Very short baseline reactor neutrino experiments

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Christian Buck
MPIK Heidelberg

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

MAX-PLANCK-GESELLSCHAFT

Reactor neutrinos

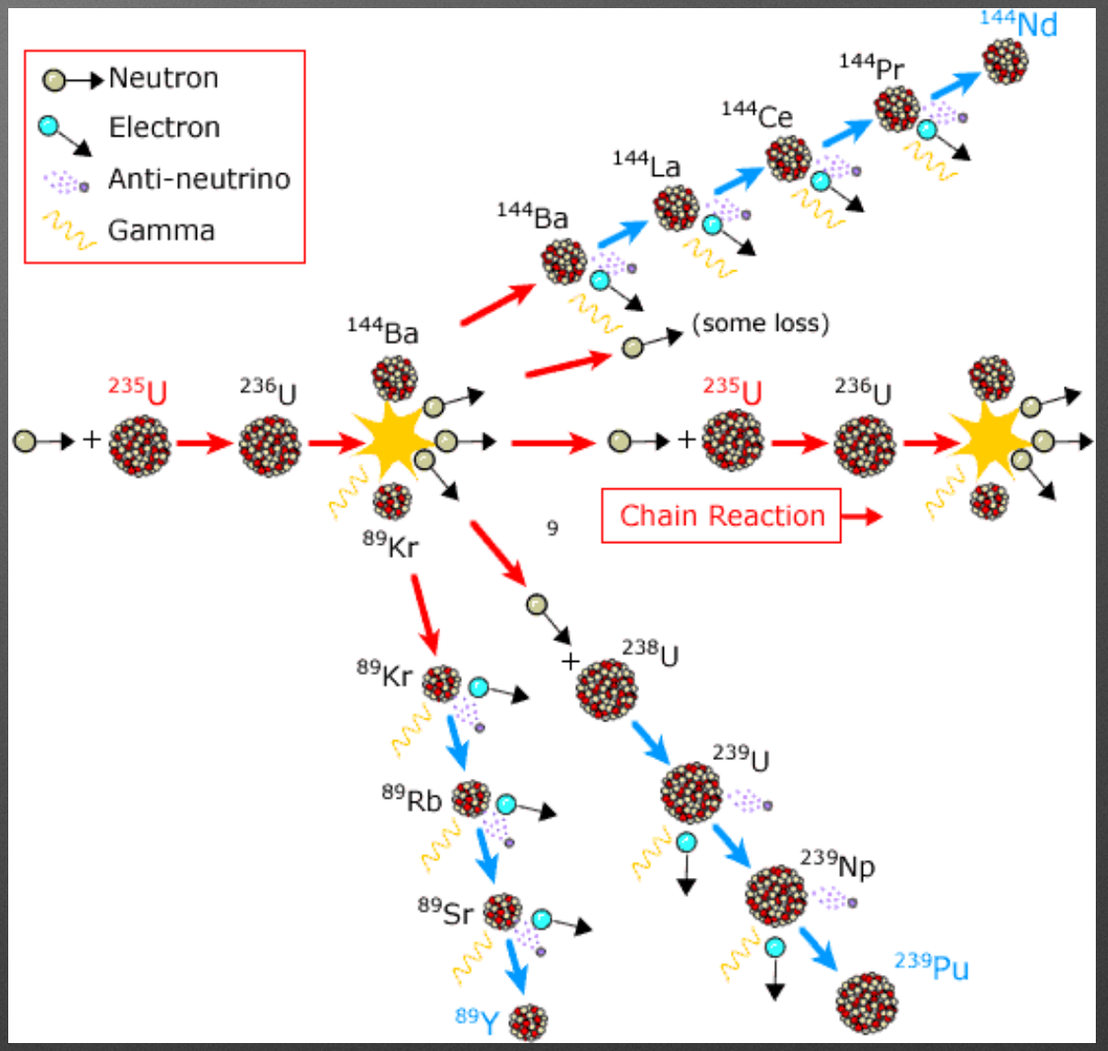
Nuclear power

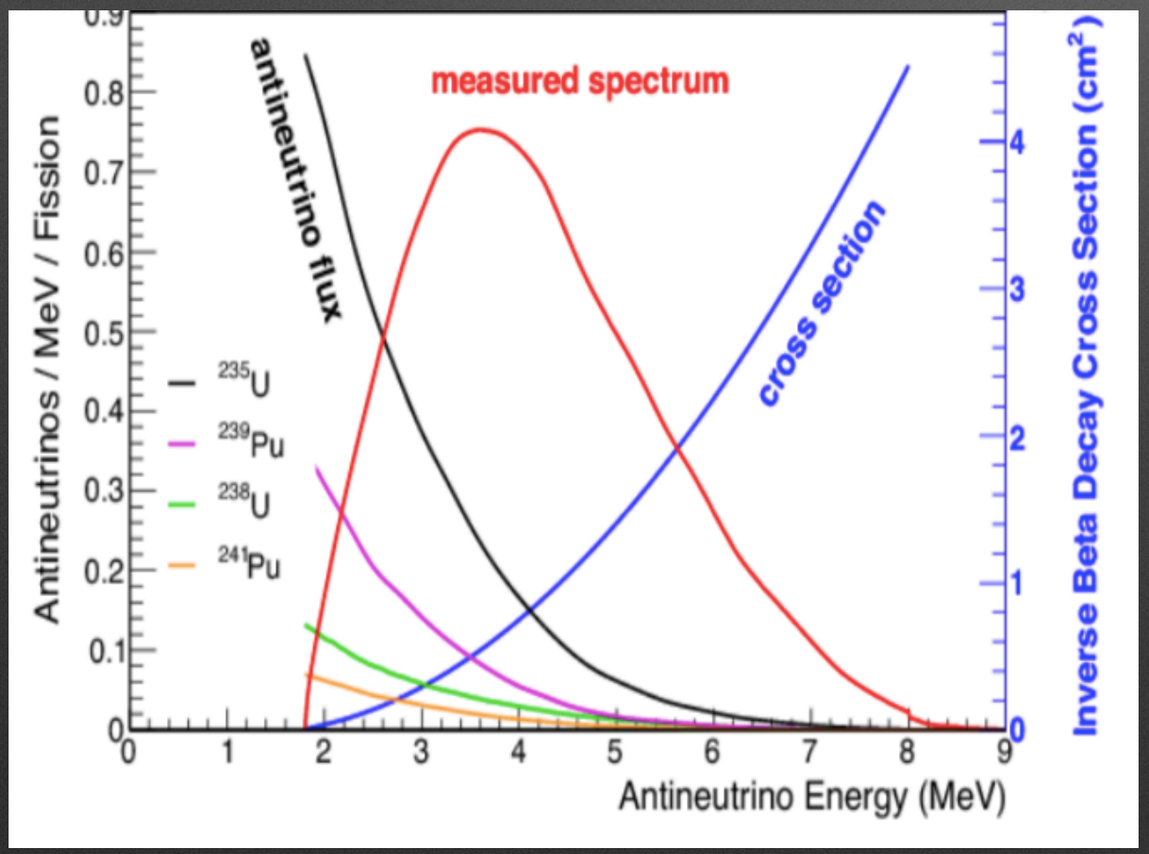
$$N_\nu^{exp}(t) \propto \frac{1}{L^2} \cdot \frac{P(t)}{\langle E_f \rangle} \cdot \langle \sigma_f \rangle$$

distance

Energy / fission

Mean cross section / fission





>99% from ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

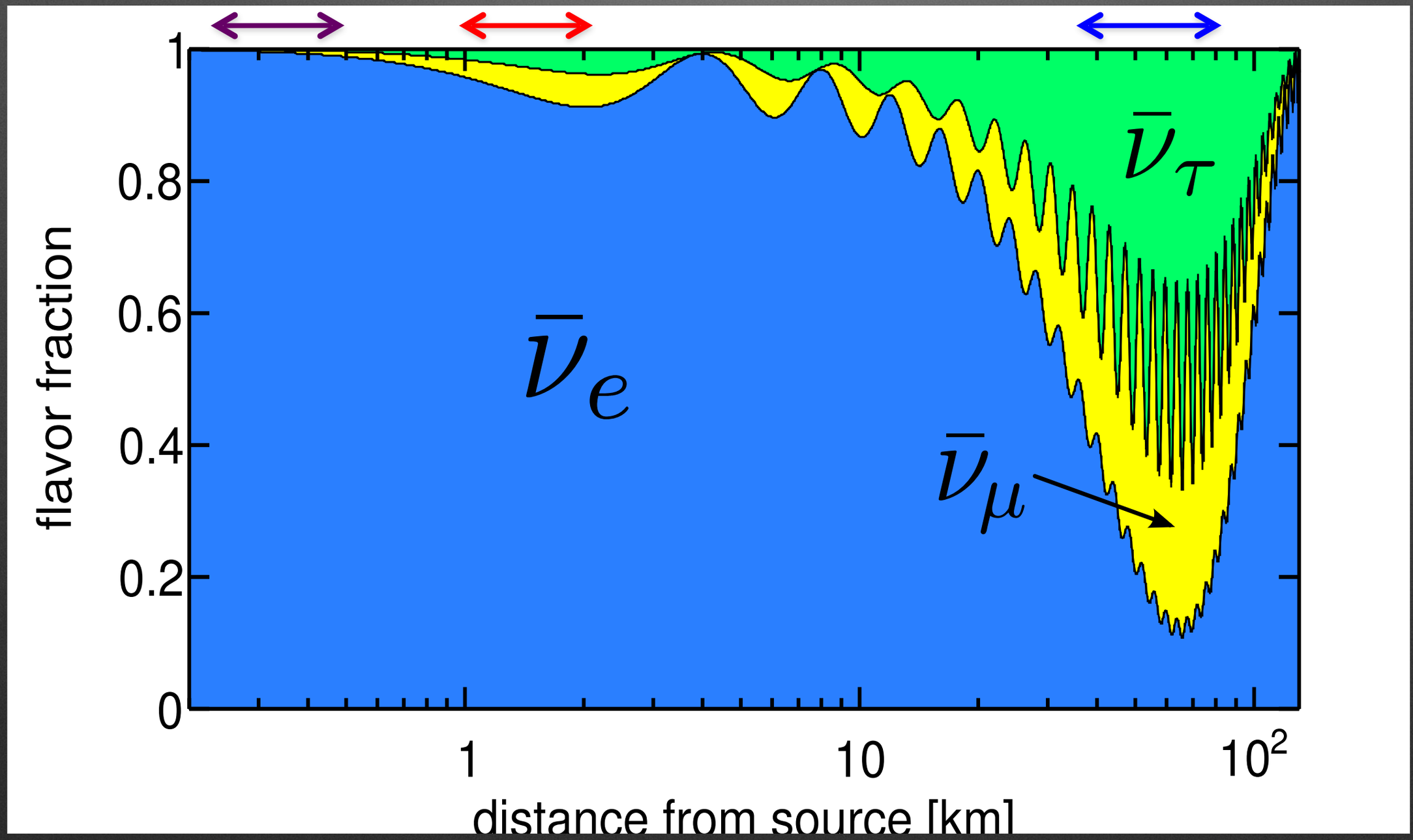
- Purely electron antineutrinos
- More than 10^{20} / (GW s) !
- Energies up to 10 MeV

Neutrino Oscillations at reactors

Short baseline experiments

θ_{13} experiments
Double Chooz
Daya Bay, RENO

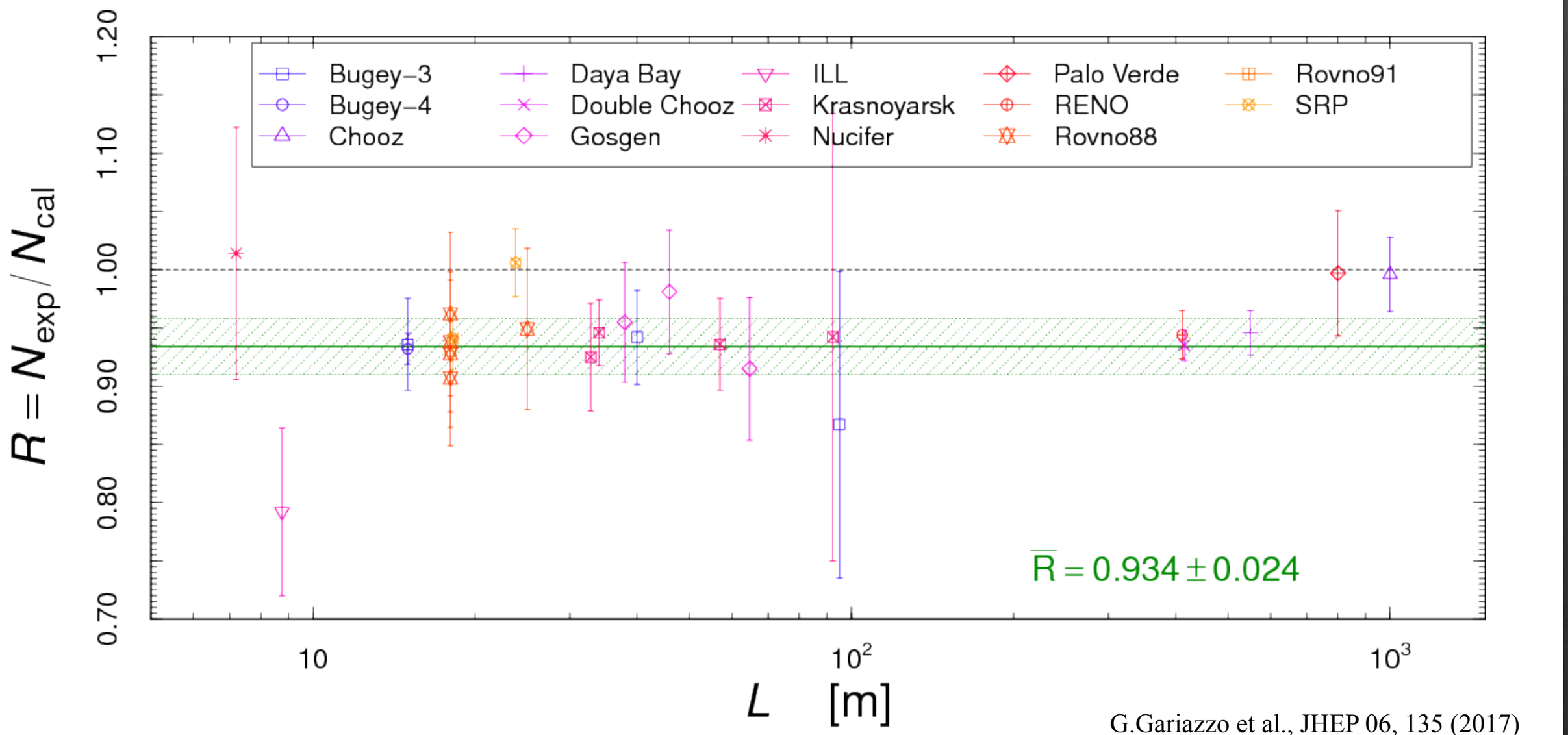
„Solar“ θ_{12}:
KamLAND,
JUNO



4 MeV
neutrinos

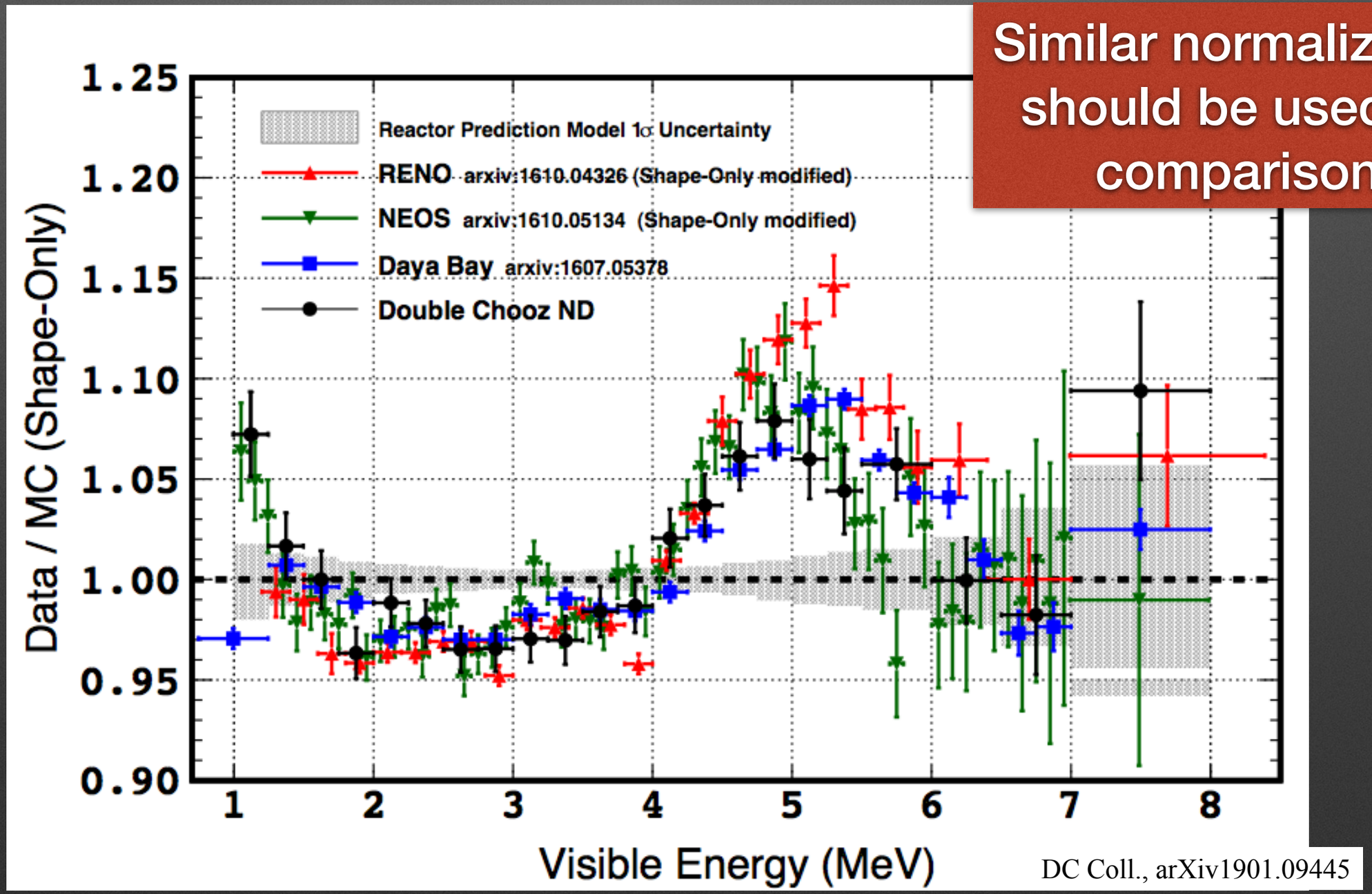
Reactor Antinneutrino Anomaly

2011: Updates on conversion from measured β-spectra at ILL (Müller et al., Huber) in context of θ_{13} experiments



