Sterile neutrinos:
Running and experiments under preparation

Stefan Schönert | TU München

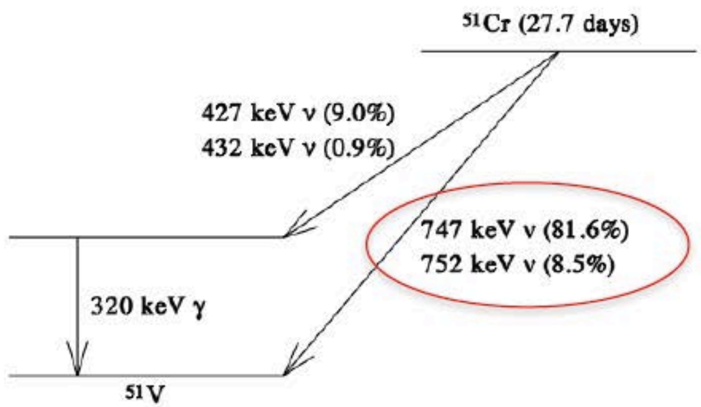
Recent Developments in Neutrino Physics and Astrophysics
Workshop 10 year anniversary of of Borexino data-taking

04-07 Septermber 2017
LNGS & GSSI, L'Aquila, Italy

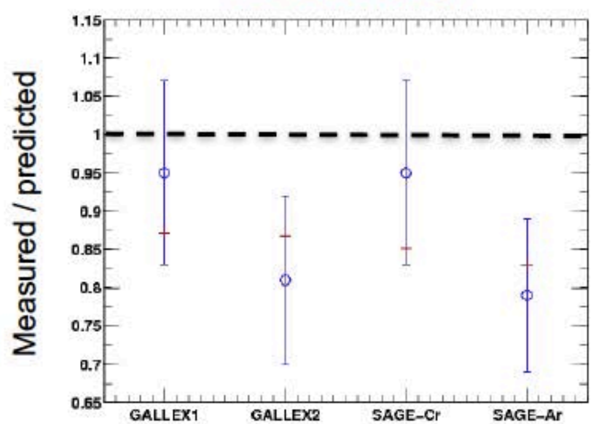
TECHNISCHE UNIVERSITÄT MÜNCHEN

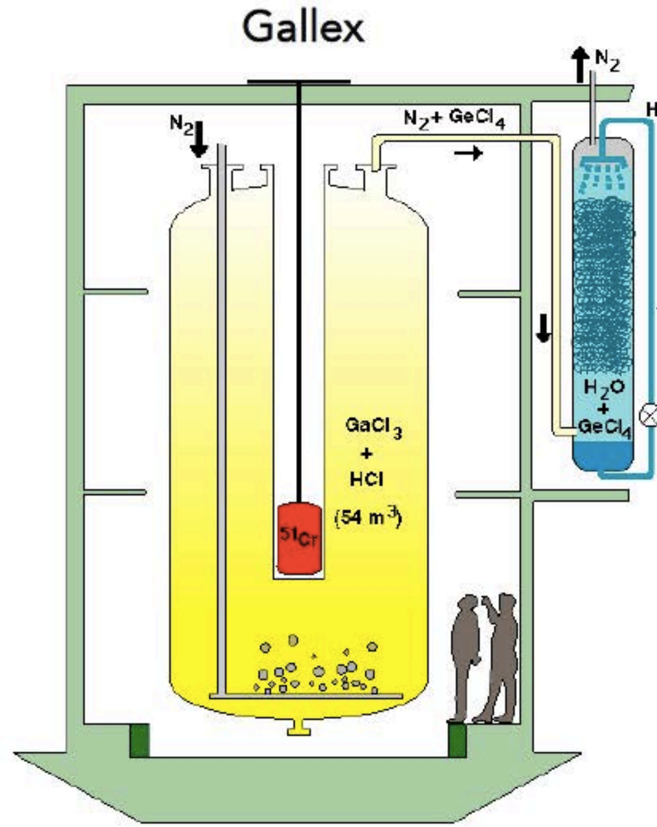
SFB 1258 Neutrinos Dark Matter Messengers

The gallium anomaly

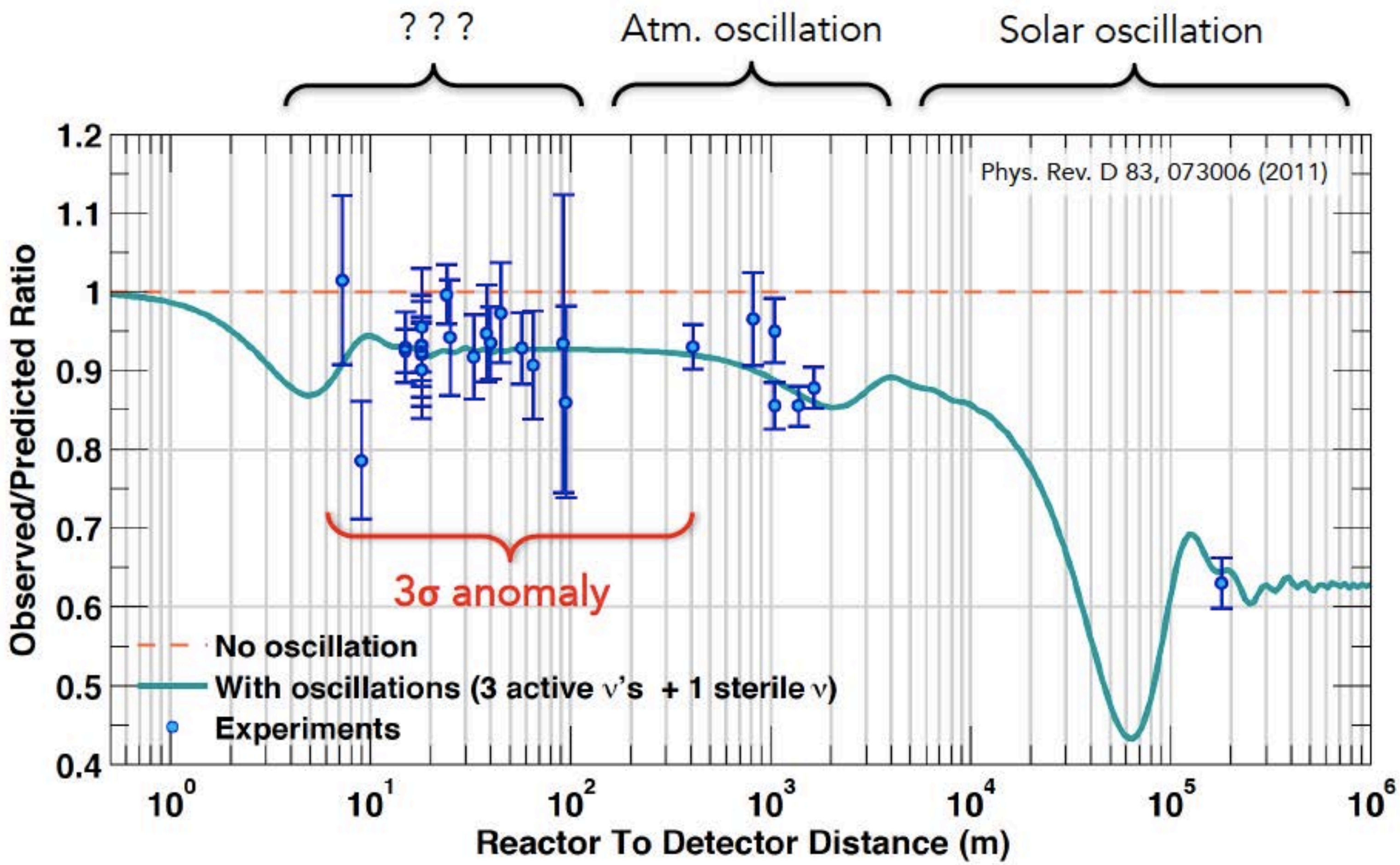


3σ anomaly



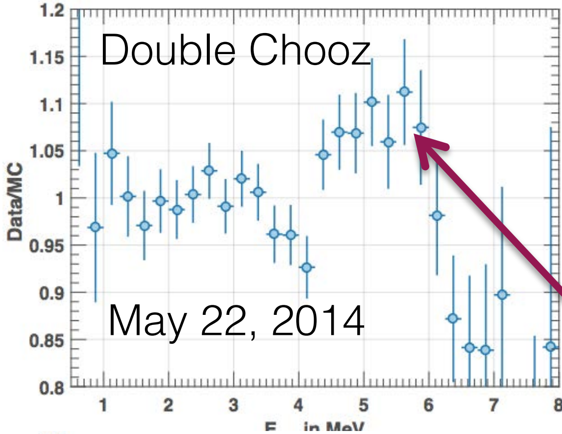


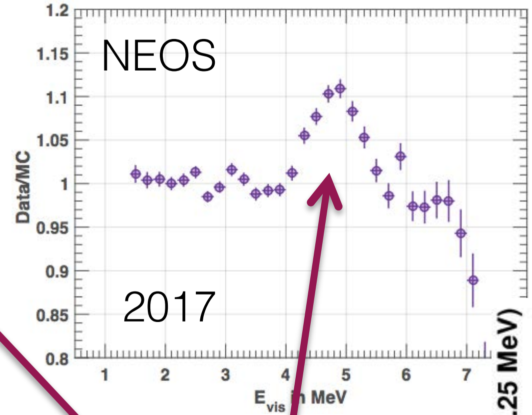
The reactor anomaly

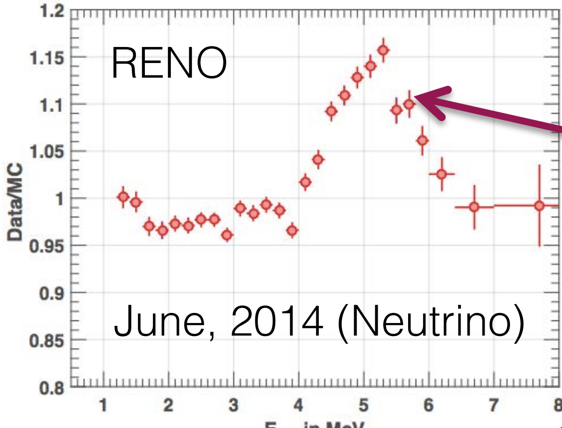


G. Mention, M. Fechner, Th. Lasserre, Th. A. Mueller, D.Lhuillier, M. Cribier, and A. Letourneau, Phys. Rev. D 83, 073006 (2011)

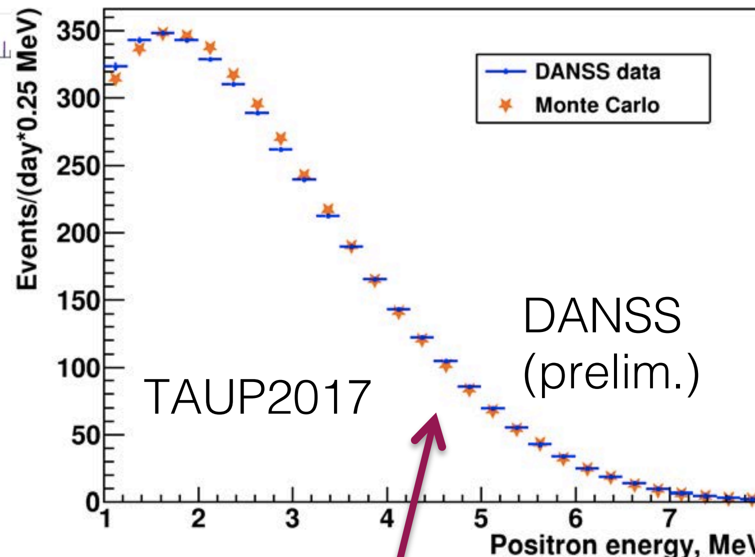
“The 5 MeV Bump(s)”

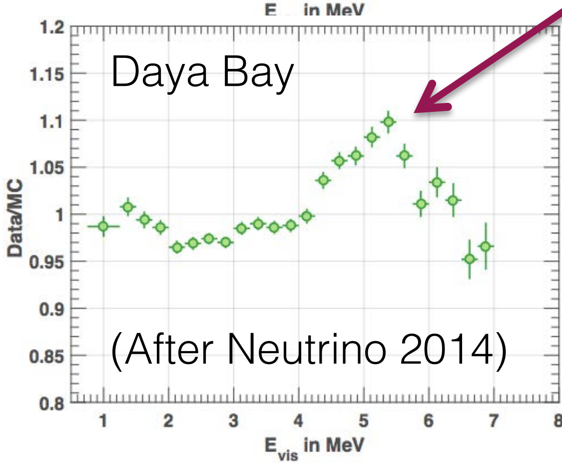


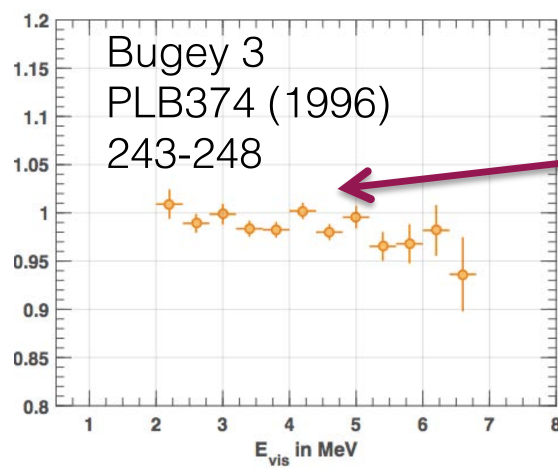




10-15% Bump





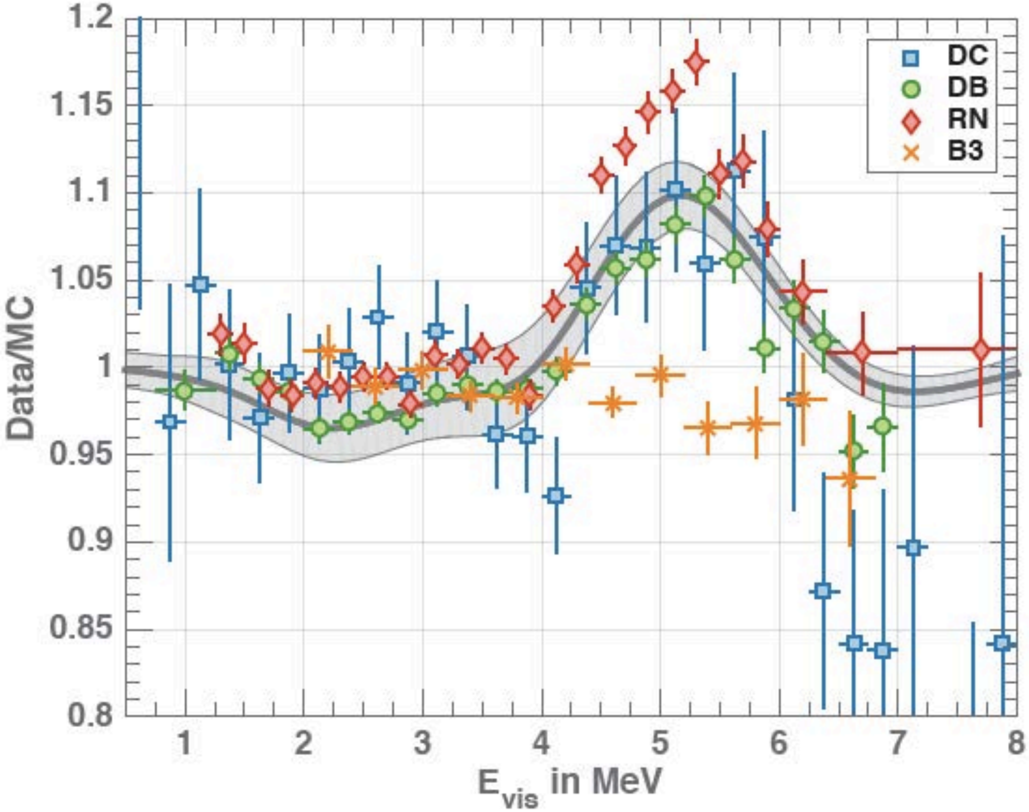


No Bump!

	^{235}U	^{239}Pu	^{238}U	^{241}Pu
Bugey 3	53.8	32.8	7.8	5.6
Double Chooz	49.6	35.1	8.7	6.6
Daya Bay	58.6	28.8	7.6	5.0
RENO	56.9	30.1	7.3	5.6

G. Mention et al., arXiv:1705.09434v1

Are the spectral shapes compatible?

