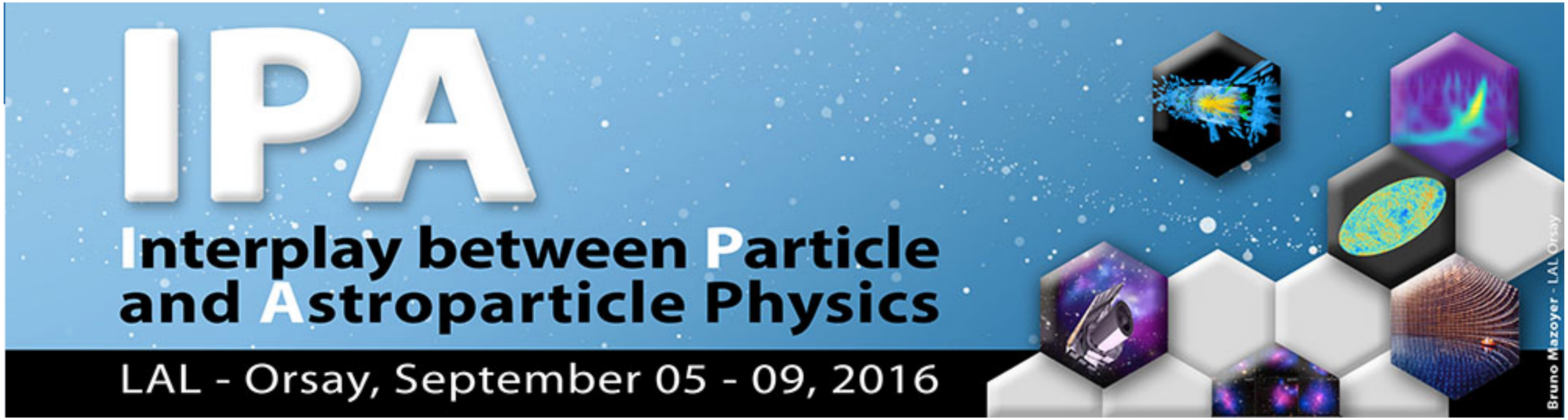
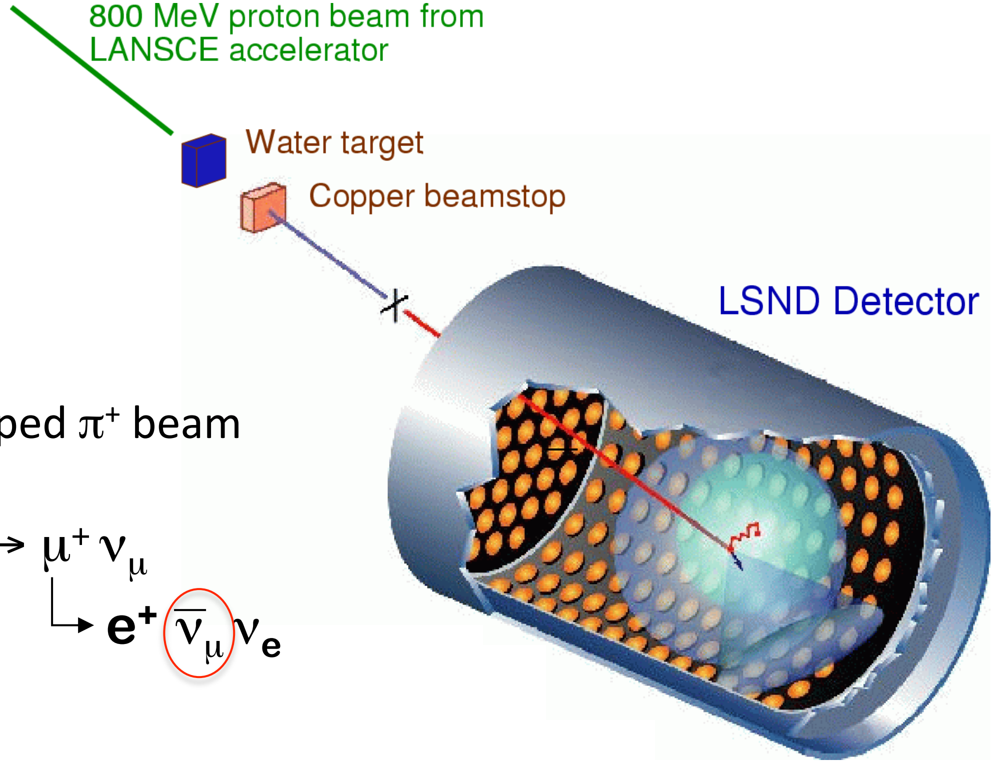


Experimental Searches for Sterile Neutrinos

D. Lhuillier
CEA Saclay

LSND experiment



Stopped π^+ beam

$\pi^+ \rightarrow \mu^+ \nu_\mu$

$\hookrightarrow e^+ \bar{\nu}_\mu \nu_e$

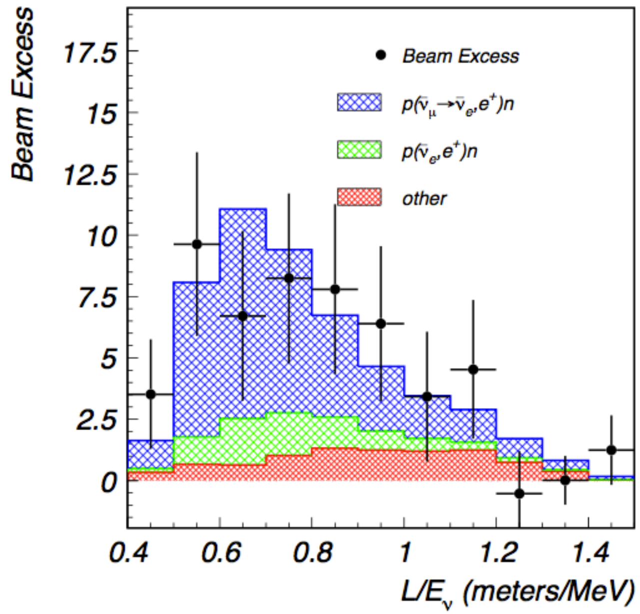
Detection reaction

$\bar{\nu}_e + {}^1H \rightarrow e^+ + n$

Baseline of 30 m

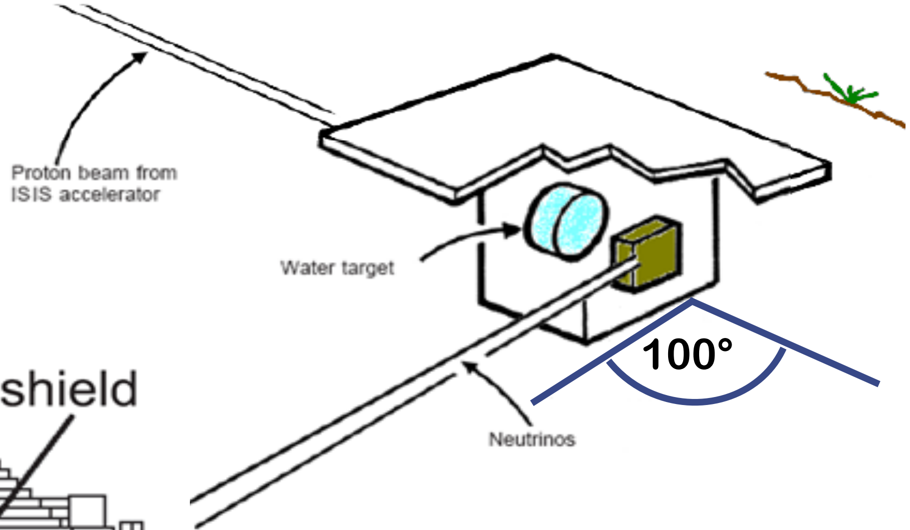
E= [20 – 50] MeV

L/E ≈1 m / MeV

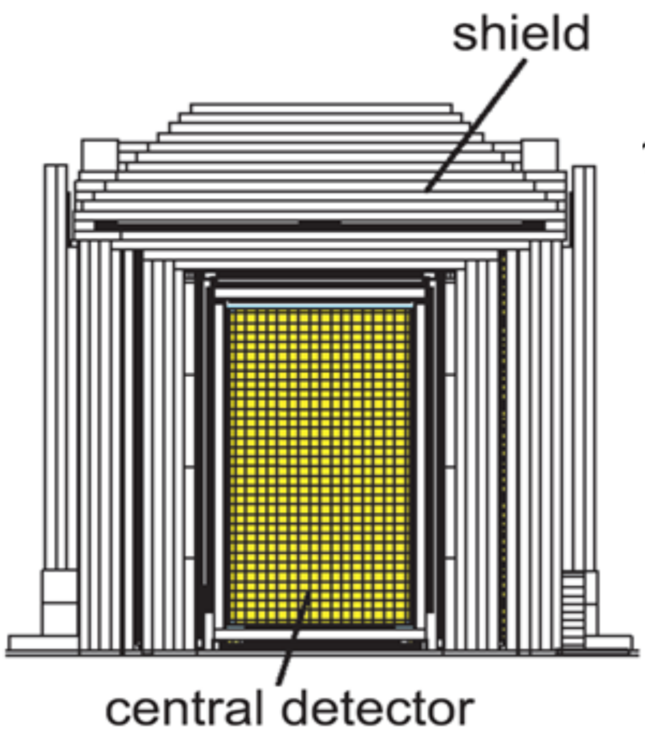


→ $\bar{\nu}_e$ excess observed
32.2 ± 9.4 ± 2.3 (3.8σ)

Karmen Experiment



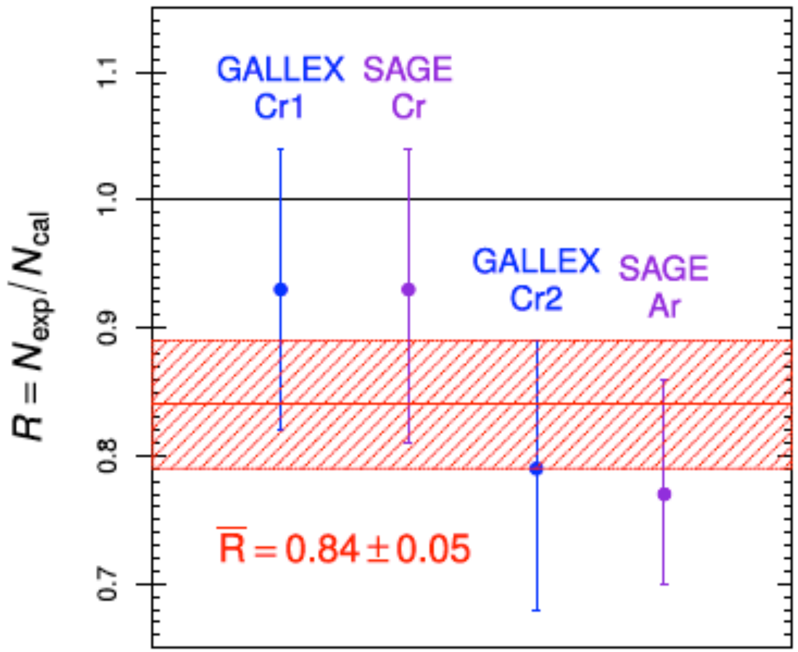
- **Detection 100° off beam axis**

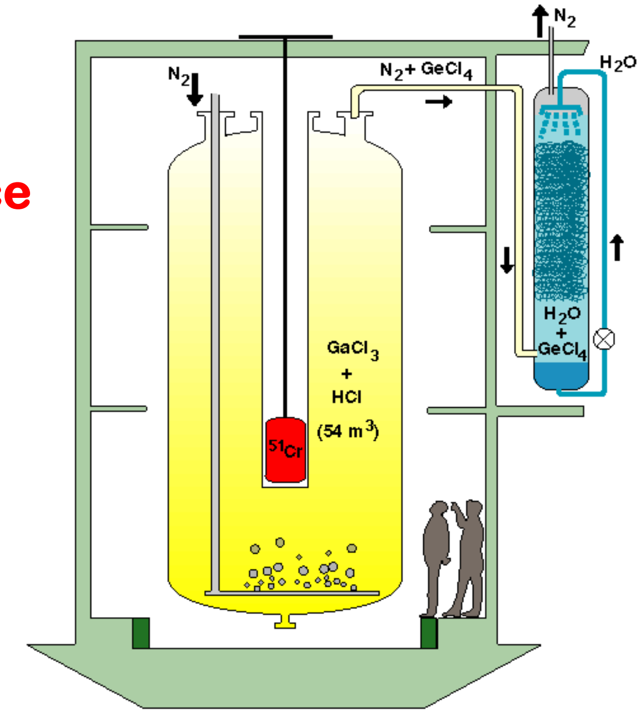


- **No ν_μ disappearance observed**
- **In tension with the new $\nu_\mu \longrightarrow \nu_e$ oscillation of LSND**

Gallium ν_e Anomaly

- **Calibration of Gallex and Sage detectors with e-Capture ν_e sources**
  - **Gallex: <L>=1.9 m, ^{51}Cr, 750 keV**
  - **Sage: <L>=0.6 m, ^{51}Cr & ^{37}Ar (810 keV)**
- **Deficit observed with combined 3σ significance**

