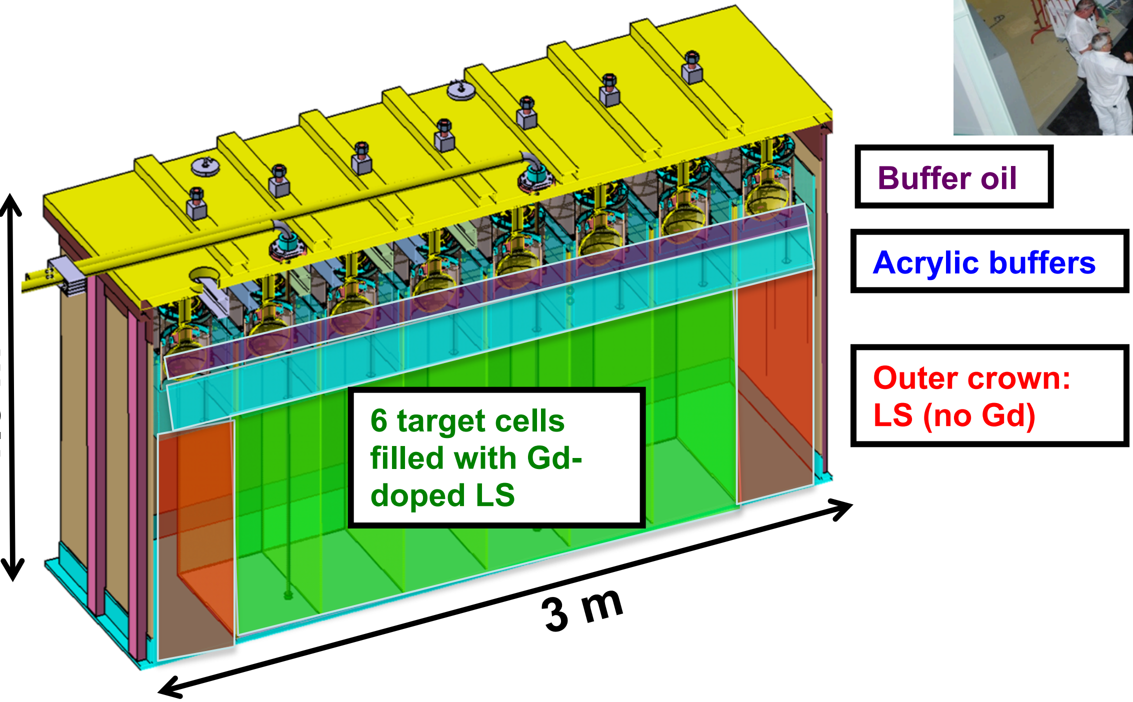


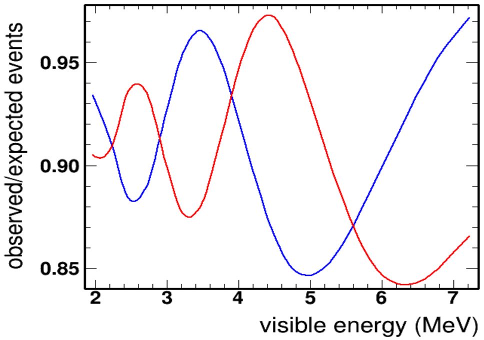


Y.Shitov, TAUP 2017

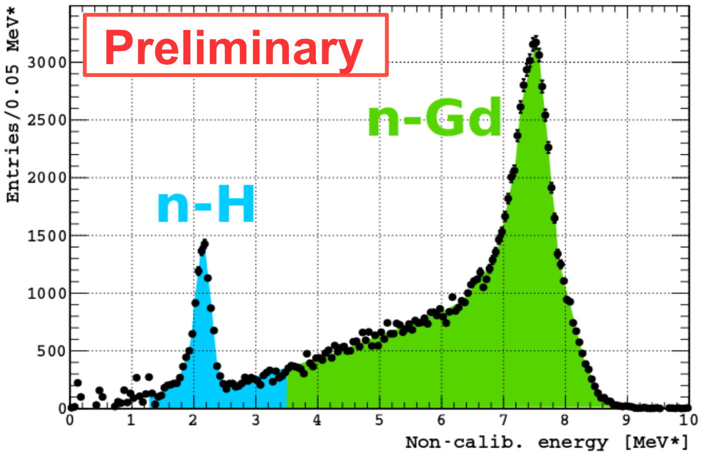
Stereo

- ILL Grenoble: 57.8 MW HEU reactor
- 10 m baseline
- Gd liquid scintillator (1800 liters)
- Segmentation (6 Target cells)