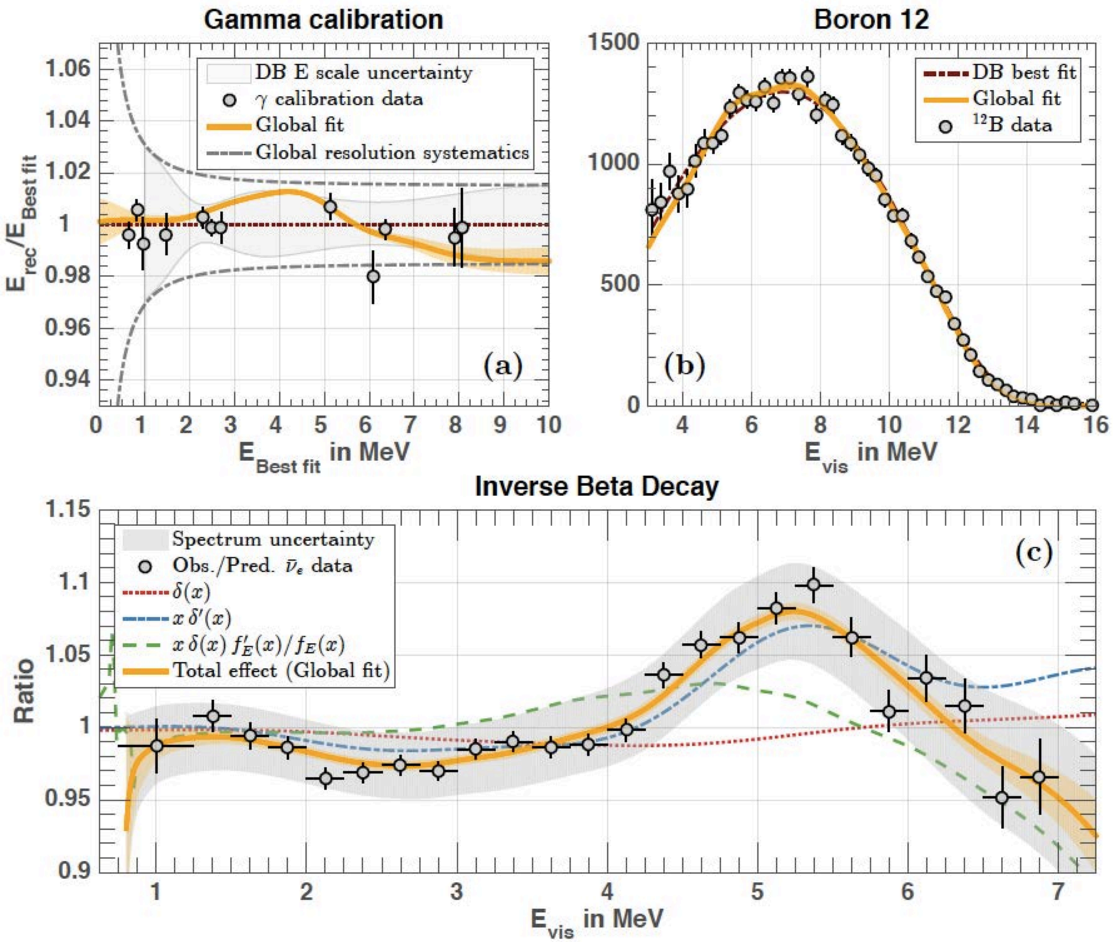


G. Mention et al., arXiv:1705.09434v1

Double Chooz (DC), Daya Bay (DB) and RENO (RN) display significant deviations around 5 MeV, while Bugey 3 (B3) does not. Not included DANSS

incompatible at 6.4σ

Instrumental effect?



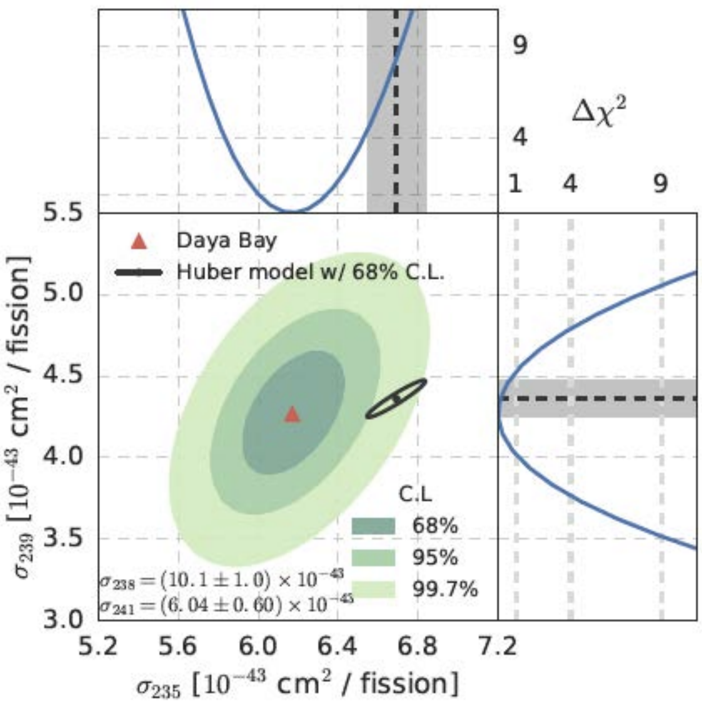
G. Mention et al., arXiv:1705.09434v1

A non-linearity of the energy scale at 1% (consistent with calibration data) *could* produce ~10% bump!

Recall the 17 keV-ν saga

Does the Daya Bay rule out sterile neutrinos?

arXiv:1704.01082v2

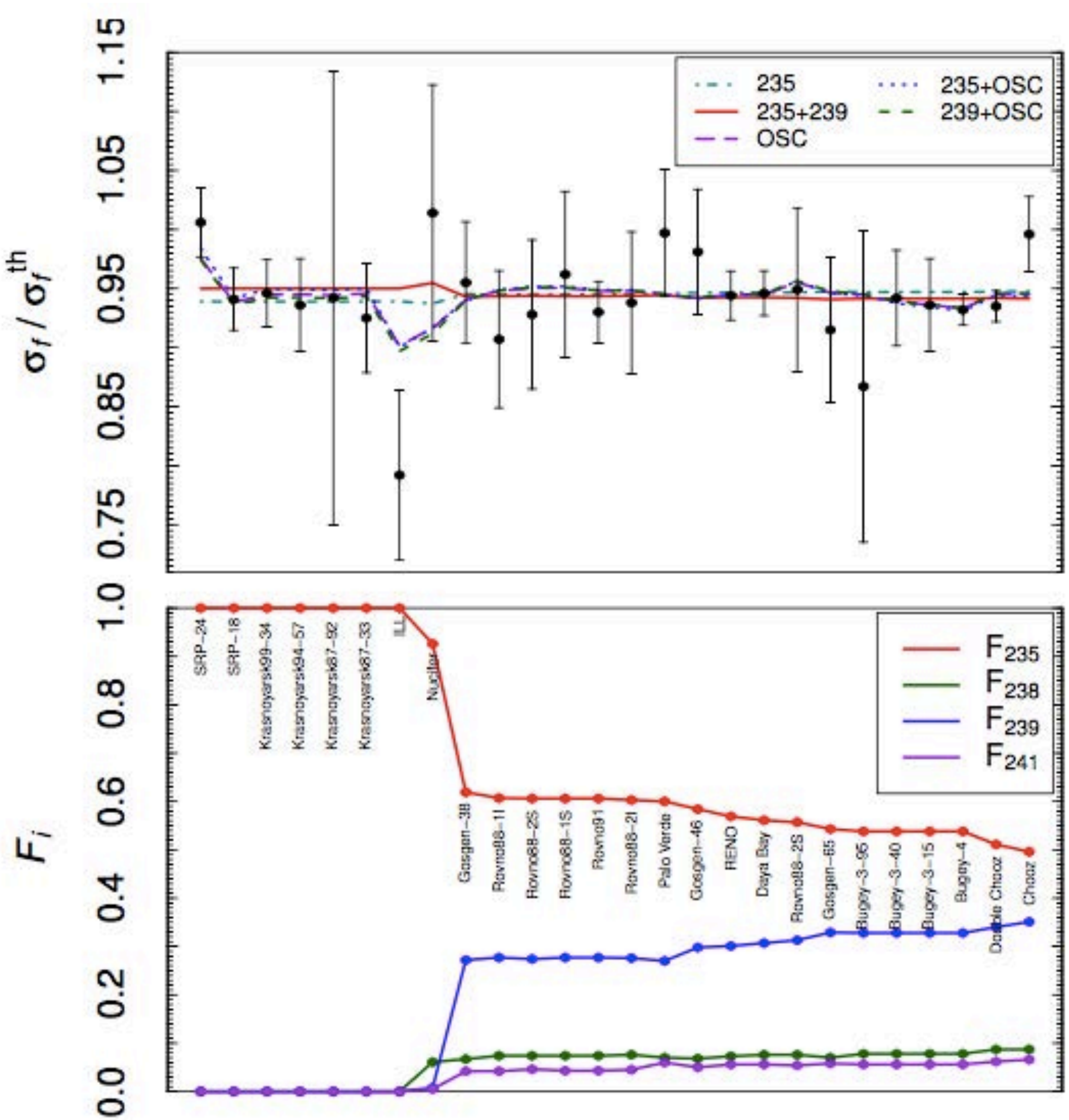


"Thus, the hypothesis that ^{235}U is primarily responsible for the reactor antineutrino anomaly is favored by the Daya Bay data, with the equal deficit and ^{239}Pu-only deficit hypotheses disfavored at the 2.8 and 3.2 confidence levels, respectively."

If correct, expect experiments with ^{235}U reactor cores would have different (stronger) anomalies than at power reactors with LEU cores. Not supported by data.
See eg. Giunti **arXiv:1708.01133v1**

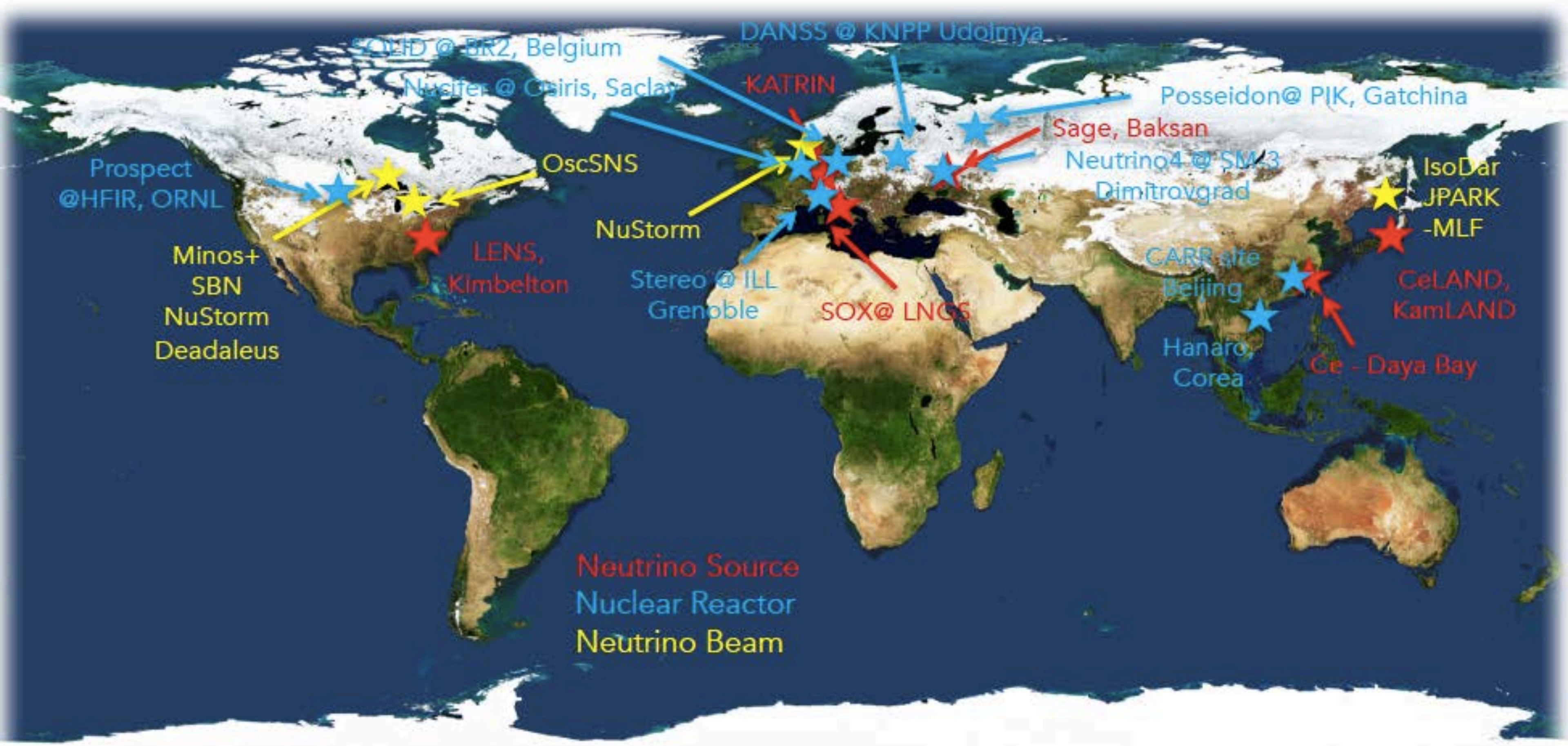
A.C. Hayes et al. arXiv:1707.07728v1 "…an analysis based on the summation method explains all of the features seen in the evolution data, but it predicts an average IBD yield that is 3.5% higher than observed. …..Resolving the issue of the existence of sterile neutrinos requires new very short baseline neutrino experiments."

No difference between U235 and LEU



Giunti et al. arXiv:1708.01133v1

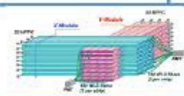
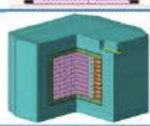
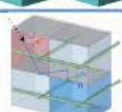
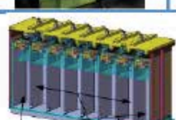
Searches for eV sterile neutrinos



This talk: (anti-) ν_e disapearance only

$$P_{ee} = 1 - \sin^2 2\theta_{ee} \sin^2 \frac{\Delta m^2_{41}}{4E} \quad \& \quad \sin^2 2\theta_{ee} = |U_{e4}|^2 \left(1-|U_{e4}|^2\right)$$

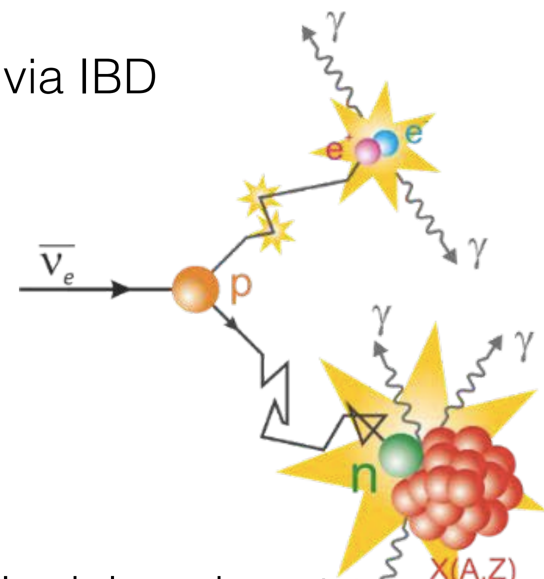
Short baseline experiments at nuclear reactors

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

N. Bowden AAP 2016

IBD experiments at nuclear reactors: different reactor types and detector concepts

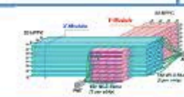
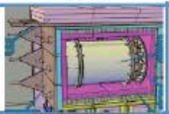
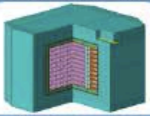
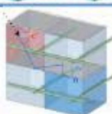
- Power reactors: large core, LEU
- Research reactors: compact core, ^{235}U
- Detection via IBD



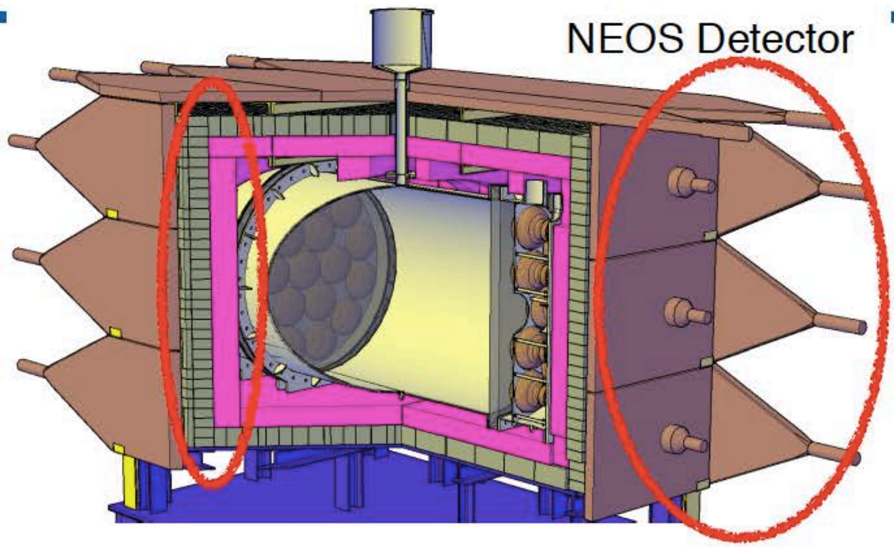
- Tagging via delayed neutron capture on Gd or Li

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

$$\mathrm{n} + \mathrm{Gd} \;\text{->}\; \mathrm{Gd} + \Upsilon + 8\ \mathrm{MeV}$$

	Experiment		Reactor Power/Fuel
Gd	DANSS (Russia)		3000 MW LEU fuel
Gd	NEOS (South Korea)		2800 MW LEU fuel
Li	nuLat (USA)		40 MW ^{235}U fuel
Gd	Neutrino4 (Russia)		100 MW ^{235}U fuel
Li	PROSPECT (USA)		85 MW ^{235}U fuel
Li	SoLid (UK Fr Bel US)		72 MW ^{235}U fuel
Li	Chandler (USA)		72 MW ^{235}U fuel
Gd	Stereo (France)		57 MW ^{235}U fuel