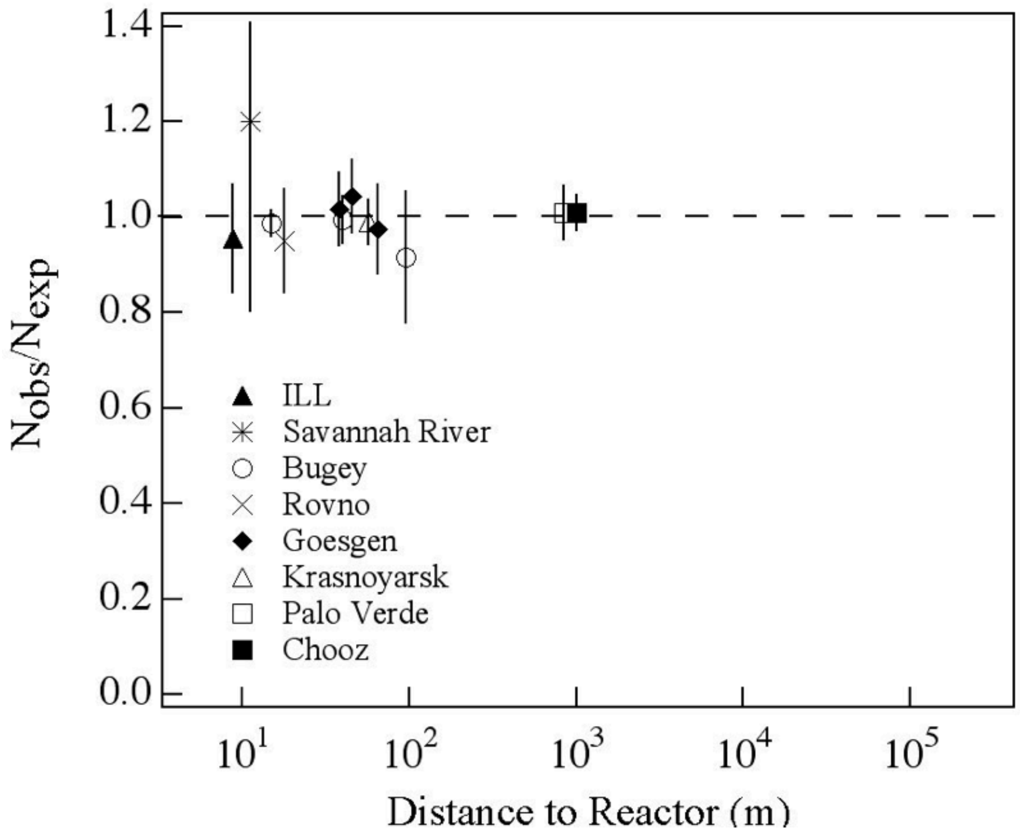




$$^{71}Ga/^{37}Ar + \nu_e \rightarrow {}^{71}Ge/^{37}Cl + e^-$$

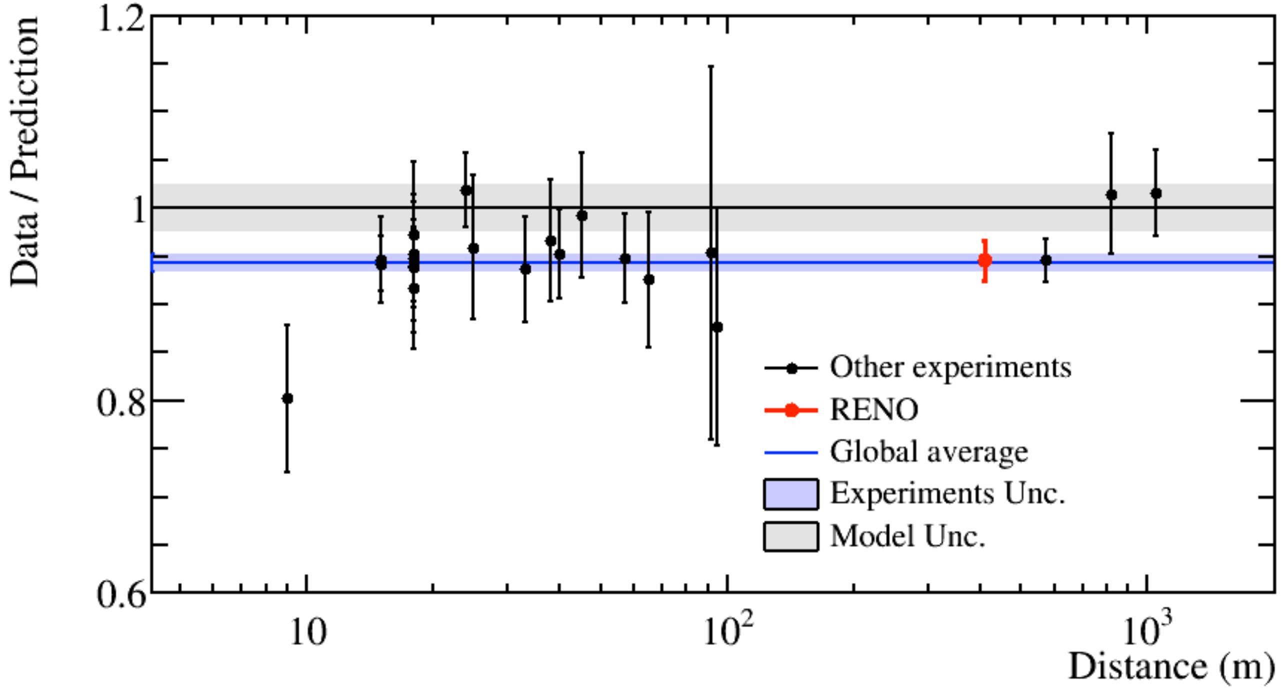
Short Baseline Reactor Experiments

Agreement of reactor data with prediction up to early 2000



Reactor Antineutrino Anomaly

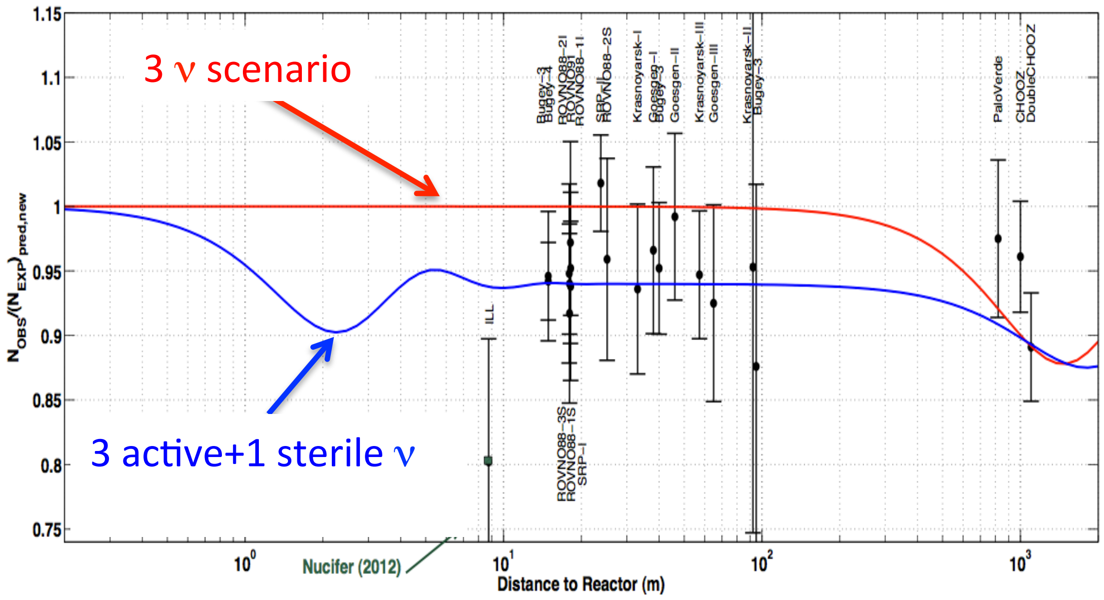
- **Re-evaluation of anti-ν spectrum (T. Mueller at al 2011, Huber 2011)**
- **6.5% deficit of observed neutrino rates w.r.t. new prediction**

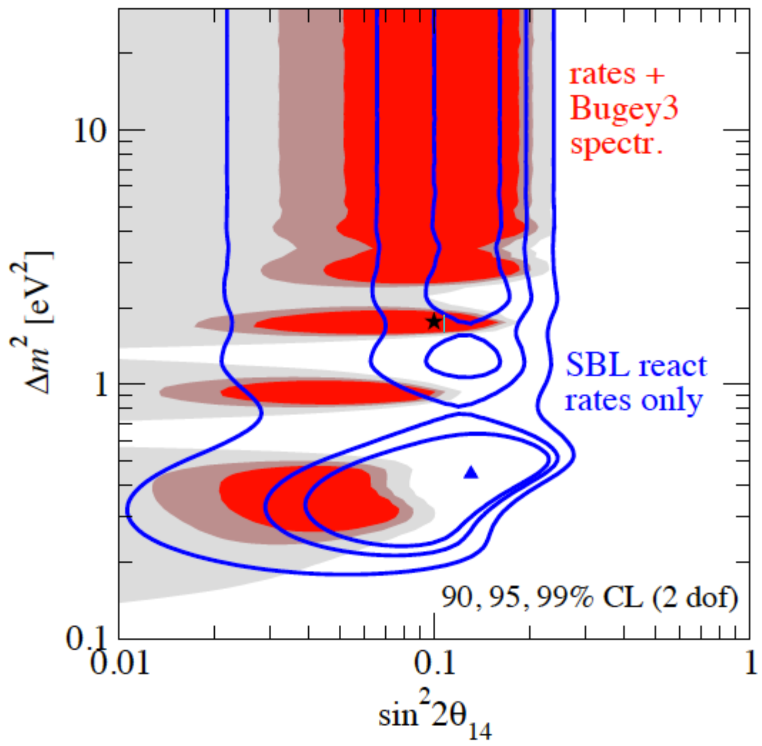


Recent Daya Bay and Reno measurements are in agreement with the average of previous measurements

Reactor Antineutrino Anomaly

Could be explained by an oscillation of the ν_e flux toward a sterile neutrino in the eV Δm^2 scale

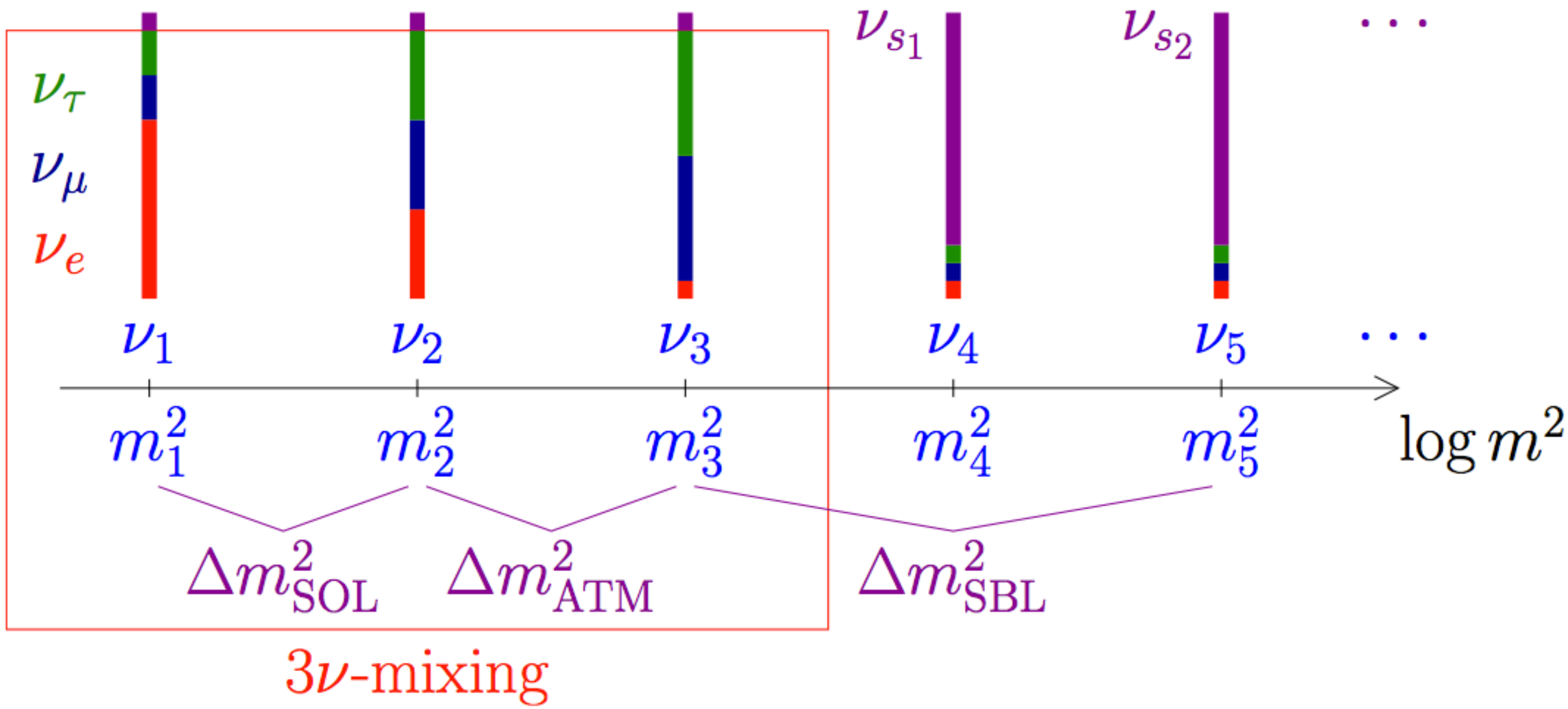




J. Kopp, JHEP 1305 (2013) 050

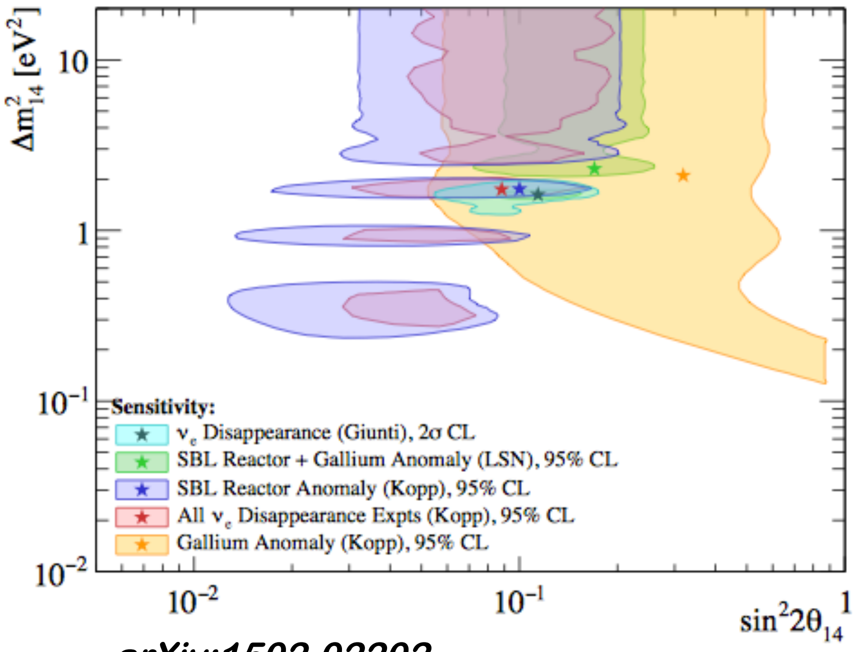
eV scale Sterile Neutrino Hypothesis

Additional neutrino state not coupling with the Z boson



eV scale Sterile Neutrino Hypothesis

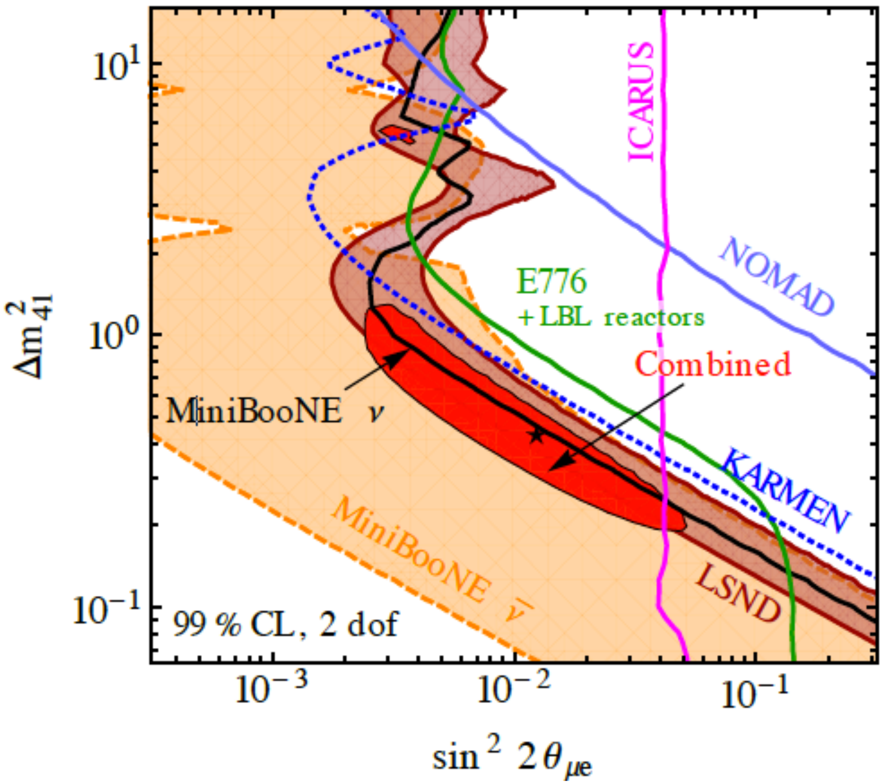
$\nu_e, \overline{\nu}_e$ **disappearance**