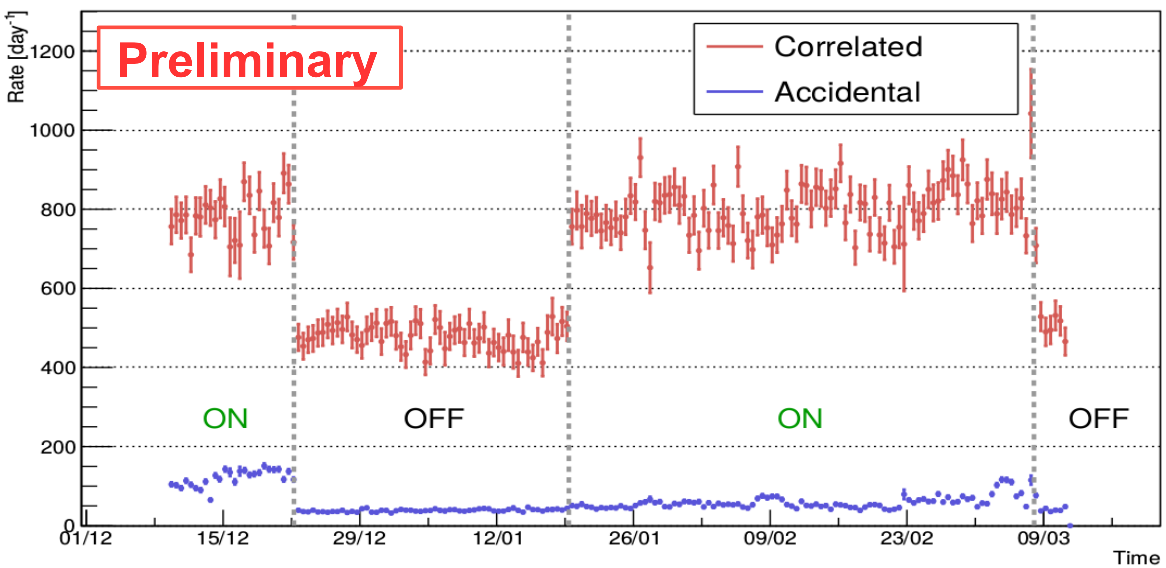


Stereo analysis

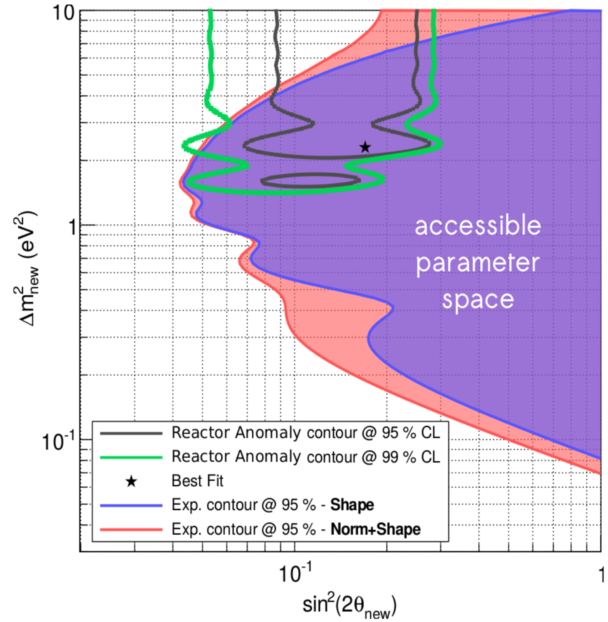


Delayed E target cell

Rate neutrino candidates



Sensitivity with 300 days



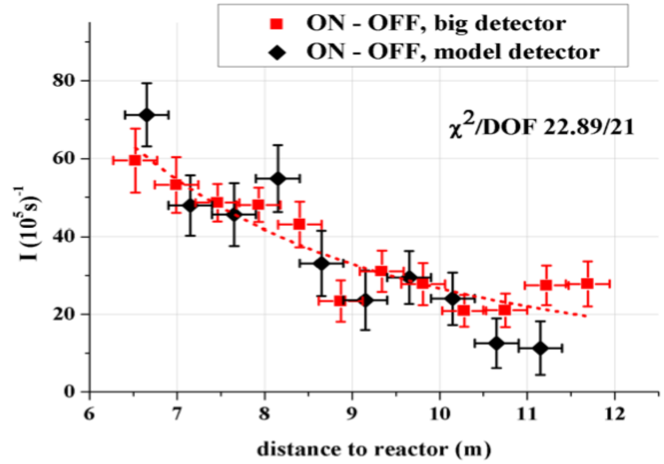
- 75 days reactor ON
- ~ 300 neutrinos/ day