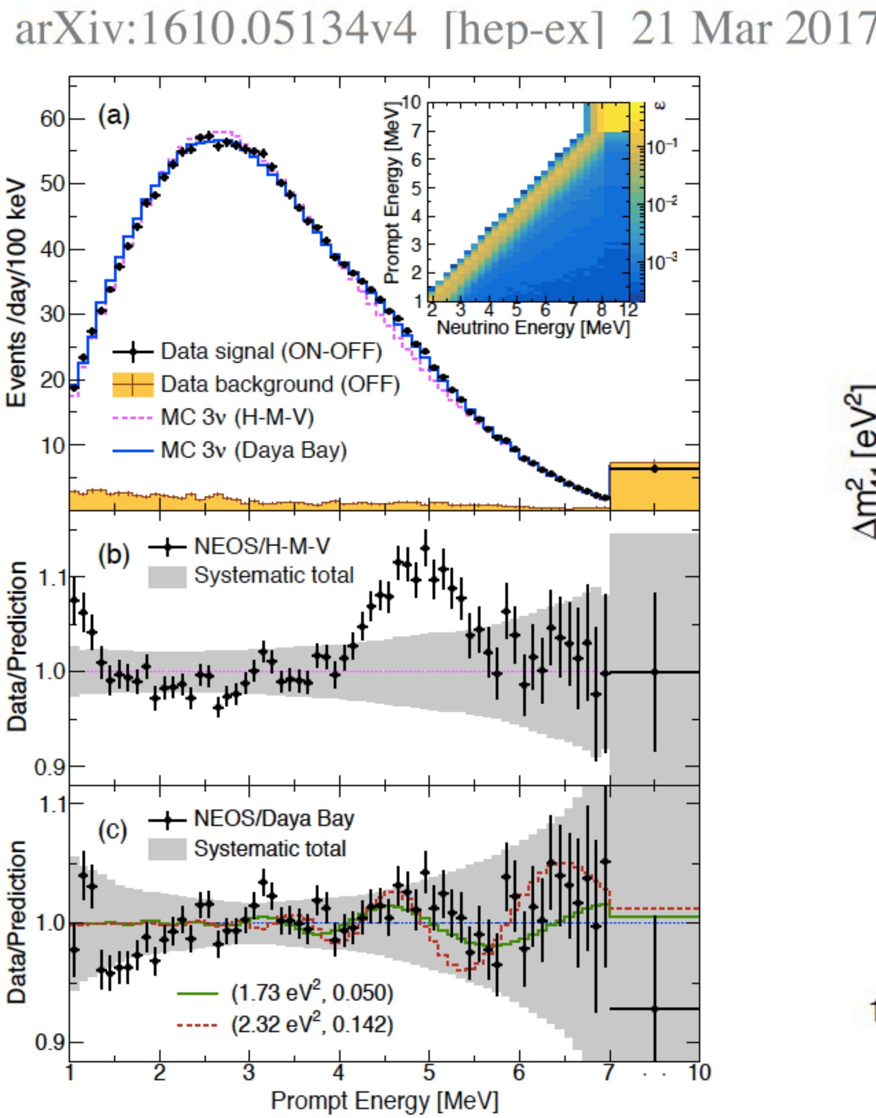
NEOS @ Hanbit (Korea)



Detector installed

- Single-volume GdLS detector with pulse shape discrimination
- Located in tendon gallery at Hanbit power reactor ~25m from reactor core, S:B~23, 2000 IBDs/day
- Initial data run in 2016

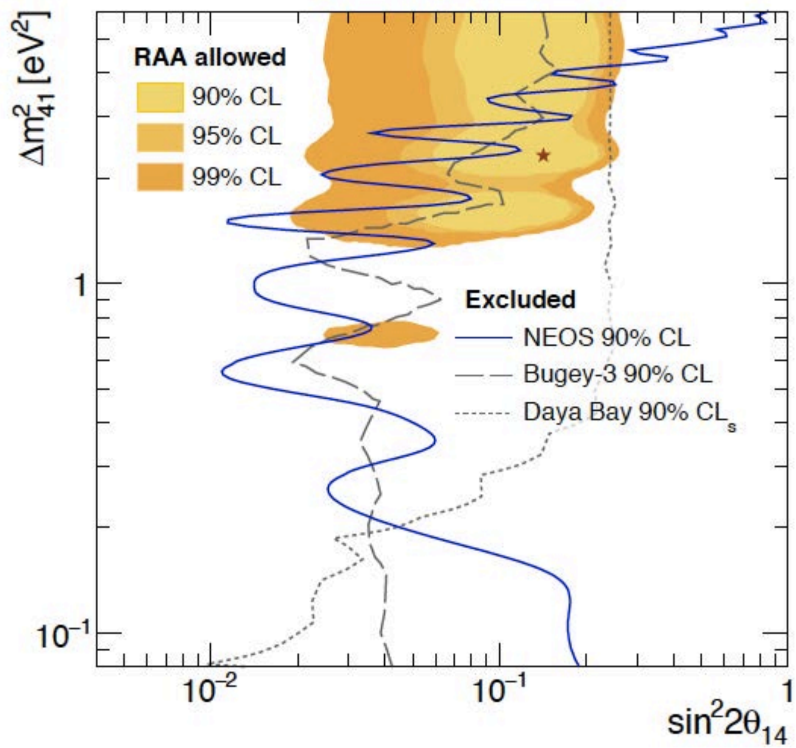
NEOS @ Hanbit (Korea)



Single detector / single distance

Analysis done with Daya Bay spectrum as reference

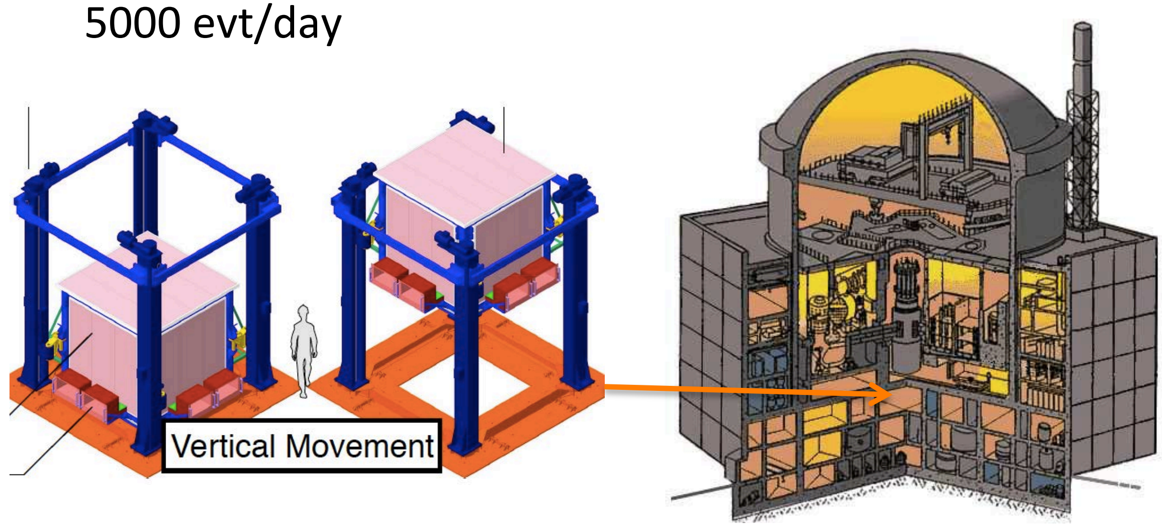
Relies on 5 MeV bumb!

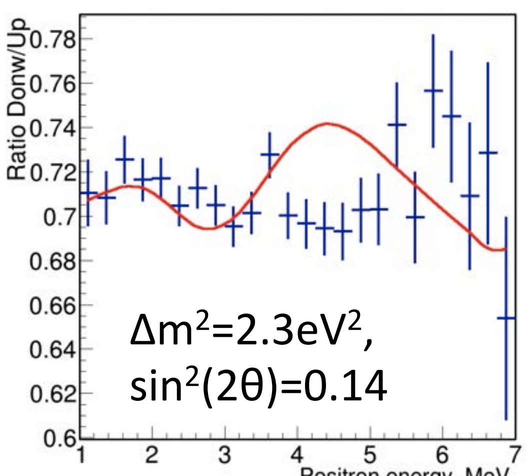


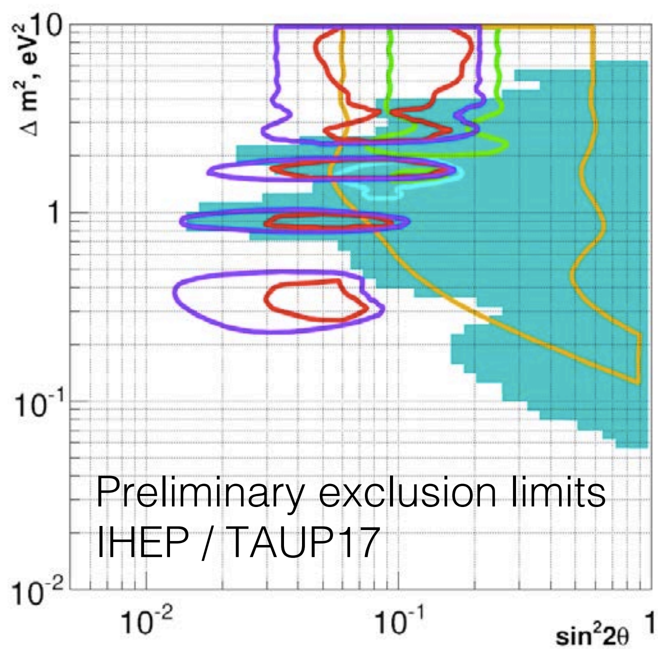
DANSS @ Kalinin

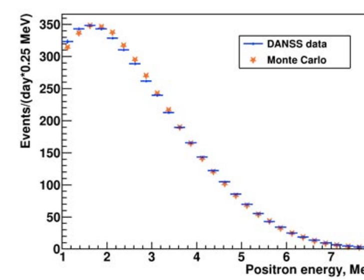
- 3 GW extended core (5000 ev/day)
- Plastic strips with Gd-loaded interlayer, WLS fibers
- Vertical motion of the detector (9.7-12.2 m)
- Independent of burn-up or spectral feature

5000 evt/day



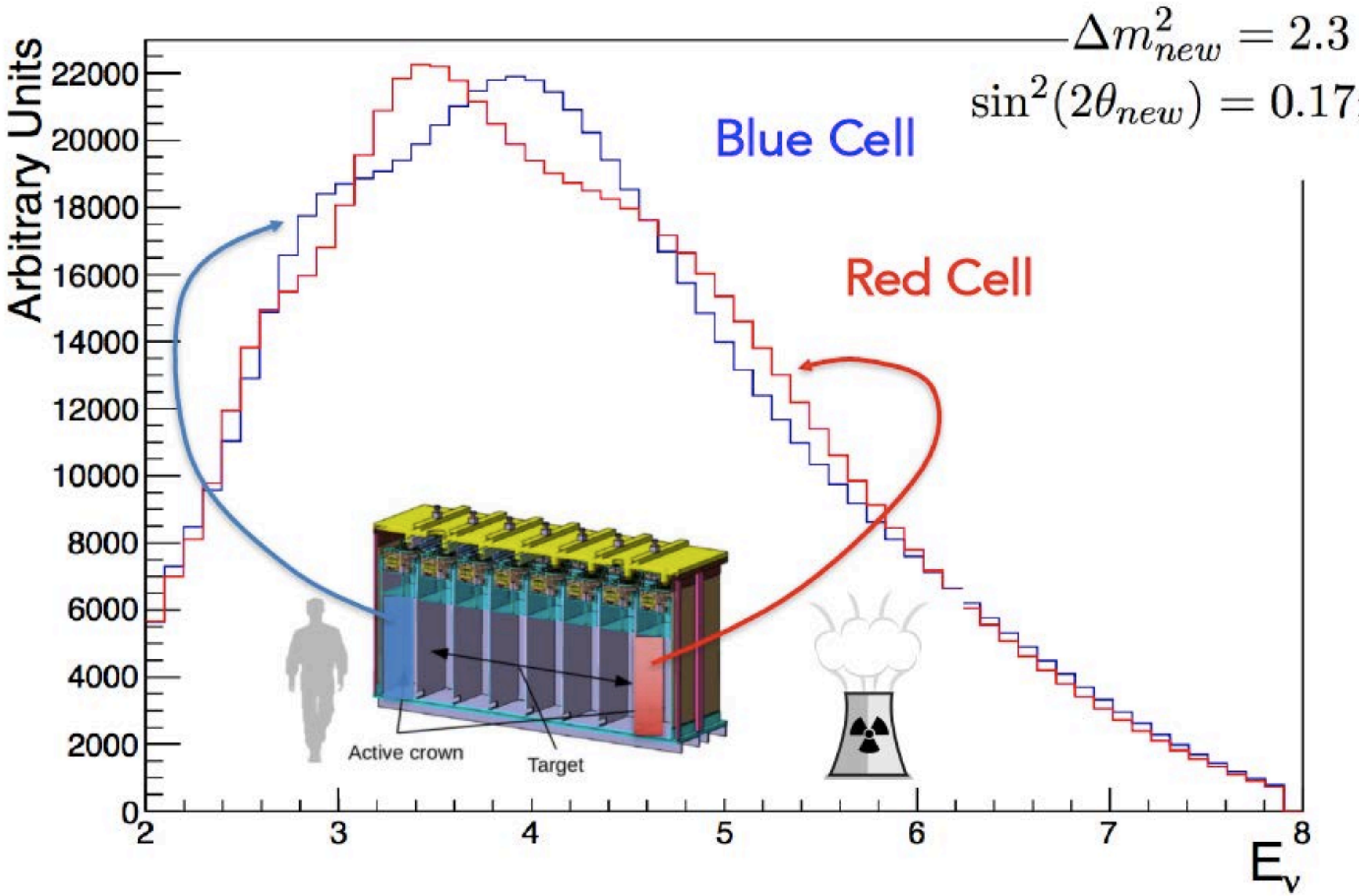






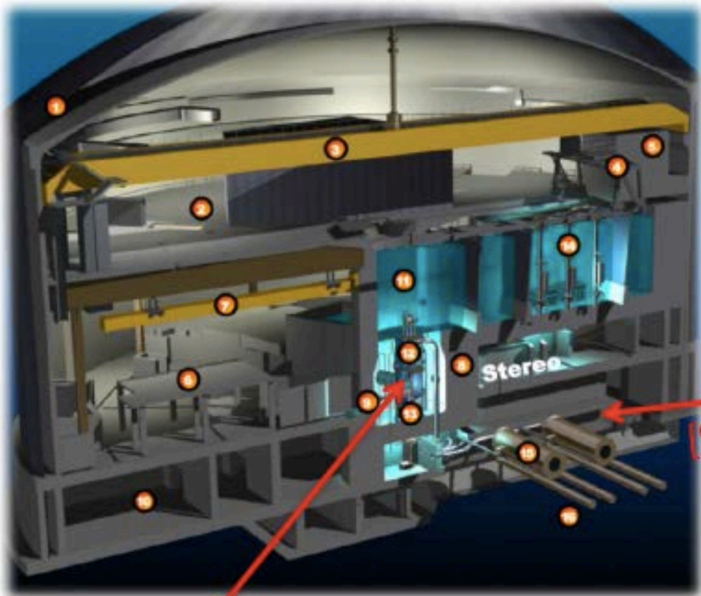
No 5 MeV bump

STEREO @ILL



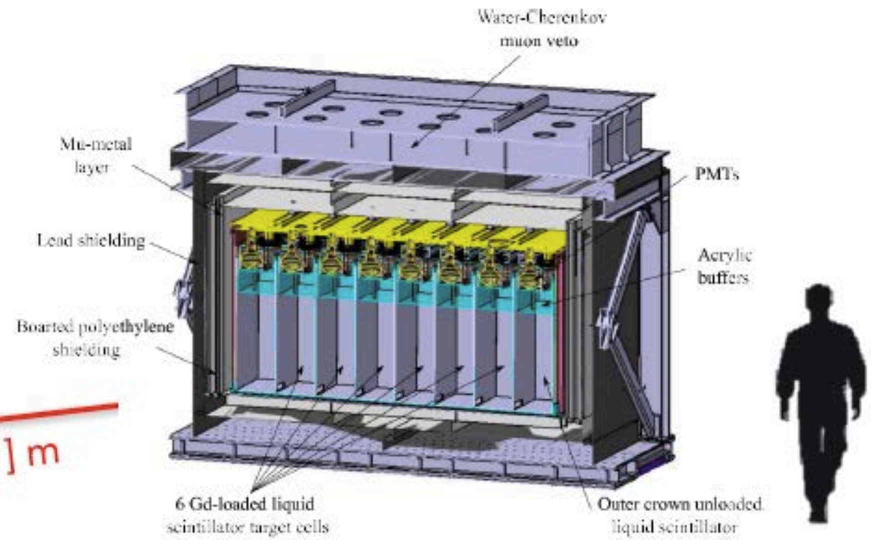
$\Delta m^2_{new} = 2.3$
$\sin^2(2\theta_{new}) = 0.17$
Arbitrary Units
22000
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
2
3
4
5
6
7
8
E_ν
Blue Cell
Red Cell
Active crown
Target

STEREO @ILL

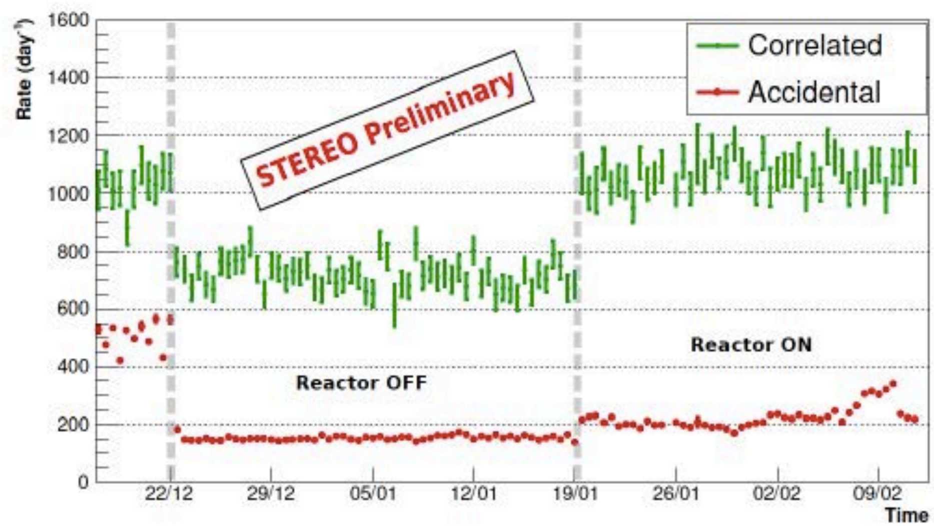


[9-11] m

50 MW
compact core



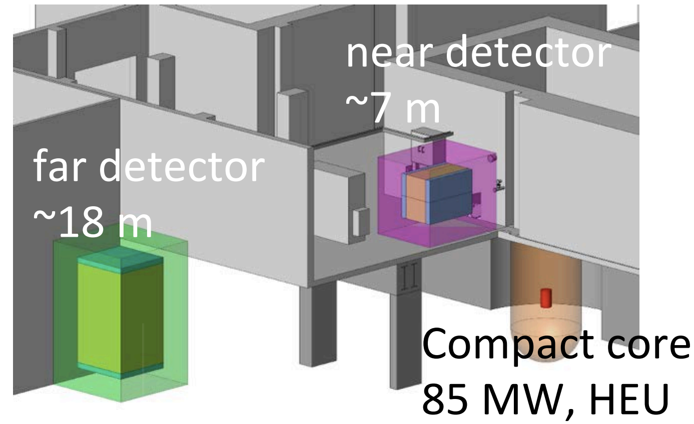
STEREO collected
>100 days of data



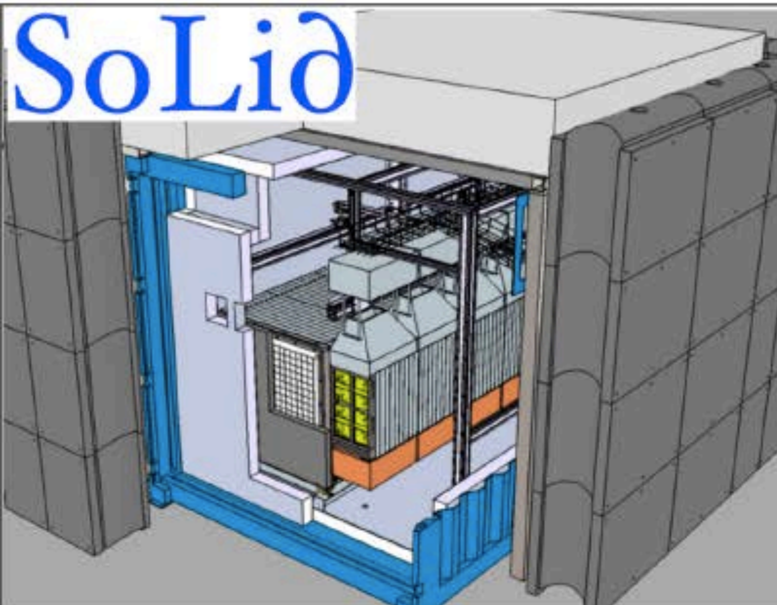
Prospect @HFIR (USA)