arXiv:1502.02202

ν_e **appearance,** ν_μ **disappearance**

J. Kopp, JHEP 1305 (2013) 050



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

$$|U_{e4}| = \sin\theta_{14}$$

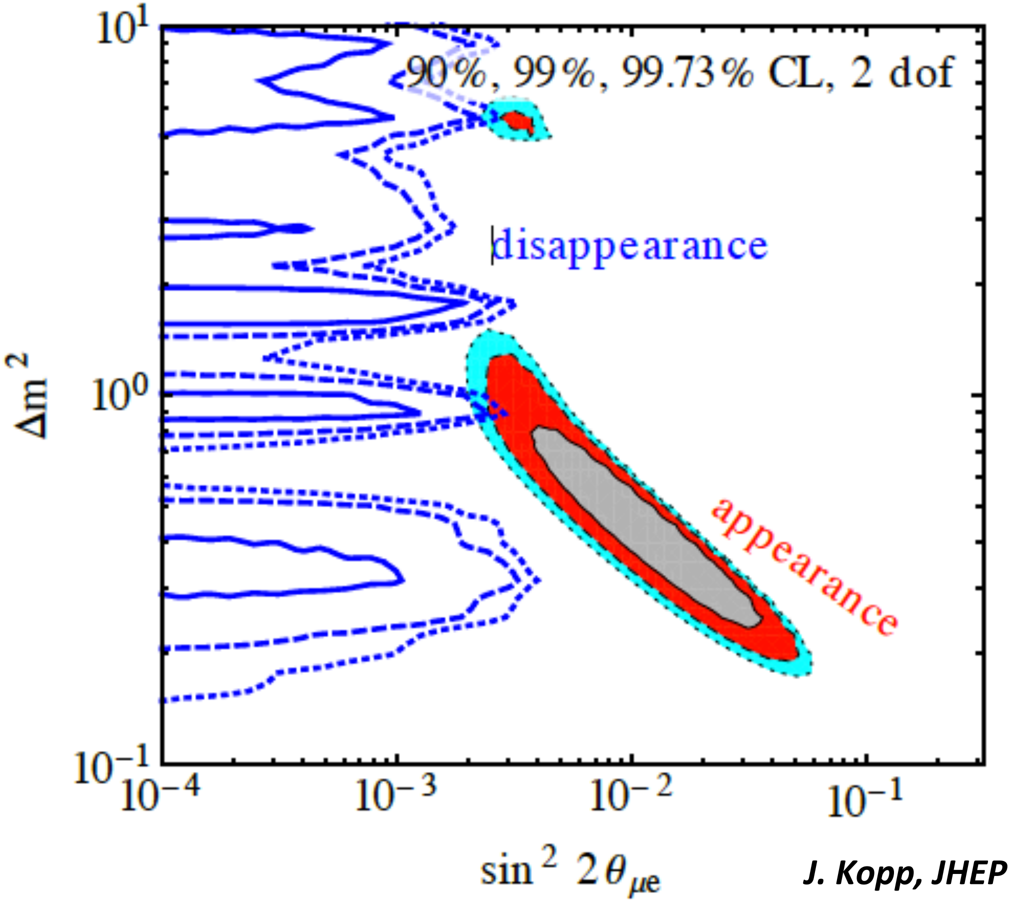
$$\sin^2 2\theta_{\mu e} \equiv 4|U_{\mu 4}U_{e4}|^2$$

$$|U_{\mu 4}| = \cos\theta_{14}\sin\theta_{24}$$

$$|U_{e4}| = \sin\theta_{14}$$

eV scale Sterile Neutrino Hypothesis

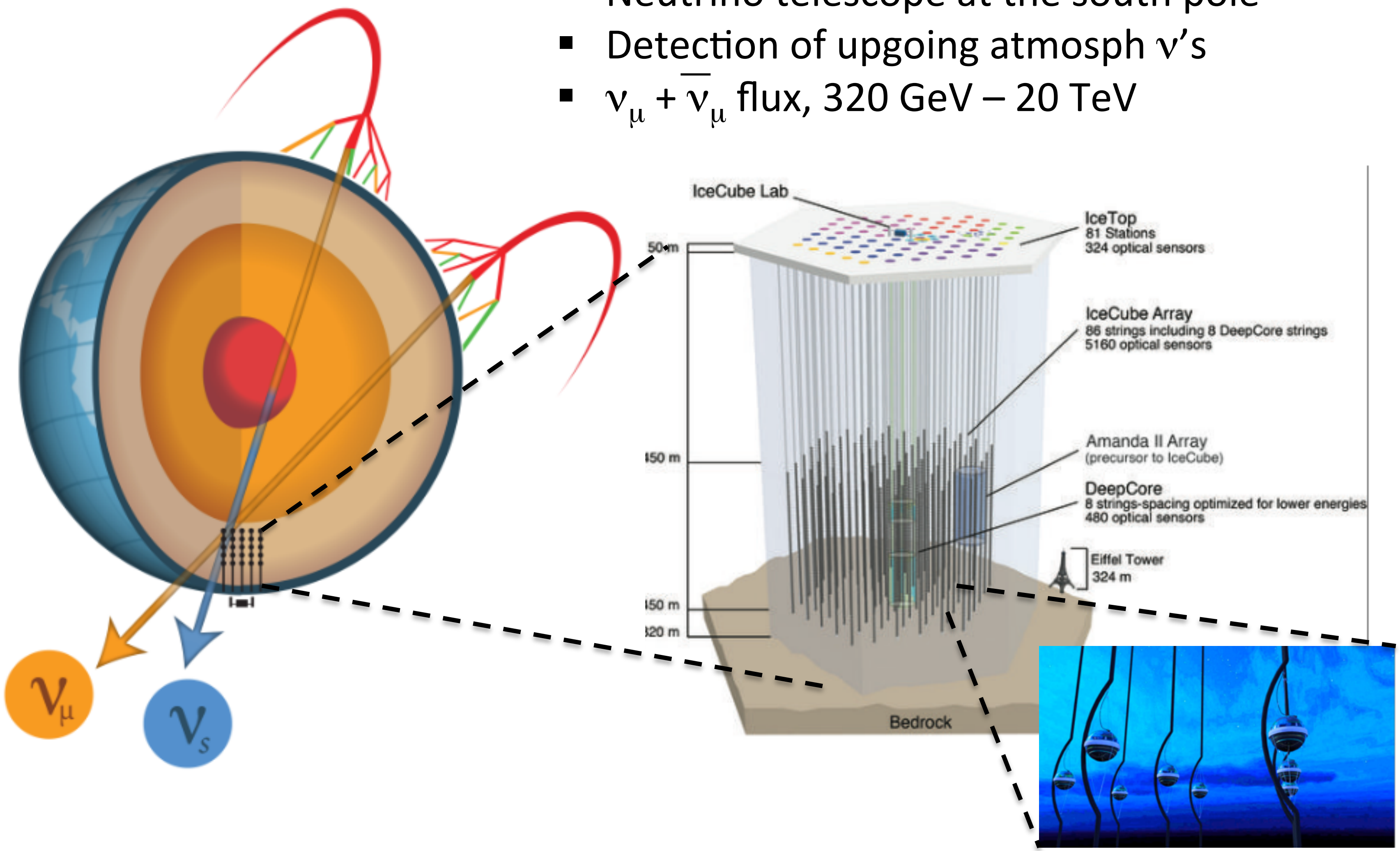
Tension between appearance and disappearance



J. Kopp, JHEP 1305 (2013) 050

ICE CUBE Experiment

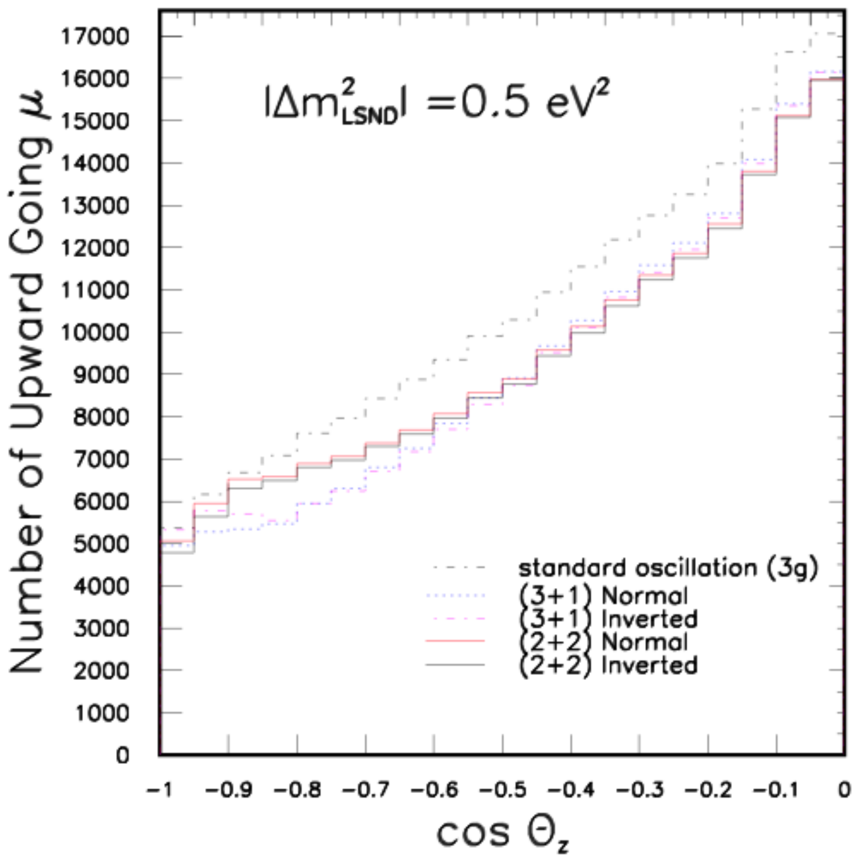
- Neutrino telescope at the south pole
- Detection of upgoing atmosph ν's
- $\nu_\mu + \overline{\nu}_\mu$ flux, 320 GeV – 20 TeV

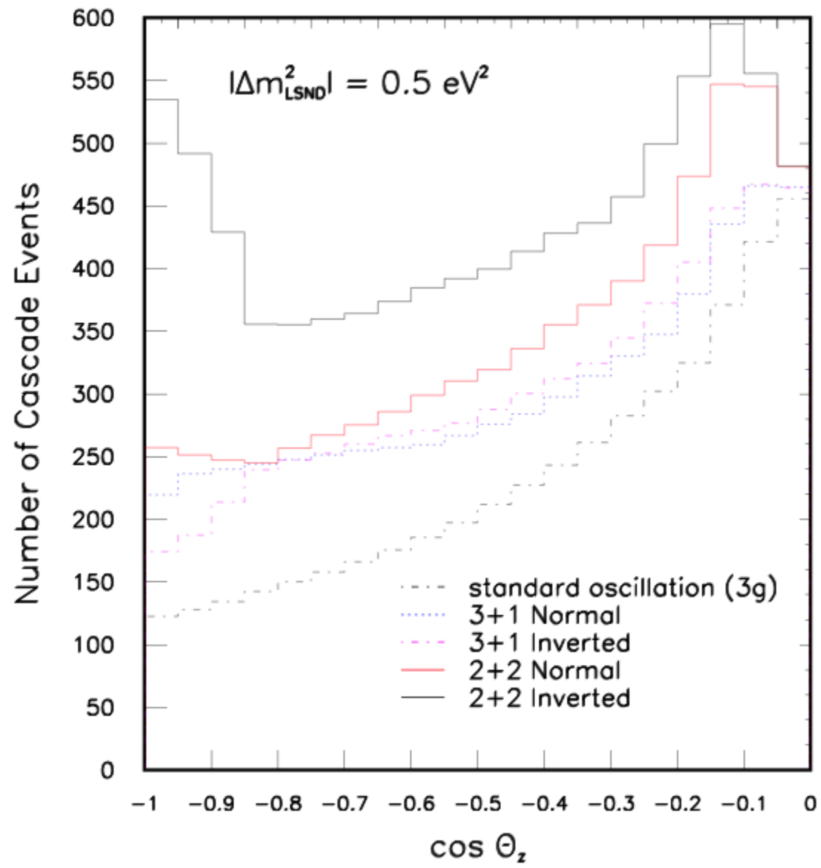


ICE CUBE sensitivity to Sterile ν's

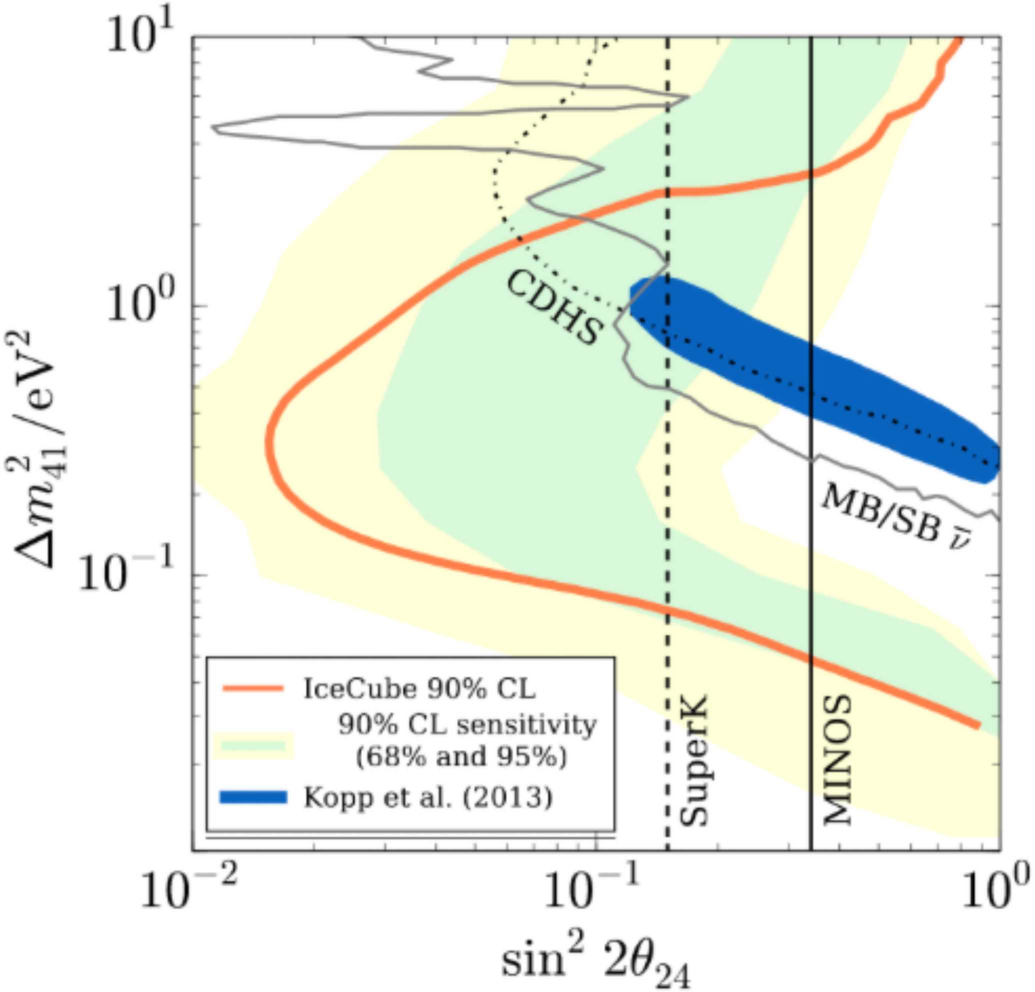
$\nu_\mu + \overline{\nu}_\mu$ disappearance through extra mixing with a sterile state

