FROM RESEARCH TO INDUSTRY

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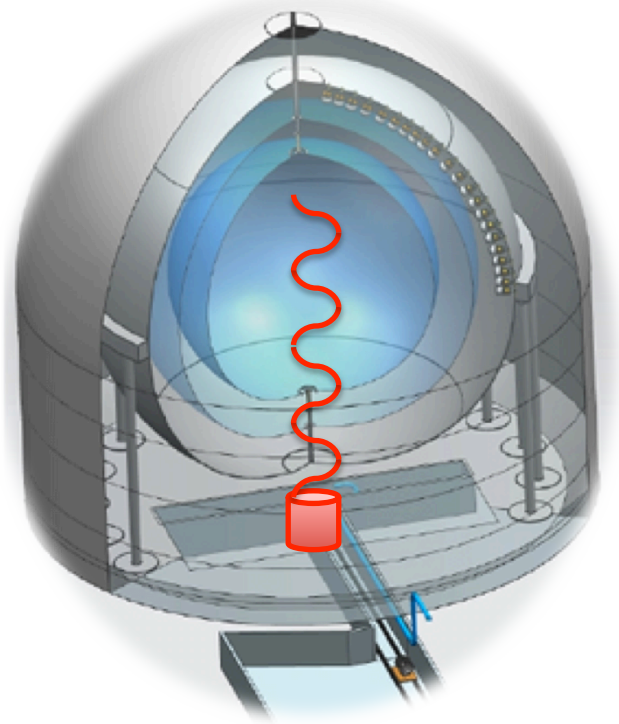
SOX: short baseline neutrino oscillations with Borexino