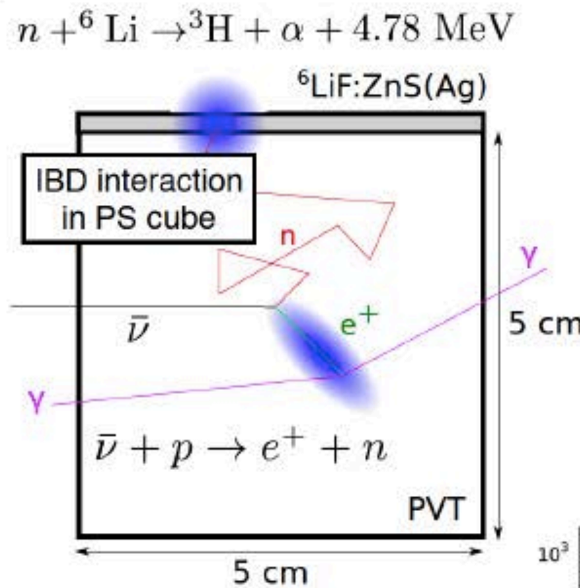
- Reactor sites
  - HFIR – 85 MW
- 7-18 m baselines
- Surface location
- Detector
  - 4t movable Segmented
  - ^{6}Li-doped (+PSD)
- Status:
  - Installation in 2017

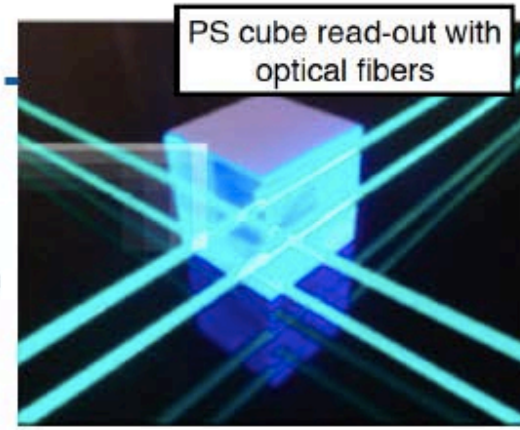
2 Detectors concept, arXiv:1309.7647

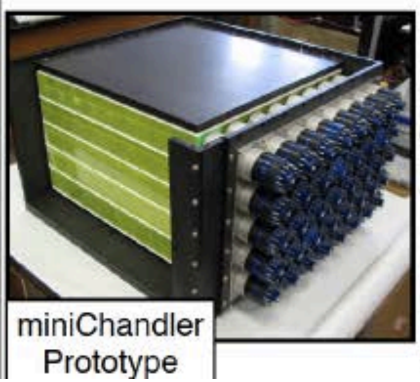


Solid @BR-2 (Belgium)

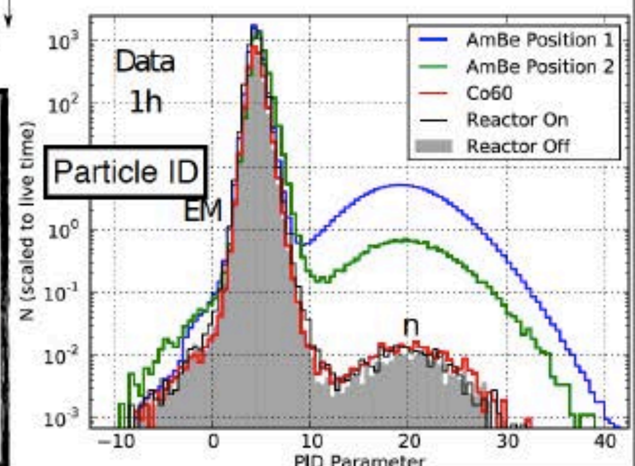




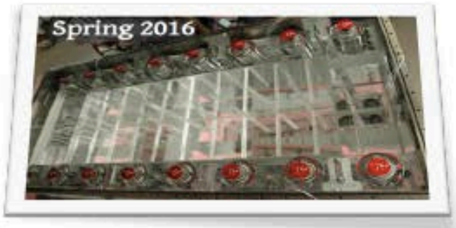




- 13000 5cm PS cubes read out by fiber
- Neutron tag from Li-loaded inorganic scintillator sheets surrounding cubes
- Deploy 1600kg detector at BR-2 reactor early 2017
- Detector R&D study (Chandler) underway, would expand high Δm^2 sensitivity



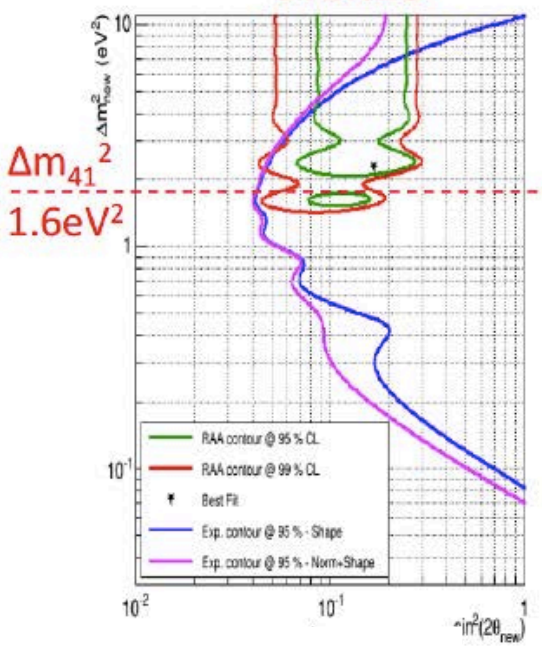
Projected sensitivities at Reactors

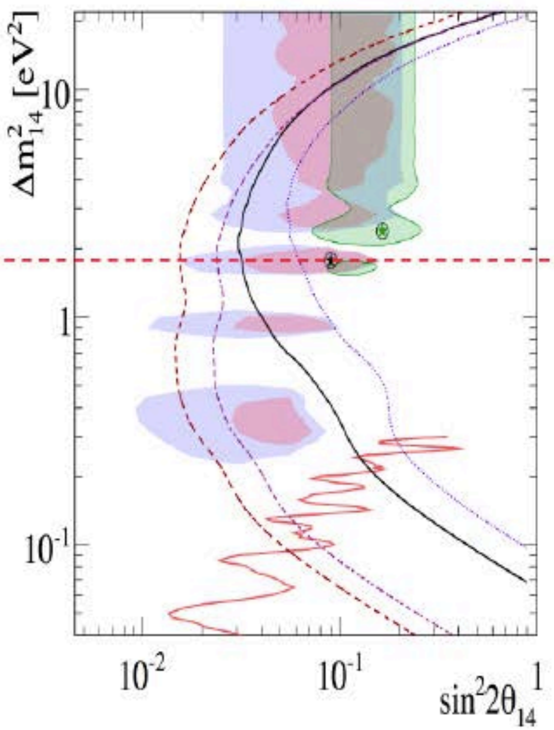


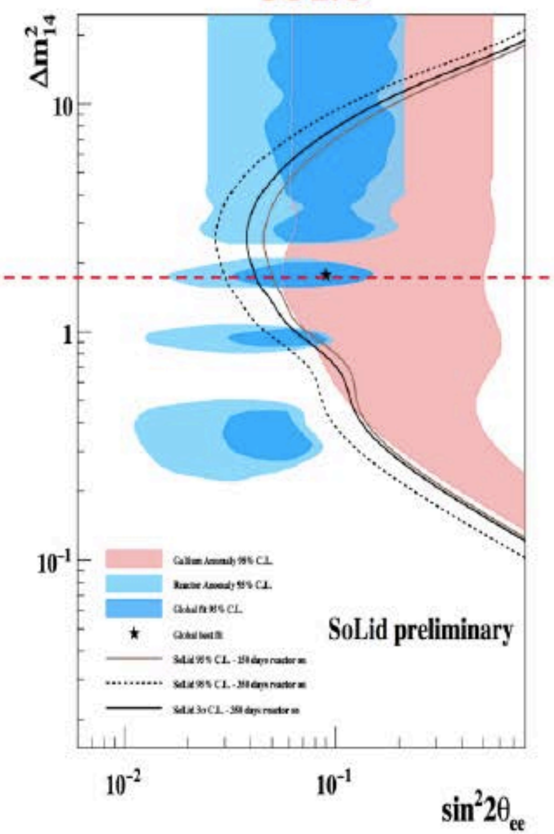
PROSPECT

SoLiδ

STEREO







Th. Lasserre – HEP 2017

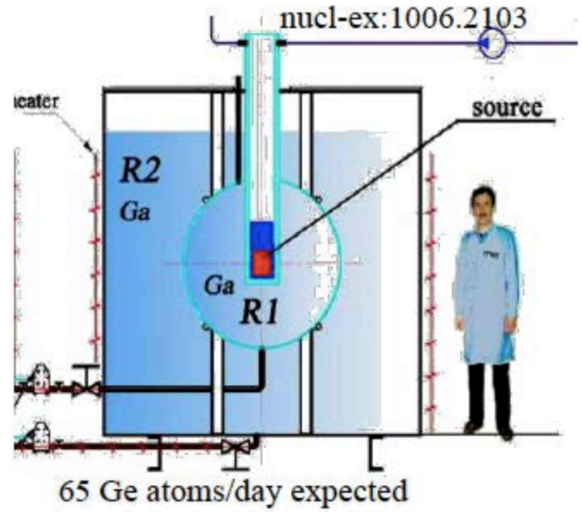
Source experiments: 2-zone Gallium detector (SAGE)

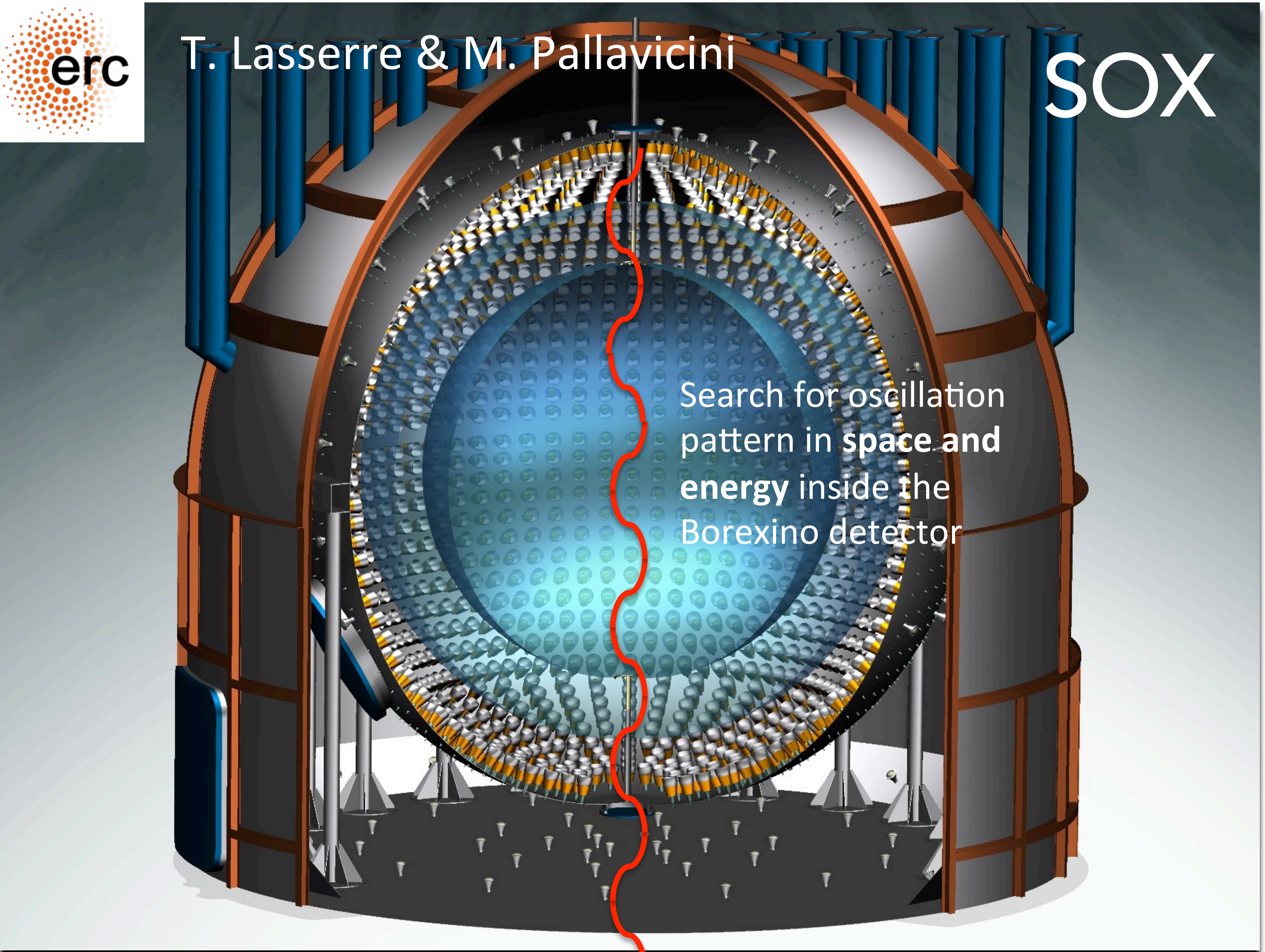
- ^{51}Cr Source:
  - Enrichment of 3.5 kg ^{50}Cr (97%)
  - Irradiation to reach 110 PBq at research reactor SM-3

- 2-layer detector in Baksan
  - Metallic Ga Target
  - Zone 1: 8 t - Zone 2: 42 t
  - SAGE procedures well understood
  - Insensitive to γ-ray background

- Observable
  - Ratio of ν_e capture rates to predicted rate in inner (R1) and outer zone (R2)

- Status: funding?