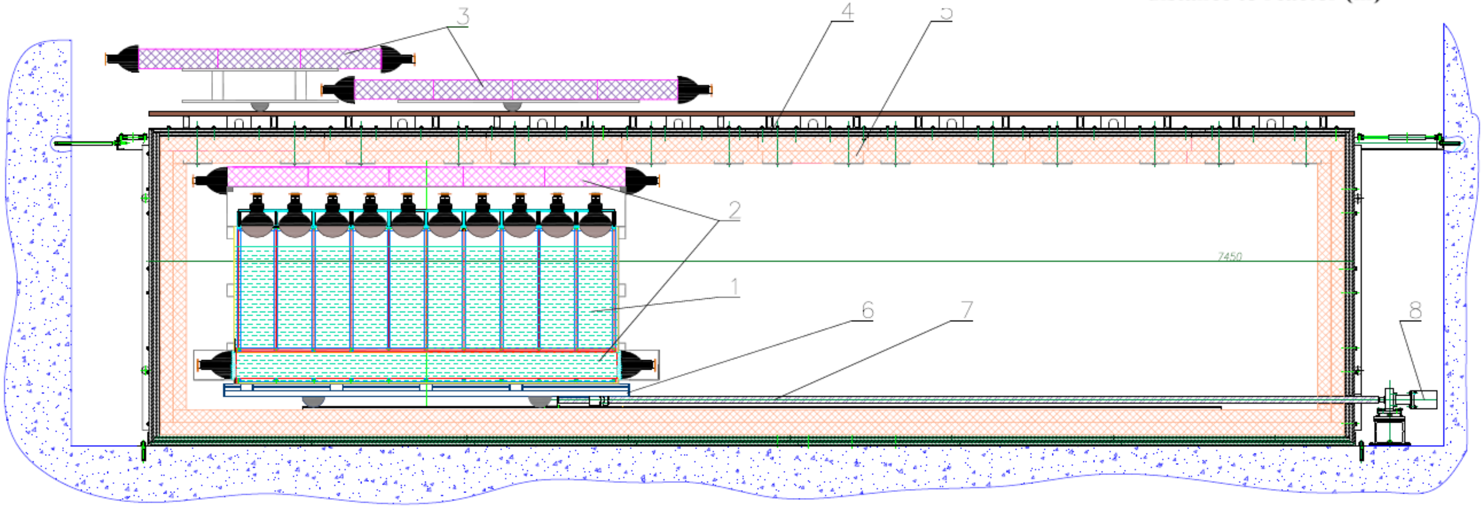
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Neutrino-4

- 90 MW reactor ($35x42x42cm^3$)
- Gd liquid scintillator ($3\ m^3$)
- 6-12 m baseline (moveable!)
- Cosmic background! (S/B ≈ 0.25)
- Full scale data since June 2016