Matthieu Vivier,
on behalf the Borexino/SOX collaboration

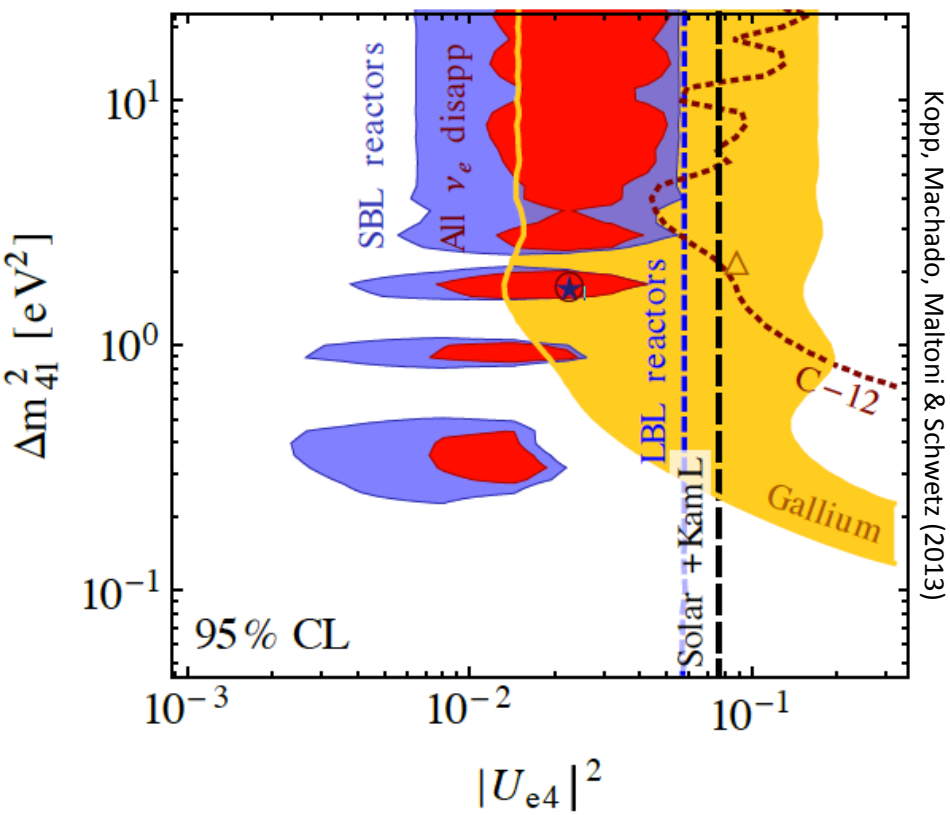


TAUP 2015 - Torino

Testing $\overset{(-)}{\nu}_e$ disappearance anomalies

- Two short baseline anomalies in $\overset{(-)}{\nu}_e$ disappearance mode, each at the 3σ level:
  - Gallium anomalies: calibration of the radiochemical solar experiments Gallex and SAGE with ^{51}Cr & ^{37}Ar ν_e sources, <L> ≈ 0.5 – 2 m [C. Giunti et al. (2010)]
  - Short baseline reactor $\bar{\nu}_e$ experiments, <L> ≈ O(100 m) [G. Mention et al. (2011)]

} rate deficits only

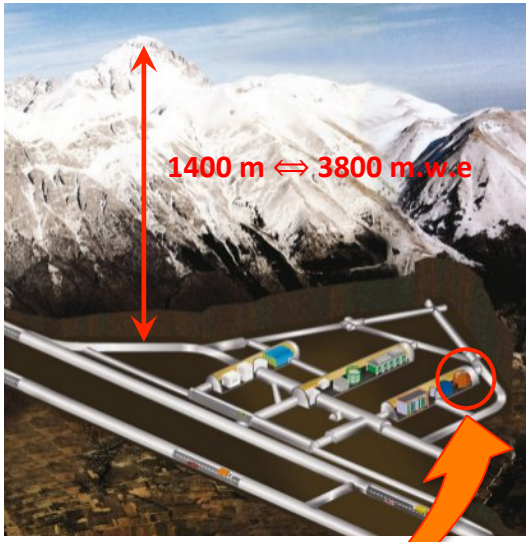


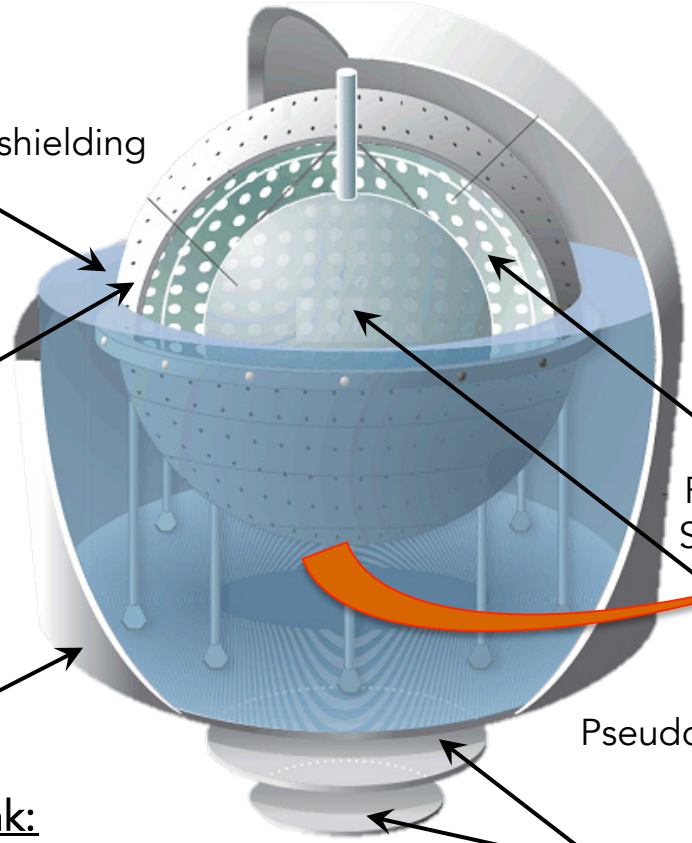
- Rate deficits can be explained by the addition of ≥ 1 sterile neutrino state
- Combined fits using a (3+1) model point toward:
  - $\Delta m^2_{new} \approx 0.1\text{-}5\ eV^2$
  - $\sin^2 2\theta_{new} \approx 0.1$
- Corresponds to meter scaled oscillation lengths for MeV $\overset{(-)}{\nu}_e$
- A decisive test requires observation of oscillation patterns: "oscillometry" concept

see J. Link's plenary talk this morning for further details and discussions

The Borexino detector at LNGS

- Ultra low background neutrino detector
- Various physics program:
  - solar ν [see G. Testera's talk]
  - geo ν [see A. Ianni's talk]
  - Neutrino oscillation
  - …