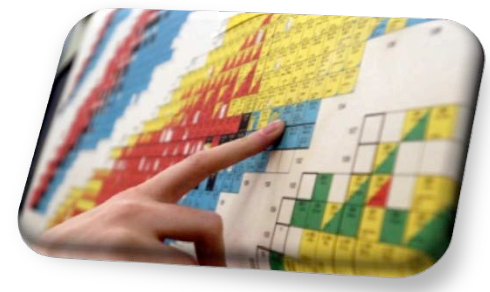




Anti-neutrino generator

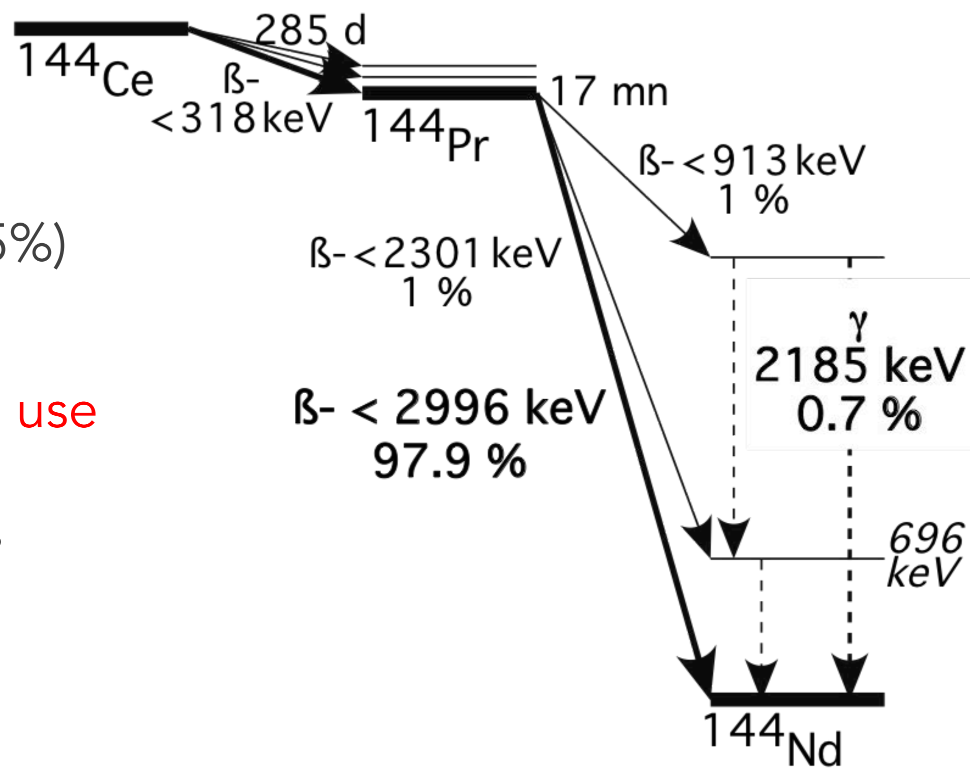
^{144}Ce-^{144}Pr Antineutrino Generator

(ITEP N°90 1994, PRL 107 201801, 2011)

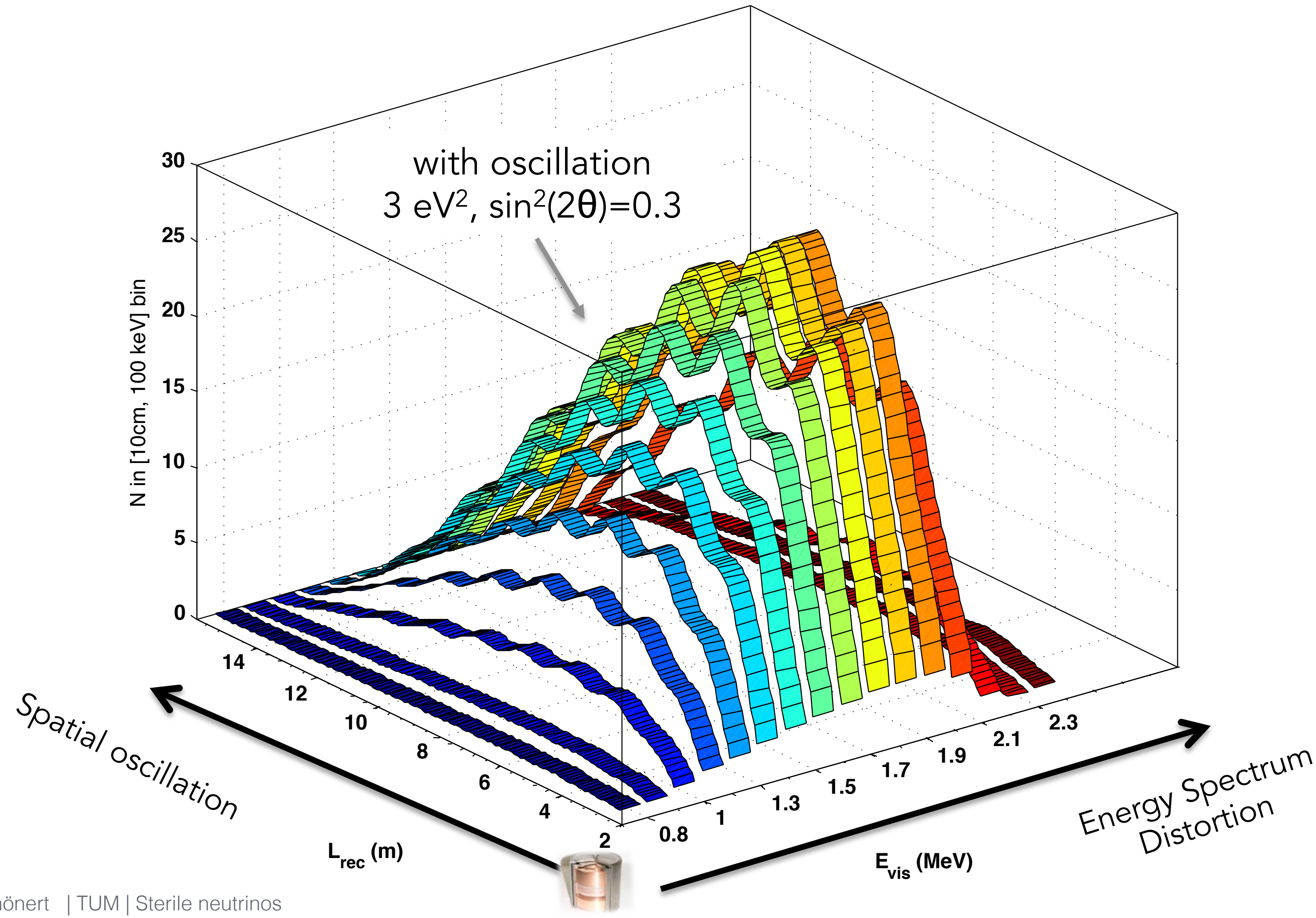


- $\bar{\nu}_e$ detection: $\bar{\nu}_e + p \rightarrow e^+ + n$
  - 10^{-42} cm^2 → 5 PBq (only) needed
  - (e^+,n) coincidence → mitigate backgrounds

- ^{144}Ce-^{144}Pr
  - abundant fission product (5%)
  - ^{144}Ce: long-lived & low-Q_β
    time to produce, transport, use
  - ^{144}Pr: short-lived & high-Q_β
    $\bar{\nu}_e$ above IBD threshold



CeSOX Concept



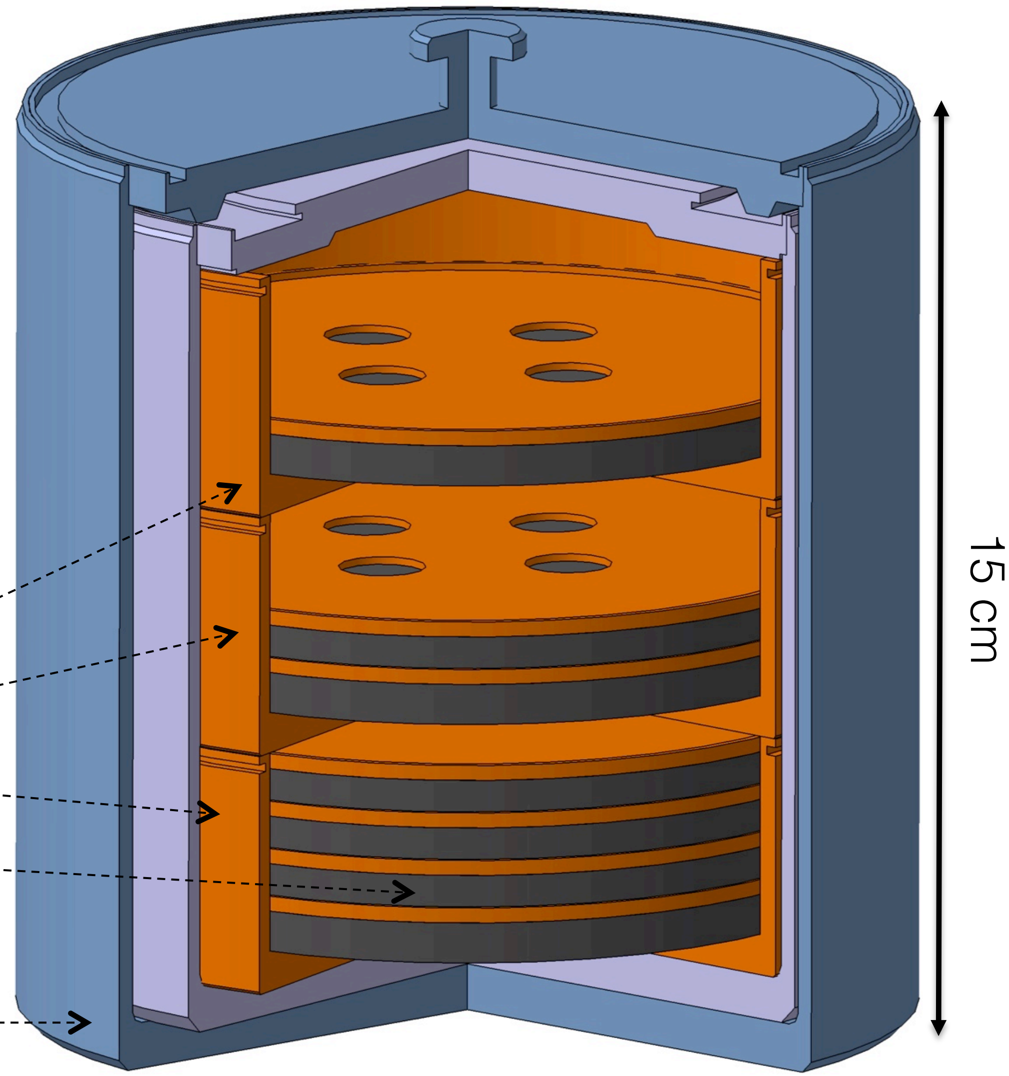
^{144}Ce Production – PA Mayak

- Seed: spent nuclear fuel (HEU)
  - High ^{144}Ce – Low Cm/Am
- Radiochemical Plant - Mayak
  - U and Pu recovered - Purex®
  - Removal of ^{137}Cs, ^{90}Sr, ^{106}Ru, Al
  - Extraction of Cerium
  - Primary encapsulation
  - Activity measurement (<u>5%</u>)
- Radioisotope Plant - Mayak
  - Secondary encapsulation
  - Certification SFRM / ISO
  - Loading into tungsten shield
  - Loading into transport cask
- 2012-15: R&D. 2017: production

Source Encapsulation

- ^{144}Ce
  3.7 – 5.5 PBq (~1200 W)

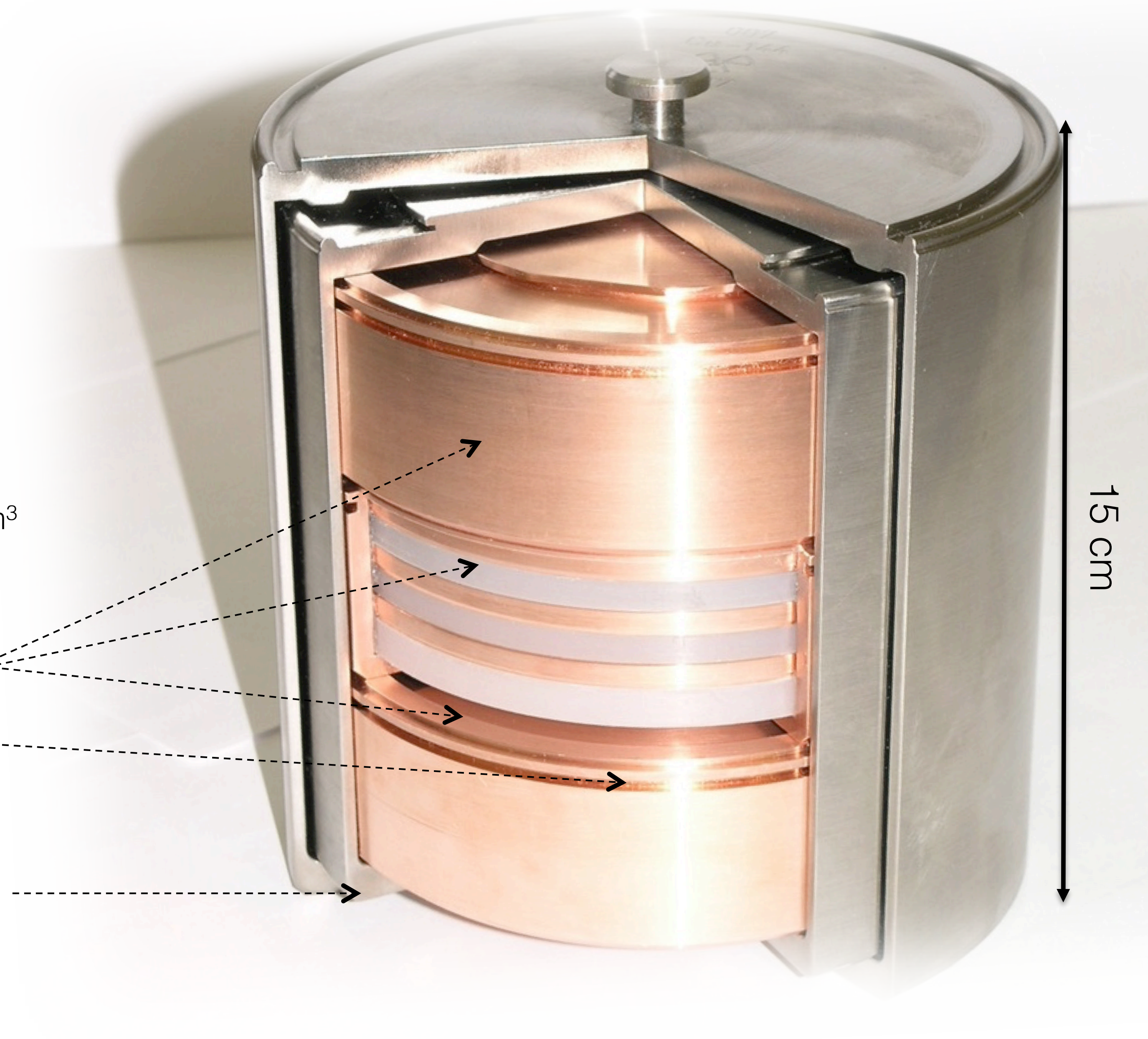
- Sketch of CeO_2 inside capsule
  - CeO_2 pellets 2.5 g/cm^3
  - Cu-disk radiators
  - 3 Cu-capsule
  - $T(CeO_2) < 600$ °C
  - T(Out Cap) < 500 °C



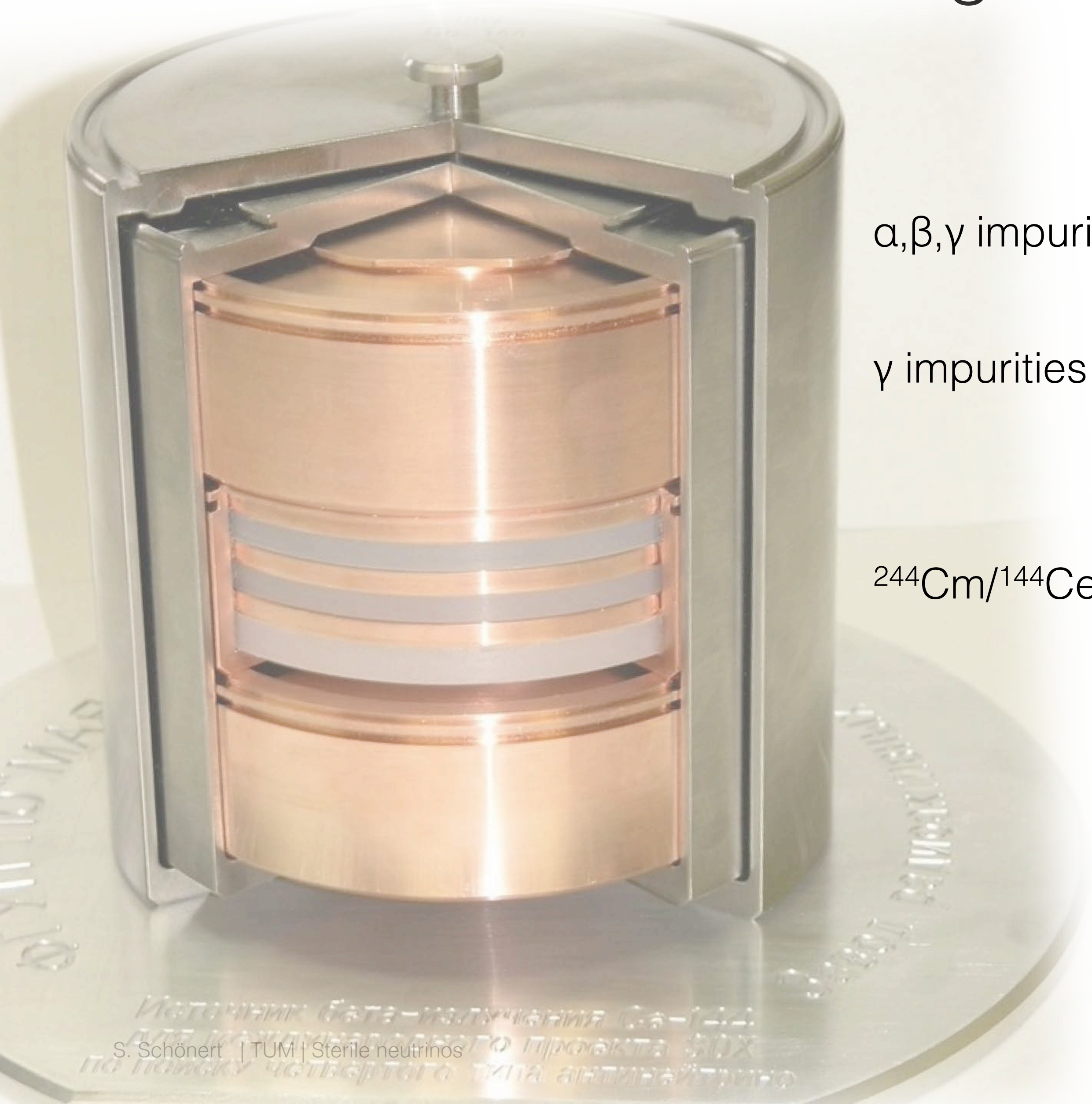
ISO 9978:1992(E) – ISO 2919
Special Form Radioactive Material

Dummy Source Delivered

- Sketch of CeO_2 inside capsule
  - CeO_2 pellets 2.5 g/cm^3
  - Cu-disk radiators
  - 3 Cu-capsule
  - T(CeO_2) < 600 °C
  - T(Out Cap) < 500 °C