Cascade events dominated by ν_μ NC currents
Sterile ν's would imply an excess through ν_e,ν_τ CC





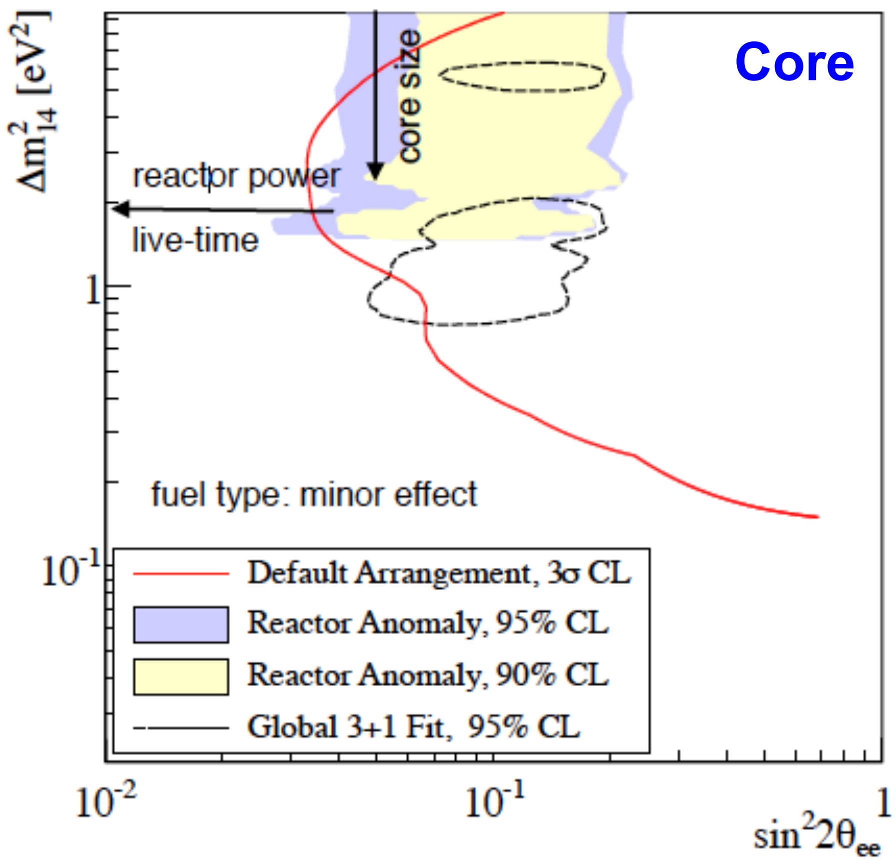
ICE CUBE Result

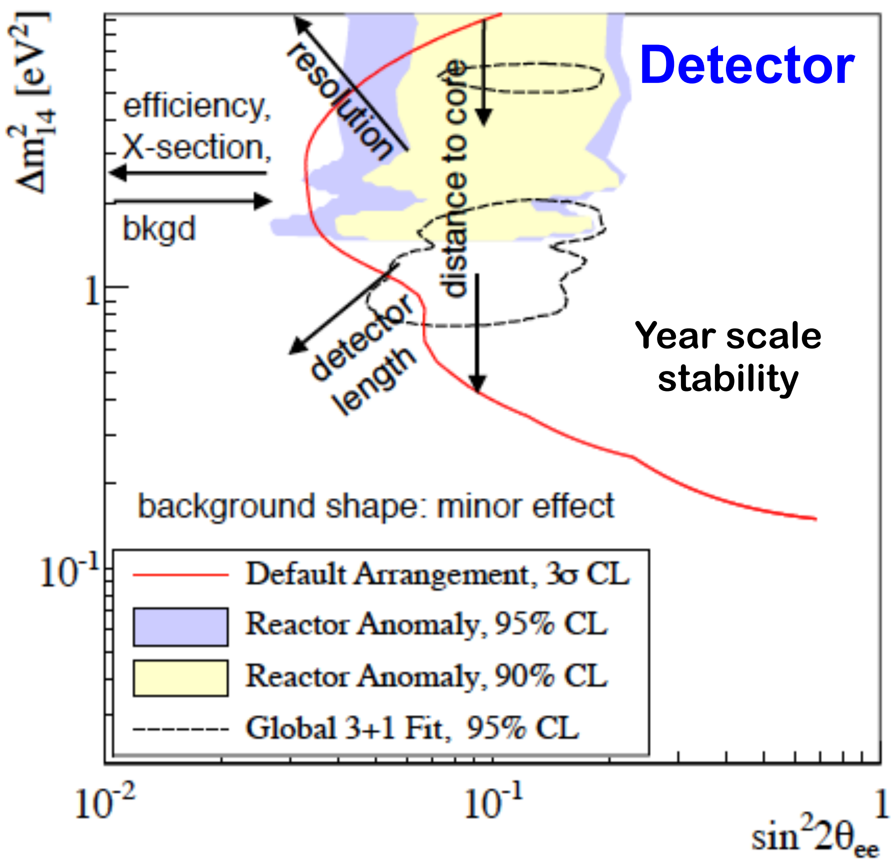


- Strengthened incompatibility with appearance signals.
- Disappearance result with high sensitivity requiring careful treatment of systematics.
- Scenario of an eV scale sterile neutrino with $\sin^2\theta_{24} << \sin^2\theta_{14}$?

Direct Tests of sinθ_{14}

Short Distance from a Compact Source

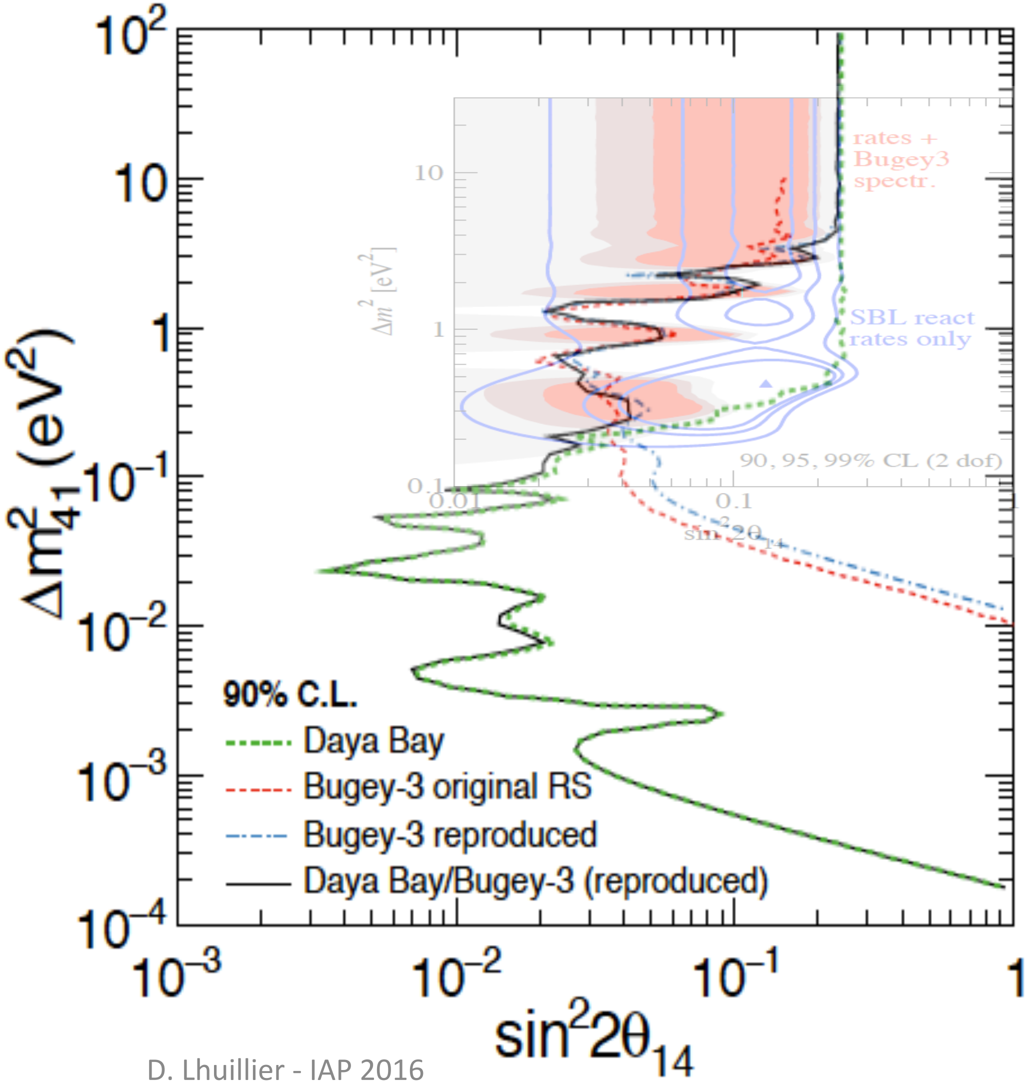




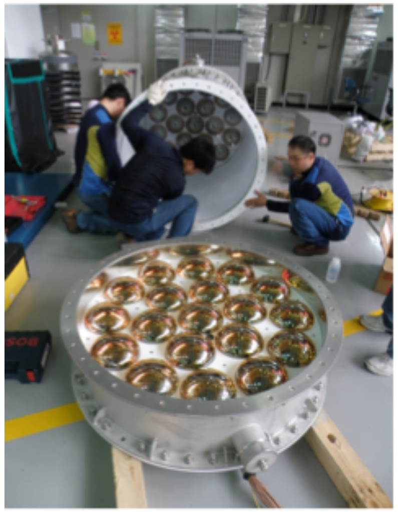
K.M. Heeger et al., arXiv:1212.2182v1

Daya Bay

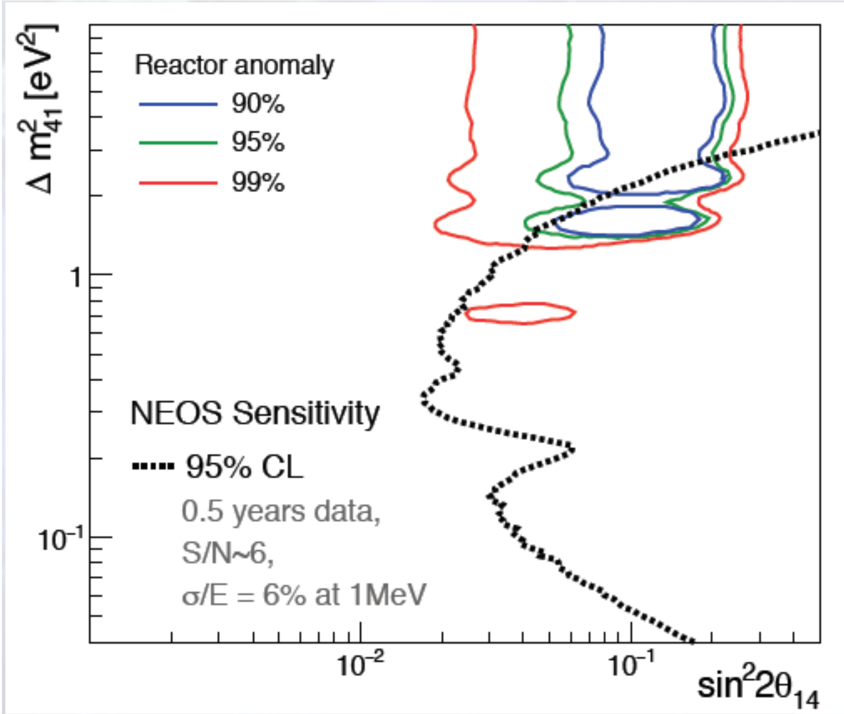
- **400 m baseline limits the sensitivity to high Δm^2**

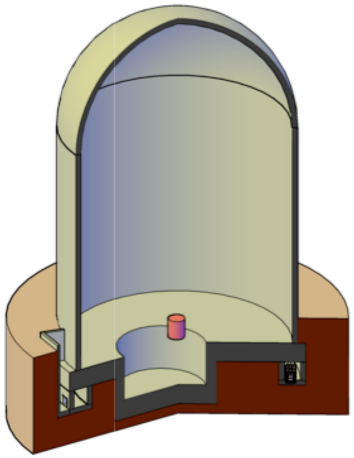


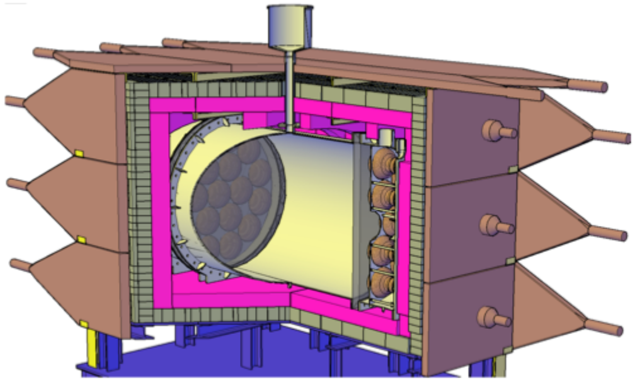
NEOS



- RENO site (Yeonggwang power plant)
- Extended core (h = 3.7 m, ⦰ =3.1 m)
- 23.7 m fixed baseline
- 30 mwe overburden,



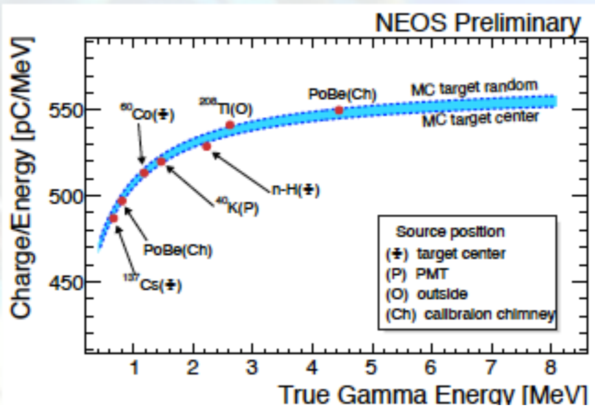


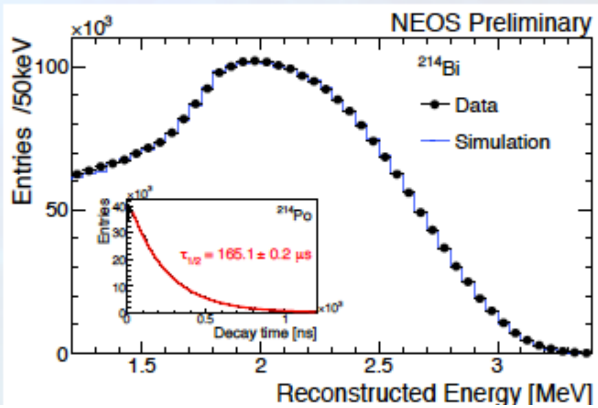


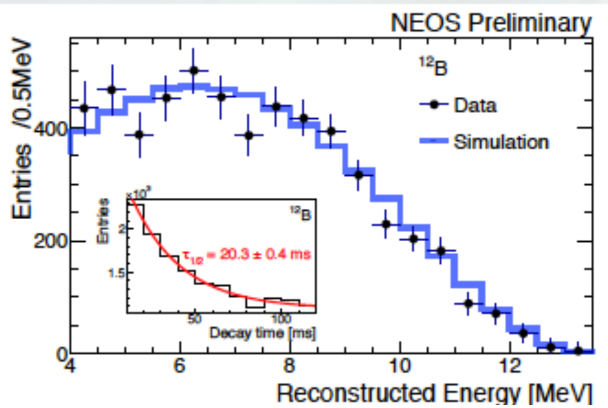
LS target: LAB + Gd (0.5%)