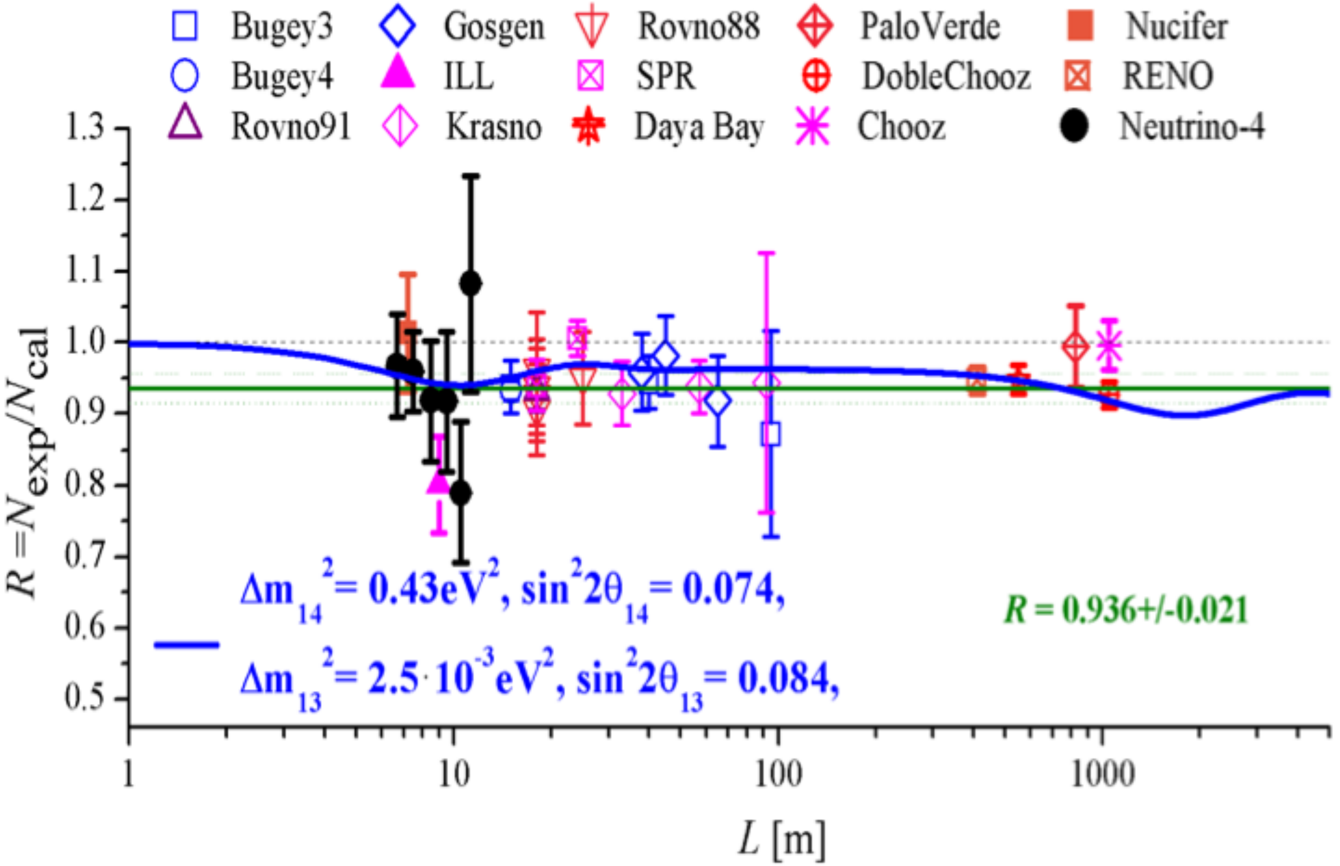
Check of $1/L^2$ behaviour





*A.P.Serebrov et al. arXiv:*1702.00941 *(2017)*

Neutrino-4: first results

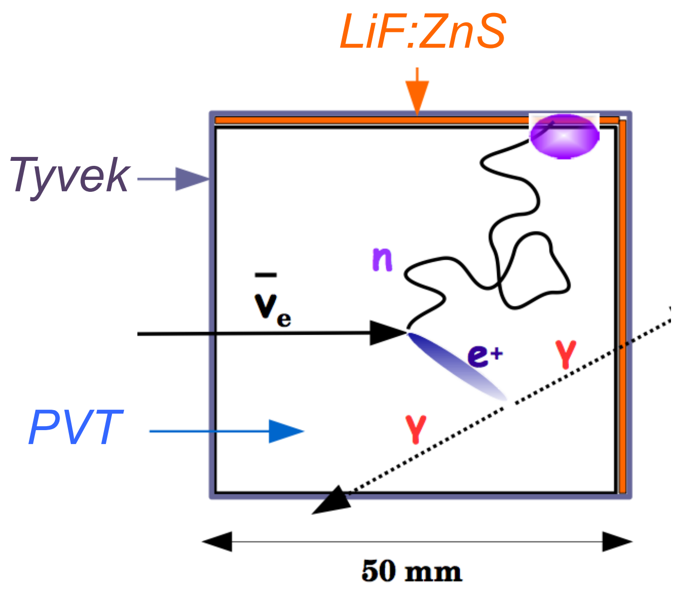


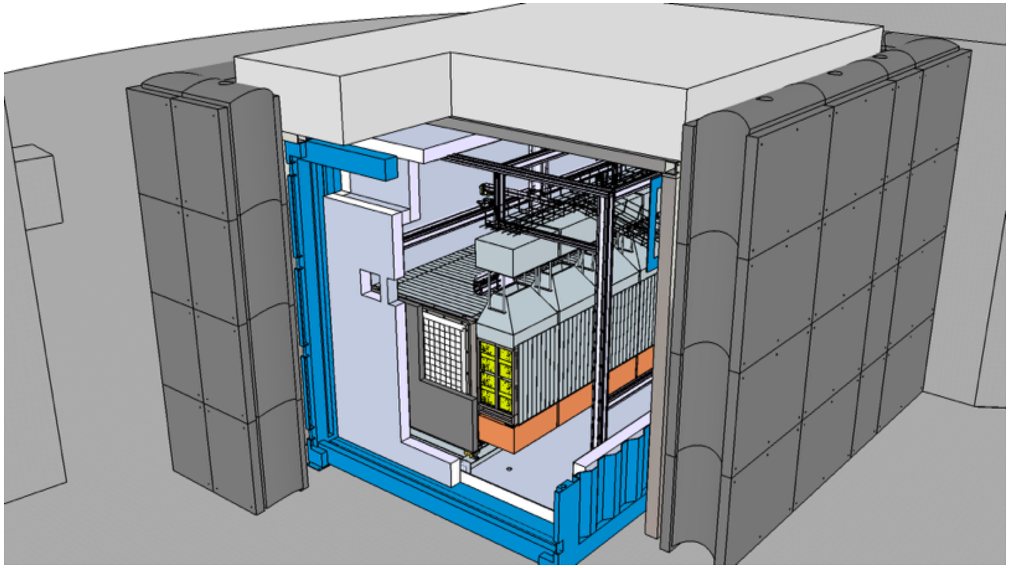
Neutrino-4 data normalized to 0.936 (lack of accurate abs. efficiency)

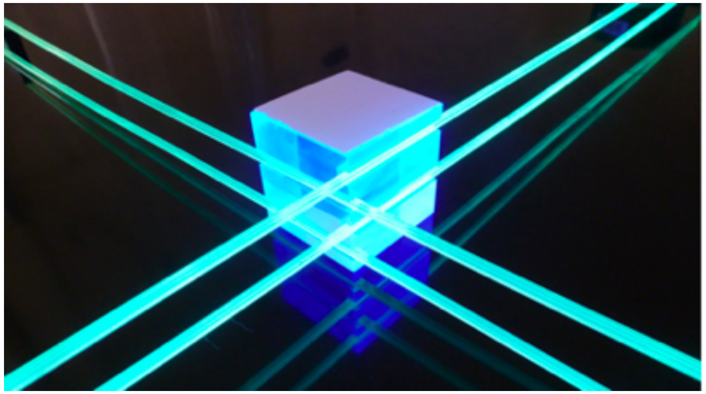
*A.P.Serebrov et al. arXiv:*1702.00941 *(2017)*