Water volume:
Muon veto & radioactivity shielding

Stainless steel sphere:
Equipped with 2200 PMTs

Buffer volumes:
PC +DMP (scintillation light quencher)
Shielding against external gamma-rays

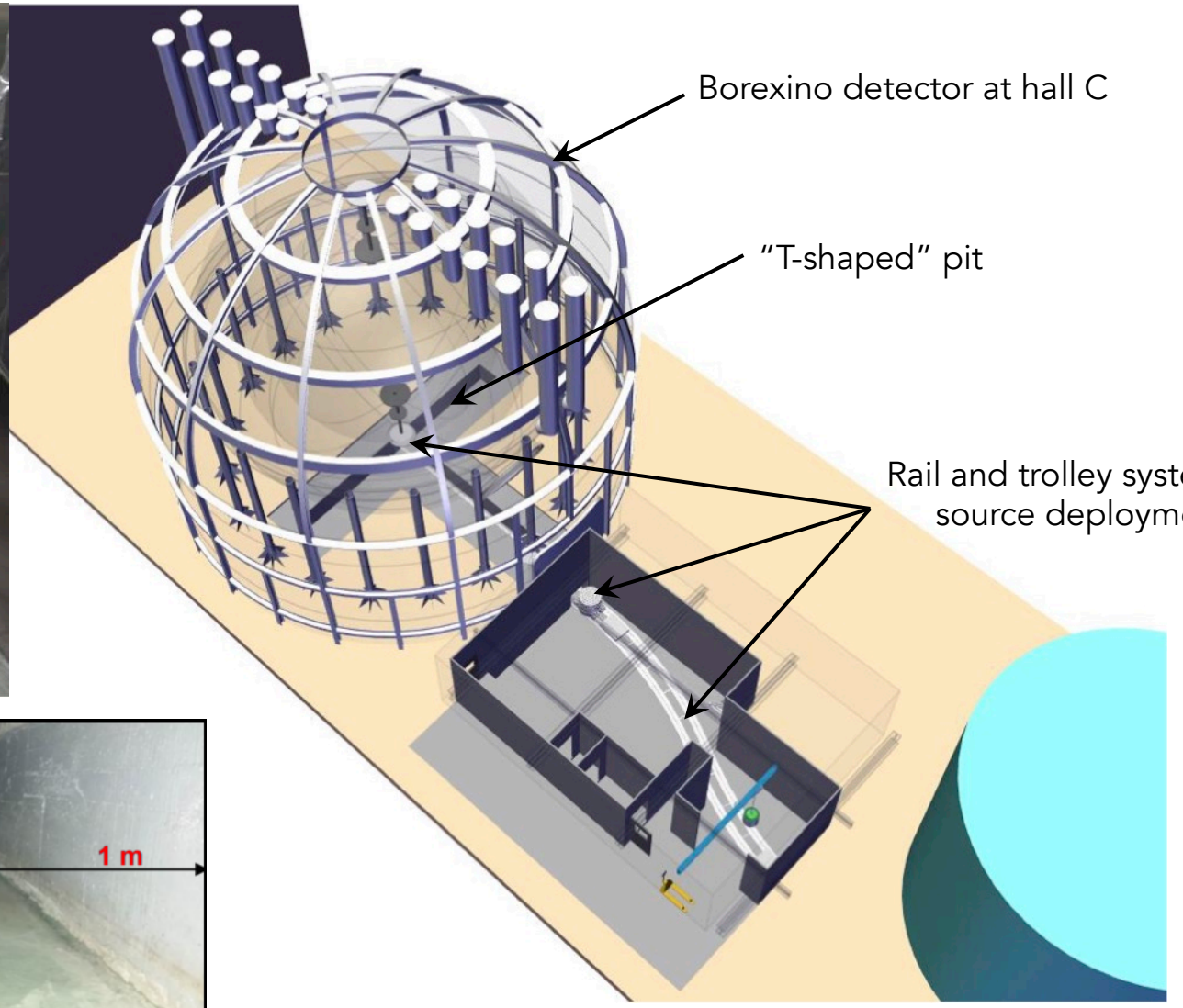
Detection volume:
Pseudocumene + PPO – R=4.25 m – M = 270 t