NEOS

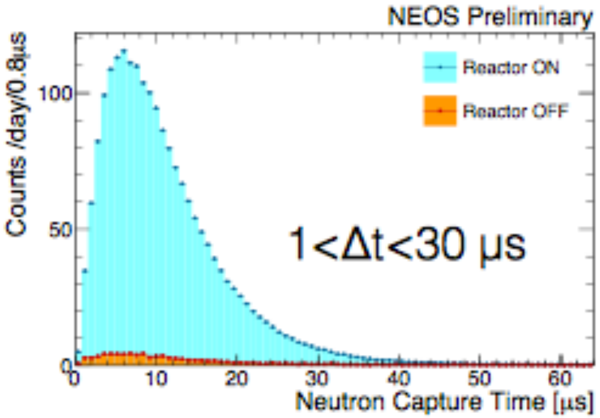
- **Data-MC agreement**

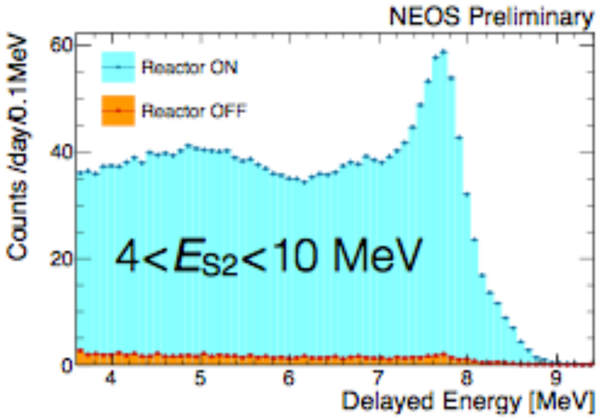


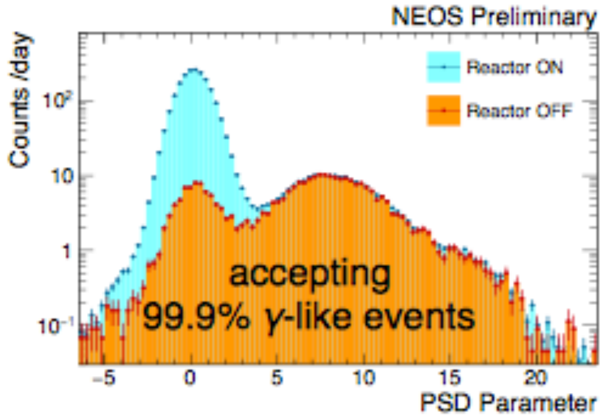




- **Low (S/N=23) and stable background.**
- **Larger baseline and extended core compensated by a huge counting rate: 1972 ν_e/day.**

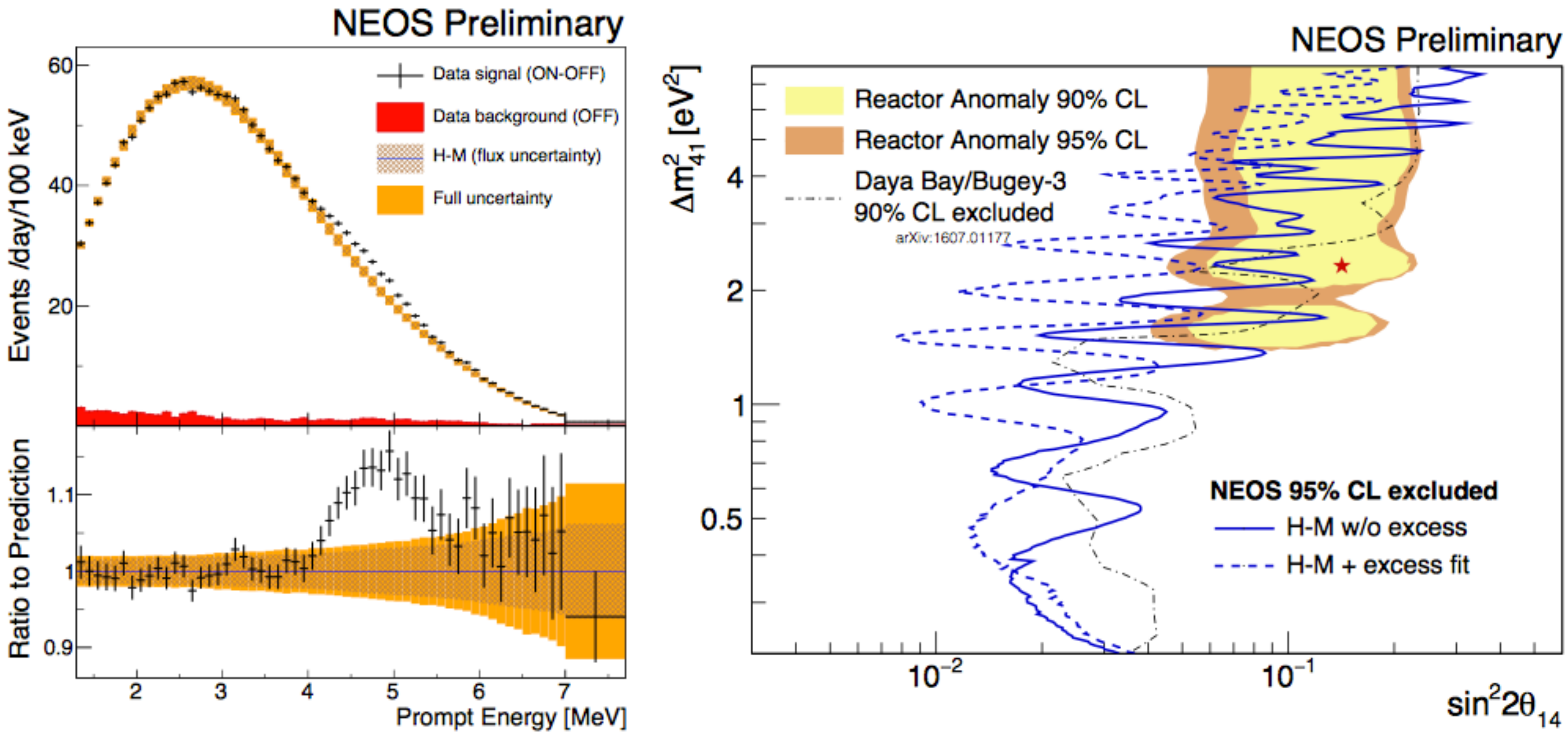






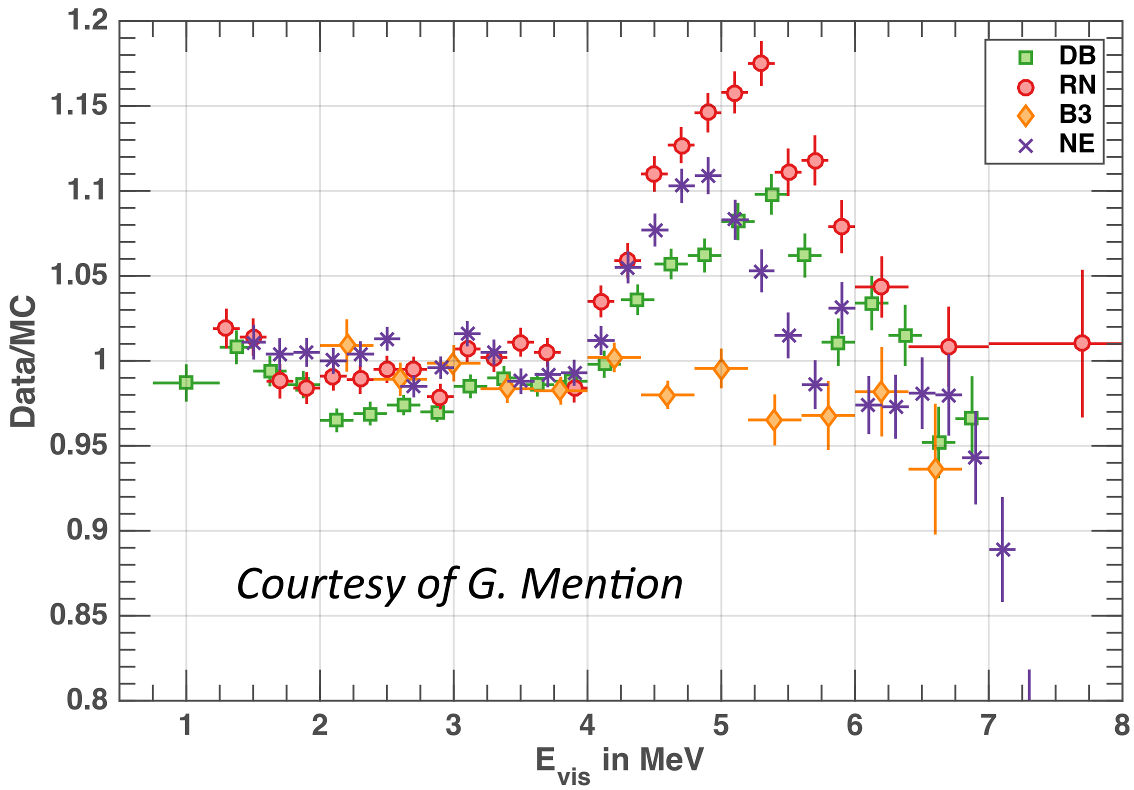
NEOS

Confirm the event excess observed by DC, DB and RENO around 5 MeV



High sensitivity contour thanks to the large statistical sample accumulated

5 MeV excess(es) – Ideas and Facts



- **Observed by Double Chooz, DayaBay, Reno and Neos**
- **However not compatible within exp uncertainties (different amplitude and/or max position).**
- **Detector response issues might remain.**

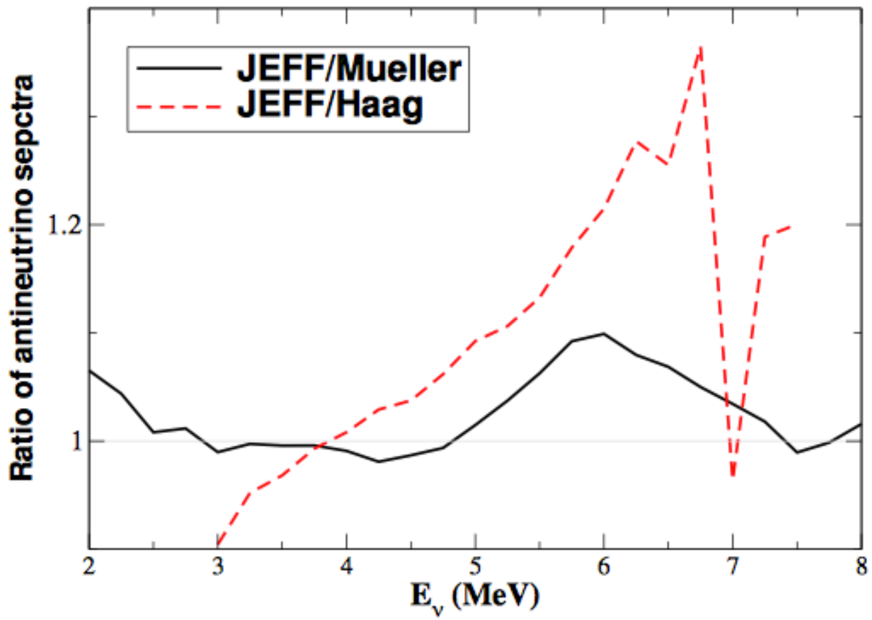
5 MeV excess – Ideas and Facts

1) **Forbidden transitions**

2) **Corrections to Fermi theory**

3) **^{238}U spectrum:**
   - **excess appears in latest ab initio calculation using the JEFF library**
   - **Enhanced contribution of 238U in the 5 MeV range.**
   - **RENO twice more sensitive**

4) **Reference beta spectra measured at ILL with a highly thermalized neutron spectrum**



A. Hayes and P. Vogel, arXiv:1605.02047

5 MeV excess – Ideas and Facts

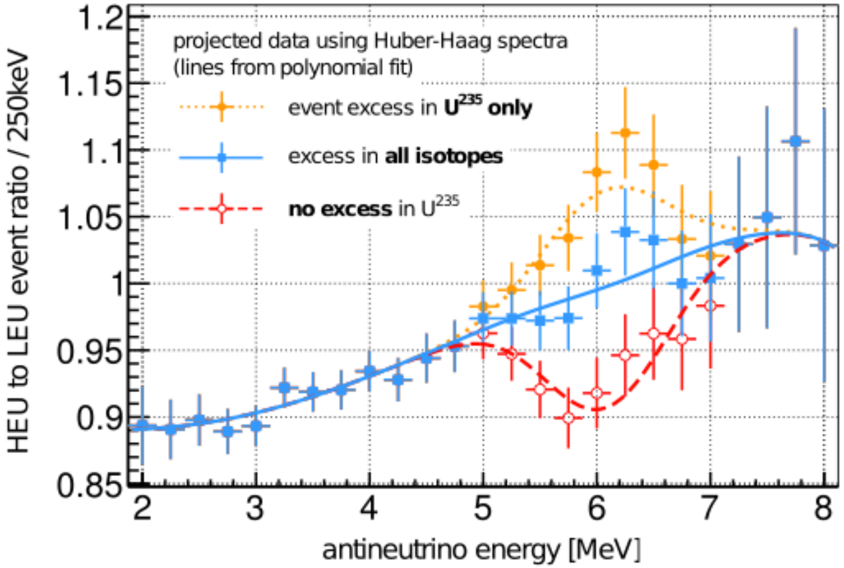
A. Hayes and P. Vogel, arXiv:1605.02047

1) **Forbidden transitions**
2) **Corrections to Fermi theory**

Not likely from numerical studies

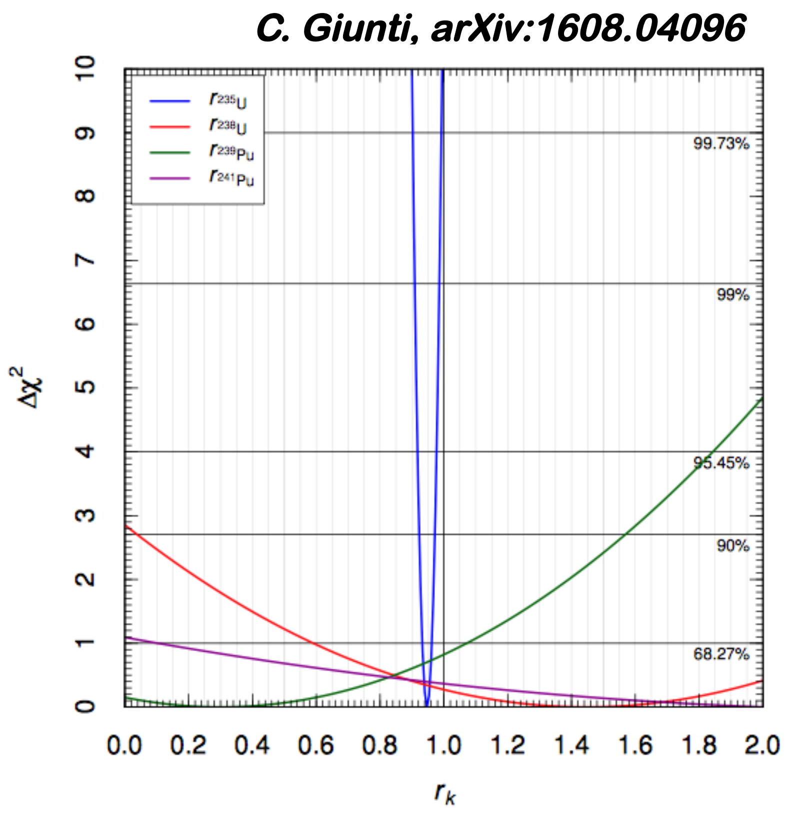
3) **^{238}U spectrum:**
   - **excess appears in latest ab initio calculation using the JEFF library**
   - **Enhanced contribution of 238U in the 5 MeV range.**
4) **Reference beta spectra measured at ILL with a highly thermalized neutron spectrum**

C. Buck et al, arXiv:1512.06656



To be tested by Research reactor experiments

5 MeV excess – Ideas and Facts

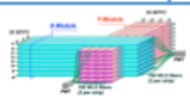
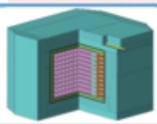
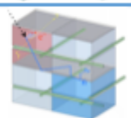
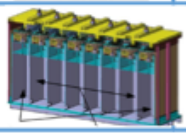


Does the 5 MeV bump jeopardize the Reactor Anomaly?