Solid

- 6-9 m from HEU reactor (60 MW)
- New technology: Composite scintillator (^{6}LiF)
- High segmentation (13000 cubes)
- Detector mass: 1600 kg

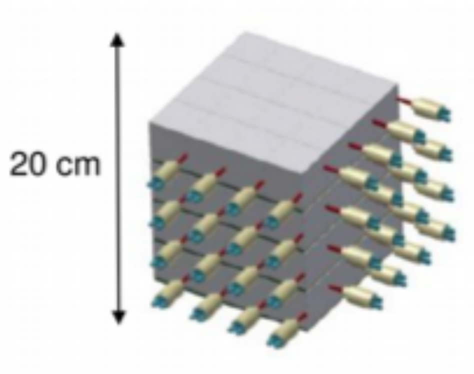




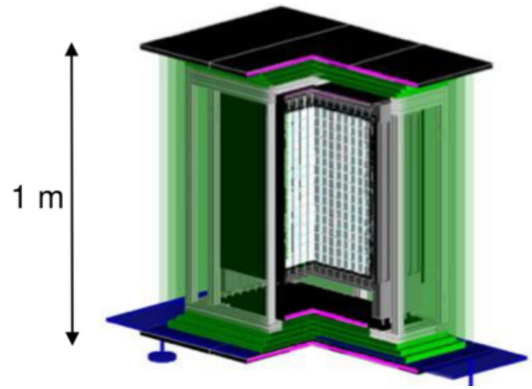


Commissioning Summer 2017, started data taking?

Solid: Prototype to full scale



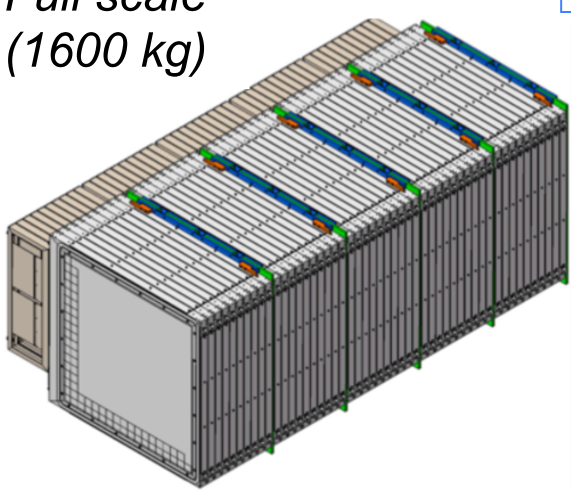
Nemenix (8 kg)