G.Gariazzo et al., JHEP 06, 135 (2017)

Antineutrino spectrum



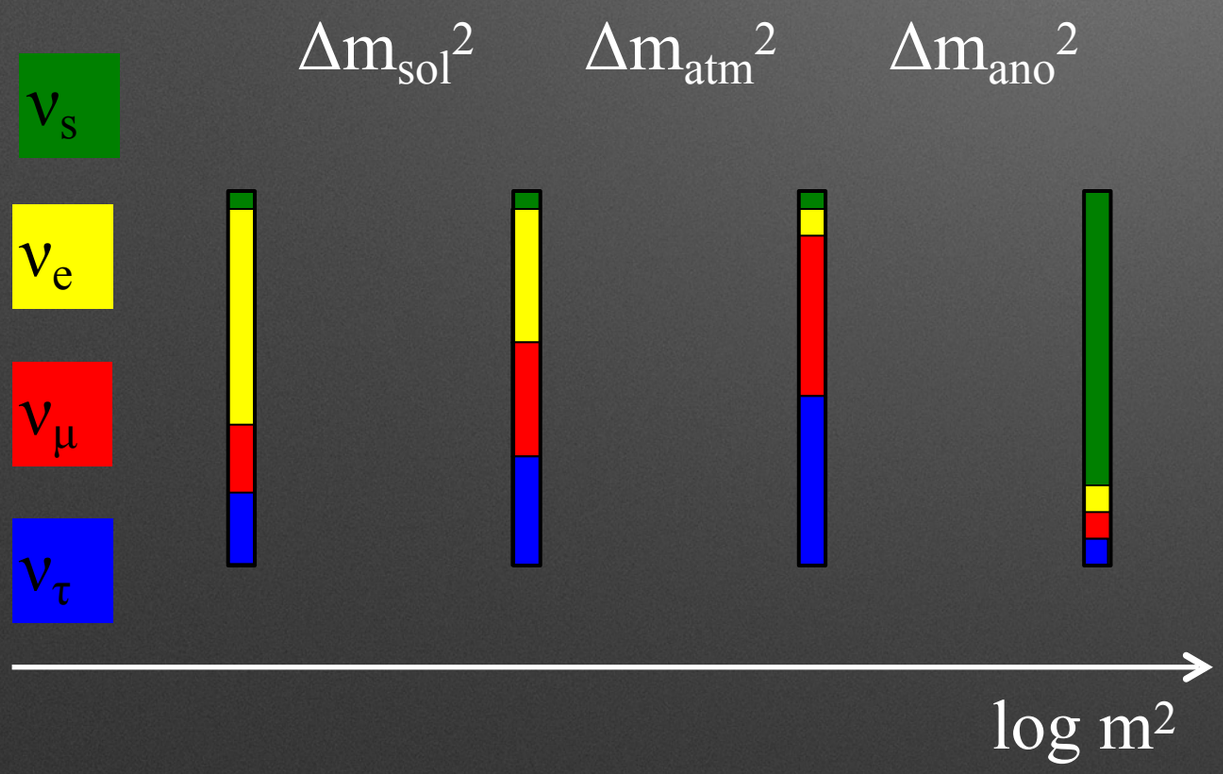
Similar normalization should be used for comparison!

DC Coll., arXiv1901.09445

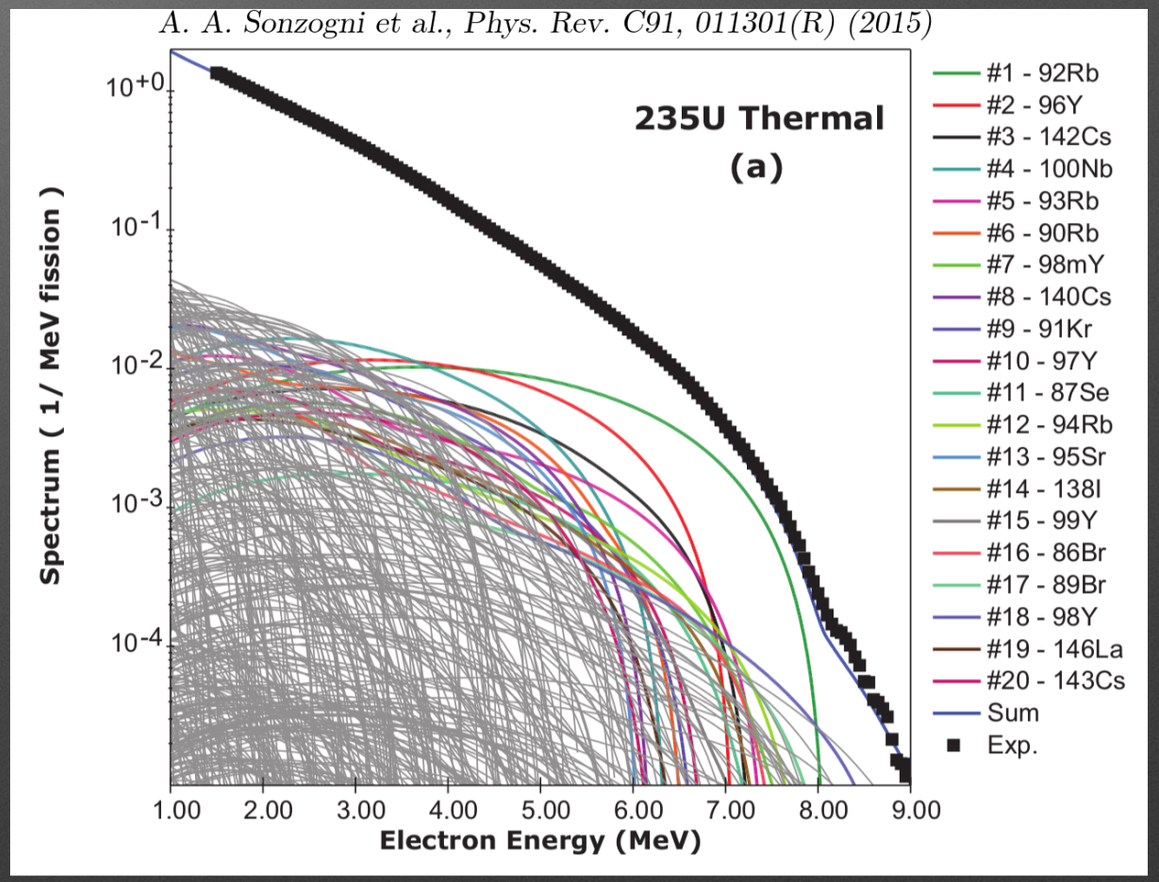
Excess events in 4 – 6 MeV region (Double Chooz, Daya Bay, RENO, NEOS)

Explanations?

Neutrino physics vs Nuclear physics



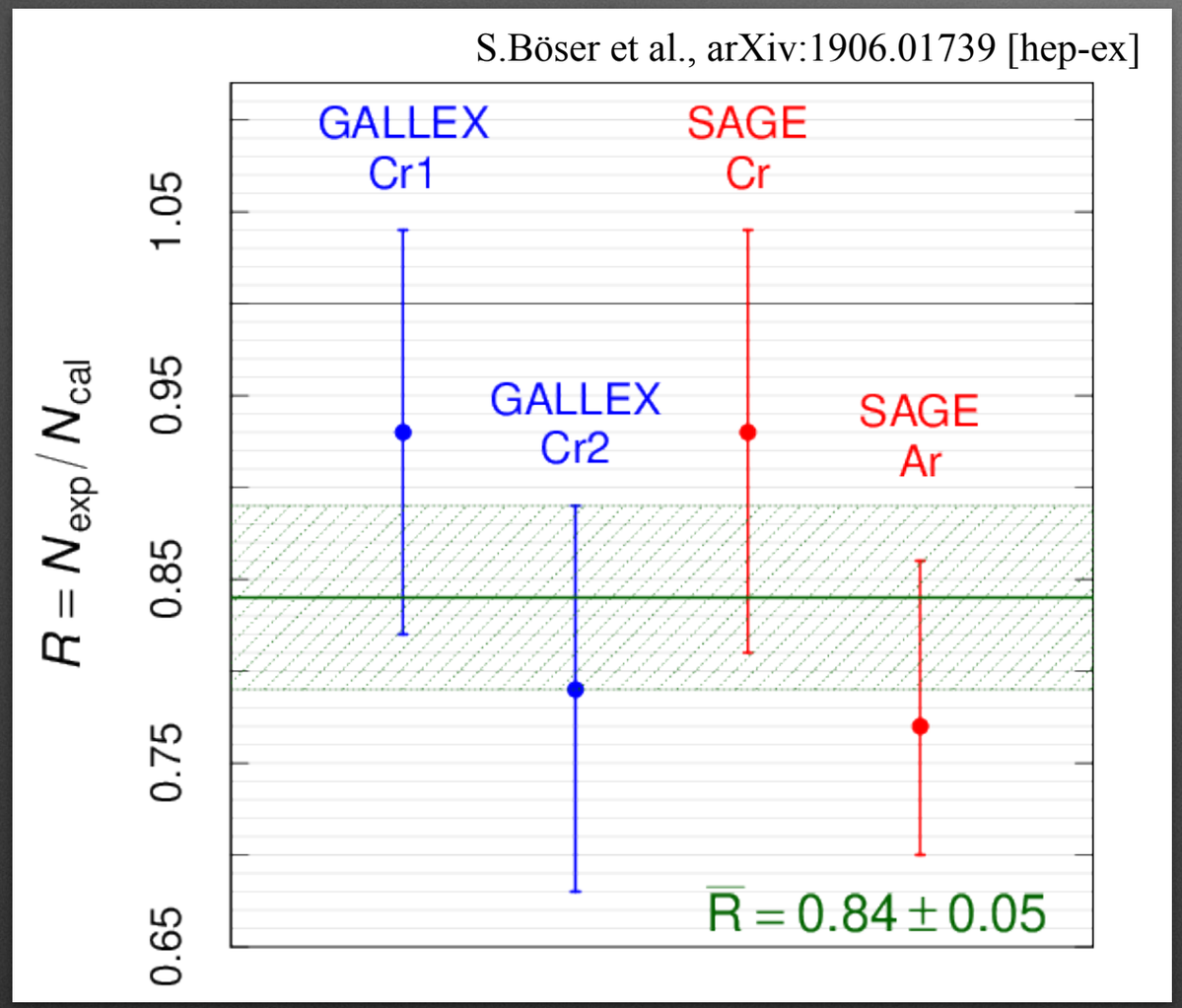
Sterile neutrino possible explanation for rate anomaly, but not spectral distortion



- Summation method: missing data
- Conversion: relying on single meas.
- ~10000 branches/isotope and non-trivial corrections

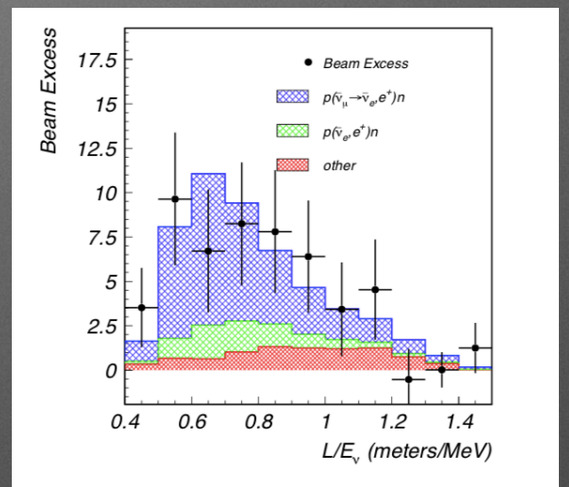
More „anomalies“

Gallium

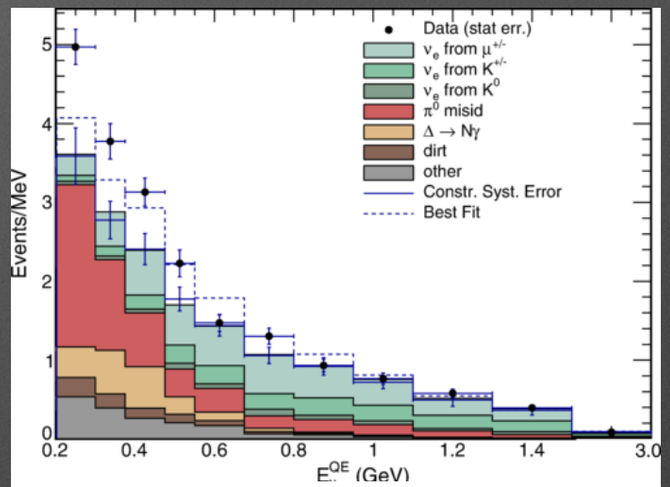


Most recent cross section calculation reduce significance from 3.0 to 2.3σ (J.Kostensalo et al., Phys.Lett.B (2019) 542)

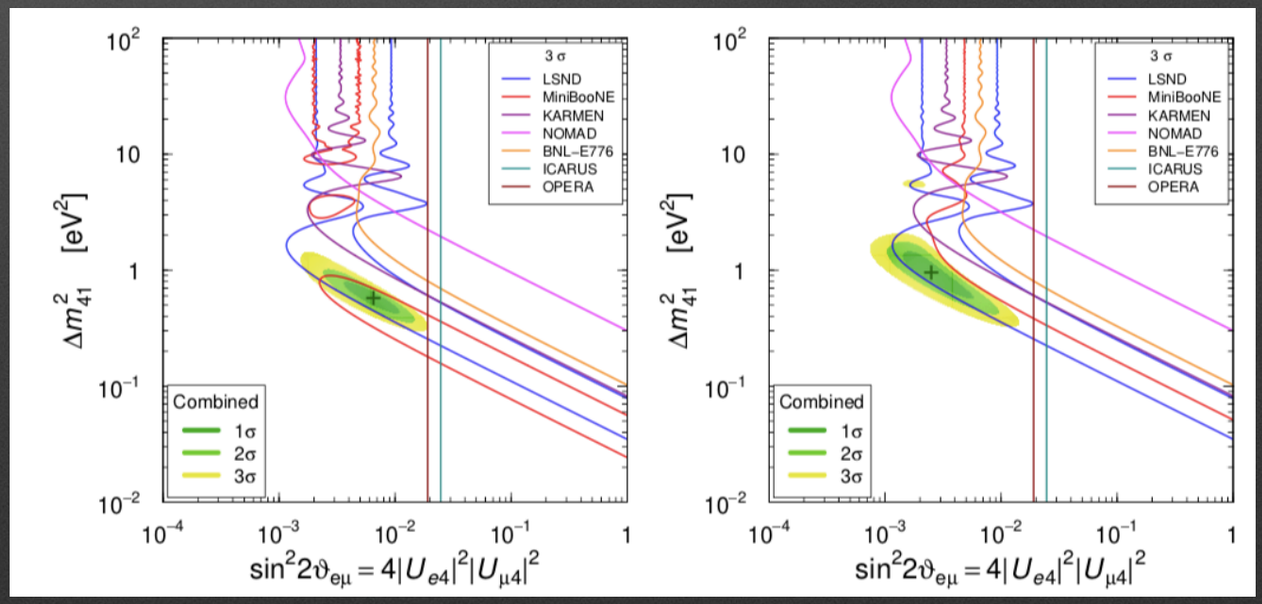
LSND/MiniBooNE



LSND Coll., PRD 64 (2001) 112007

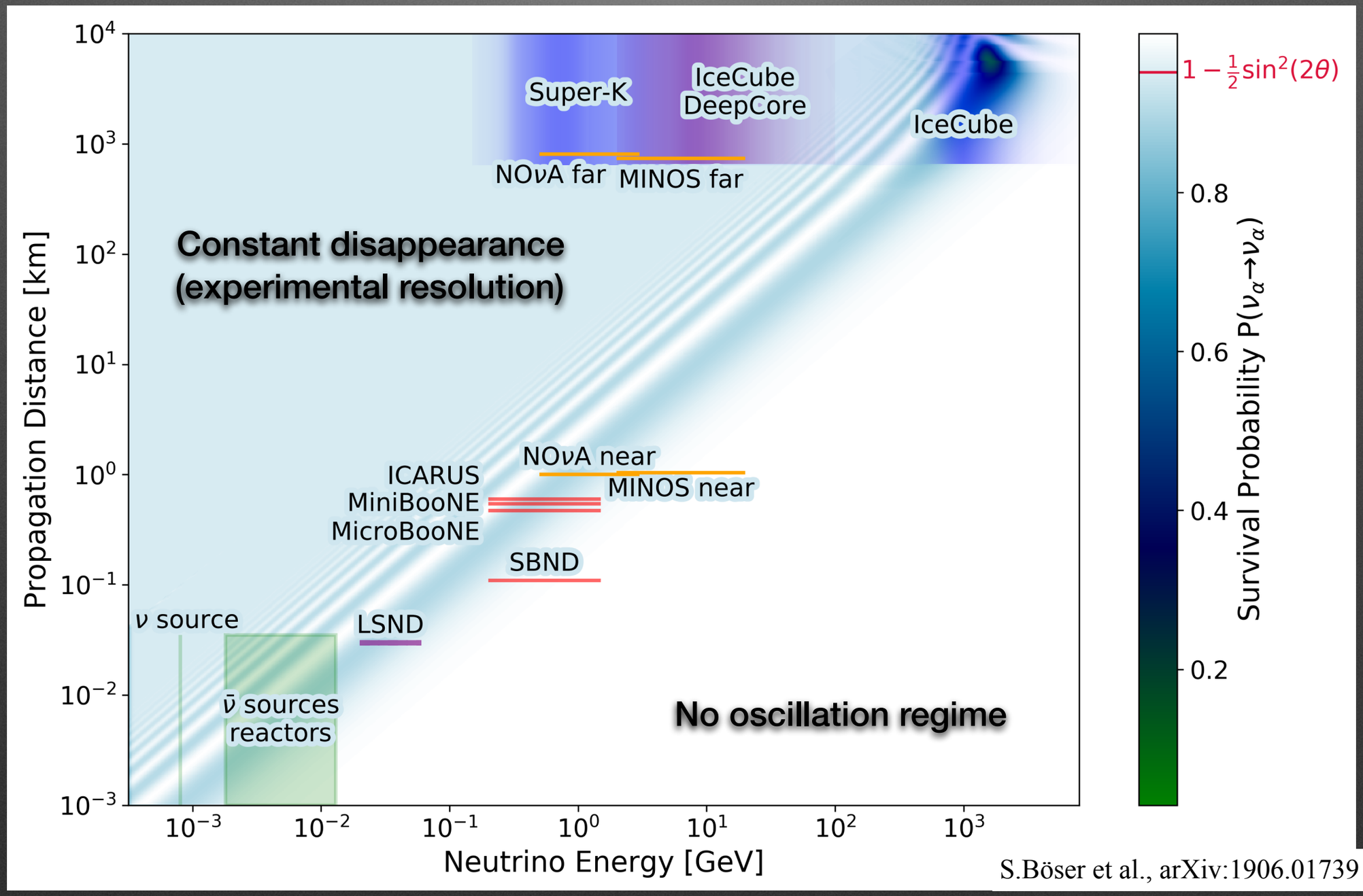


MiniBooNE Coll., PRL 121 (2018) 221801



Combined w/ and w/o low E MiniBooNE data (C.Giunti, T.Lasserre, arXiv1901.08330)