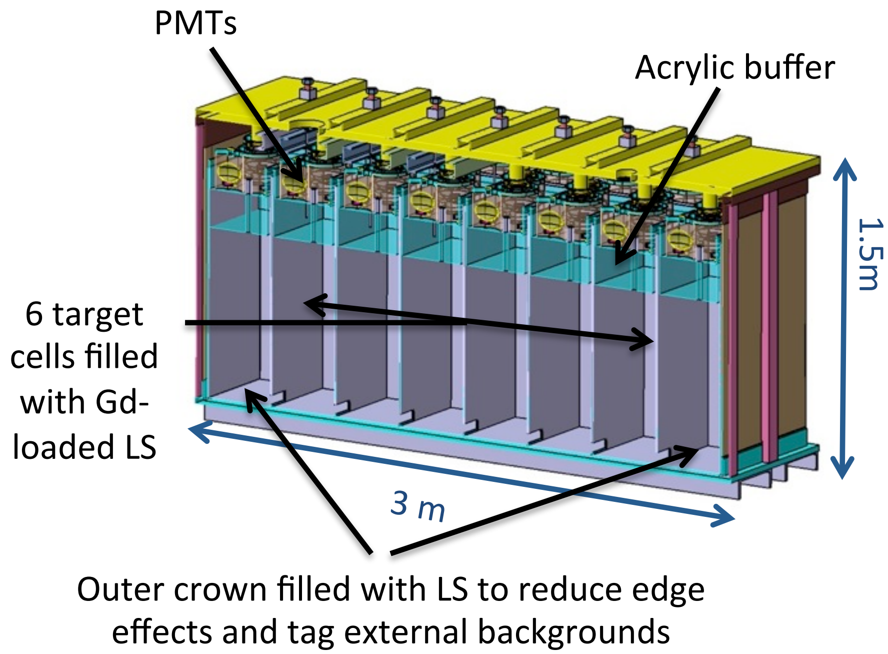
- **The 5 MeV bump is about 1% of the total flux**
- **Rather good shape agreement at low energy**
- **235U has to be the main culprit (normalization?)**

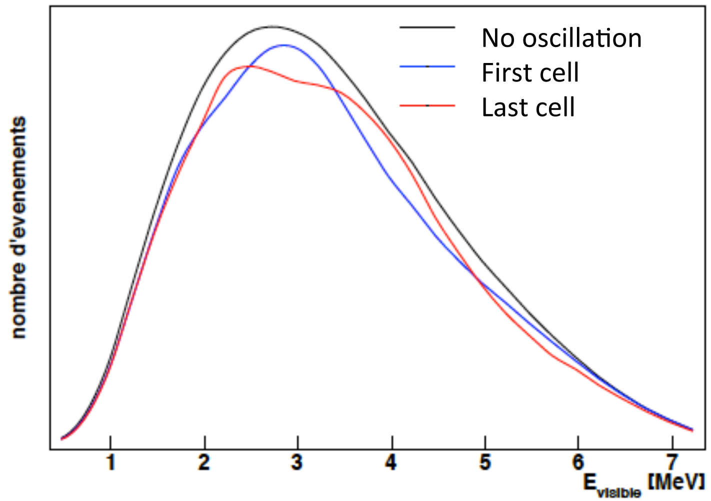
… open issue to be settled by running/ upcoming short baseline measurements

Short Baseline Reactor Experiments

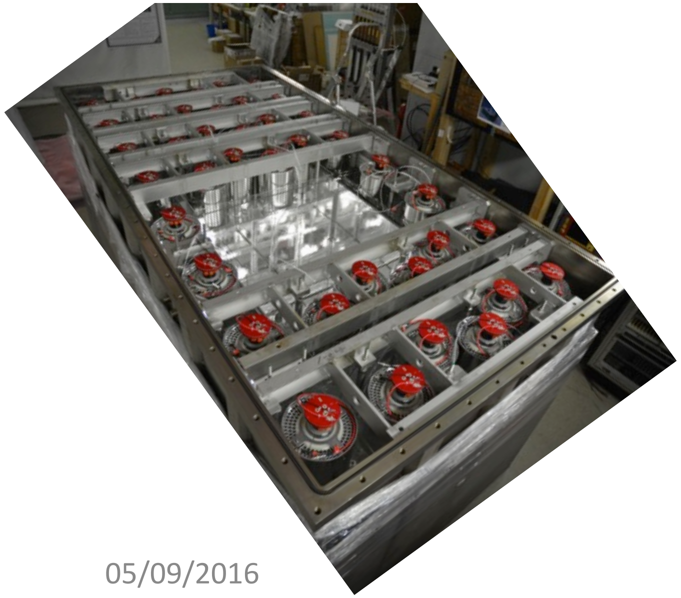
Experiment	Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia) 	3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only
NEOS (South Korea) 	2800 MW LEU fuel	~20	Homogeneous Gd-doped LS	none	Direct double 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 topology

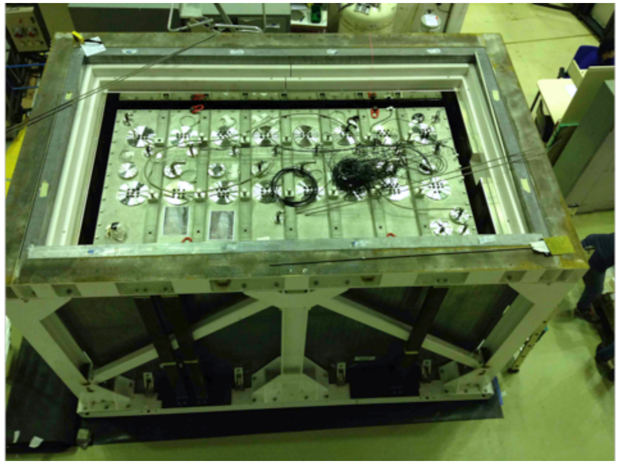
- [8.9–11.1] m from the compact (<1m) 57 MWth ILL core, in Grenoble-France
- 6 target cells (Gd-doped LS)
- Outer crown (undoped LS)
- 48 PMTs in upper acrylic buffer
- Looking for oscillation patterns: relative shape in the 6 identical cells



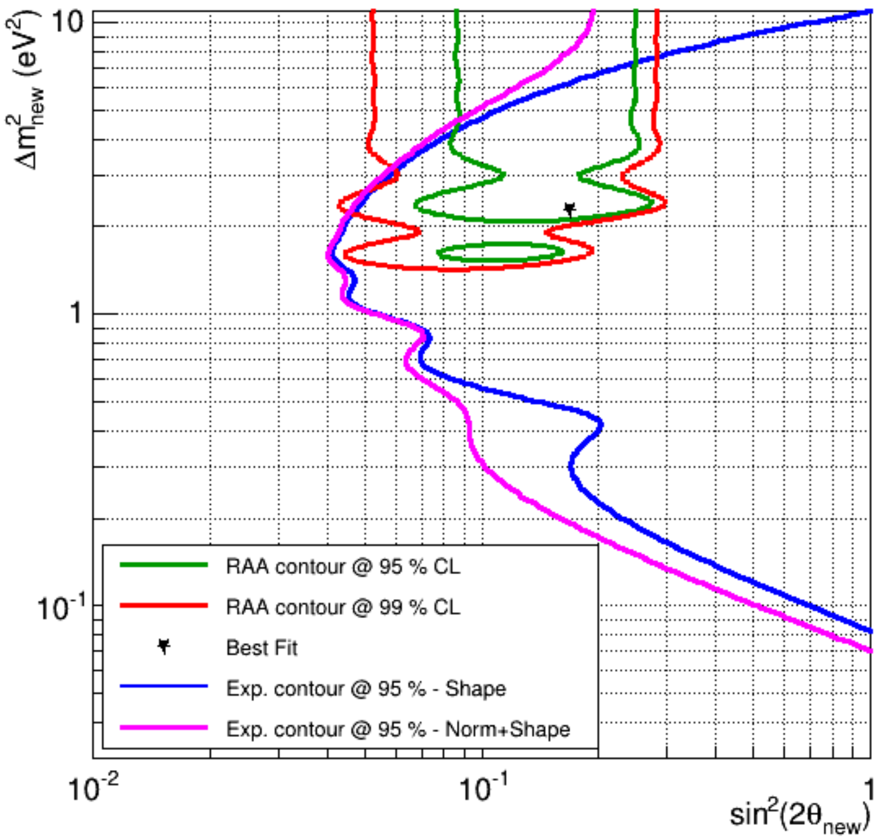


- VM2000 + air-gap + acrylic sandwiches (total reflection) to transport light to PMTs
- Detector vessel inserted inside its shielding.
- Installation to be completed end of this month.





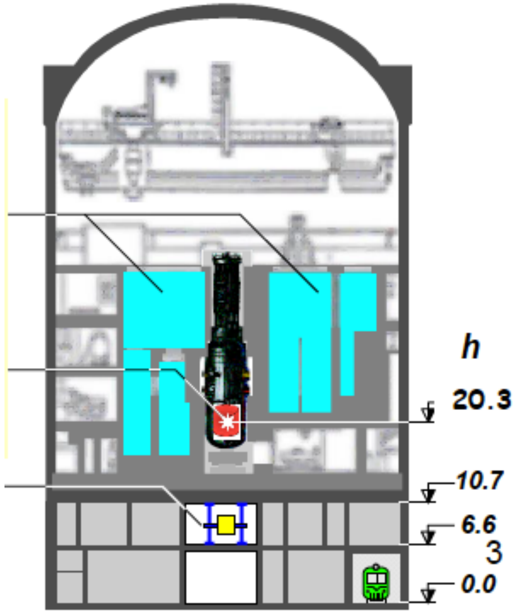
- **Data taking this autumn, two reactor cycles expected by spring 2017.**



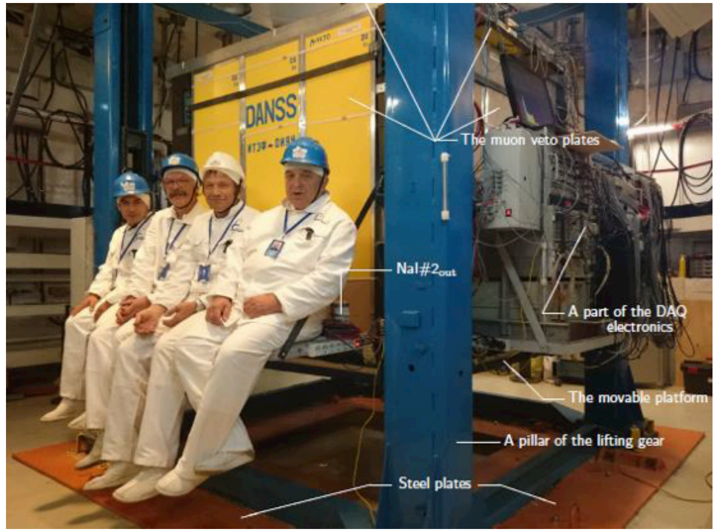
- **STEREO aims at covering the reactor anomaly region in ~1 year of reactor on data.**

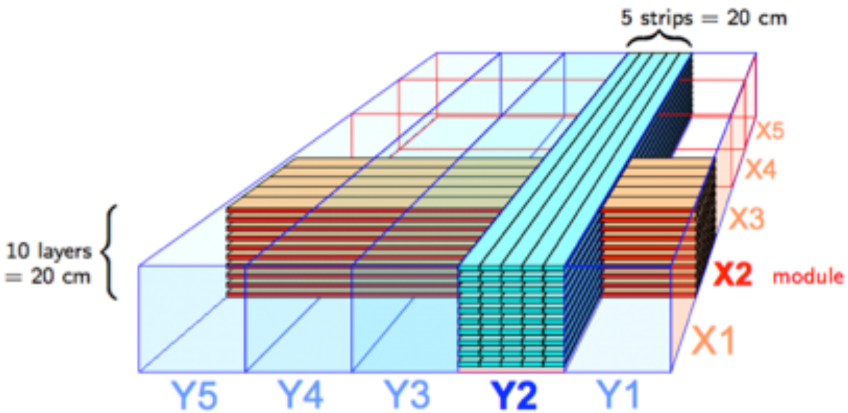
  - 300 days, L_0 = 10 m
  - E_{prompt}>2 MeV, $E_{delayed}$>5 MeV
  - 400ν_e/day
  - δE_{scale} = 2%
  - All syst. of predicted spectra
  - S/B = 1.5, 1/E+flat model
  - Norm 4%

DANSS



- **Detector vertical motion**
- **9.5-12.5 Baseline**
- **Factor 6 reduction of cosmic rays underneath the 3GW Kalinin reactor- Russia**