Stringent Specifications

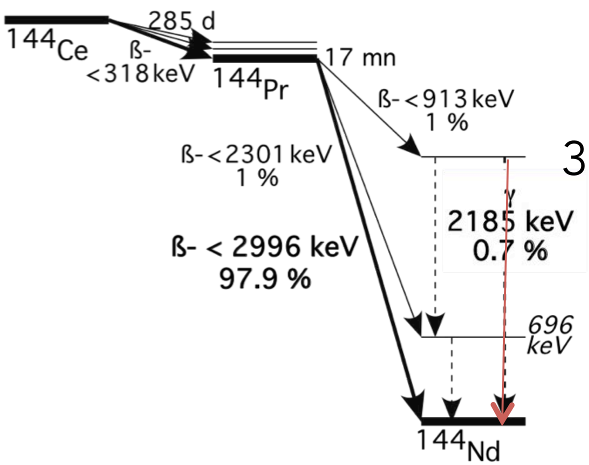


α,β,γ impurities / (^{144}Ce +^{144}Pr) < 10^{-3} W/W

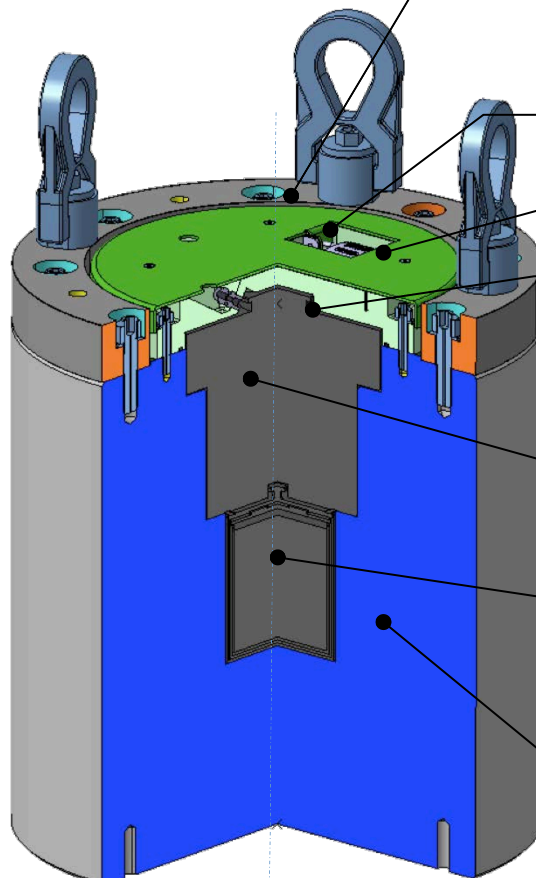
γ impurities / ^{144}Ce < 10^{-3} Bq/Bq

^{244}Cm/^{144}Ce < 10^{-5} Bq/Bq

High Density Tungsten Shield



$3\ 10^{10}\ \gamma$ /sec



Handling crown

Top lid

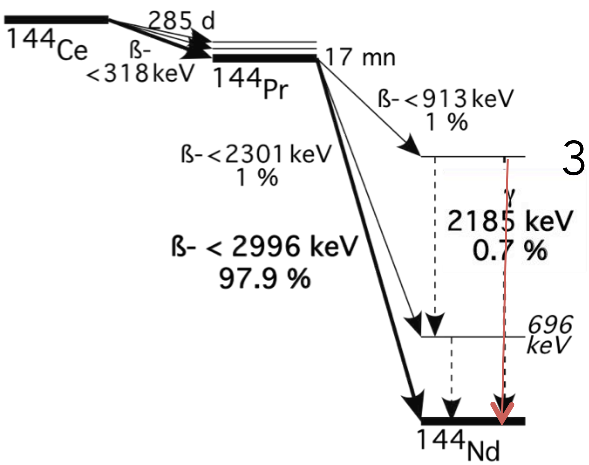
Closure flange

18.g/cm^3 W
alloy Plug

Cerium source

2.3 tons

High Density Tungsten Shield

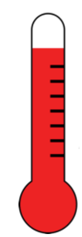


$3\ 10^{10}\ \gamma$ /sec

10^7 attenuation
for 2.2 MeV γ's

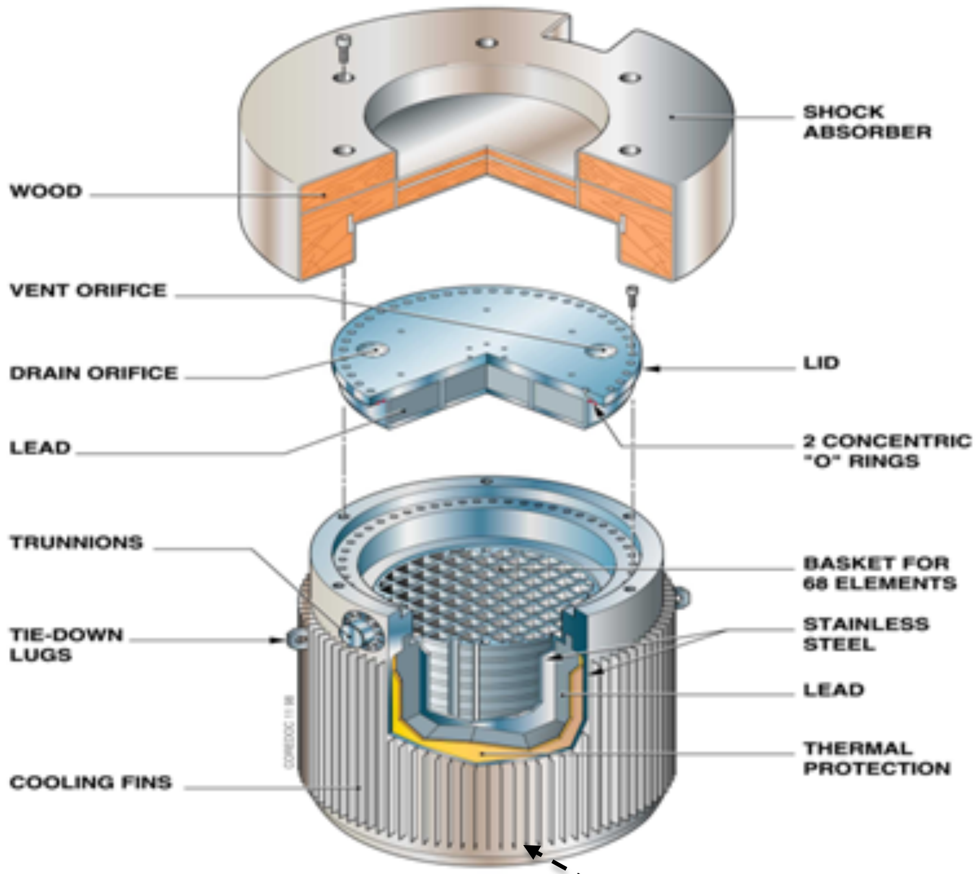
< 8 μSv/h @1 m

<80°C



Transportation cask – TN MTR

25 g of ^{144}Ce – 25 ton cask – Certified for CeSOX



insertion test

tungsten shield

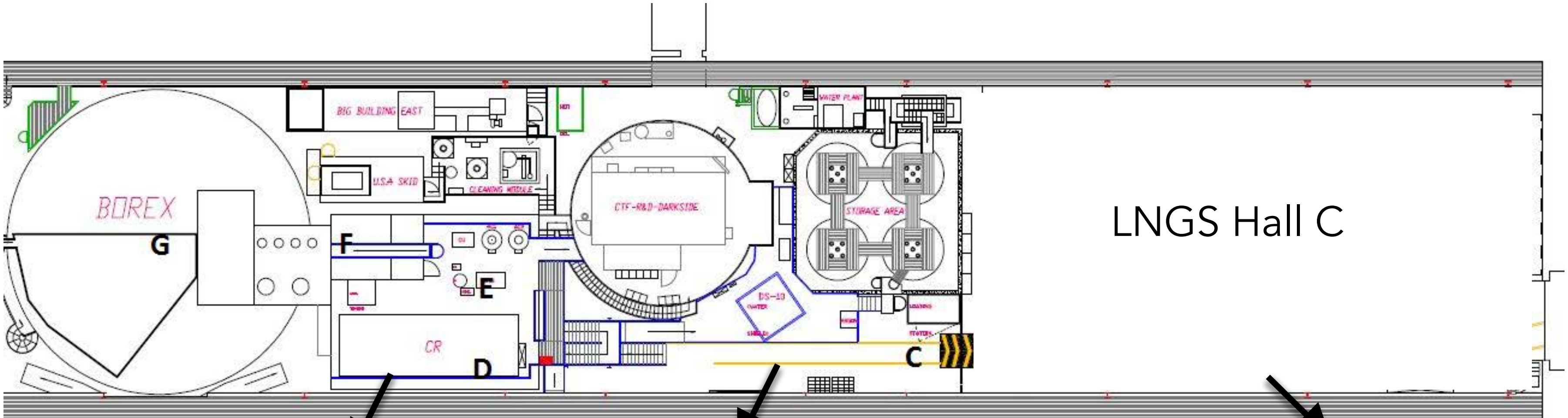
Transportation Routes

Under the responsibility of AREVA & CEA

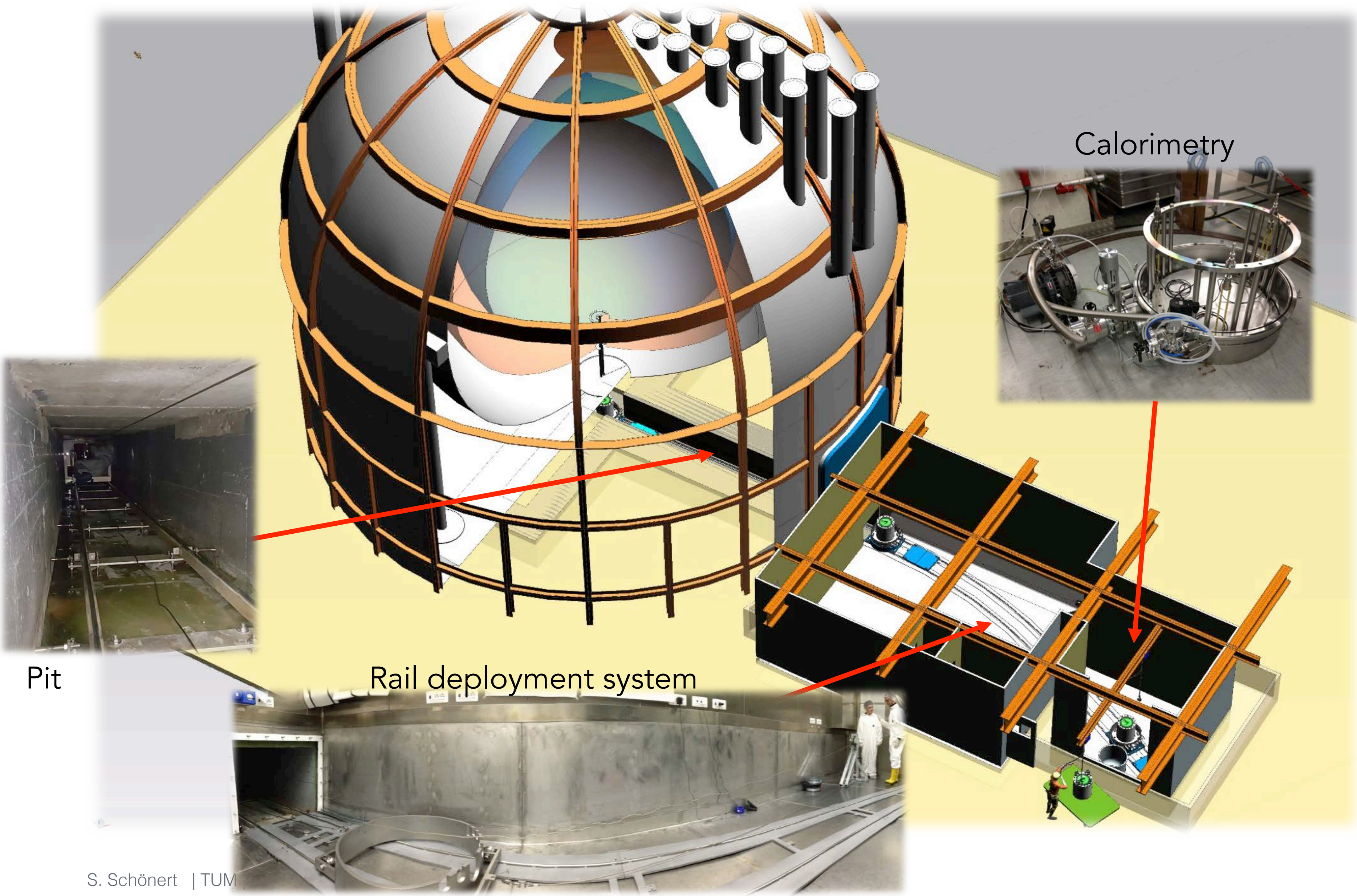
A 3 week journey through Russia (train), France (boat), and Italy (truck)

TN-MTR Cask

Deployment Rehearsal

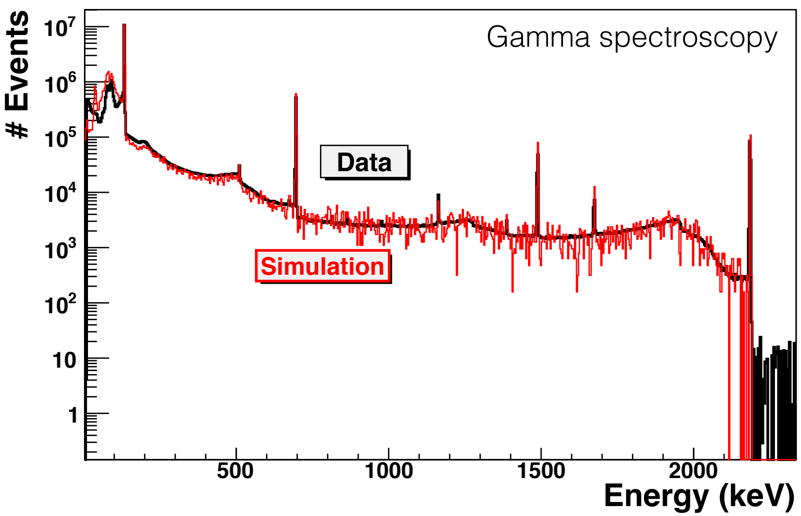


Borexino/SOX Facilities

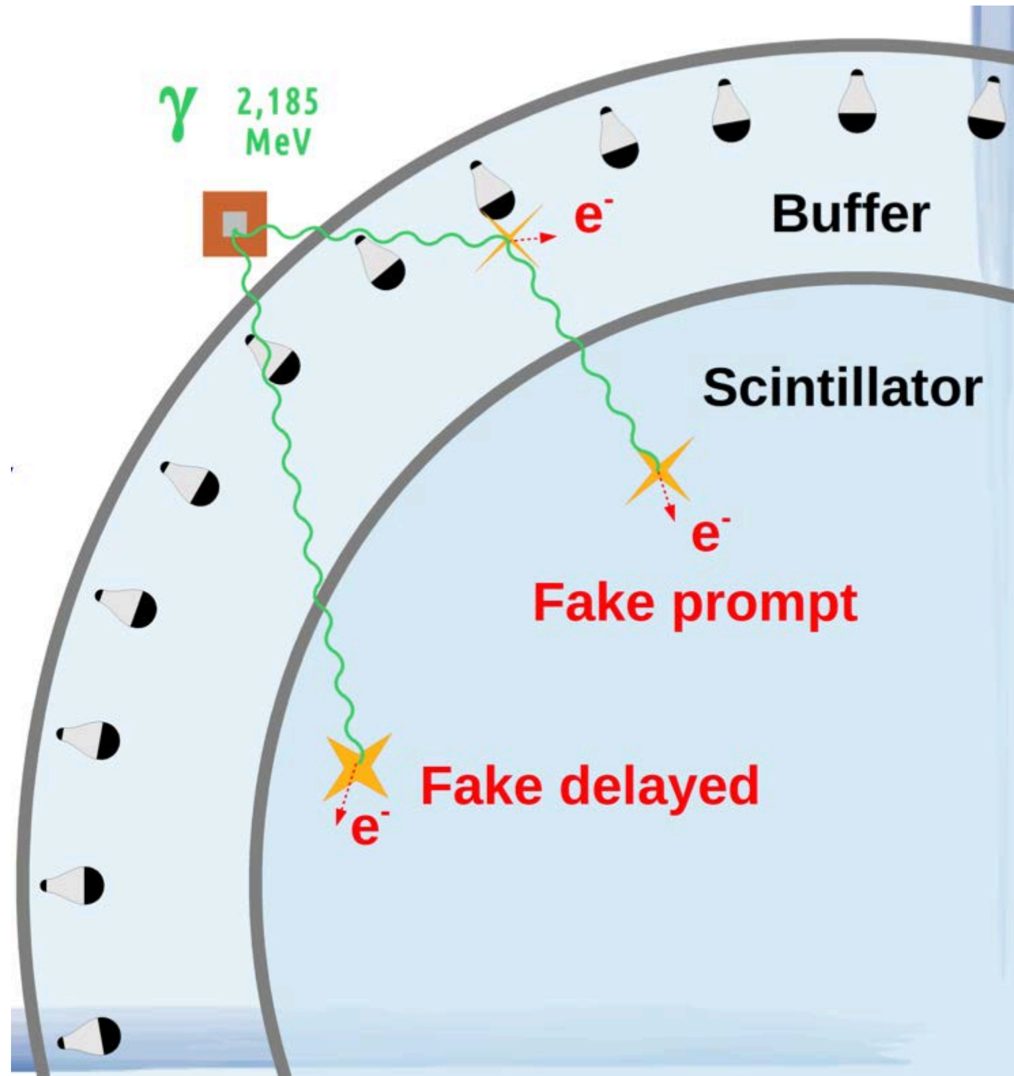


Gamma induced background

- Random coincidence between two γ's from the ^{144}Ce source
- ^{144}Ce pilot production