Sterile neutrino searches



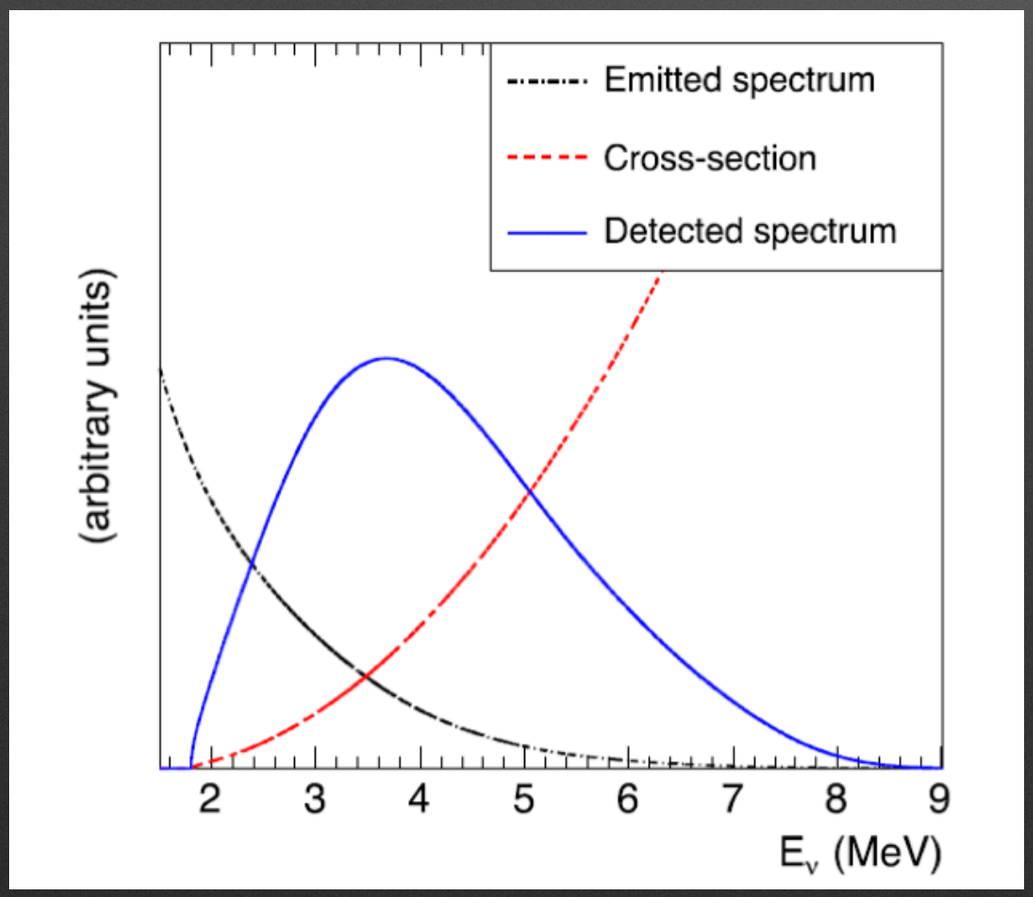
S.Böser et al., arXiv:1906.01739 [hep-ex]

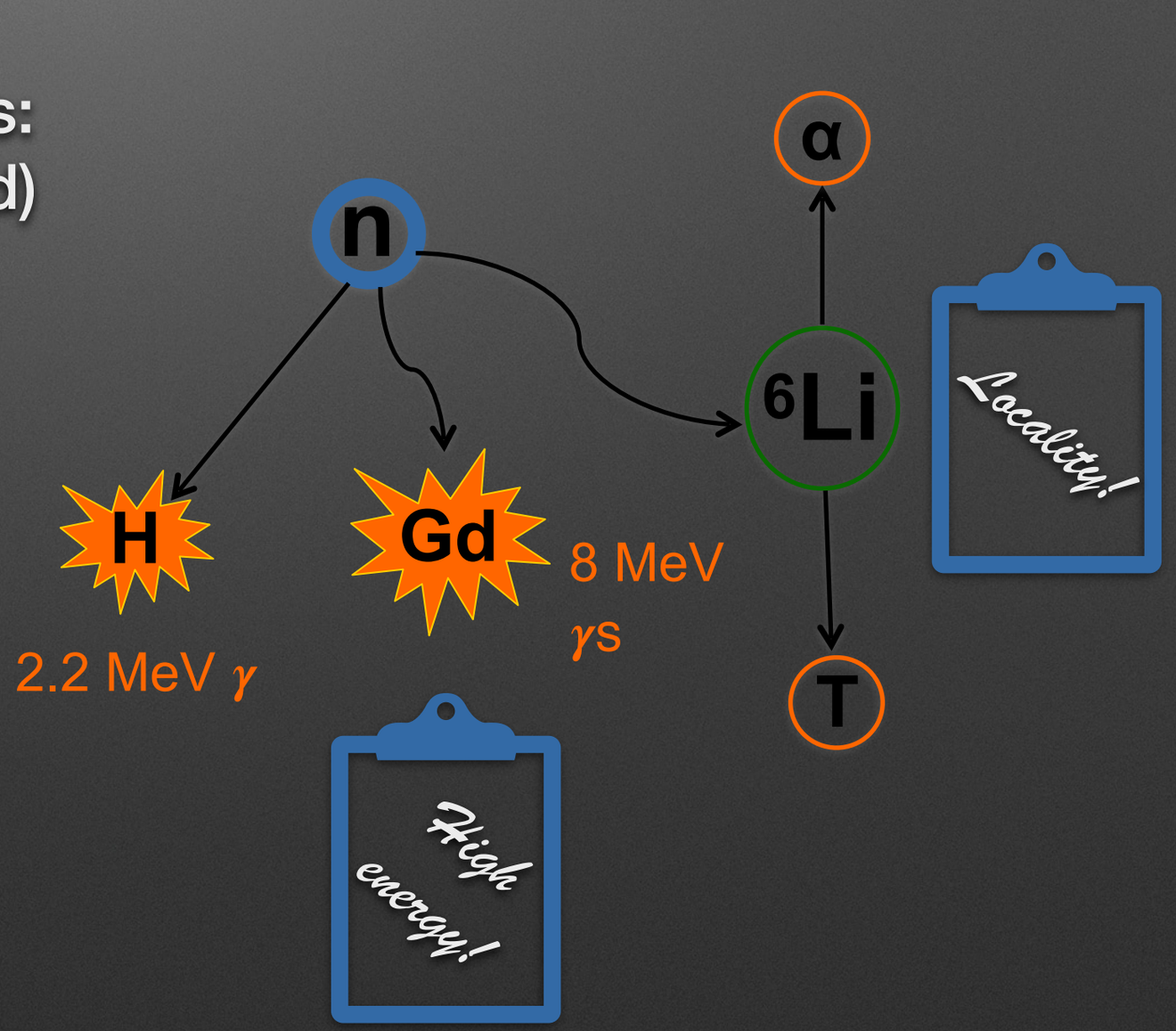
Oscillation probability in 2 flavor model for $\Delta m \cong 1 eV^2$

Detection principle

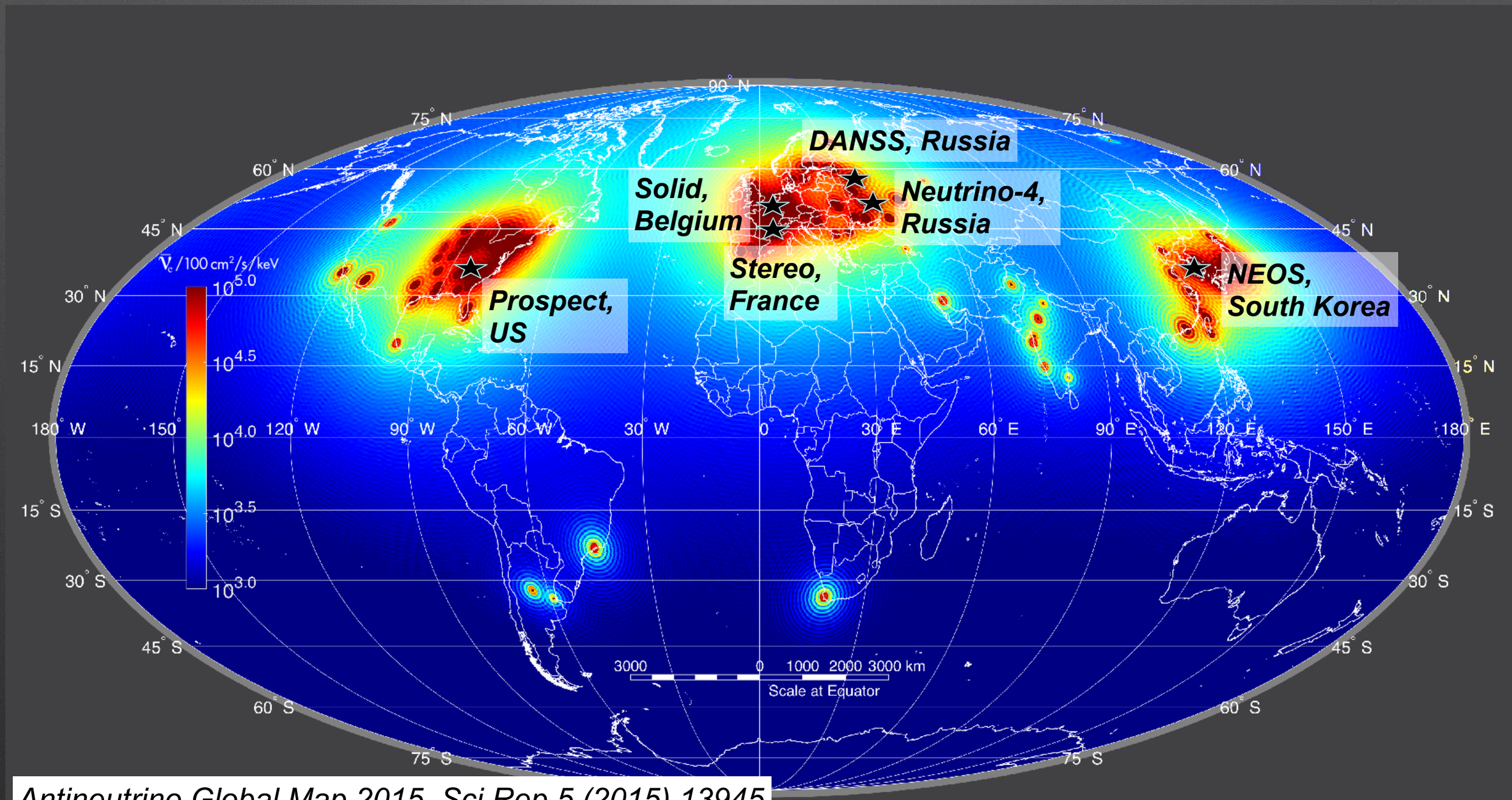
- Inverse beta decay on protons (organic scintillators)
- Coincidence signal of prompt positron and delayed neutron
- Energy threshold: 1.8 MeV
- Detector technology since Reines: organic scintillators (metal loaded)

$$\overline{\nu_e} + p \rightarrow e^+ + n$$





Reactor experiments worldwide

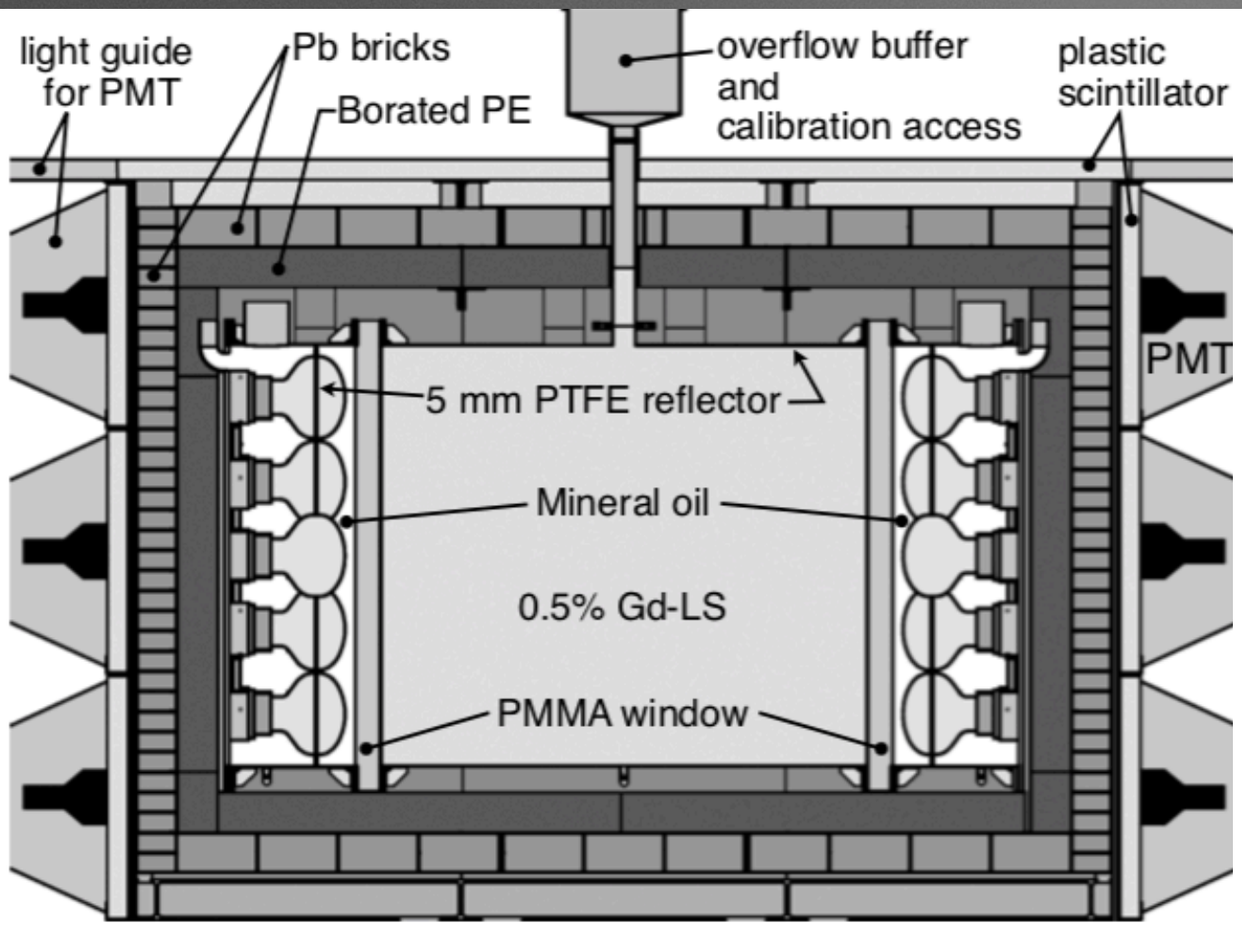


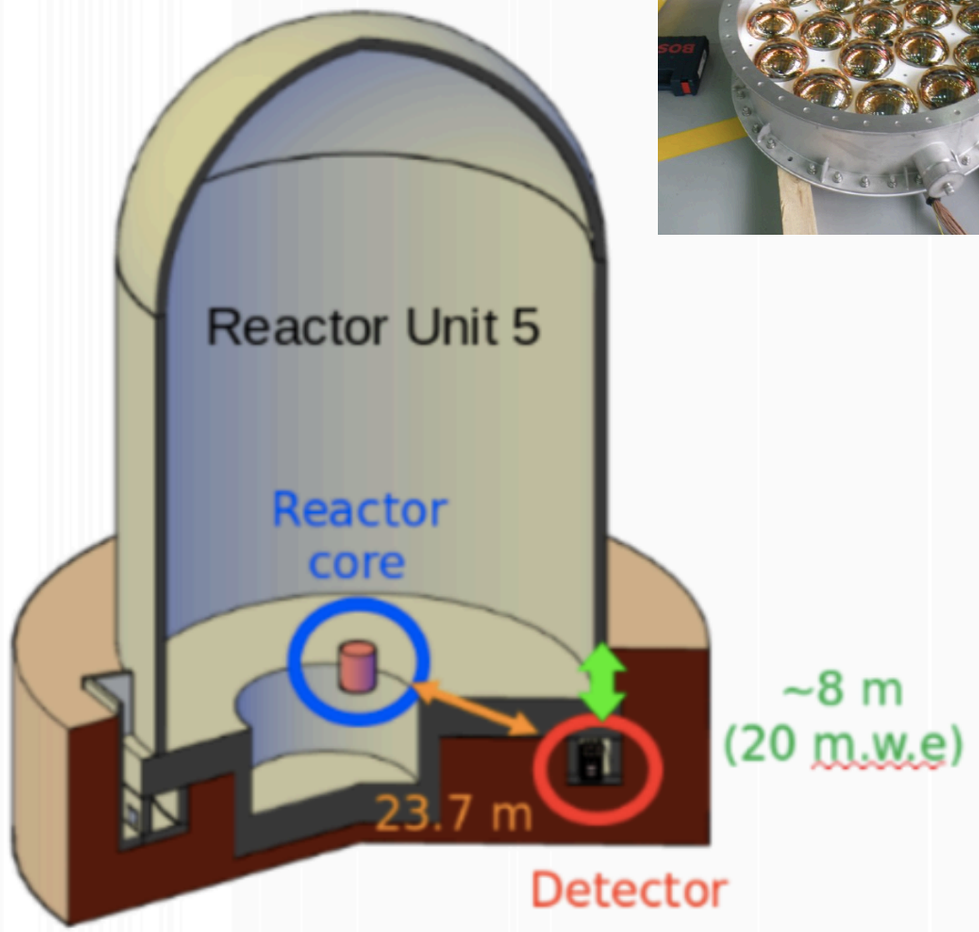
Antineutrino Global Map 2015, Sci.Rep.5 (2015) 13945