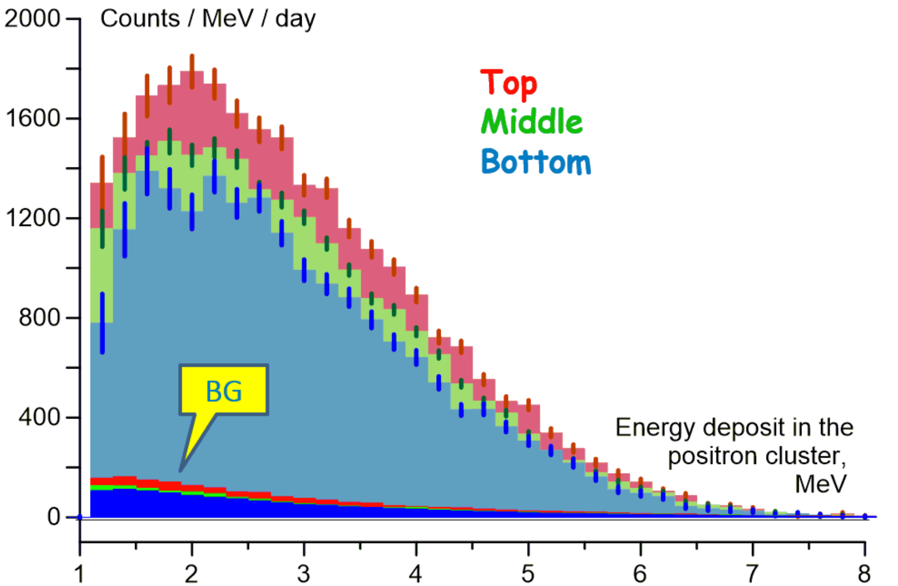
- **Extended core (h=3.5m, f=3.1 m)**
- **Very high neutrino rate (5000/day)**

- **Highly segmented plastic scintillator**
- **Gd doped coating**

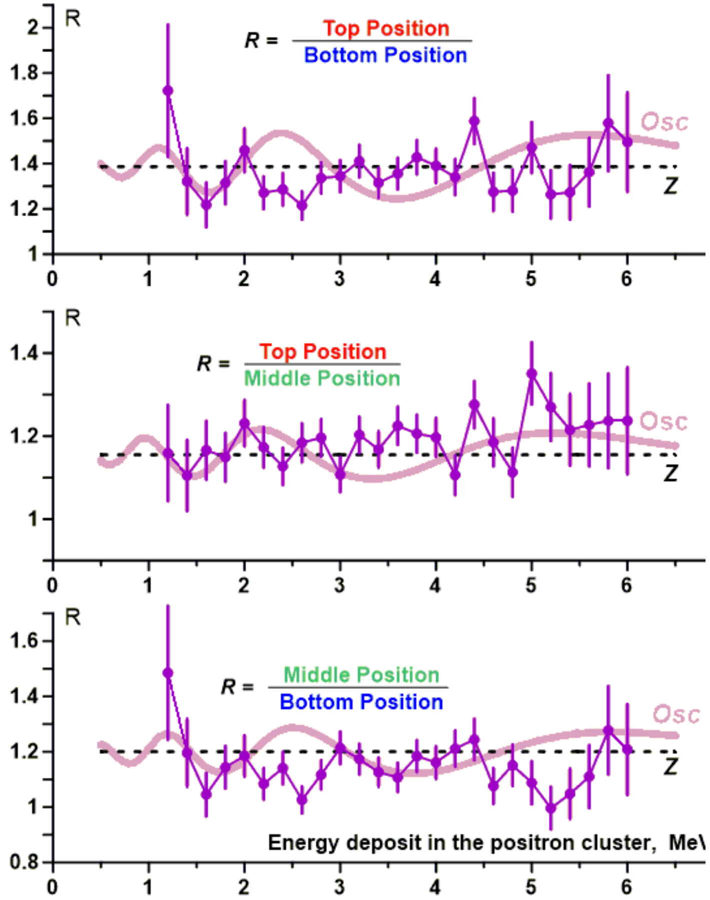
DANSS

On-going analysis

- **Data taking started in April 2016**
- **About 5000 neutrino events/day with ~5% cosmic background in a fiducial detector volume of 78%**



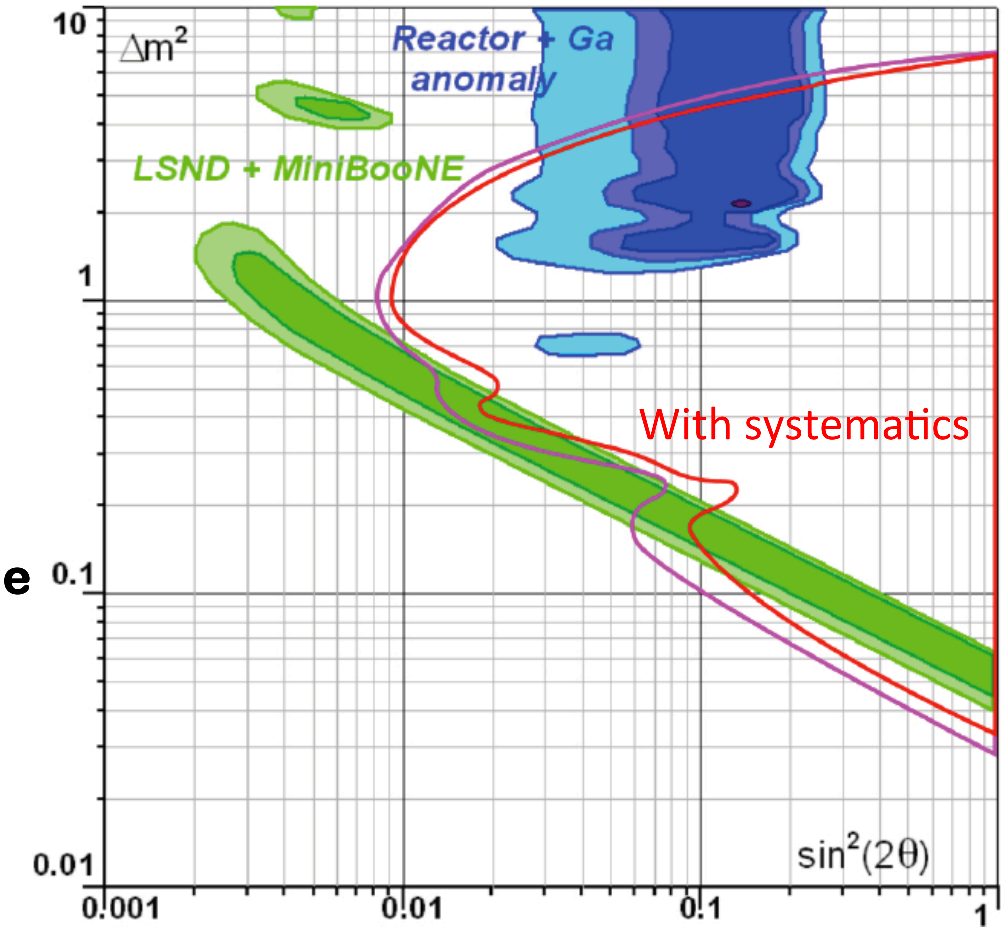
Energy spectra of positron cluster measured at different detector position *(random and muon-induced background subtracted)*



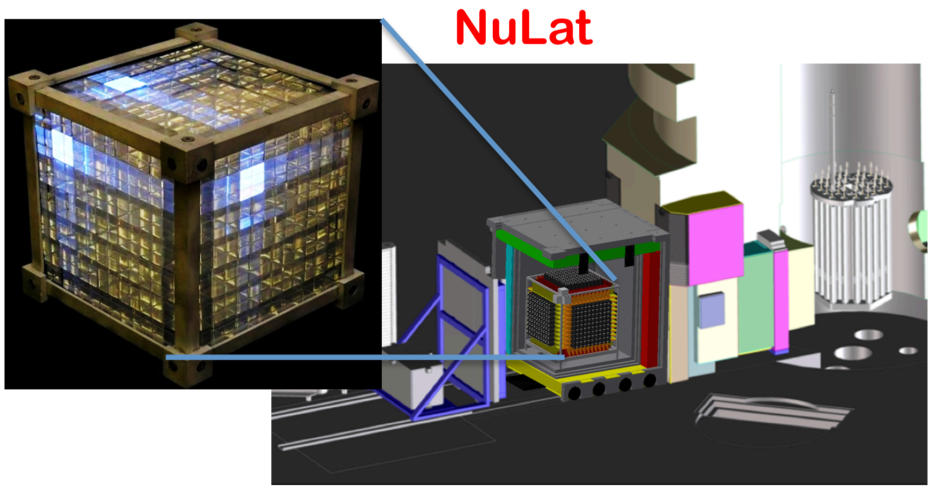
DANSS

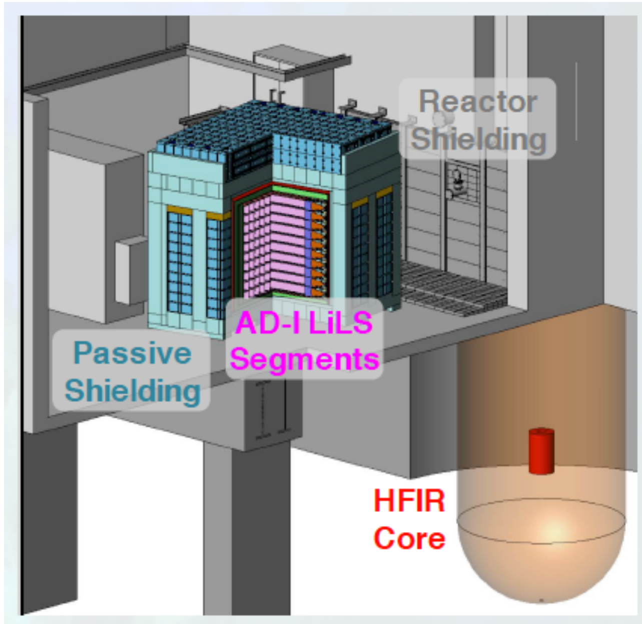
- **Expected sensitivity for 1 year, 95% CL, shape-only analysis**

- **Assumed systematic effects:**
  - **1% on the E scale**
  - **1% Background (~E-2) at one distance from the core**



Highly Segmented – ^{6}Li doped detectors



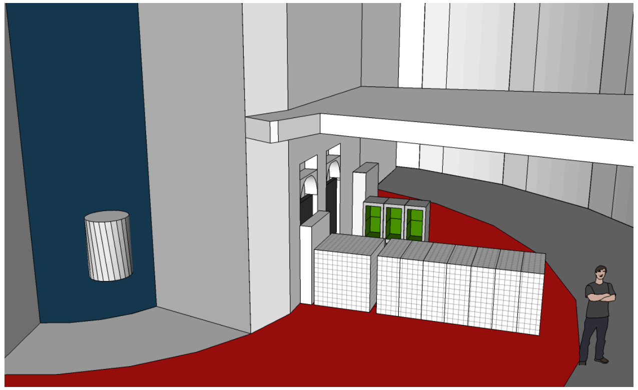


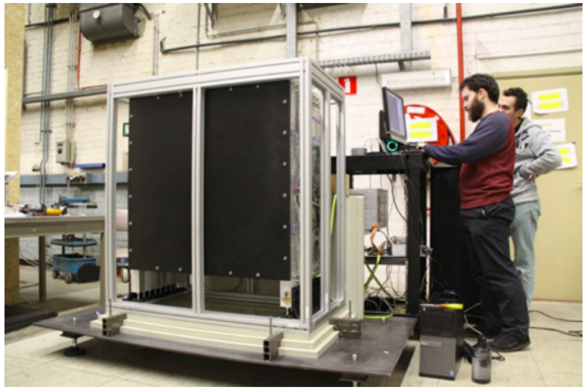
- Finely 3D segmented detector: 15x15x15 6Li-loaded (0.5%) plastic scintillator
- 2.5" cubes spaced by thin air gaps (arXiv: 1501.06935)
- 5x5x5 demonstrator to be tested this fall.

- Oak ridge compact HFIR reactor
- 3t of Li-doped liquid in 120 optical cells

- First phase with near detector 7-10 m in 2017
- Second phase with far det at 15-18 m.

Solid @ BR2



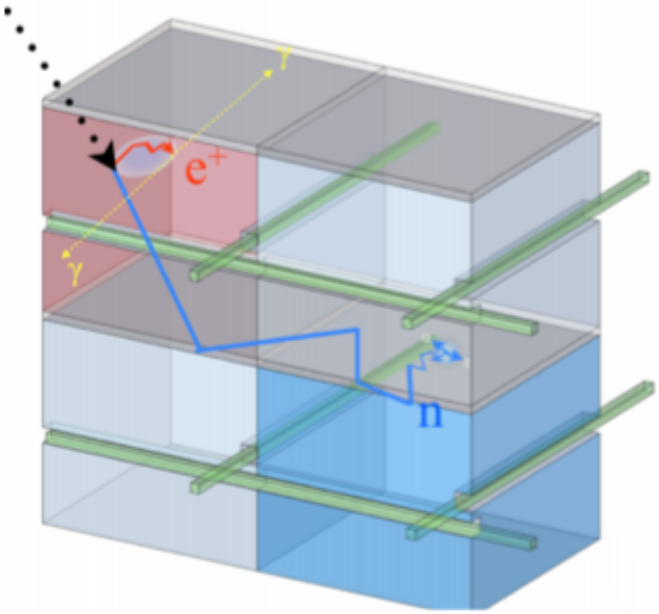


- 60 MW compact core
- baseline range ~ 5.5 - 10 m
- Phase-1, 1.6 t det to be deployed early 2017.

- Highly 3D segmented detector
  - 5x5x5 cm^3 PVT cubes (optically separated)
  - 6LiF:ZnS(Ag) for neutron identification
  - Optical fibers and silicon PMTs

- Event topology used to identify IBDs
  - e+ scintillation E deposit contained
  - e+ annihilation γ's escaping the first cell
  - n-capture near first cell, identified via PSD

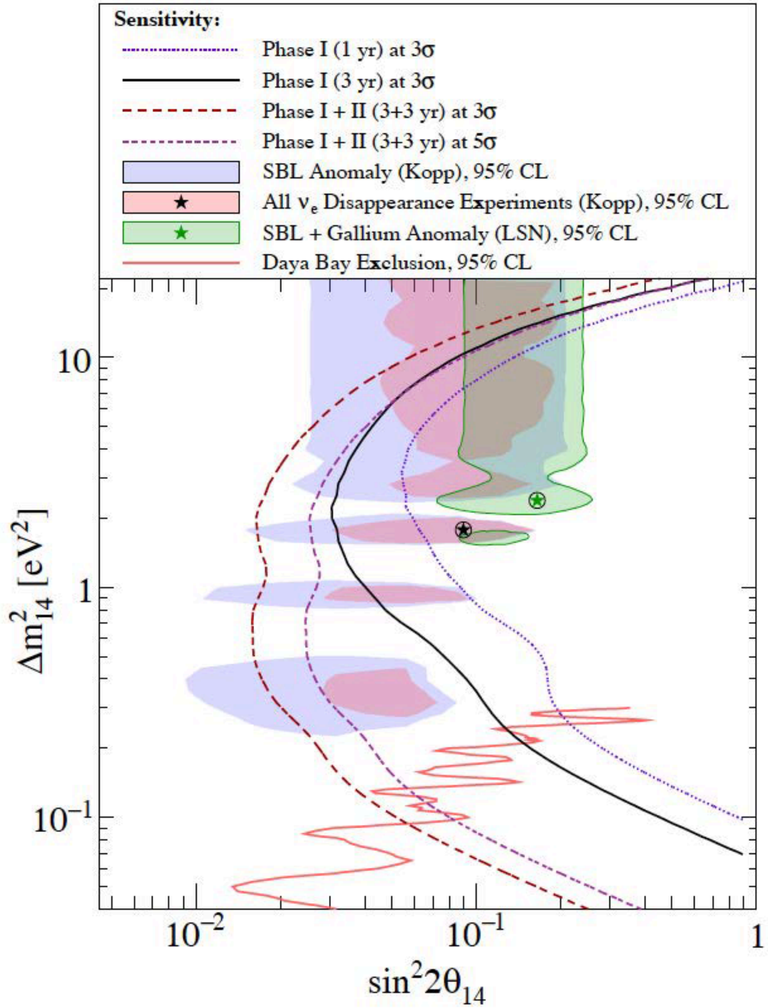
→ Efficient and unique n-capture signal.