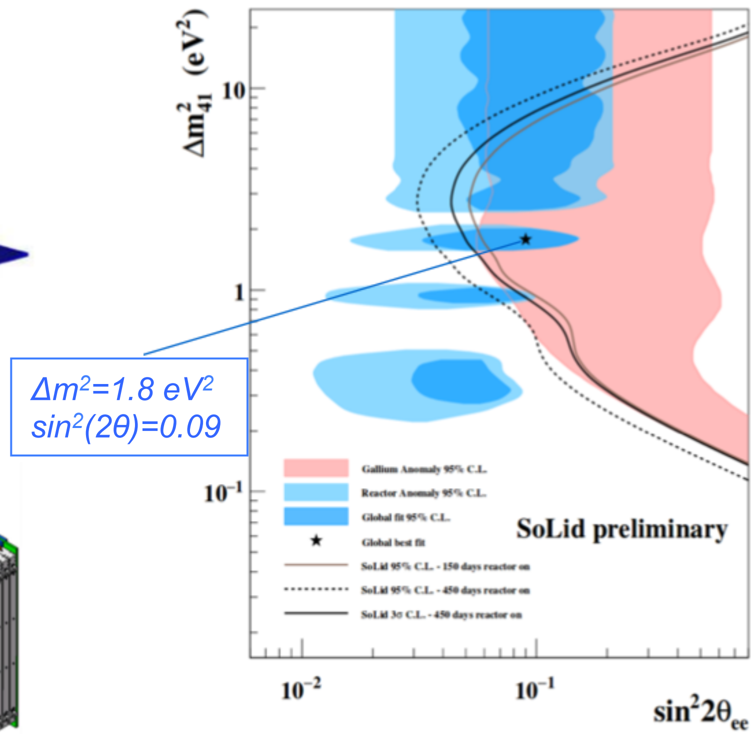


SM 1 (288 kg)

- 2013: Nemenix Proof of concept
- 2014/15: SM1 Background and scalability
- 2017: Phase 1

Full scale (1600 kg)