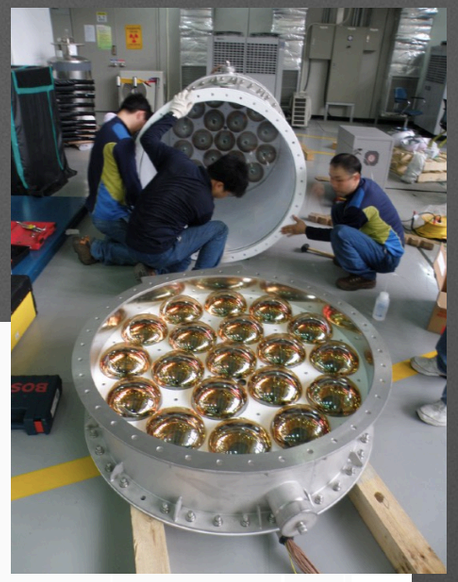
Comparison of experiments

Experiment	P_{th} (MW)	U enr.	L (m)	$M_{targ.}$ (t)	Tech.	Seg.	Dep. (mwe)	S/N
NEOS	2700	LEU	24	1	Gd-LS	N	20	22
DANSS	3100	LEU	10-12	0.9	Gd-PS	Y	50	≈20
Neutrino4	100	HEU	6-11	1.5	Gd-LS	Y	5-10	<1
STEREO	57	HEU	9-11	1.7	Gd-LS	Y	15	≈1
SoLid	80	HEU	6-9	1.6	^{6}Li-PS	Y	10	0.3
Prospect	85	HEU	7-9	4	^{6}Li-LS	Y	<1	> 1

NEOS setup

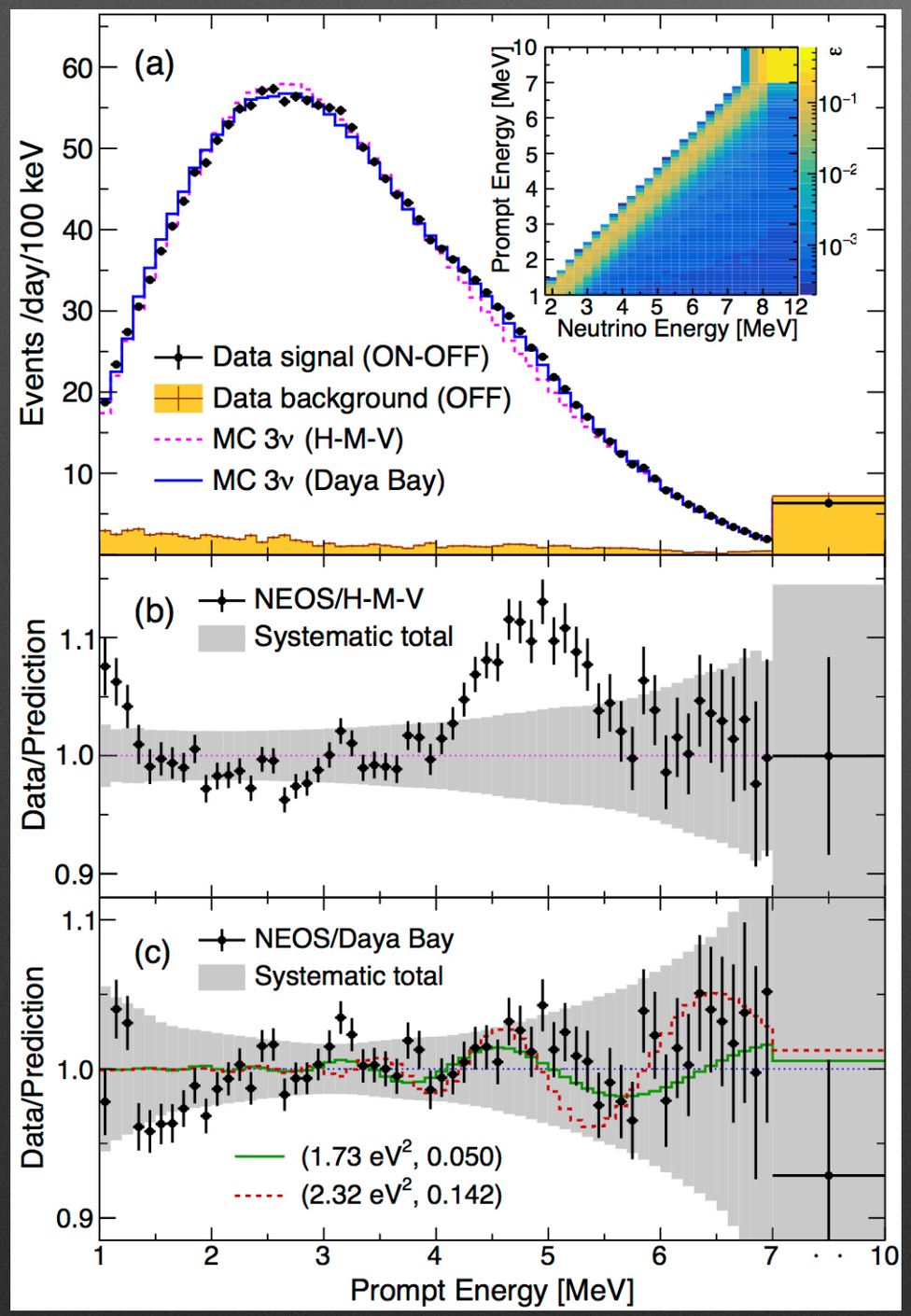


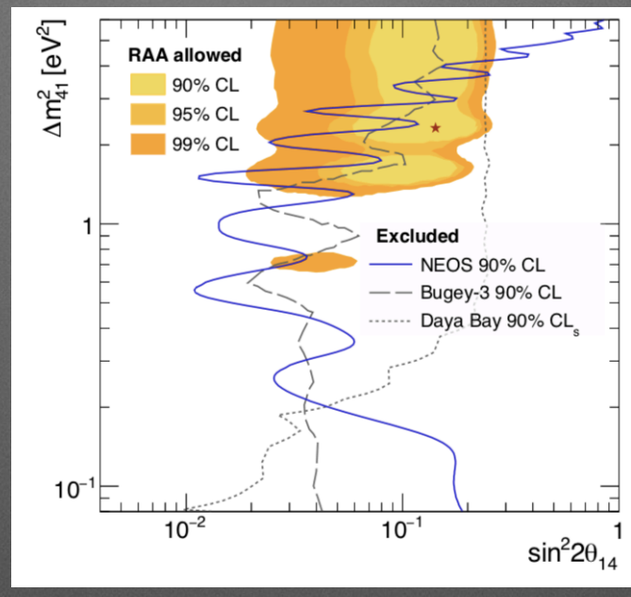


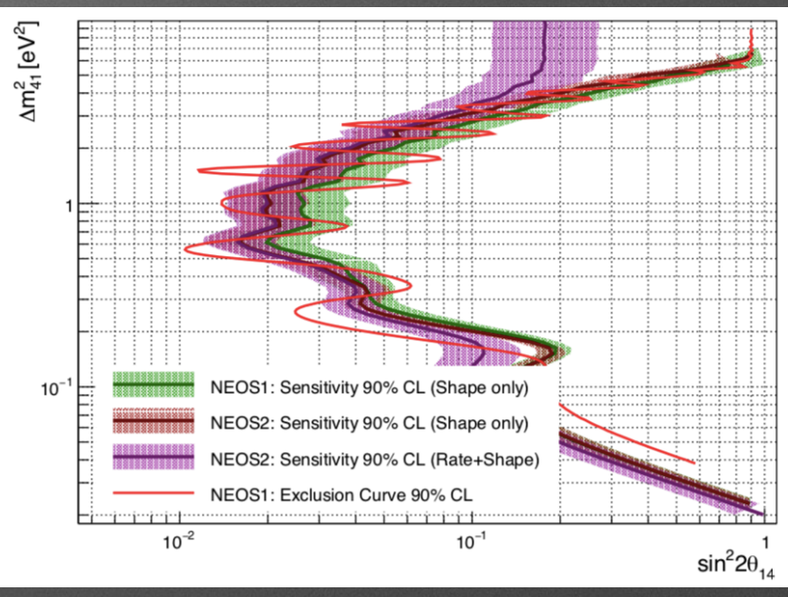


- Hanbit Nuclear Power Plant (2.8 GW), Yeonggwang, Korea (RENO site)
- Phase I: Sep 2015 - May 2016 (180/46 live days with reactor on/off)
- Phase II: Running since Sep 2018 (goal 500 live days, full cycle)

NEOS results



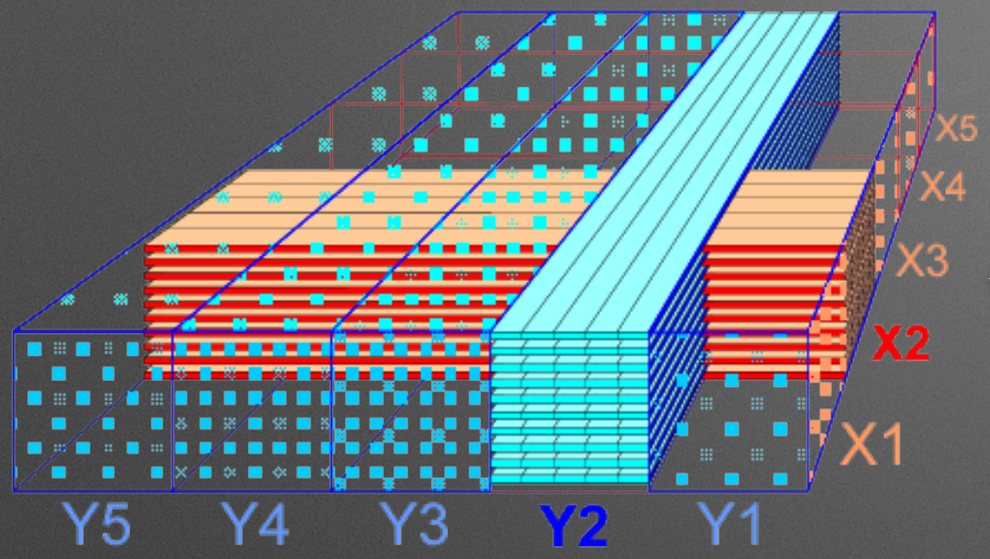




NEOS Collaboration, PRL 118, 121802 (2017)

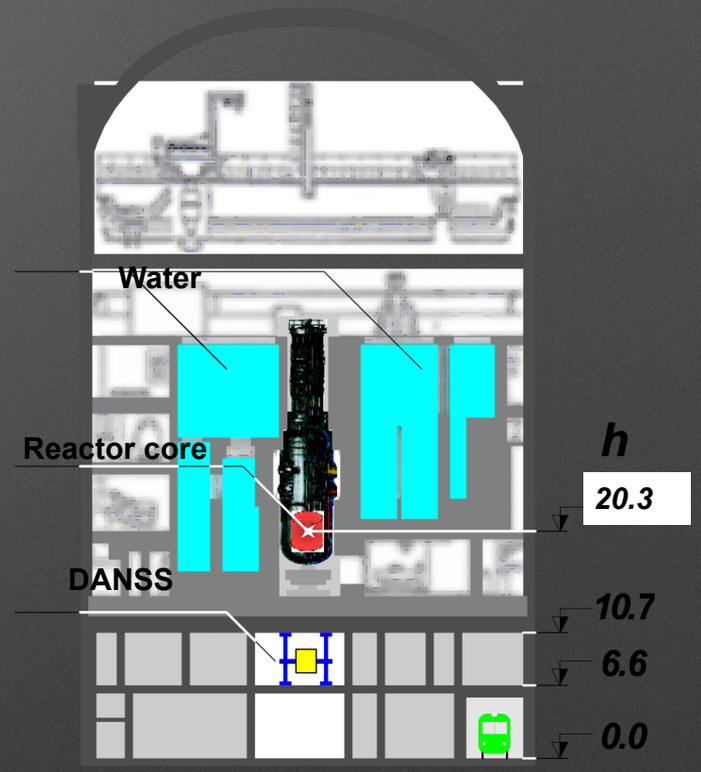
- Phase I: Large part of RAA parameter space excluded; Best fit Δm=1.73 eV², $\sin^2(2\theta)$=0.05
- Phase II: Neutrino flux vs. fuel evolution (sterile neutrino scenario isotope independent suppression)

DANSS setup



One out of five sections

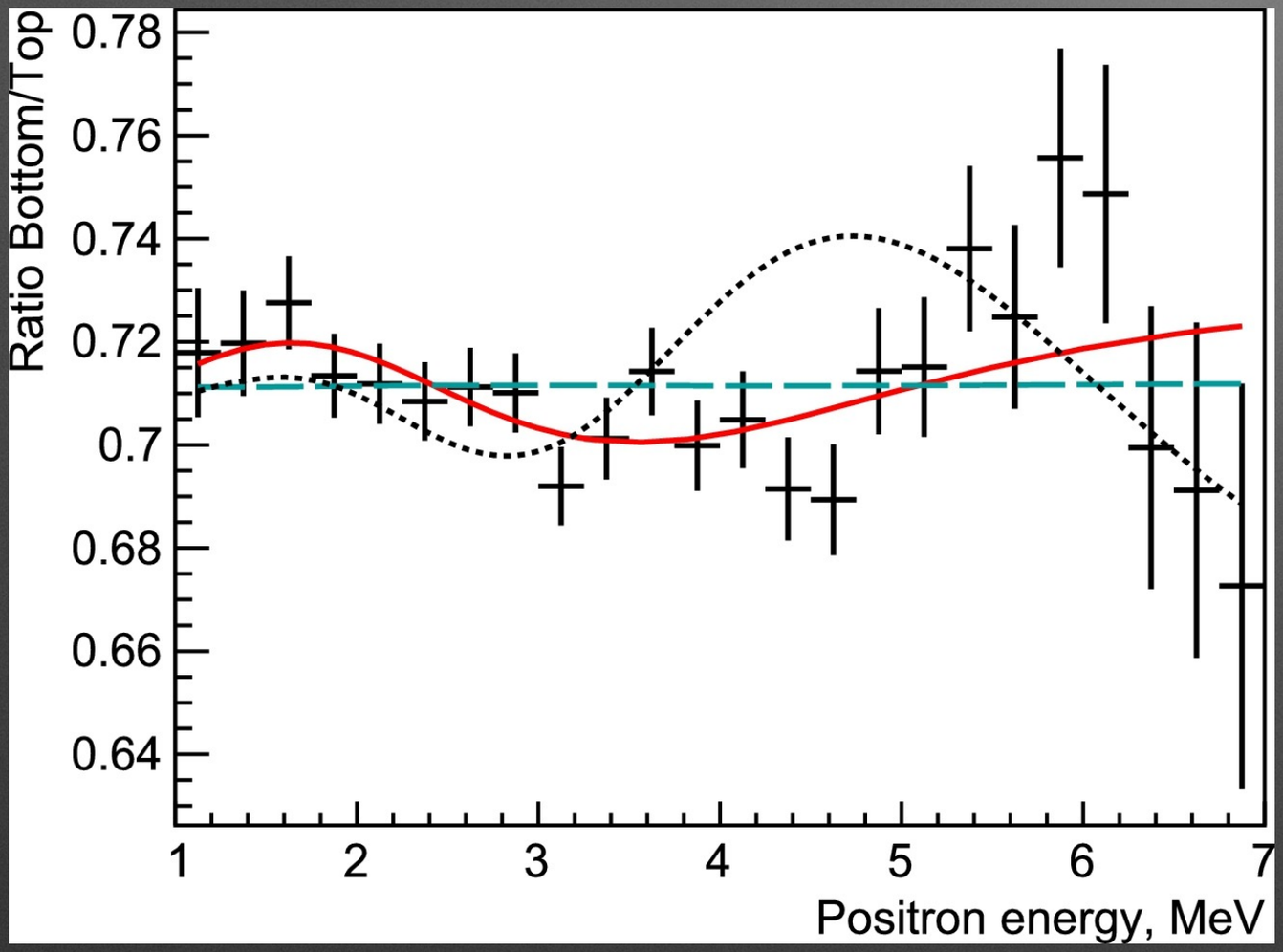
Overburden: 50 mw.e.