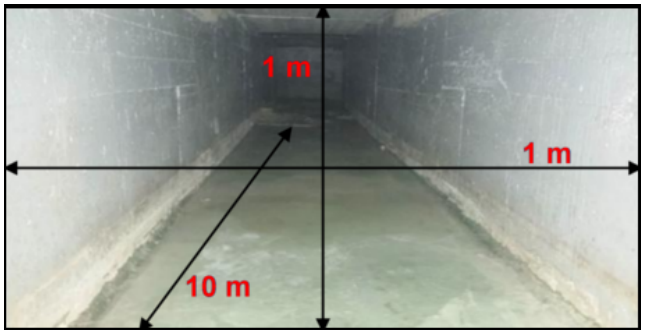
Stainless steel water tank:
Equipped with 208 PMTs

Stainless steel plates

The SOX experiment

- Deployment of an intense (anti)neutrino source in a pit underneath the detector

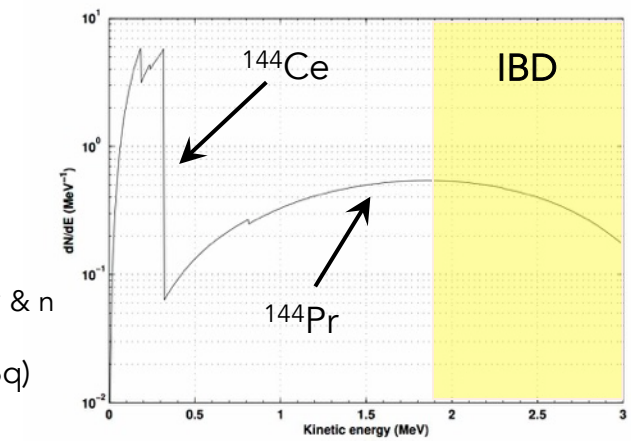


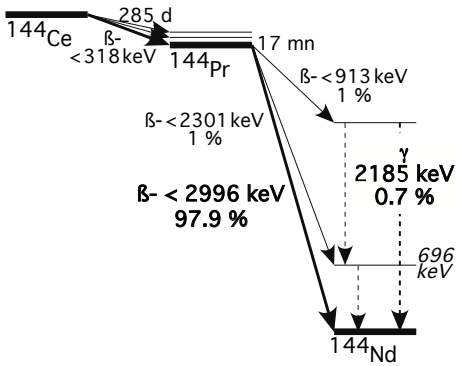


The SOX experiment

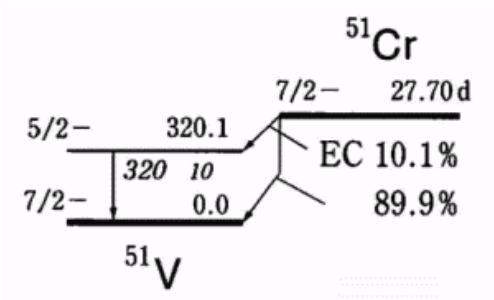
- Deployment of an intense (anti)neutrino source in a pit underneath the detector
- Two-phase experiment:

1. <u>CeSOX:</u> ^{144}Ce-^{144}Pr $\bar{\nu}_e$ generator:
   - β^- emitter: $\bar{\nu}_e$ up to 3 MeV
   - ^{144}Ce $T_{1/2}$ = 285 days
   - Extracted from spent nuclear fuel
   - Detection via IBD:
     - threshold of 1.8 MeV
     - time coincidence between e^+ & n
     - ≈ background free
   - Activity: ≈ 100 kCi (≈ 3.7 × 10^{15} Bq)