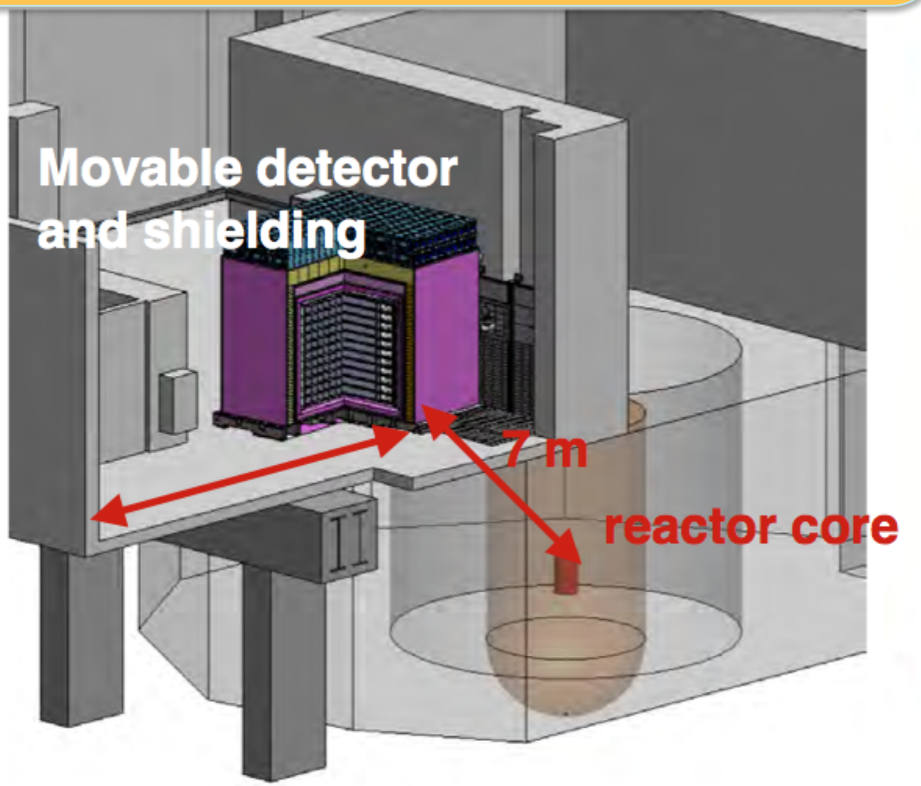


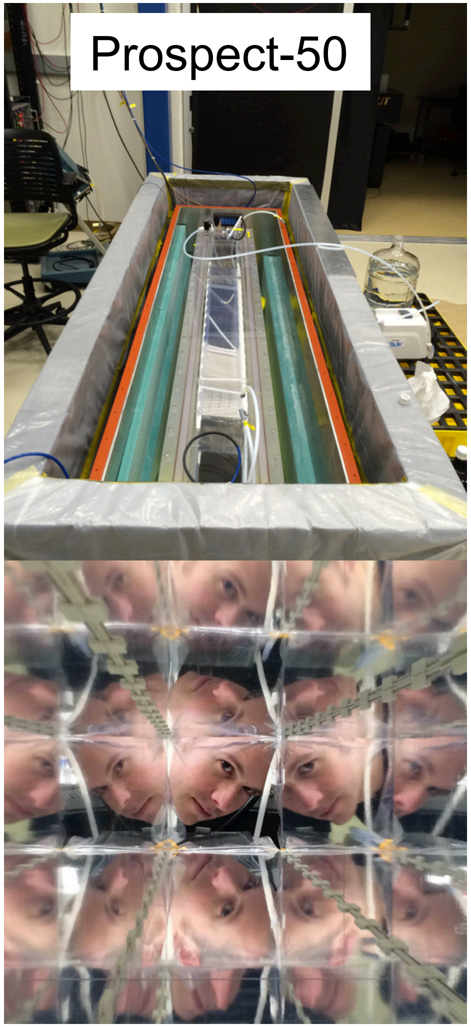


L. Manzanillas, TAUP 2017

Prospect (US)

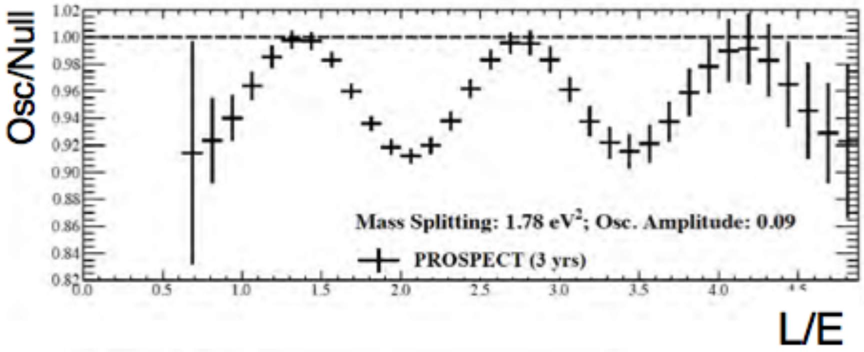
- HFIR: 85 MW, 7-12 m baseline
- 3000 liter Li-loaded liquid scintillator
- 10x12 segmented optical array
- S/B projected ≈3