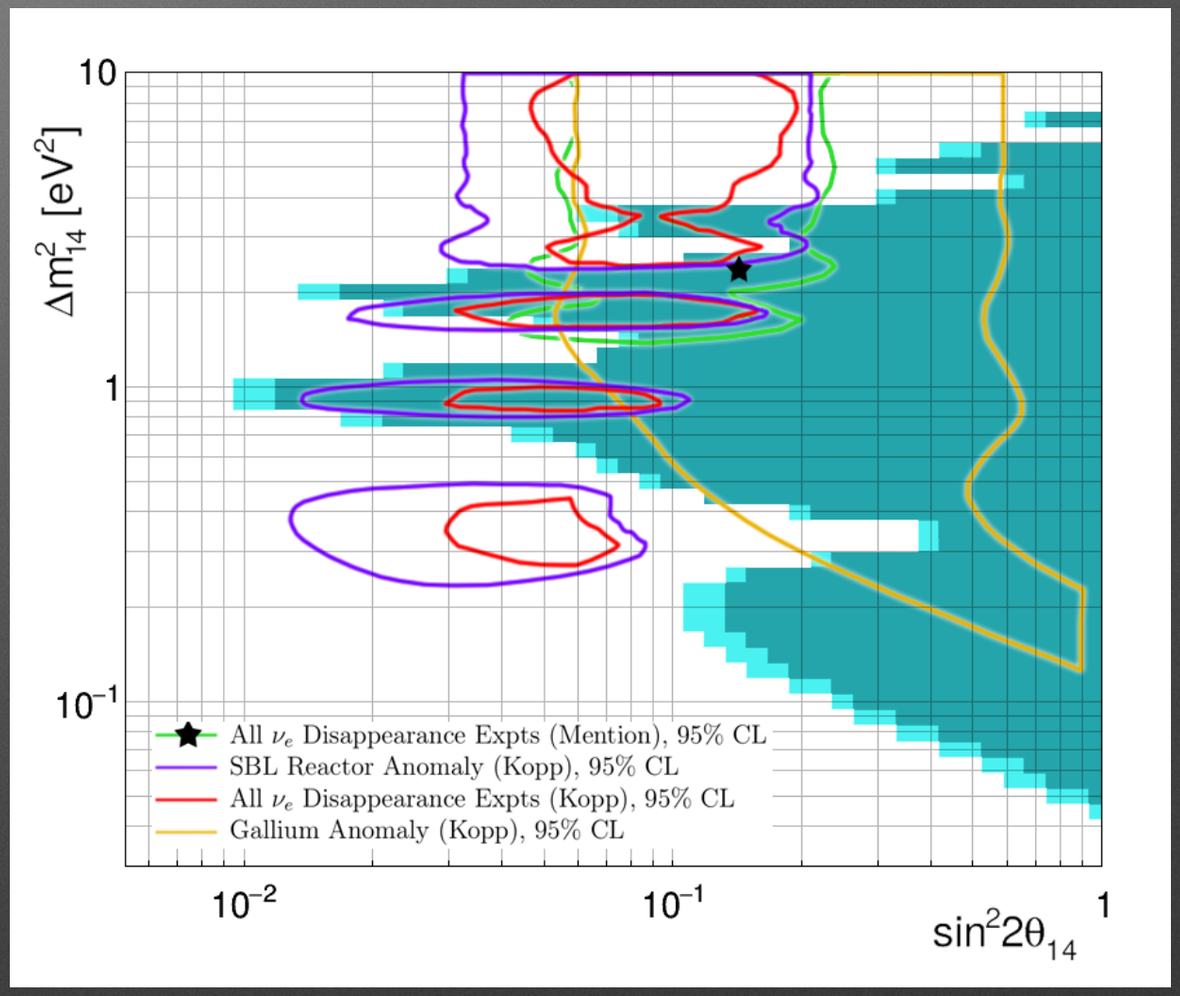


DANSS Collaboration,
JINST 11 (2016) P11011

- Kalinin Nuclear Power Plant (3.1 GW, LEU), 350 km NW of Moscow
- 10.7 - 12.7 m baseline (moveable)
- 1 m^3 plastic scintillator strips (2500!) covered by Gd
- Low background site and high statistics (~5000 events/day)

DANSS results

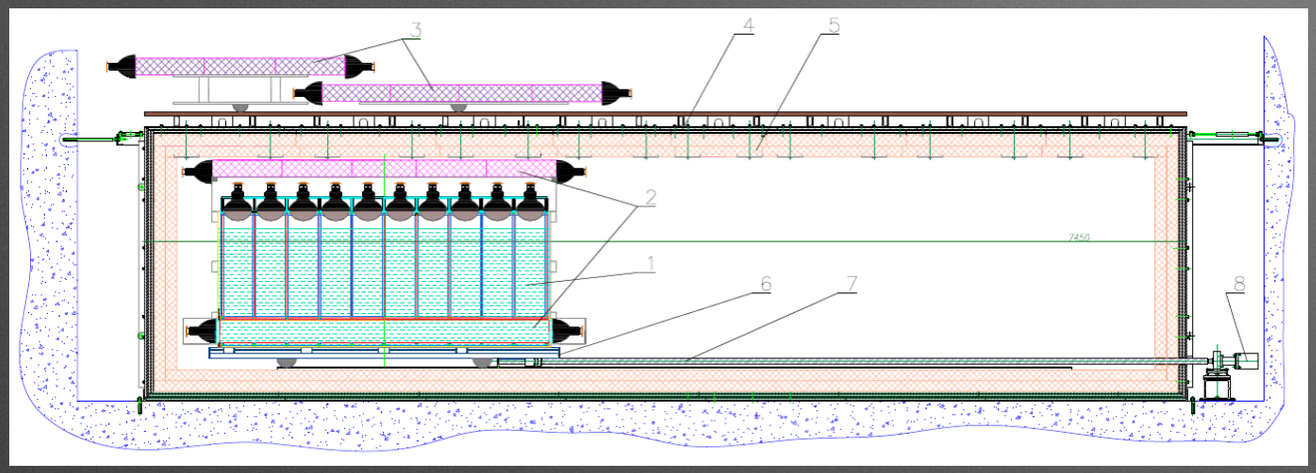




DANSS Collaboration, Phys.Lett. B787 (2018) 56-63

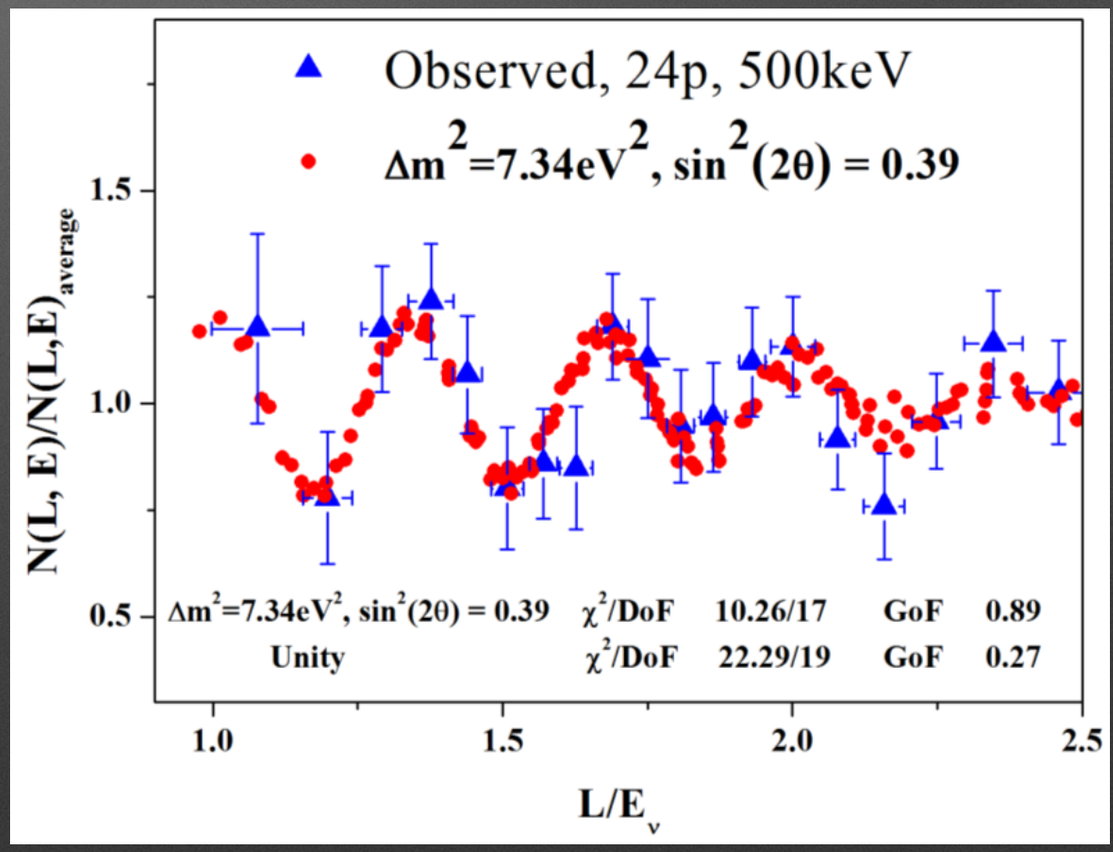
- Large part of RAA parameter space excluded
- Best fit: Δm=1.4 eV², $\sin^2 2\theta$=0.05, systematic studies incomplete
- Analysis update in Summer 2019…

Neutrino-4



- 100 MW SM-3 HEU reactor (Dimitrovgrad, Russia)
- Gd-loaded liquid scintillator (1.8 m³)
- 6-12 m baseline (moveable platform!)
- High cosmic background and lack of PSD (S/B ≈ 0.5)
- Full scale data since June 2016: 3σ signal reported in 2018 at very high mass splitting and mixing angle

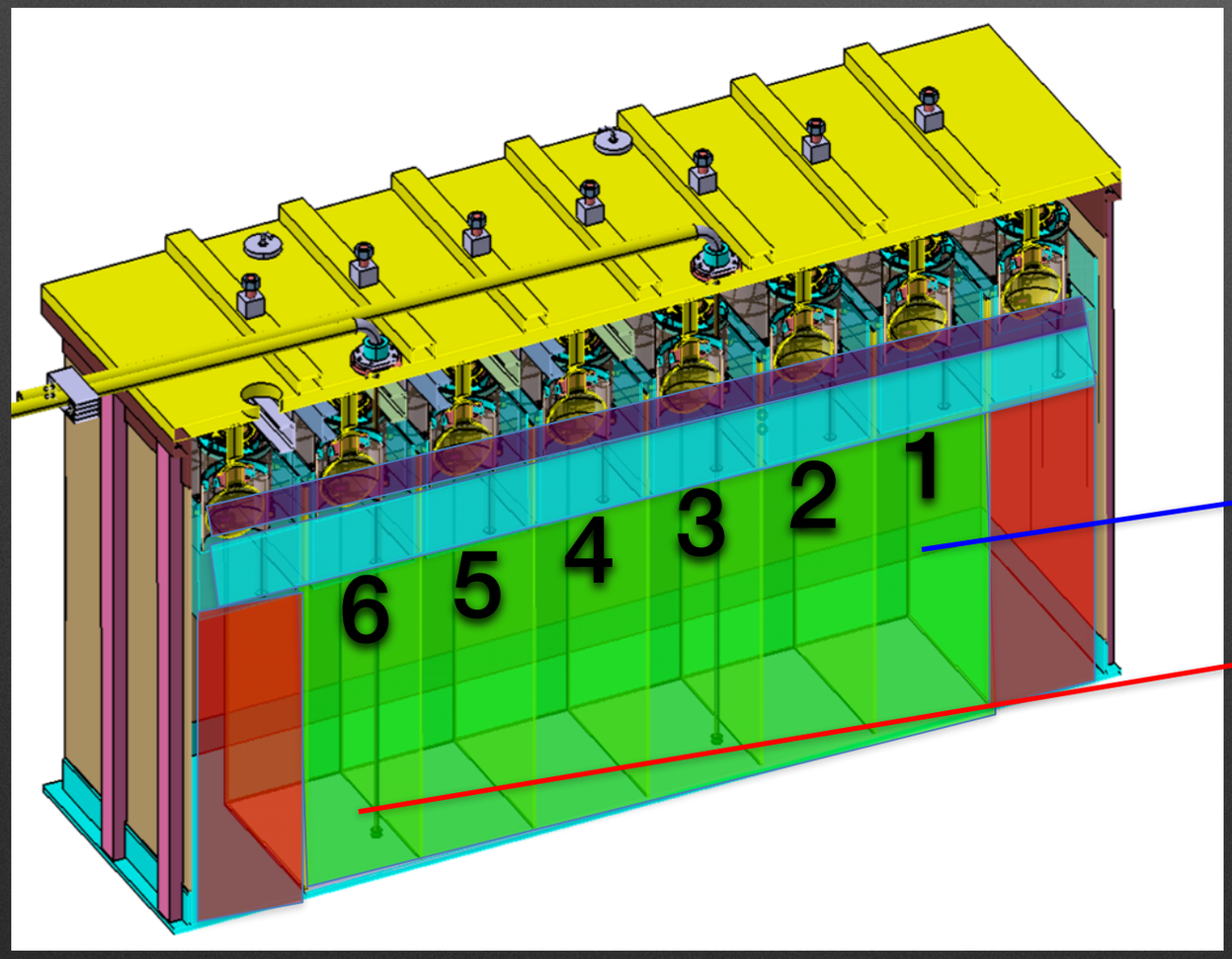
L/E dependence for data (blue) compared to expectation (red) for best fit value

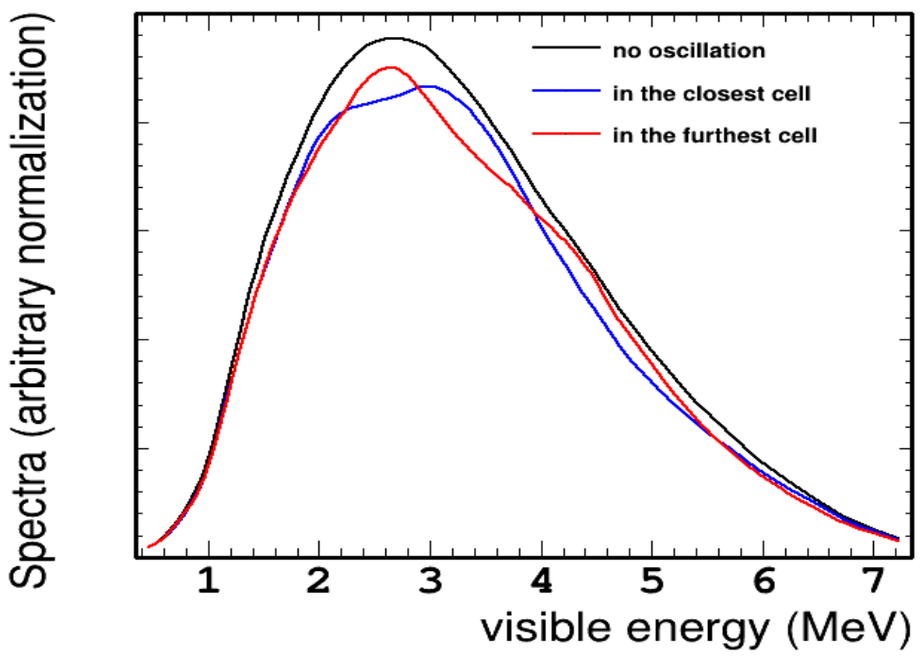


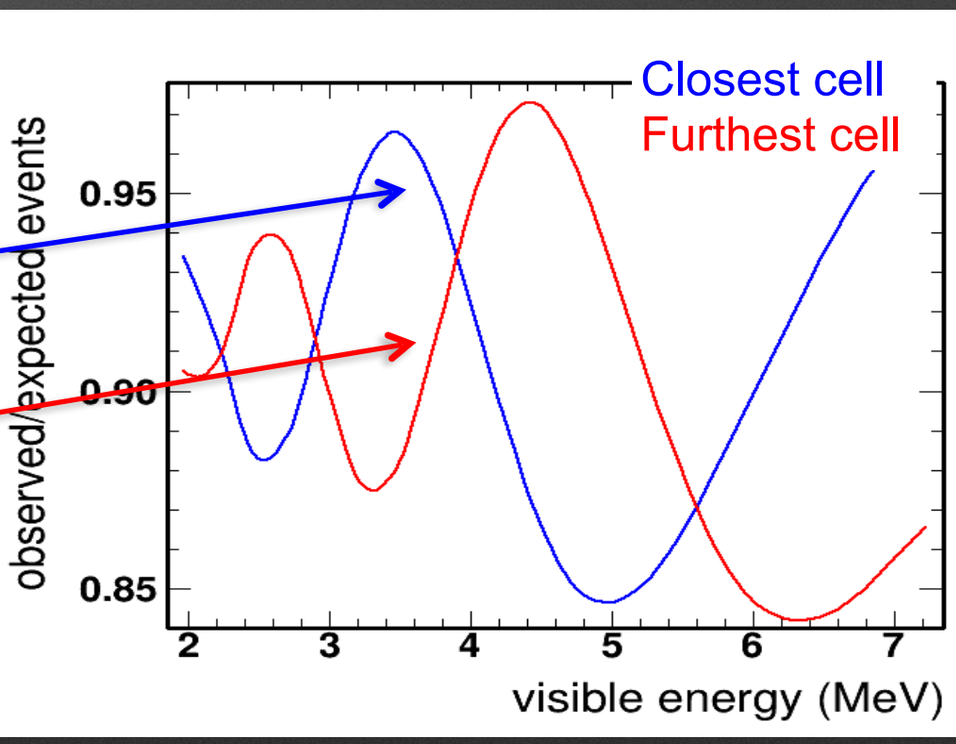
Neutrino-4 Collaboration, JETP Letters 109 (2019) 213-221.

Stereo principle

- 58 MW HEU reactor (ILL Grenoble, F)
- Gd-loaded liquid scintillator (1.8 m^3)
- Baseline: 9.4 m < L < 11.2 m
- 6 identical target cells
- Overburden: 15 m w.e.