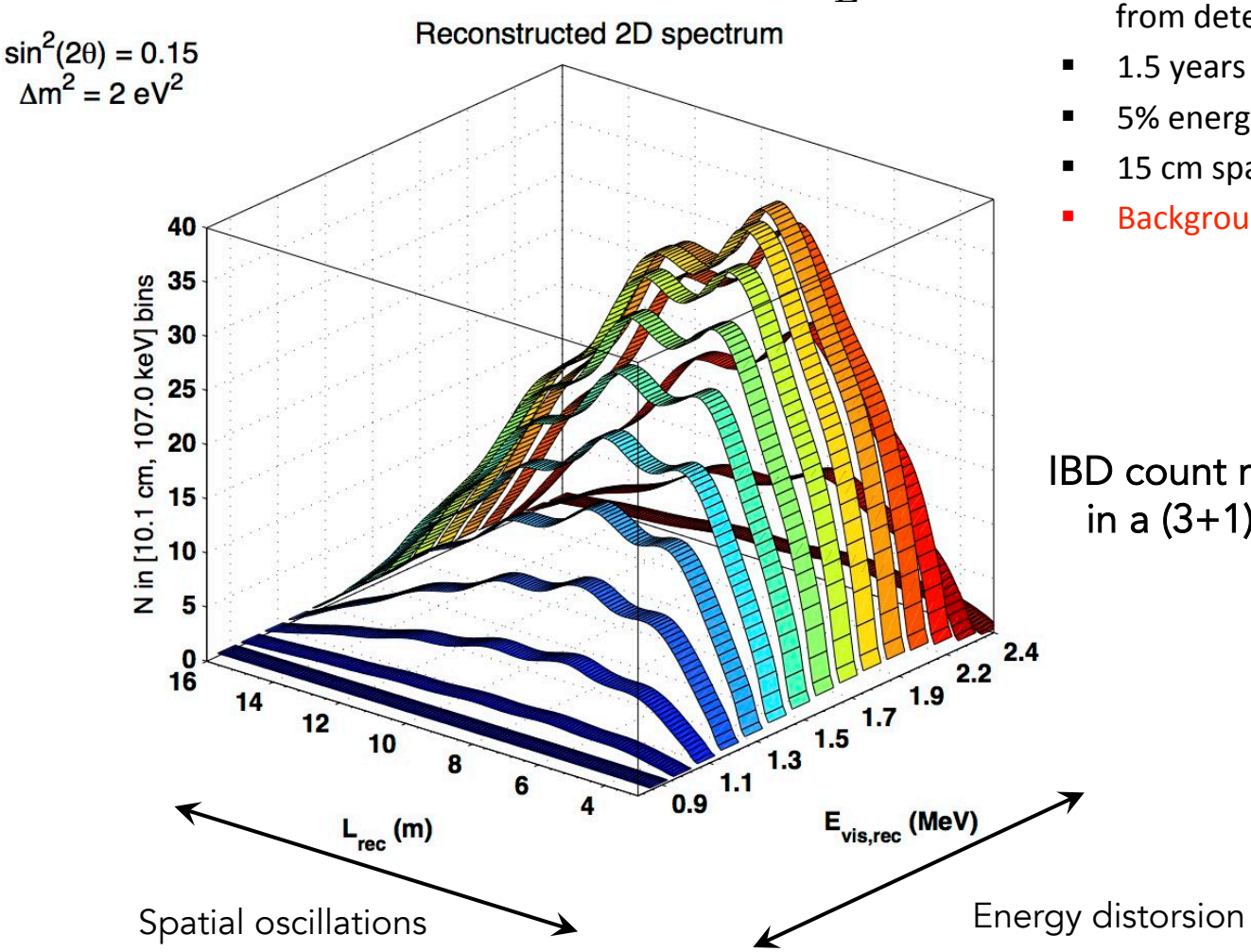
2. <u>CrSOX:</u> ^{51}Cr ν_e generator:
   - EC source, monoenergetic ν_e: 753 KeV (90%) & 433 keV (10%)
   - $T_{1/2}$ = 27.7 days
   - Produced by neutron irradiation of (stable) ^{50}Cr
   - Detection via e^- scattering
   - Backgrounds: ^{210}Po, ^{210}Bi and solar ν_e
   - Activity: ≈ 10 Mci



- Mostly CeSOX latest developments will be covered in the next slides.