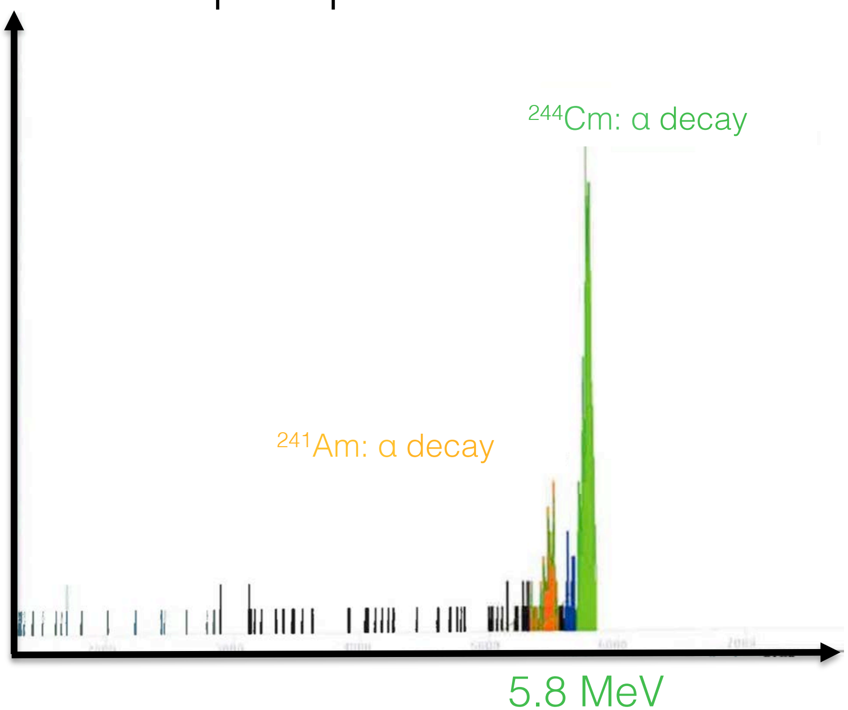
- No impurity at < 10^{-4} Bq/Bq of ^{144}Ce → negligible

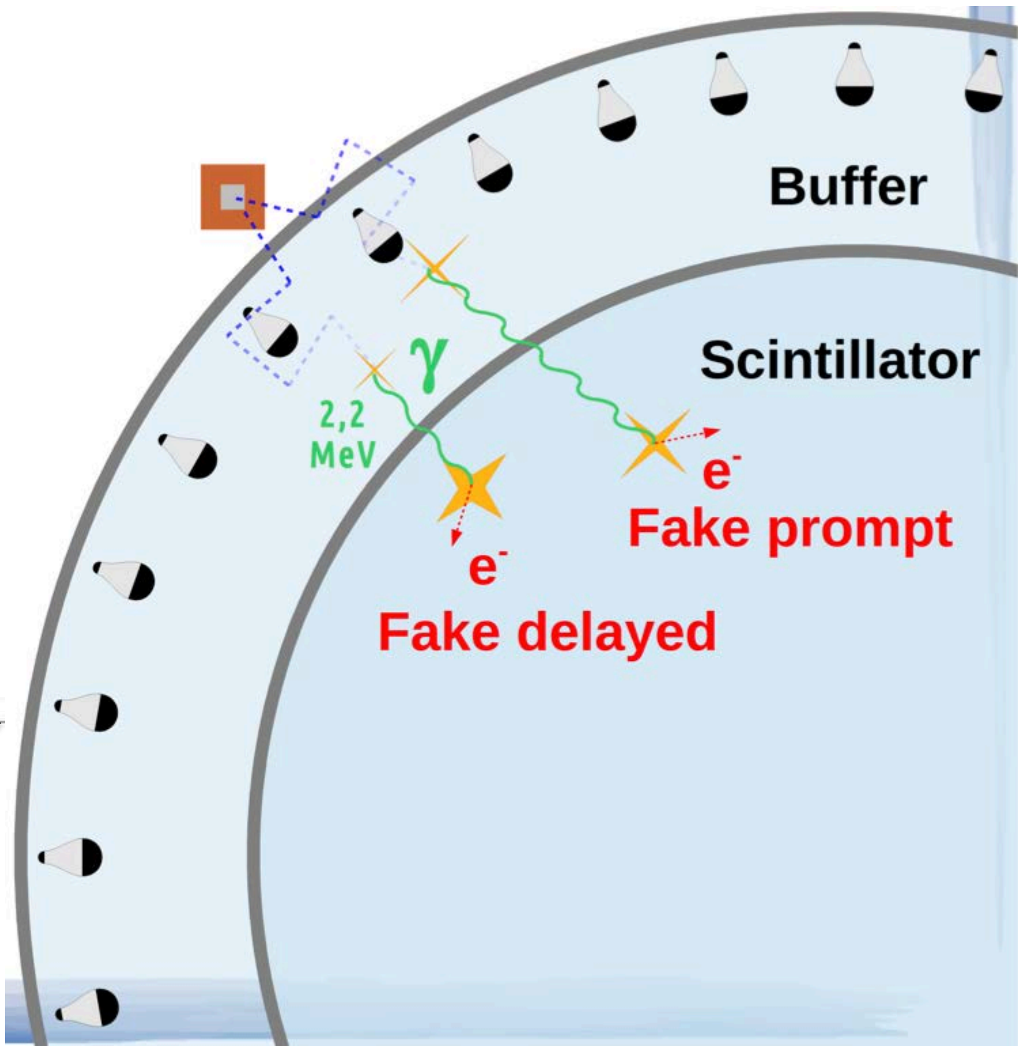


Neutron induced background

- Neutrons from spontaneous fission
→ 2 neutron captures → 2 γ's

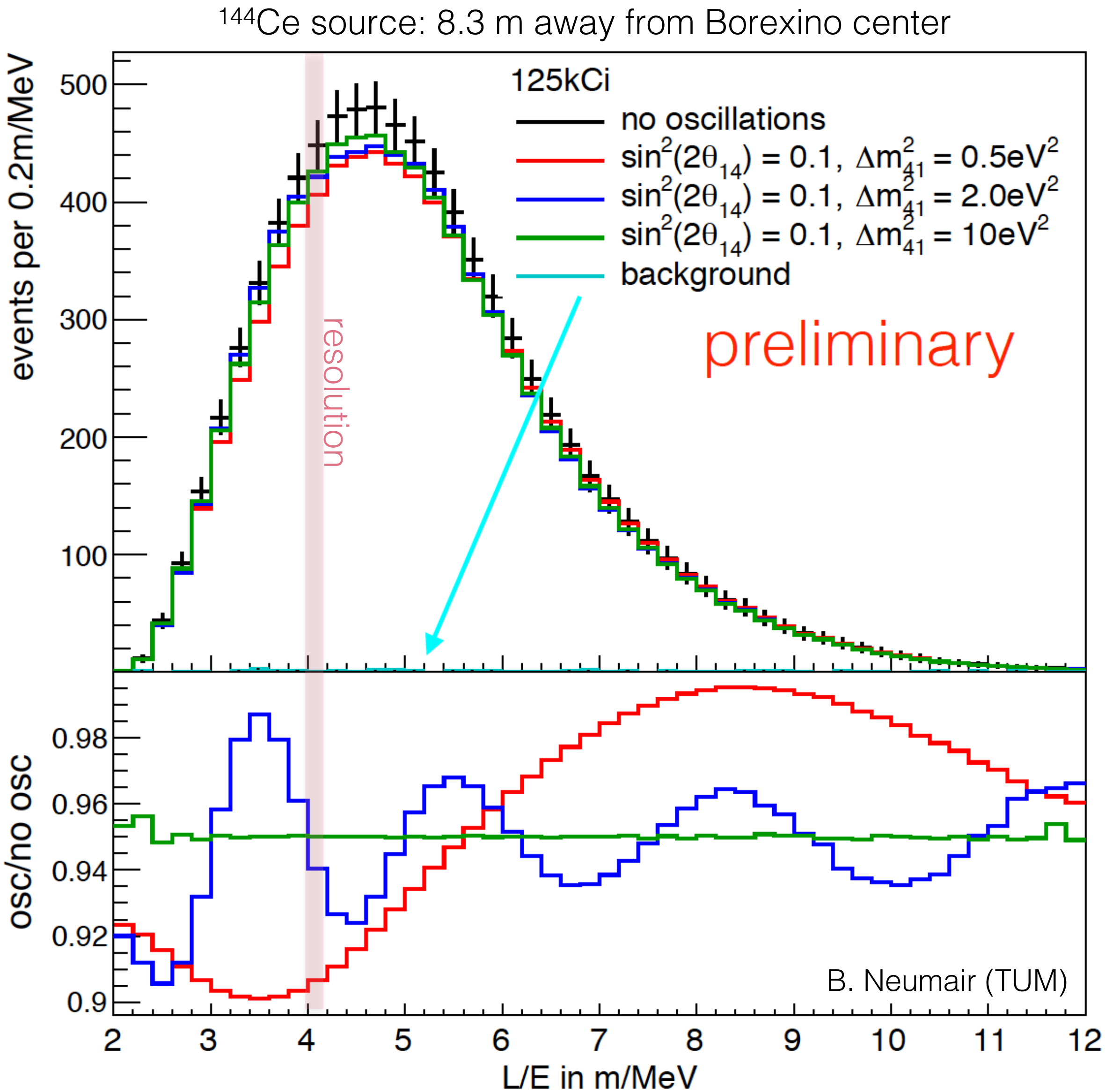
- ^{144}Ce pilot production





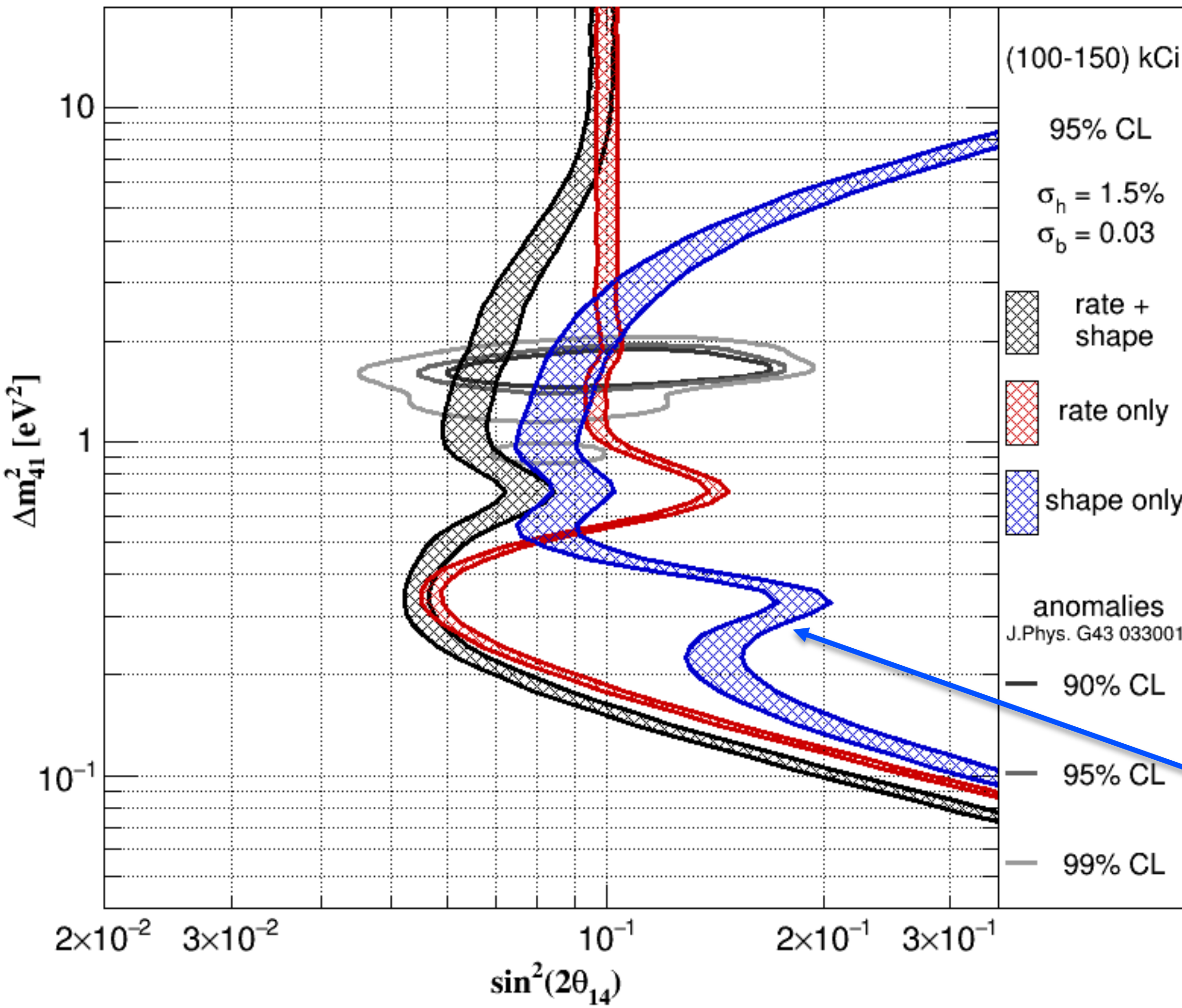
- 10^{-5} Bq ^{244}Cm / Bq ^{144}Ce
→ negligible

A background free sterile ν search

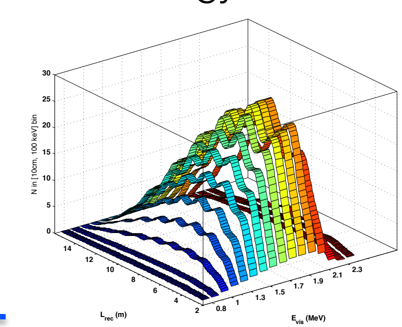


- 270 tons (4m radius)
  1.5 y - 90% efficiency
- ^{144}Ce Signal - 4.6 PBq
  - 8500 ν's
- Backgrounds
  - from detector
    < 50 (data)
  - from ^{144}Ce source
    < 1