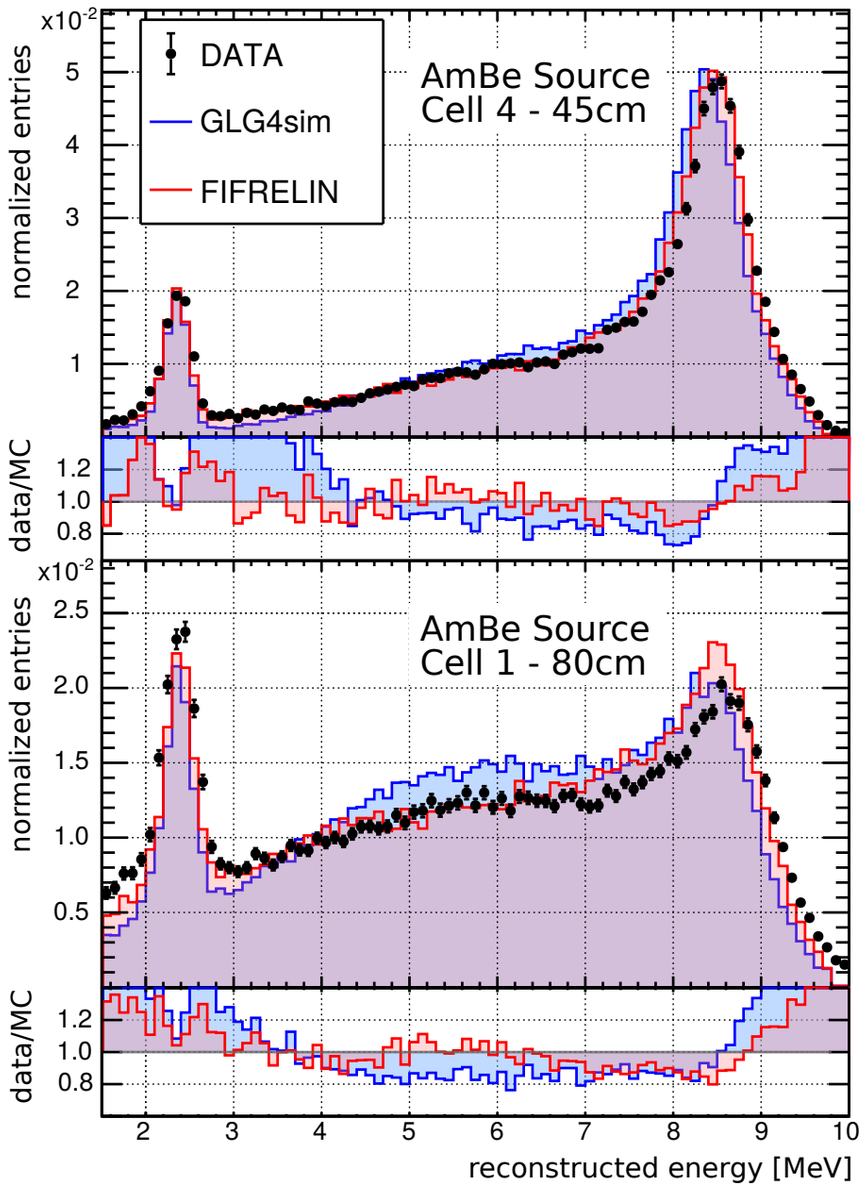






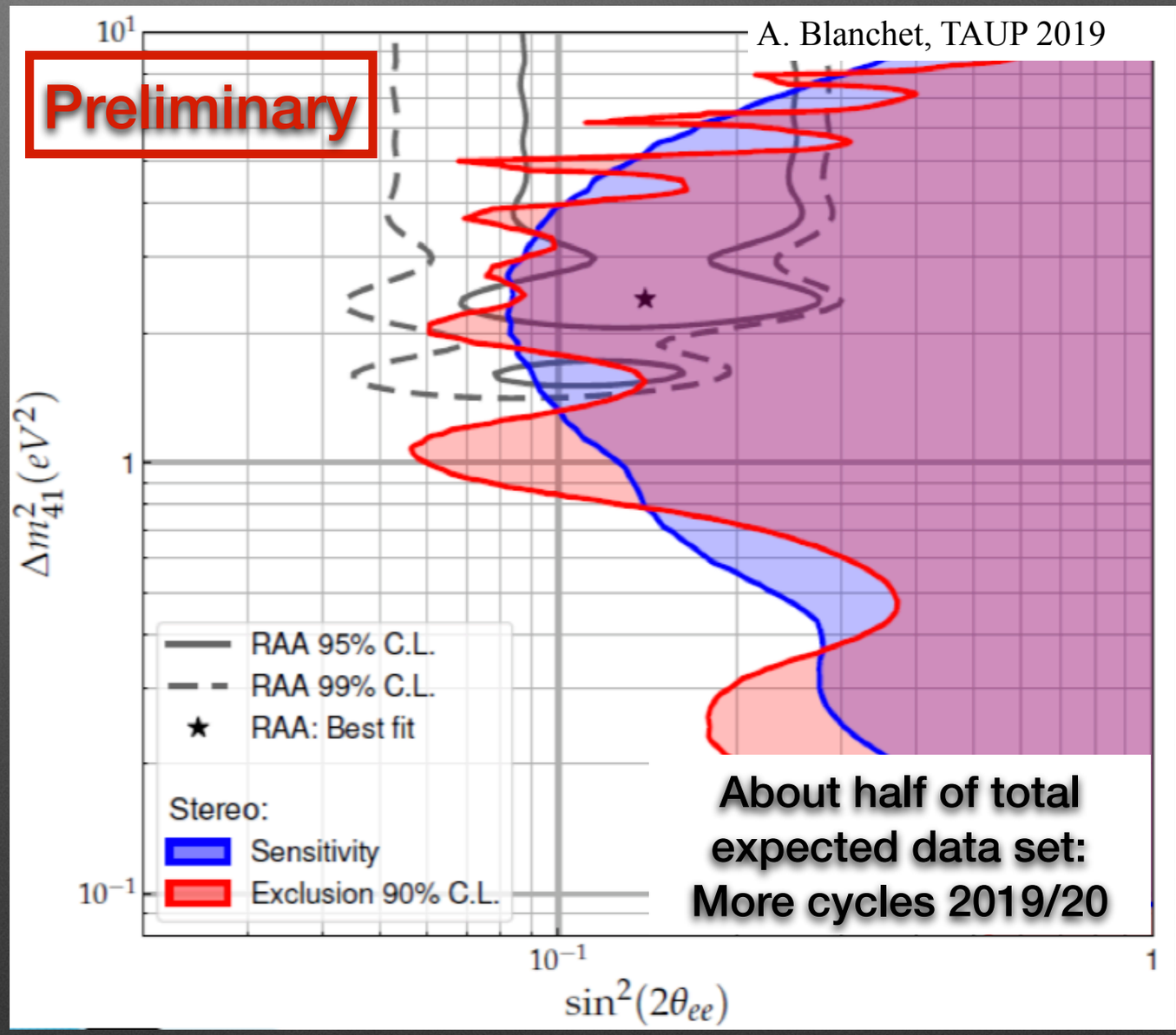
Stereo results

Stereo Collaboration, arXiv:1905.11967.



New Gd gamma ray spectra (now also used in DANSS)

A. Blanchet, TAUP 2019

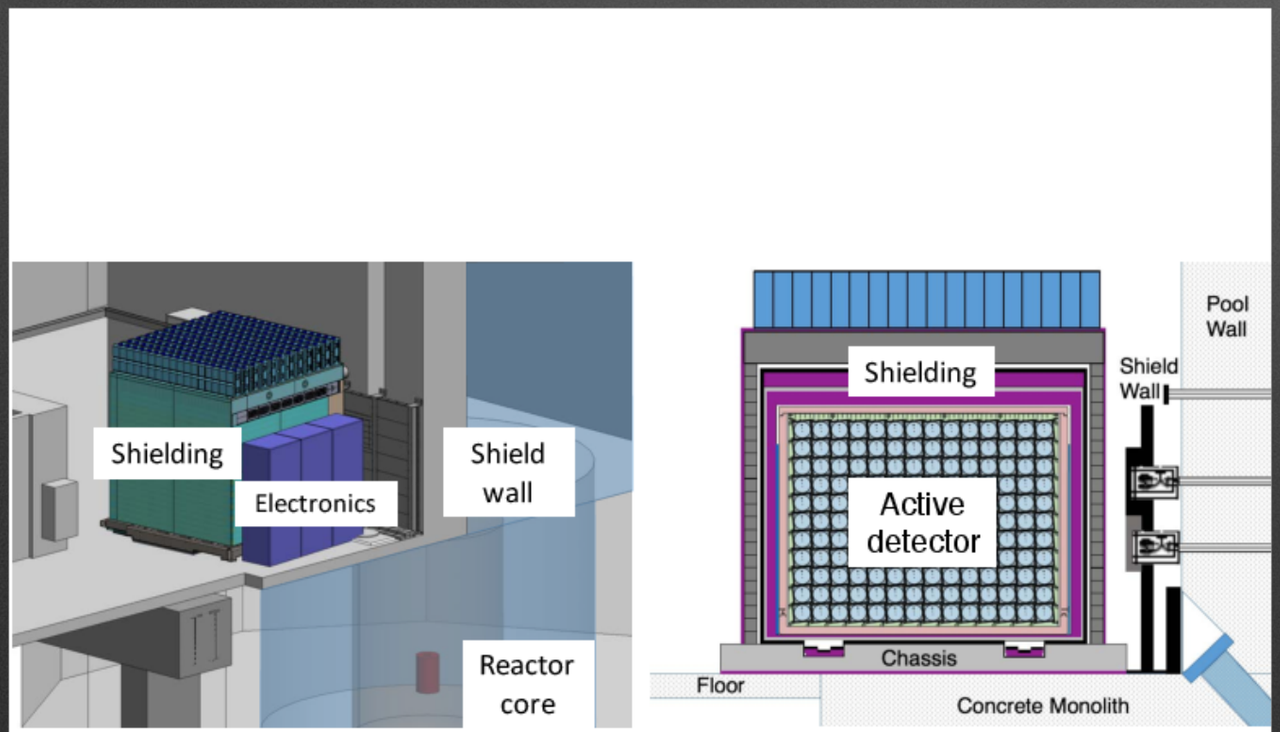


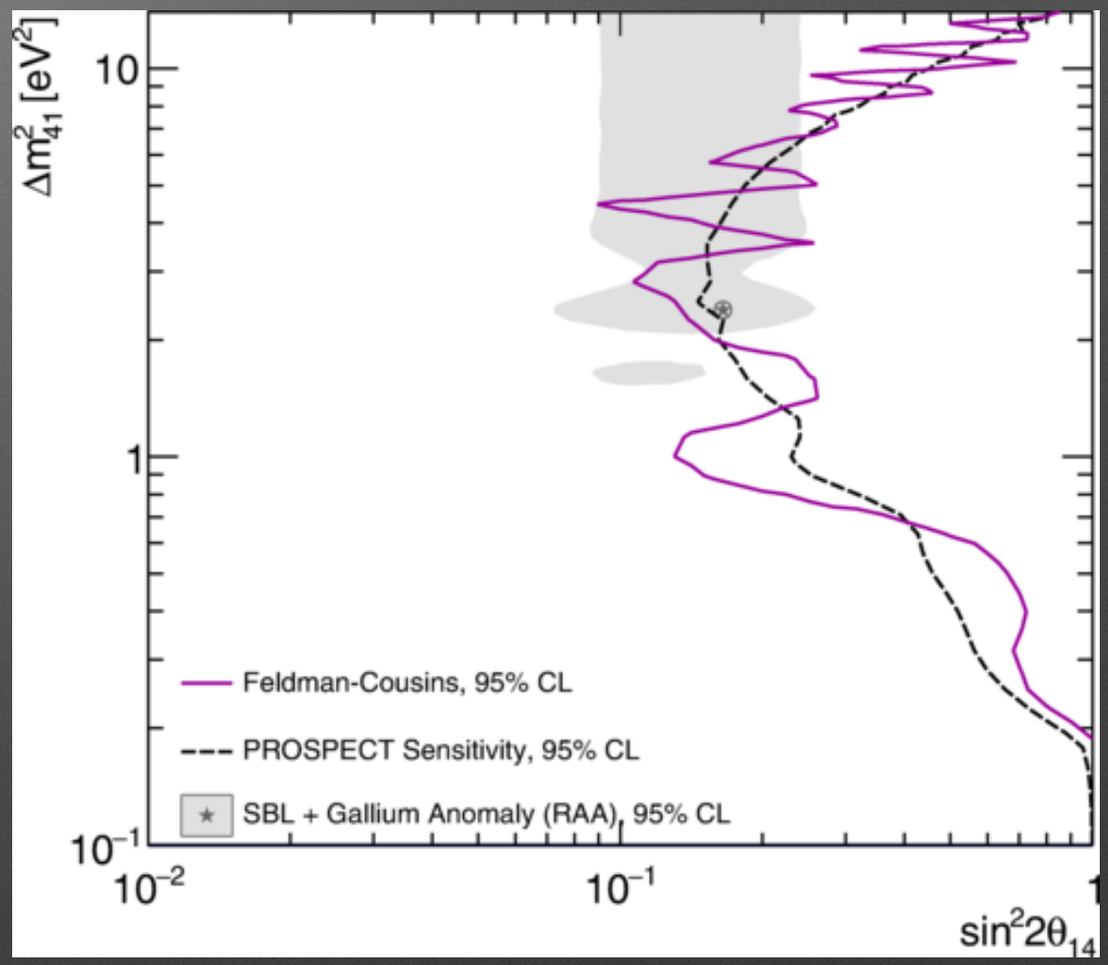
Other studies:

- Spectral distortion (HEU reactor!)
- Absolute flux measurement

Prospect: oscillation analysis

- 85 MW HEU reactor (HFIR, US)
- 4 tons ^{6}Li-doped scintillator
- Baseline: 6.7 m < L < 9.2 m
- 154 optically isolated segments
- Overburden: < 1 m w.e.



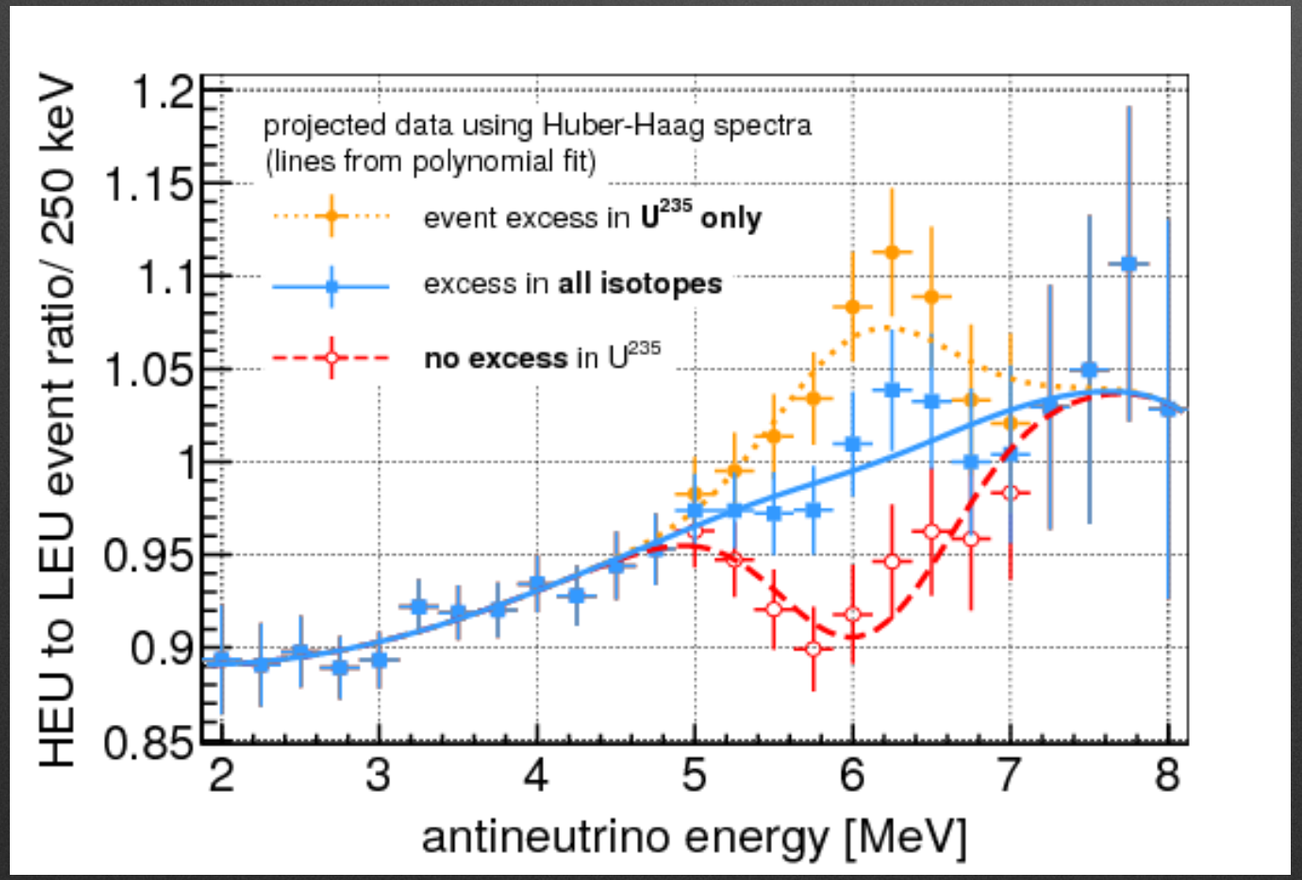


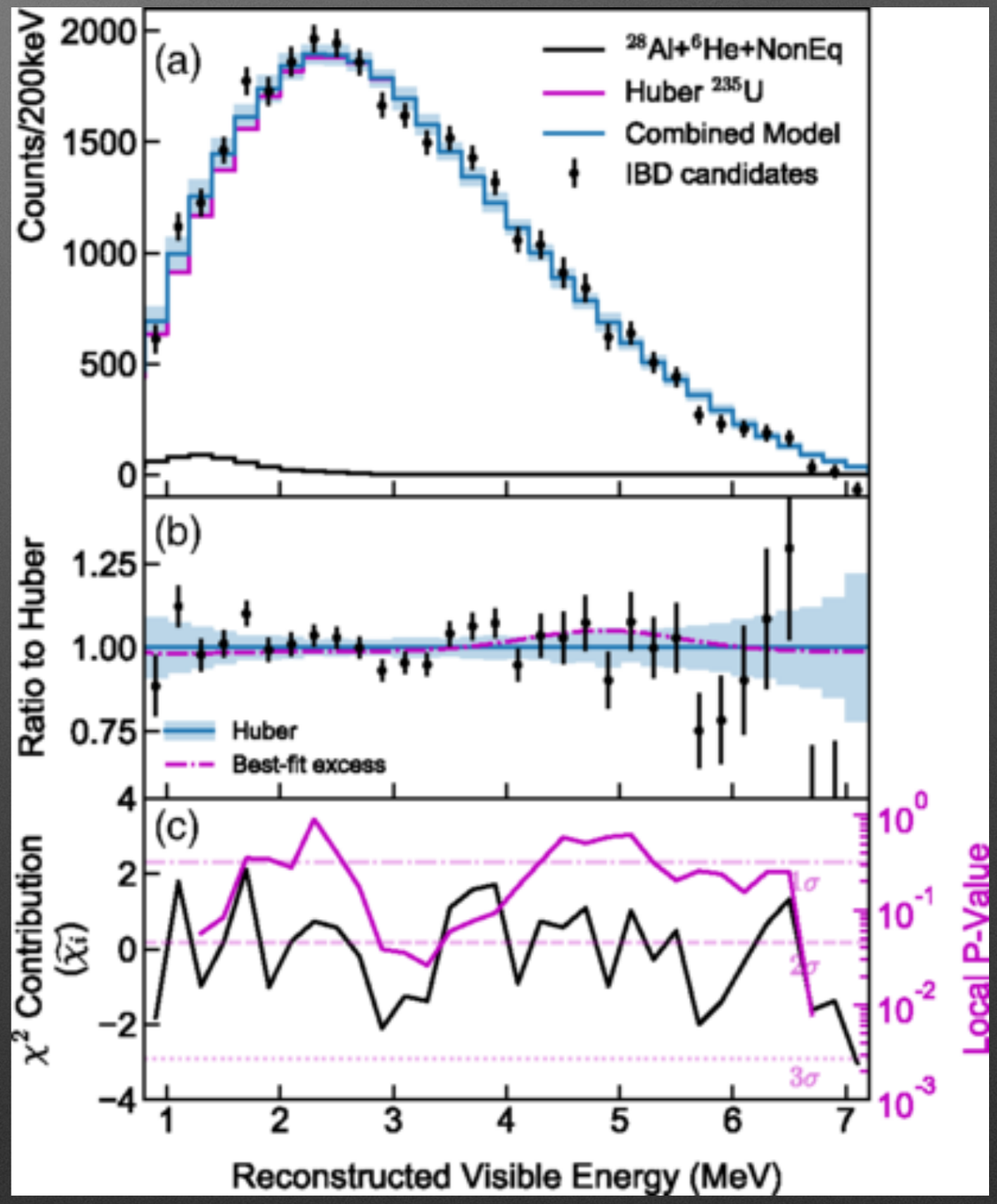
Prospect Collaboration, PRL 121 (2018) 251802