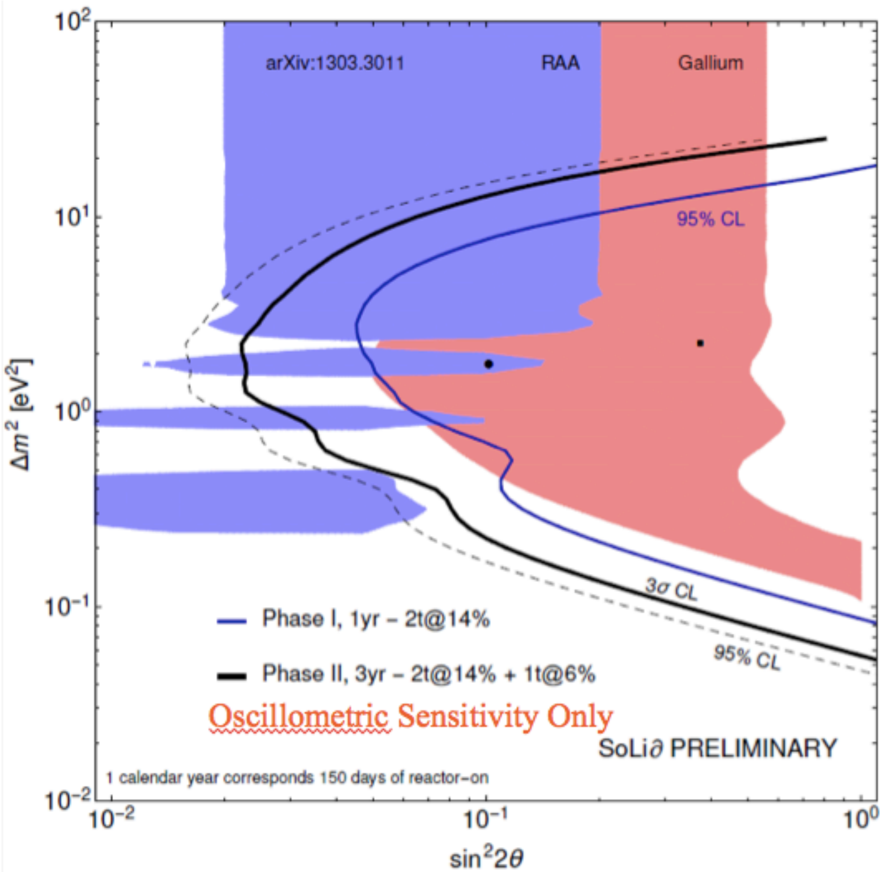
$$n + {}^6\mathrm{Li} \rightarrow {}^3\mathrm{H} + \alpha + 4.78\ \mathrm{MeV}$$

Sensitivities

Prospect



Soliδ

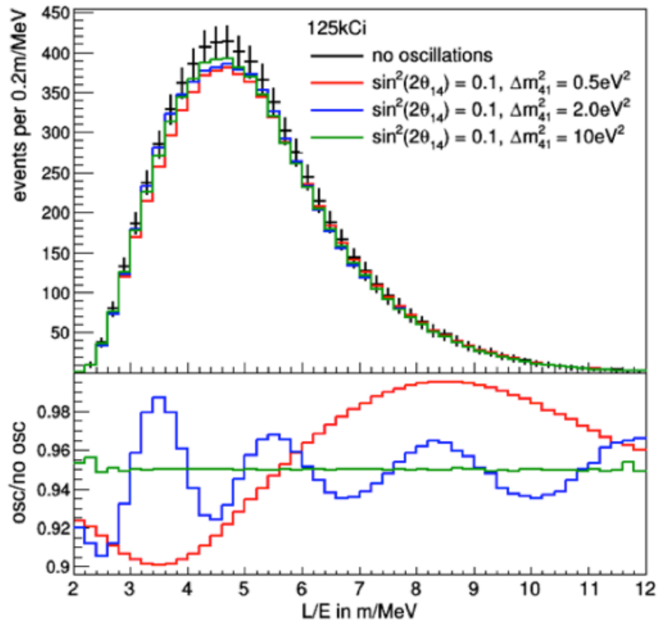


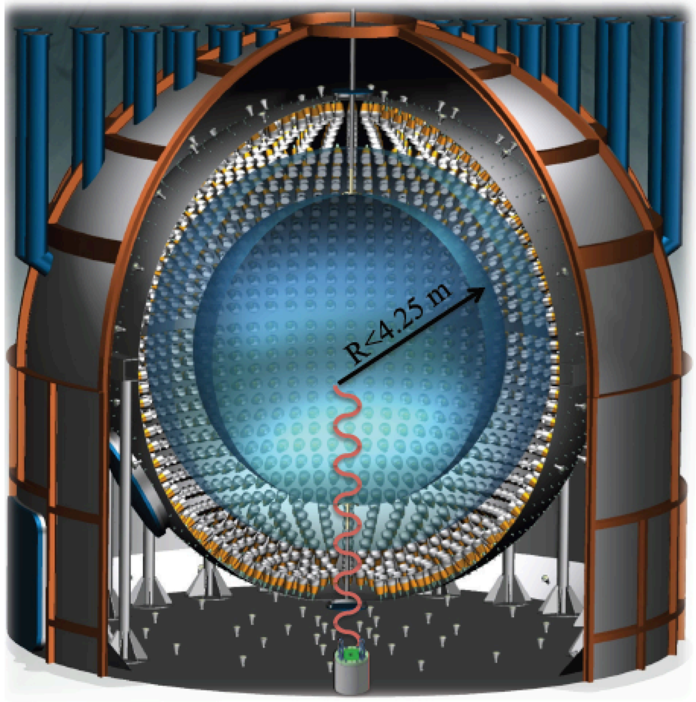
Sterile ν Search with a source: SOX

- **Strong physics case of a quasi background-free measurement**

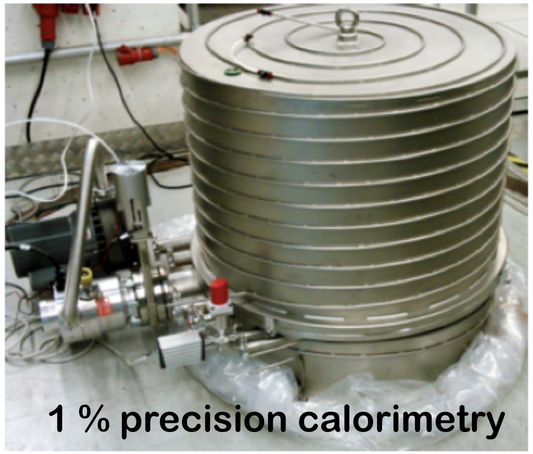
- **SOX uses a 144Ce source ($\beta-$, $T_{1/2}$=285 days) and the BoreXino detector**
- **LS purification**
- **Good spatial (12 cm @ 2 MeV) and energy resolution (~3.5% @ 2 MeV)**

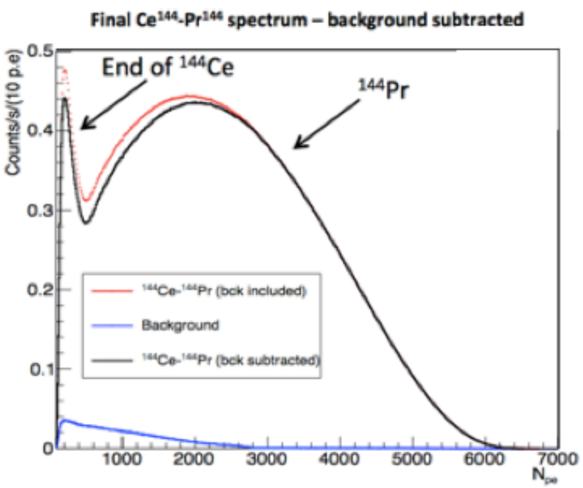
- **Few PBq activity required for 10^4 evts in 1.5 y**





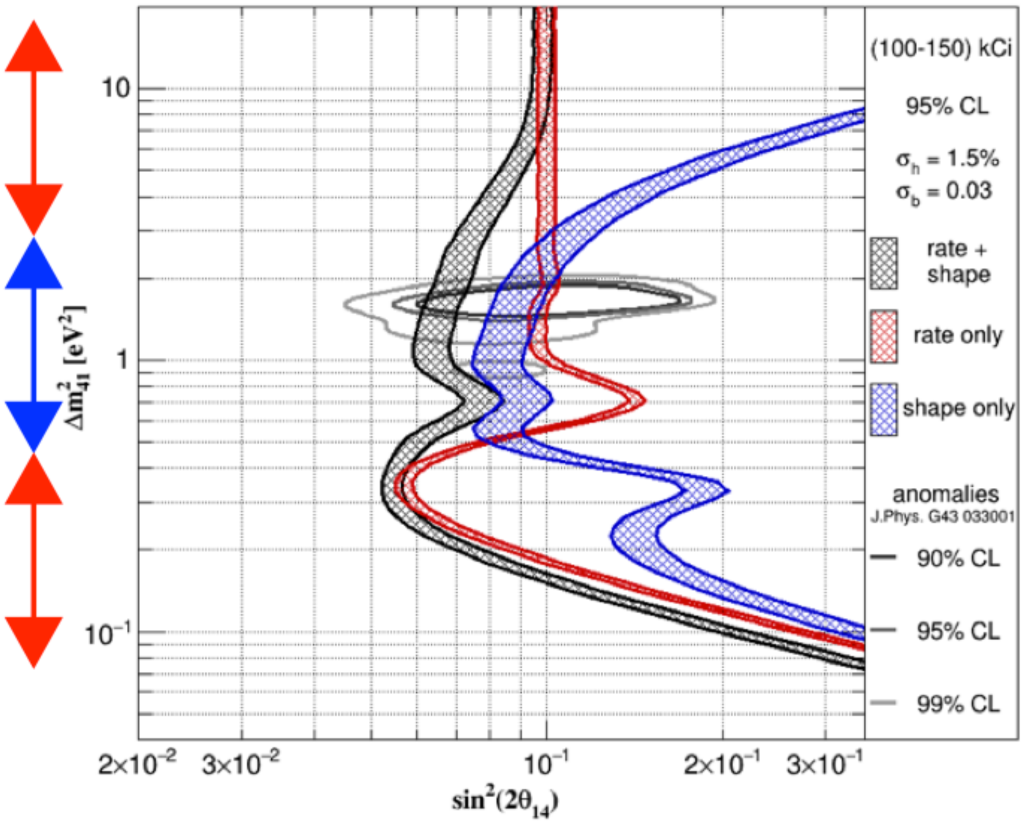
Sterile ν Search with a source: SOX





Accurate spectrum shape measurement

Sensitivity

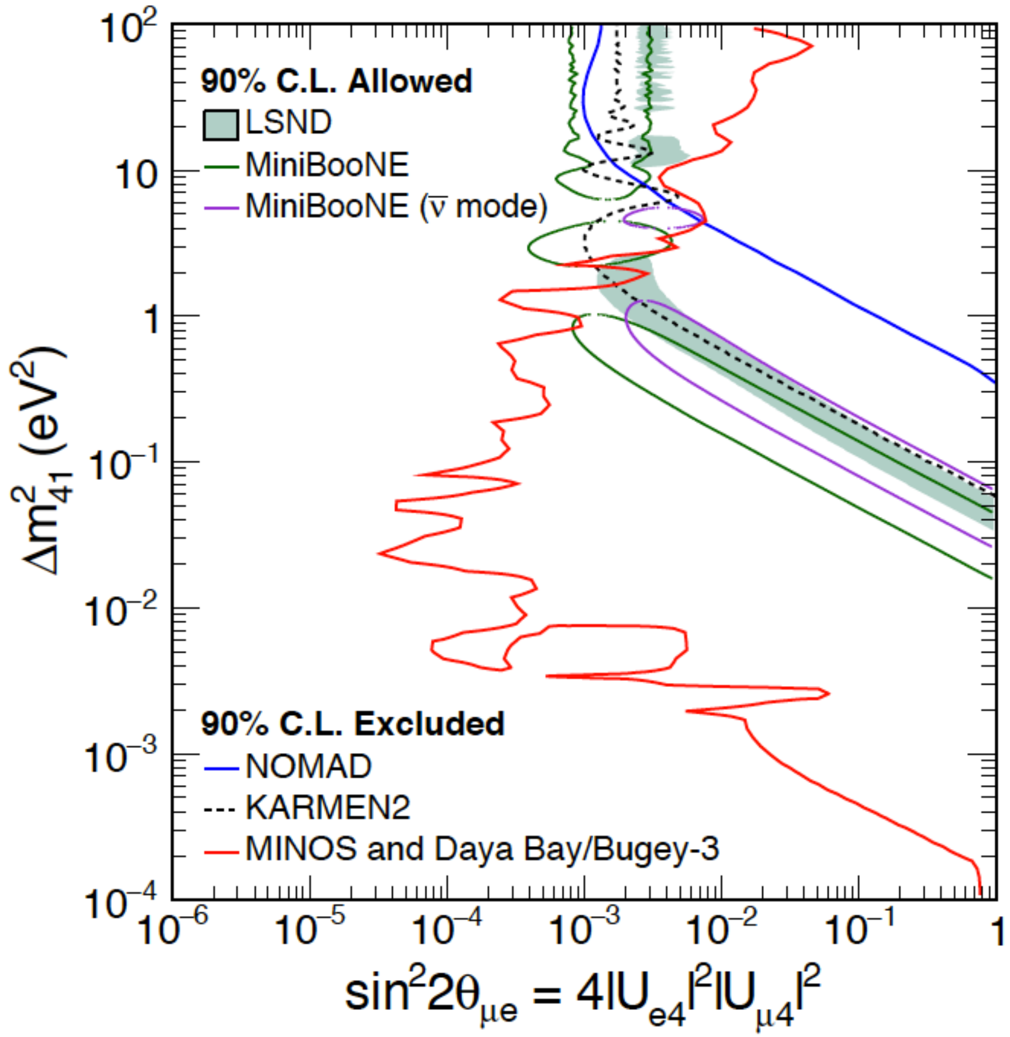


Source expected end of 2017

Conclusions

- **Exciting time of the sterile neutrino search with many running and upcoming experiments.**
- **Recent Ice Cube null result strengthens the tension between appearance and disappearance data in the LSND anomaly region.**
- **The Reactor Anomaly region will be covered by many experiments with fairly different technologies.**
- **Accurate disappearance measurements very sensitive to systematics.**
- **Precision measurements of the 235U reactor spectrum at research reactors will provide new tests and constrains to the reactor models.**

Daya Bay



90% C.L. Allowed
LSND
MiniBooNE
MiniBooNE ($\bar{\nu}$ mode)
90% C.L. Excluded
NOMAD
KARMEN2
MINOS and Daya Bay/Bugey-3
Δm^2_{41} (eV^2)
$\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2$
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1