“Shape-only” analysis

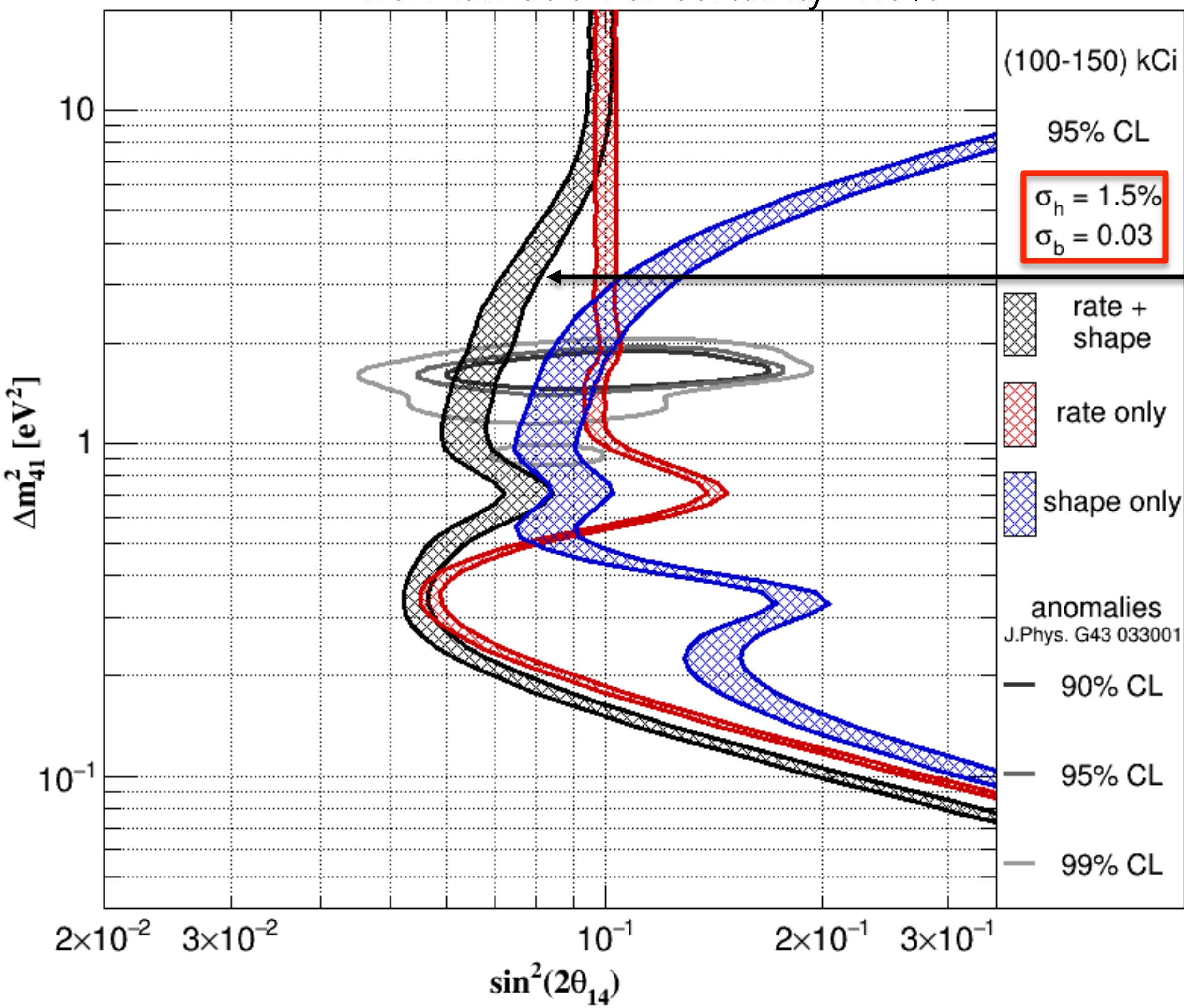


Vertex+Energy reconstruction

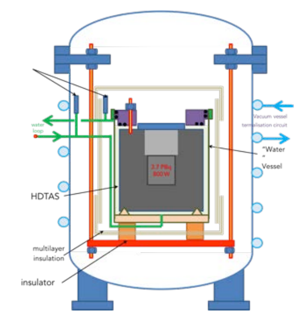


“Rate+Shape” Sensitivity

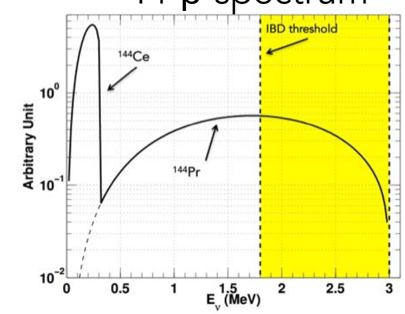
normalization uncertainty: 1.5%



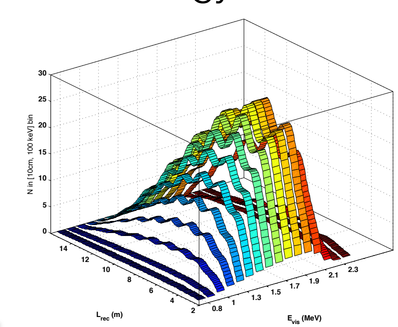
^{144}Ce activity



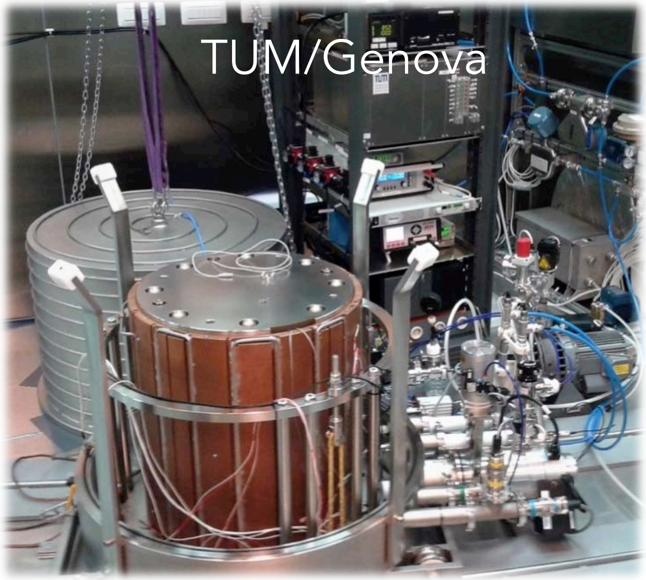
^{144}Pr β-spectrum

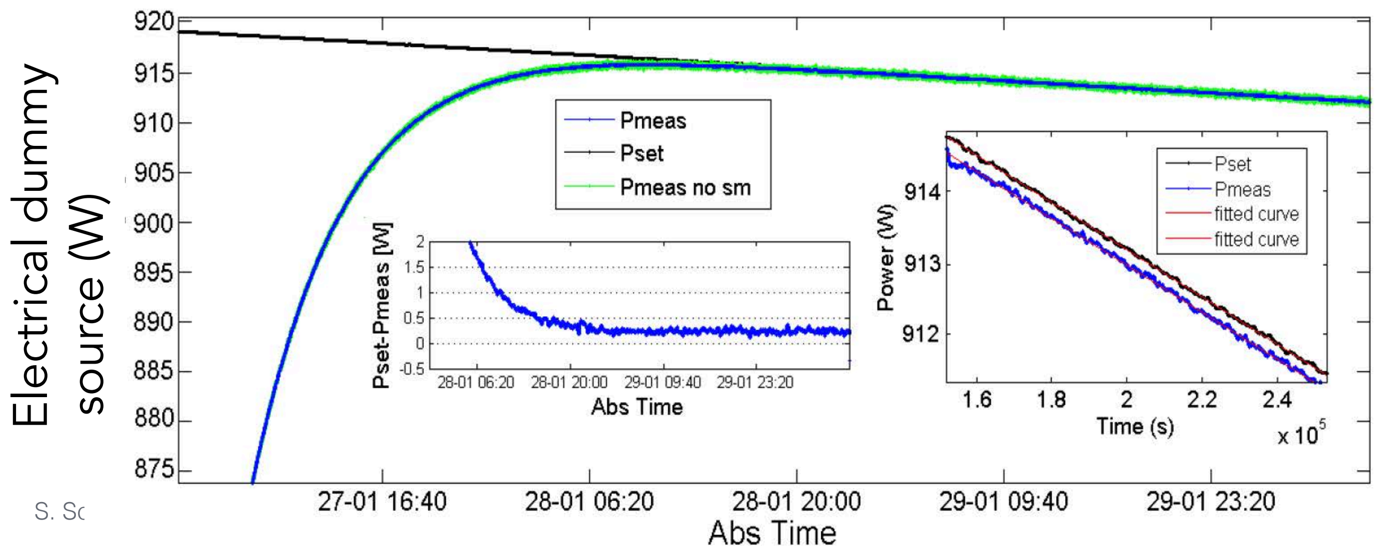


Vertex+Energy reconstruction



Calorimetric measurement of source power



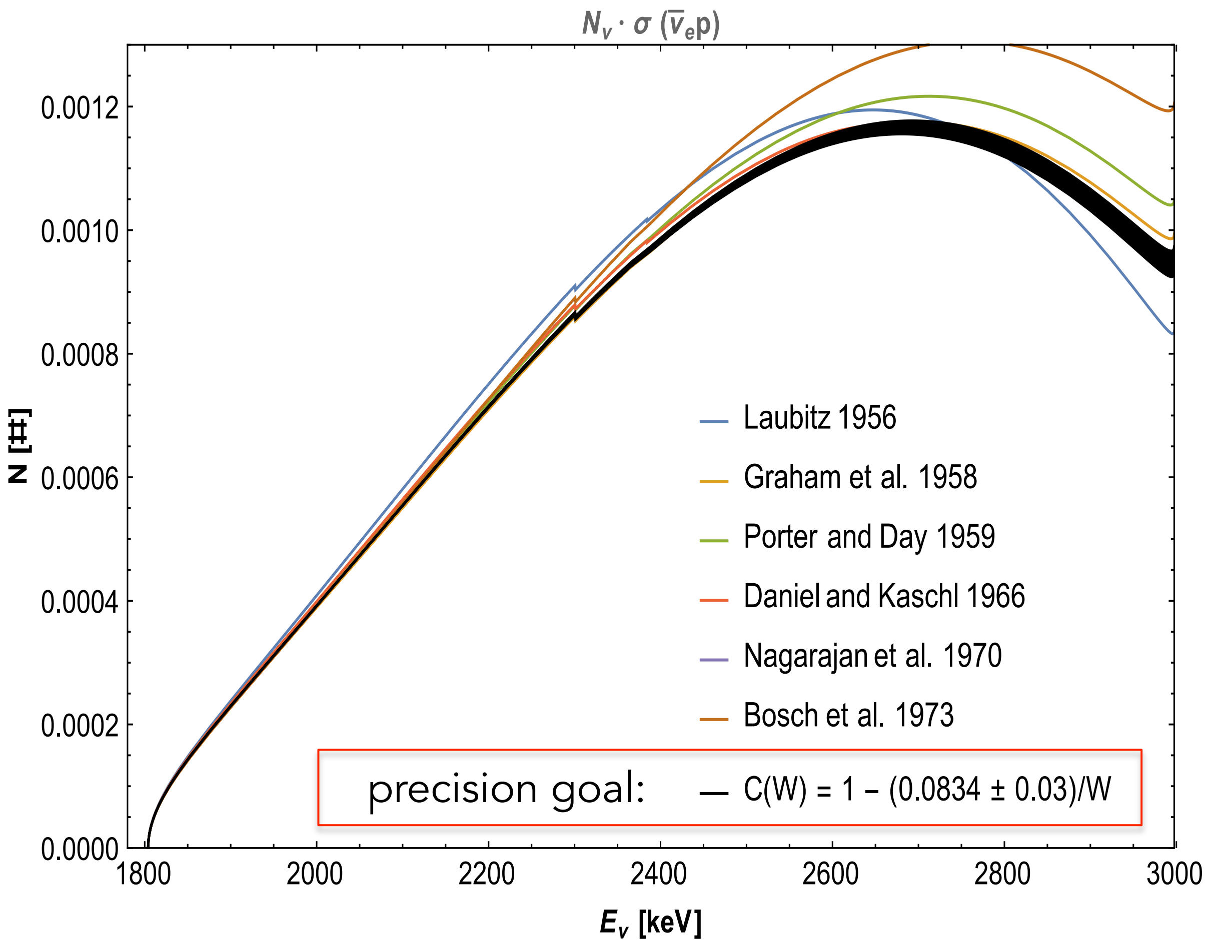


Blind measurement:

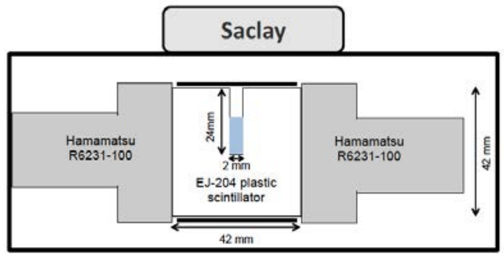
0.3% precision

Precision measurement of ^{144}Pr β spectrum

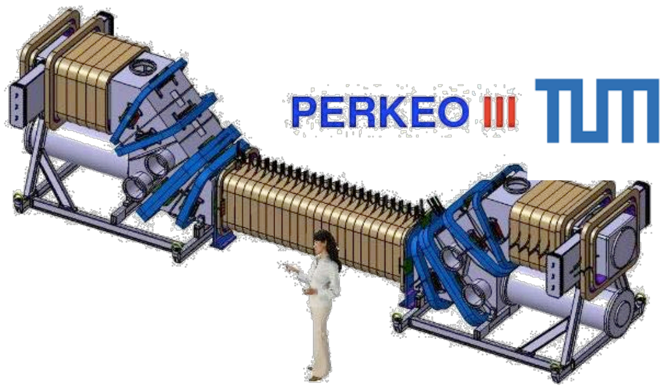
First forbidden non-unique decay



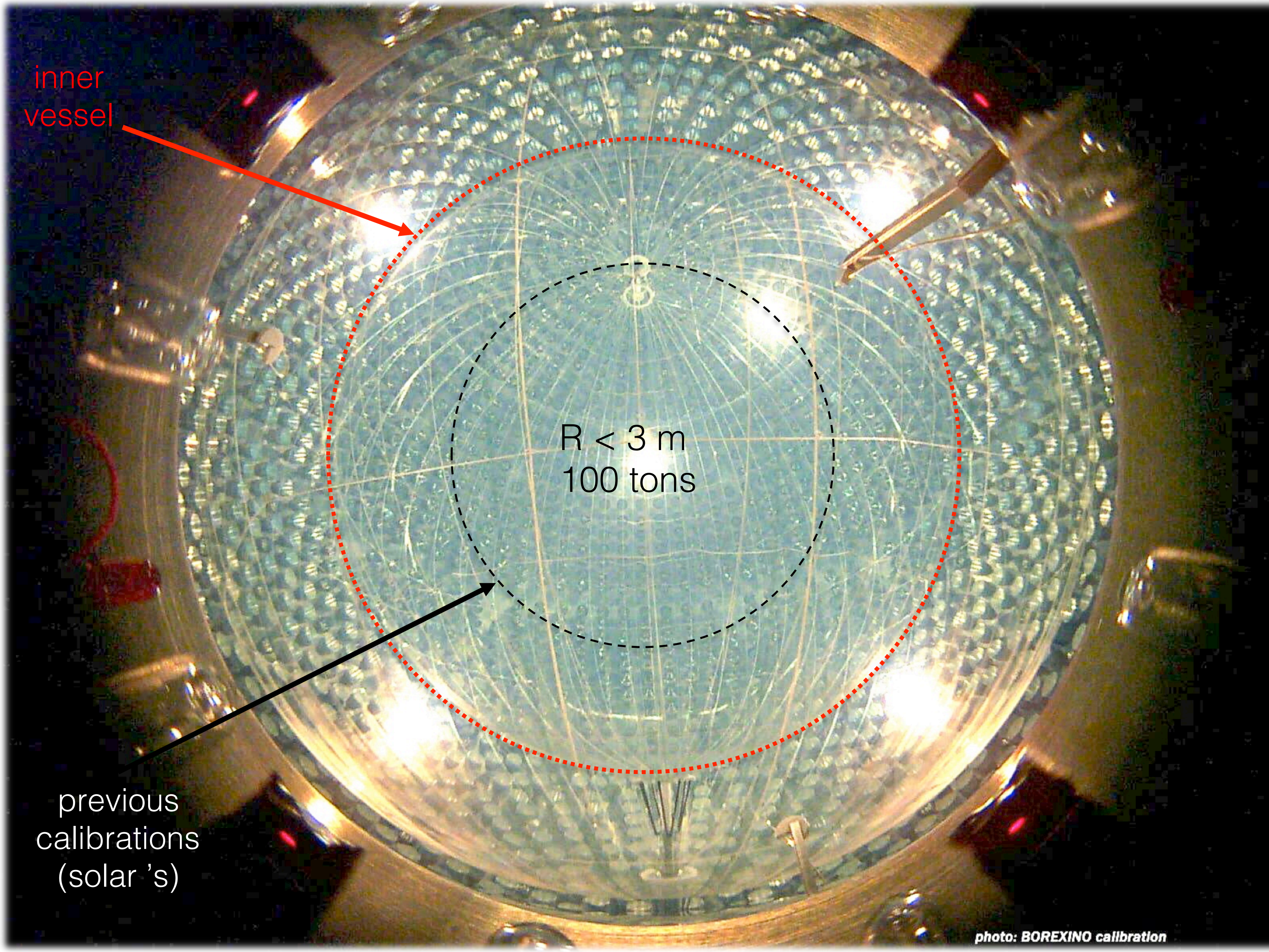
^{144}Pr



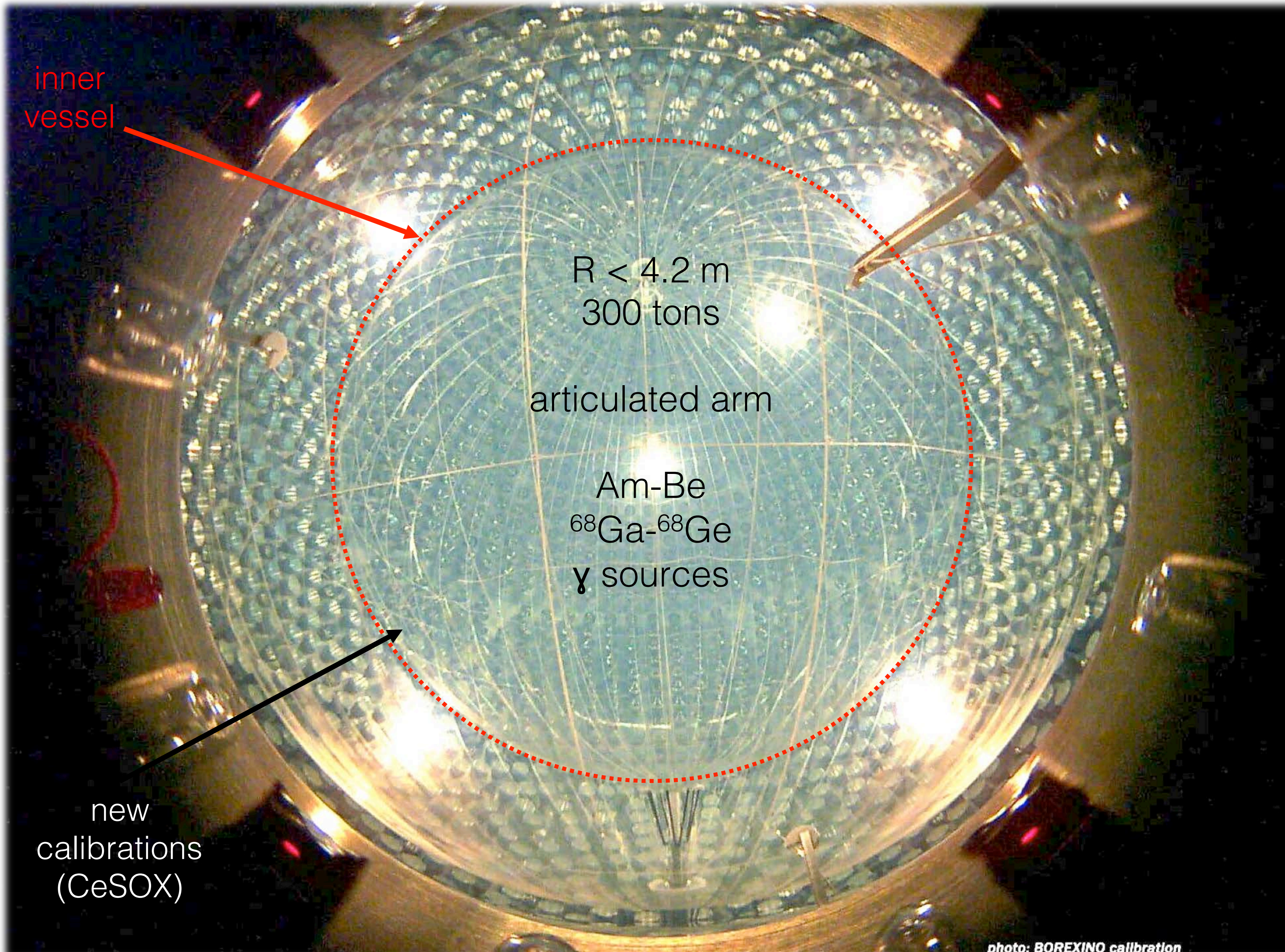
^{144}Ce-^{144}Pr



Dedicated calibration campaign



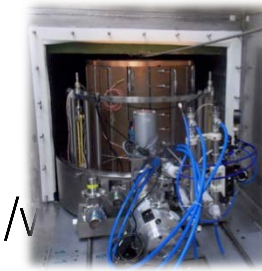
Dedicated calibration campaign



- ^{144}Ce source in production – at Mayak

- Tungsten shield delivered – at LNGS

- Transport cask & basket ready – at CEA



- Borexino facilities ready – calibration autumn/v 7

- Calorimeters being commissioned – at LNGS

- β-spectrometers under construction
- Many authorizations/certifications required – Underway

Summary & conclusions

- 5 MeV bumps inconsistent; needs clarification; however no impact on experiments with movable or 2 identical detectors
- Anomalies alive – also after DB fuel evolution analysis
- New dedicated experiments are getting operational
- Several reactor experiments: different cores and different detector concepts
- One source experiment (SOX); maybe second (SAGE)
- Hot phase in 2018/19
- Need redundant and convincing results amongst reactor experiments and source experiment(s)
- Accelerator based SBL experiments 2019+