- 33 live days reactor ON
- 25461 ± 283 IBD events
- Compatible with 3v framework

Prospect: antineutrino spectrum

- Do HEU antineutrino spectra follow LEU features?
- Closer to models in 5 MeV region than most LEU experiments
- In good agreement with antineutrino spectrum measured in Stereo

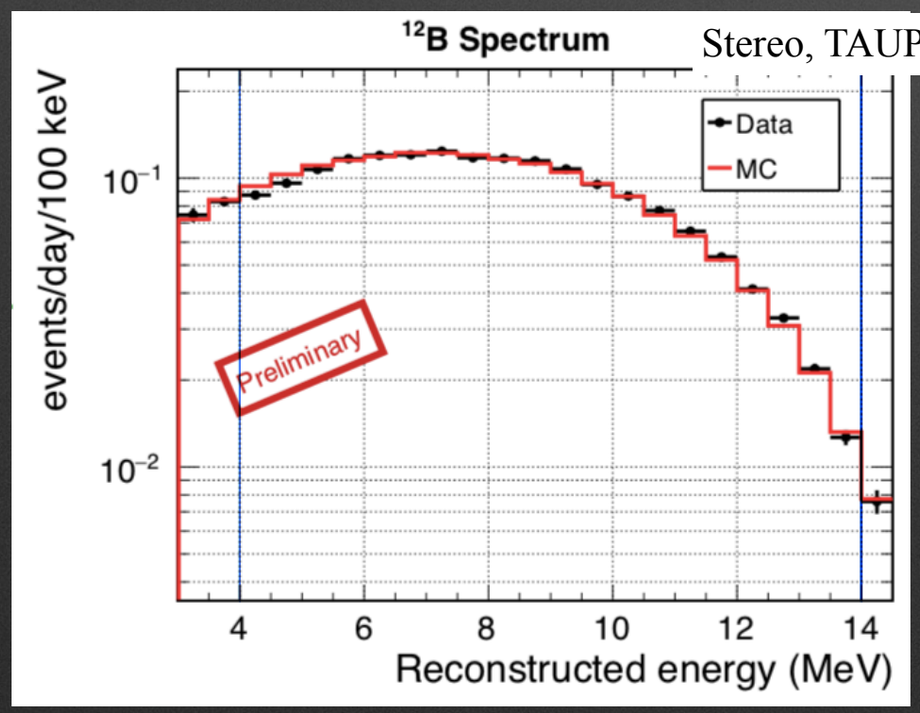




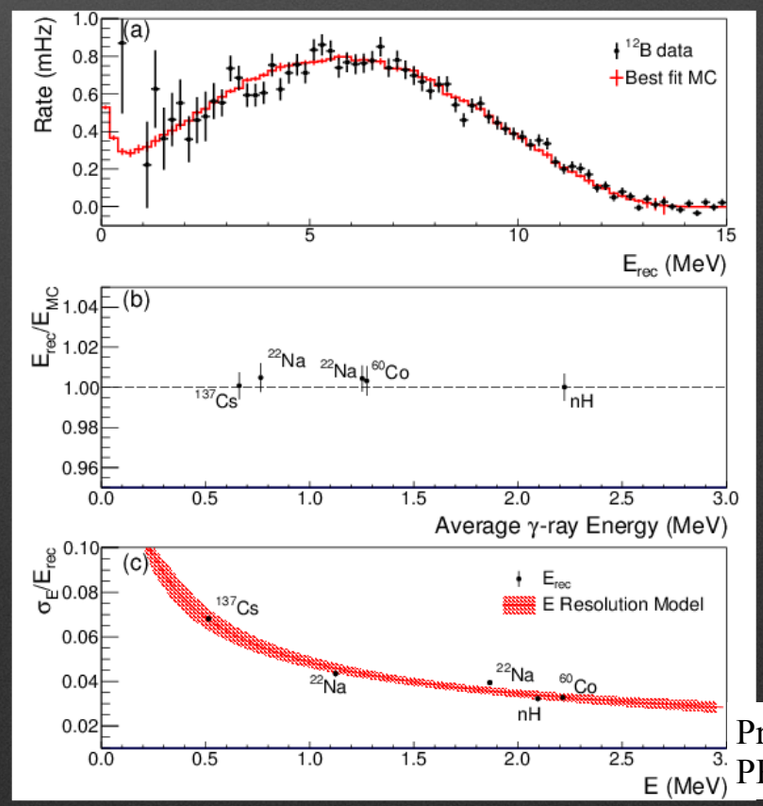
Prospect Collaboration, PRL 122 (2019) 251801

Summary on 5 MeV „bump“

- Significant excess in Daya Bay, Double Chooz, RENO and NEOS with some differences in shape and amplitude
- „Indications“ in other experiments: Chooz, Gösgen, Rovno
- No distortion observed in Bugey 3
- Prospect, Stereo, DANSS in between: not conclusive yet ==> Energy scale systematics!



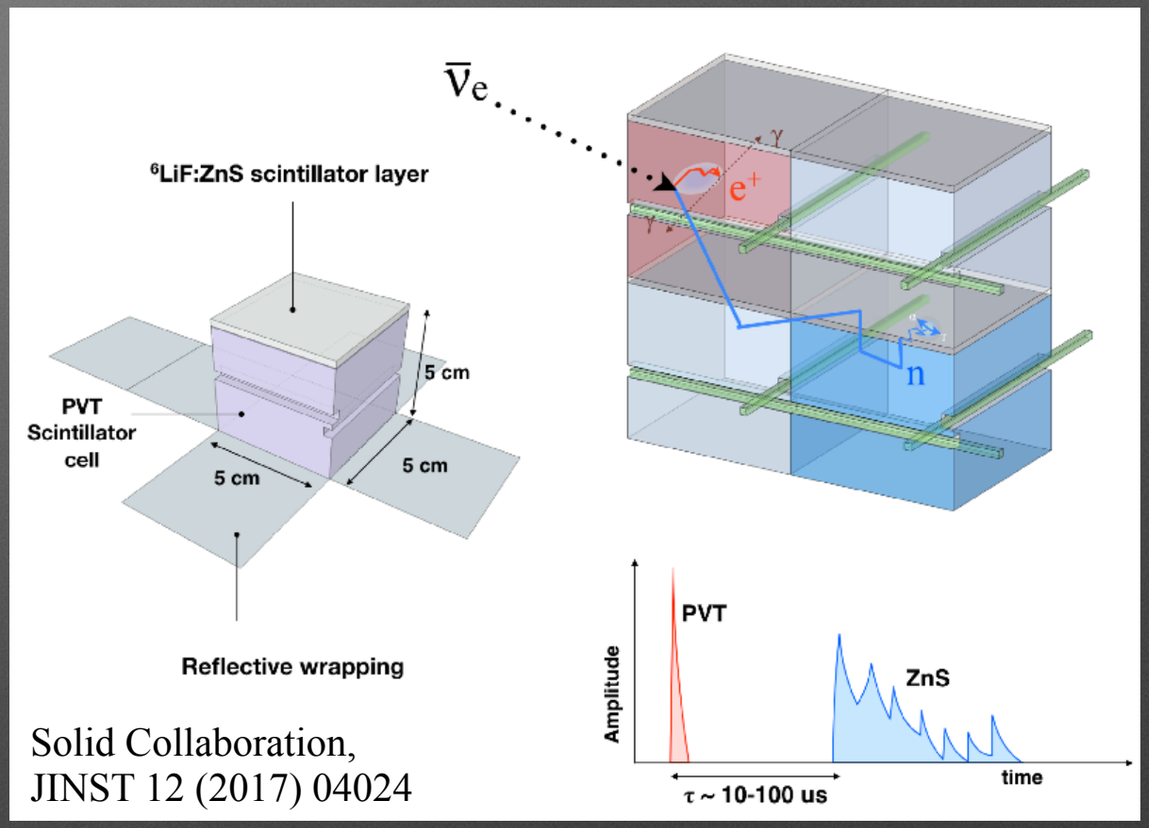
Stereo, TAUP 2019



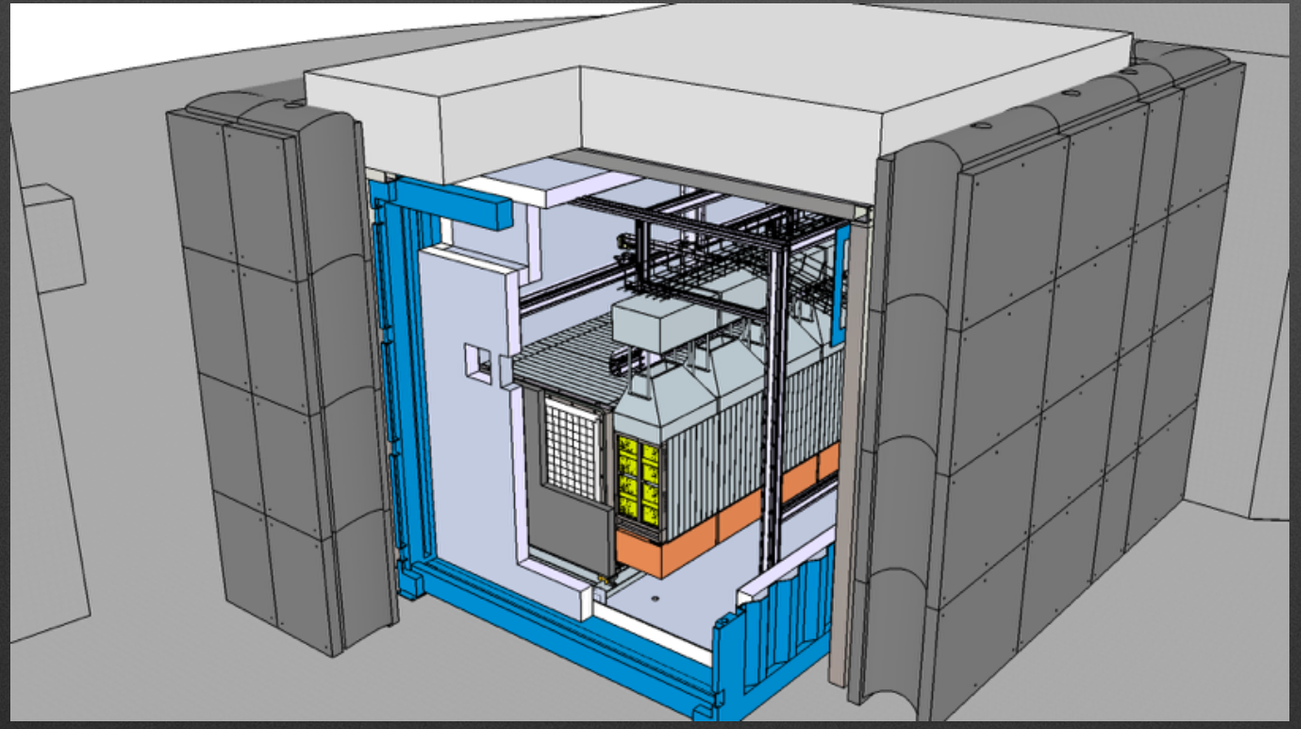
Prospect Collaboration, PRL 122 (2019) 251801

Solid

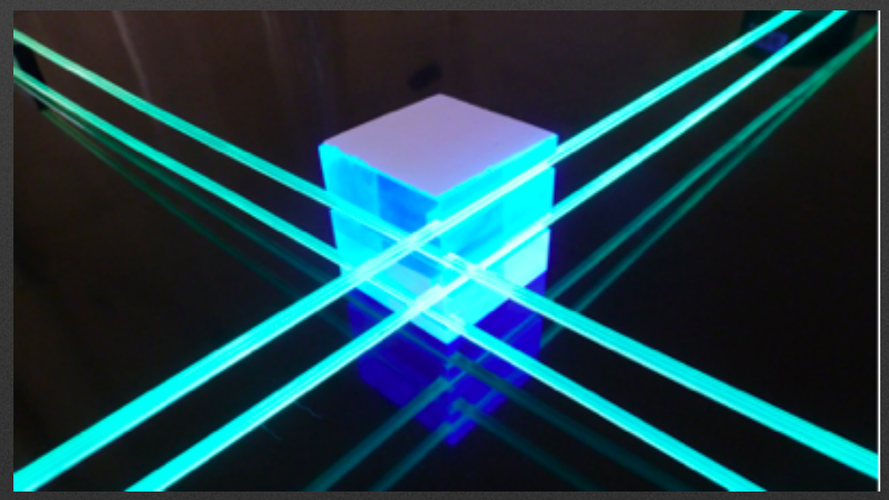
- 80 MW HEU BR2 reactor (Belgium)
- Baseline: 6-9 m, 5 moduls on rails
- New technology: Composite scintillator (^{6}LiF)
- High segmentation (12800 cubes)
- Detector mass: 1600 kg