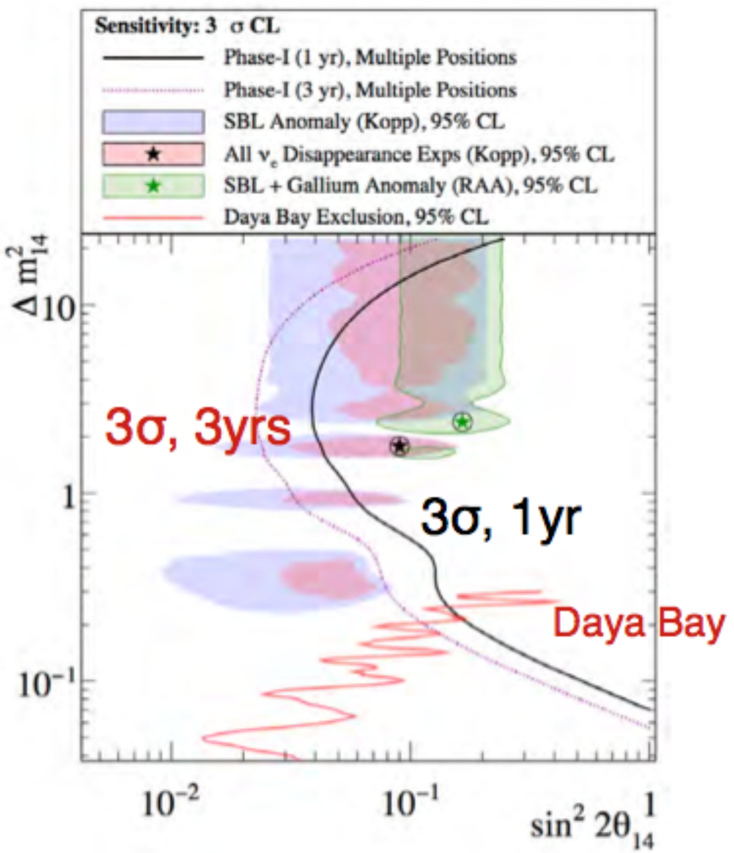




K.Heeger, TAUP 2017

Prospect Outlook





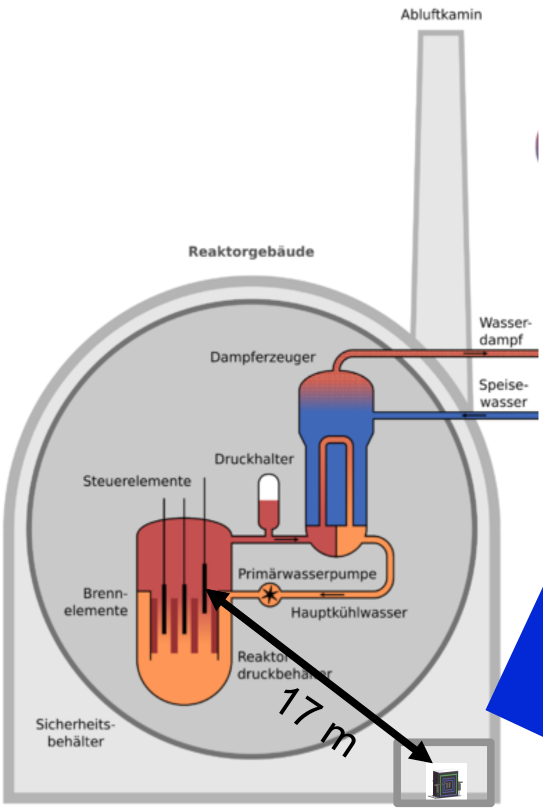
- Start data taking 2017
- About 160 kevents/y
- 4 σ test of best fit in 1 y

Sterile neutrinos at reactors

Name	P_{th} (MW)	L (m)	Dep. (mwe)	$M_{targ.}$ (t)	Tech.	Seg.	S/N	Start
Neos	2700	25	20	1	Gd-LS	N	22	2015
DANSS	3000	9-12	50	0.9	Gd-PS	Y	≈20	2016
Neutrino4	90	6-12	5-10	1.5	Gd-LS	Y	<1	2016
Stereo	57.8	9-11	15	1.7	Gd-LS	Y	≈1	2016
Solid	100	6-11	10	1.6	^{6}Li-PS	Y	≈1	2017
Prospect	85	7-12	few	3	^{6}Li-LS	Y	3	2017

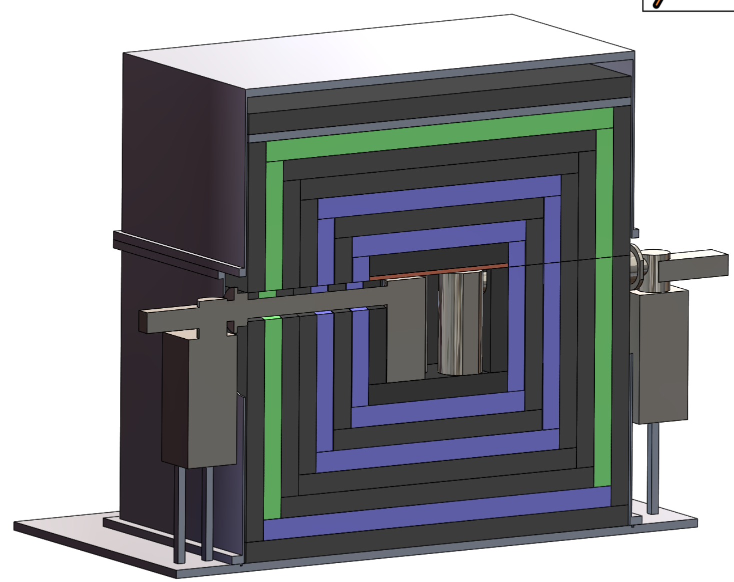
Other detection techniques

Coherent elastic neutrino nucleus scattering (CEvNS)



Nuclear Power Plant
Brokdorf, 3.9 GW

CONUS shielding



Start data taking this year!

Summary

- All mixing angles and mass splittings measured in three flavor neutrino model
- Reactor neutrinos at short baseline observe anomalous behavior for rate and shape (correlated?)
- Worldwide search for light sterile neutrinos at reactors
- Several experiments started or are close to full scale data taking
- Sensitivity of experiments should allow to test most important allowed regions within the next two years