Solid Collaboration,
JINST 12 (2017) 04024

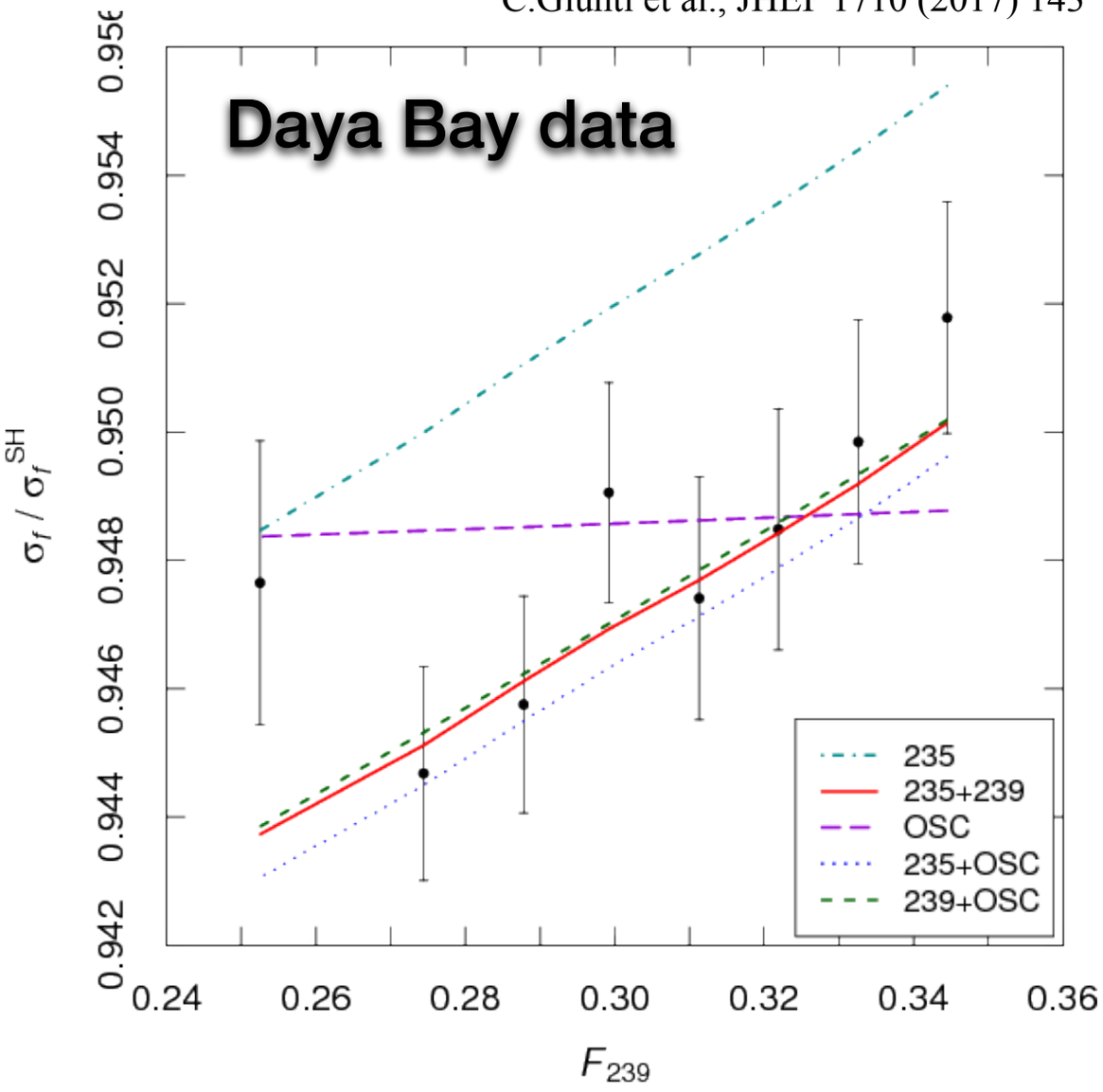


Data taking since April 2018

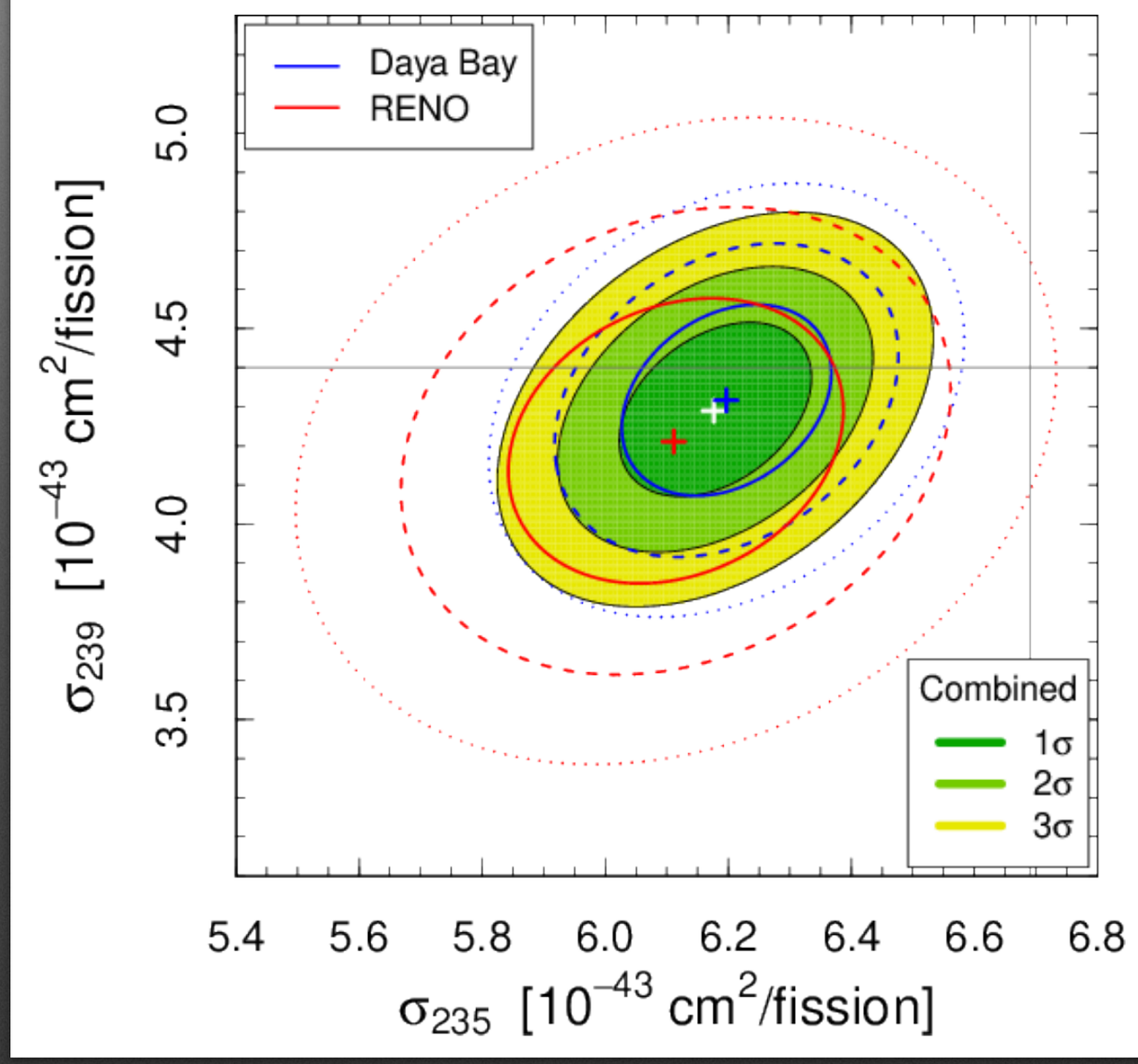


Fuel evolution data

C.Giunti et al., JHEP 1710 (2017) 143



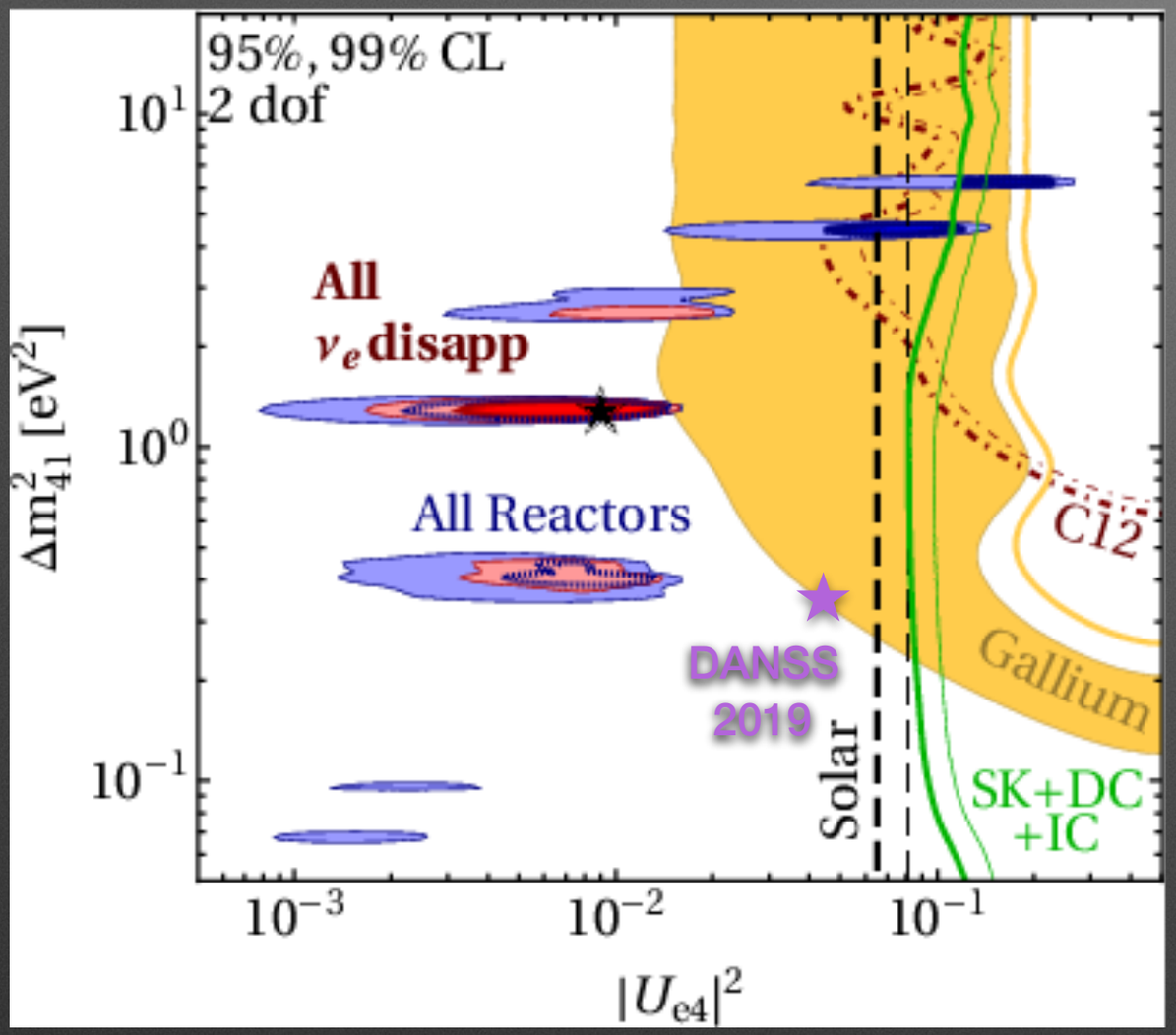
C.Giunti et al., PRD 99 (2019) 073005



Similar findings with RENO data

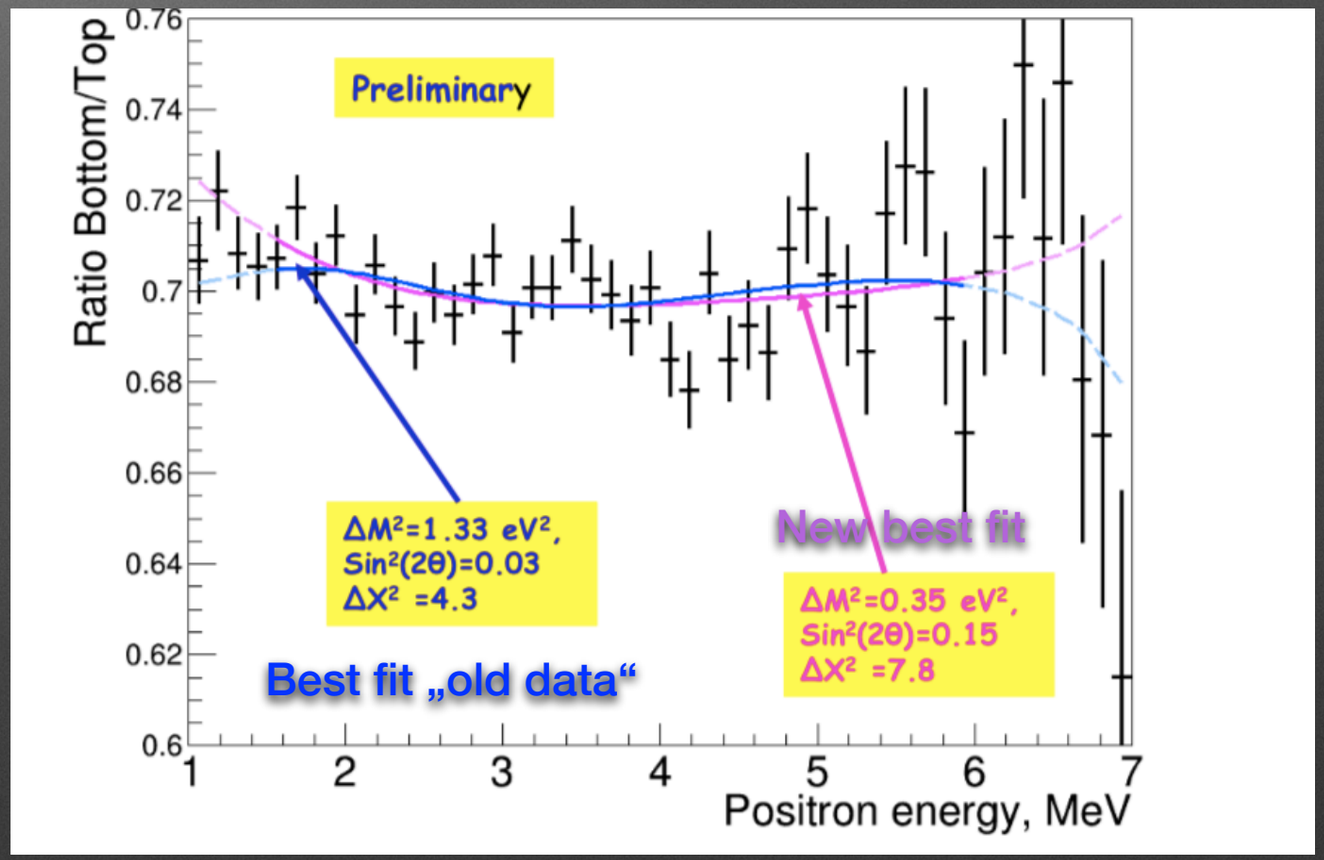
IBD yield just of for 1 isotope?
Stereo/Prospect should answer

Global picture



- Global disappearance analysis in 3+1 scenario (2018)
- Significance driven by DANSS and NEOS, although DANSS missing systematics!

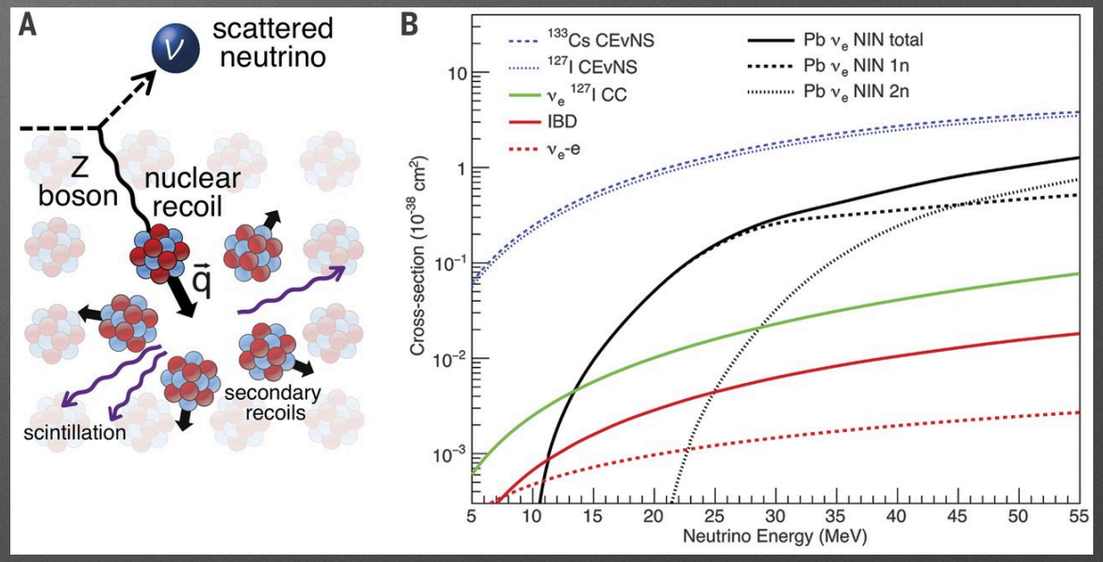
NEOS/DANSS agreement diminished after new DANSS data (EPS 2019)



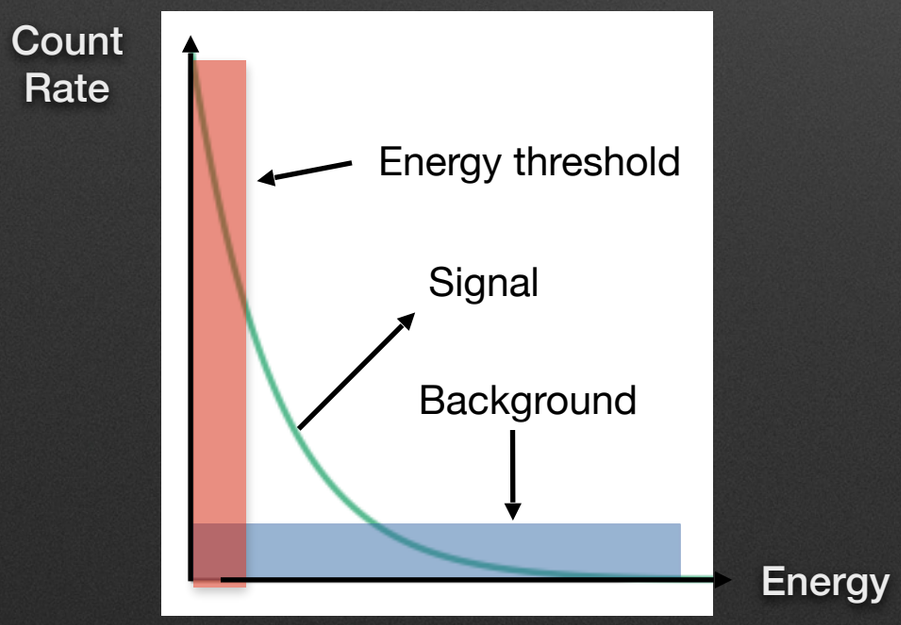
- New DANSS result: best fit at much higher mixing angle
- Significance of 4ν only 1.8σ

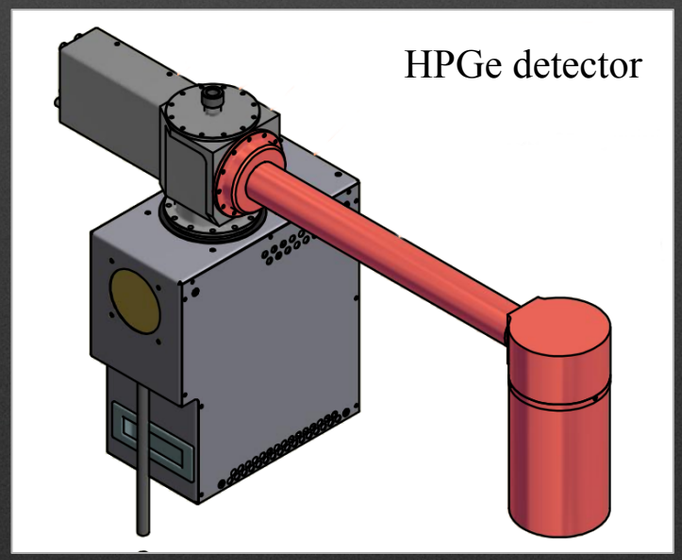
Other detection channels

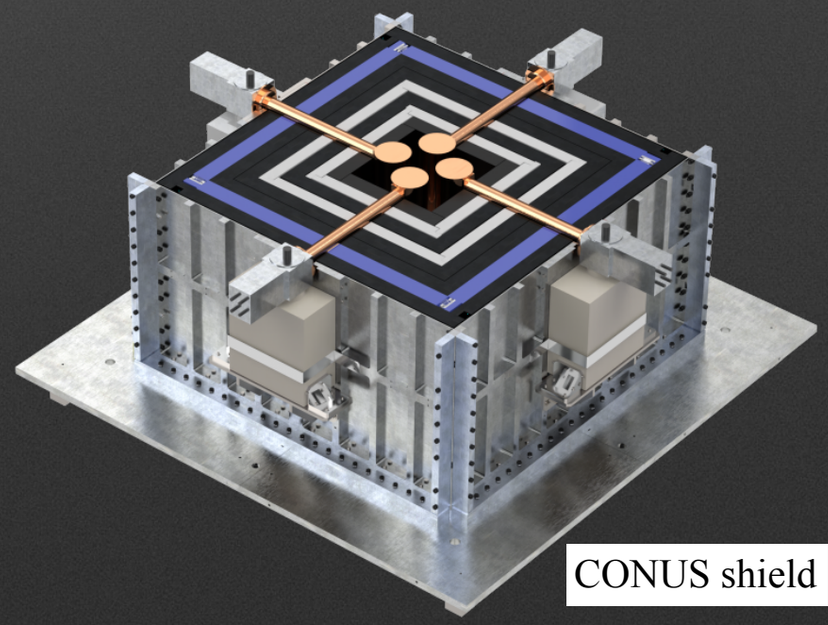
- CEvNS (low E, but high cross section!), neutrino magnetic moment
- Low energy threshold Ge detectors: GEMMA, Texono, CONUS
- Baselines ≳ 10 m
- Other ideas for target materials: bolometers, liquid noble gases,…
- Also potentially sensitive to oscillation studies involving sterile neutrinos



D. Akimov et al. Science 2017;357:1123-1126







Summary

- Nuclear reactors suitable sources to study neutrino properties at very short baselines
- Indications for short baseline oscillations getting weaker in the last ≲ 1 y:
  - Fuel evolution data of Daya Bay / RENO
  - Prospect, Stereo, DANSS and NEOS exclude large parameter space
  - Significance of Gallium anomaly 3.0 —> 2.3 σ
  - New DANSS analysis: best fit less compatible with NEOS data
- Next generation of very short baseline reactor neutrino experiments studying elastic neutrino nucleus scattering