CeSOX sterile neutrino signature

$$\mathcal{P}(\theta, \Delta m^2, L, E) = 1 - \sin^2(2\theta)\sin^2(1.27\Delta m^2 \frac{L}{E})$$



- 100 kCi ^{144}Ce source in pit @ 8.5 m from detector center
- 1.5 years of data taking: ≈ 10^4 events
- 5% energy resolution @ 1 MeV
- 15 cm spatial resolution
- Background free

IBD count rate as a function of L & E in a (3+1) sterile neutrino model

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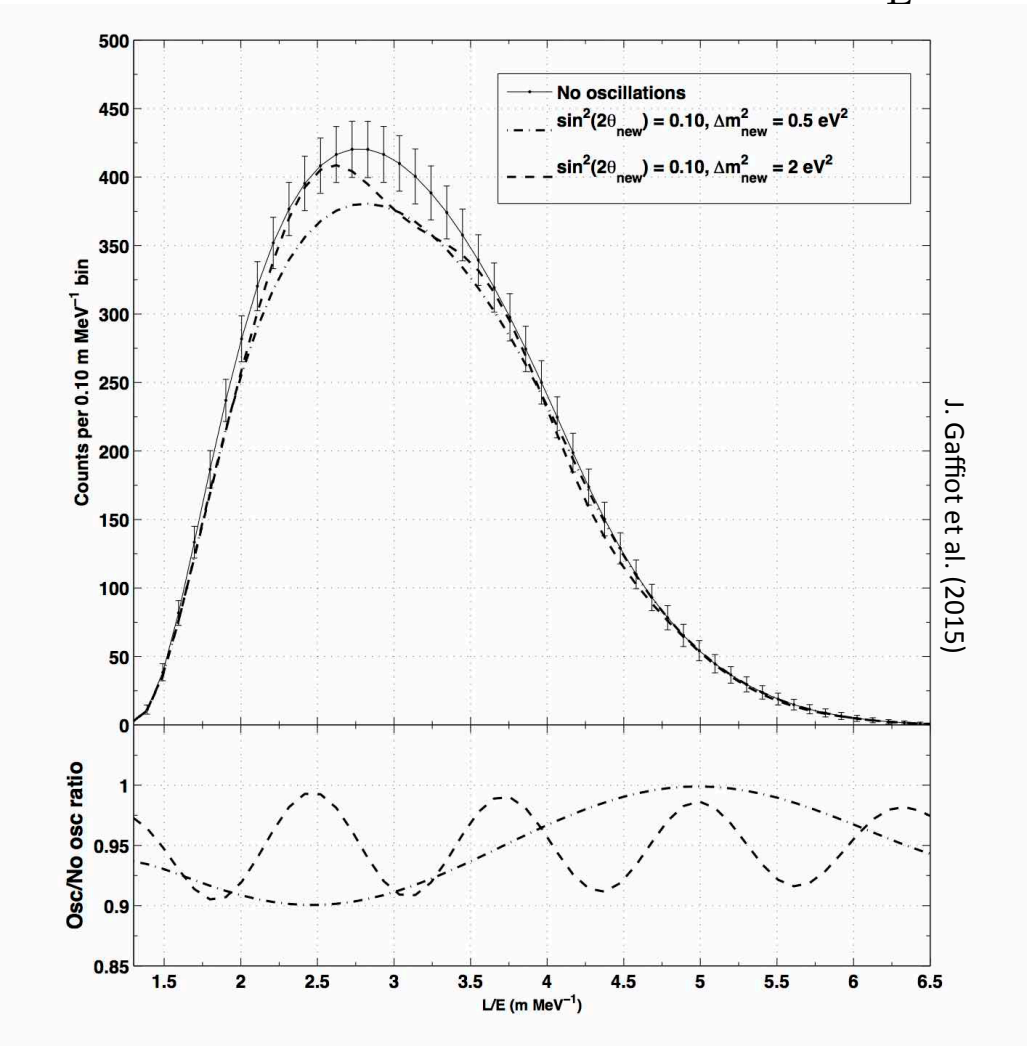

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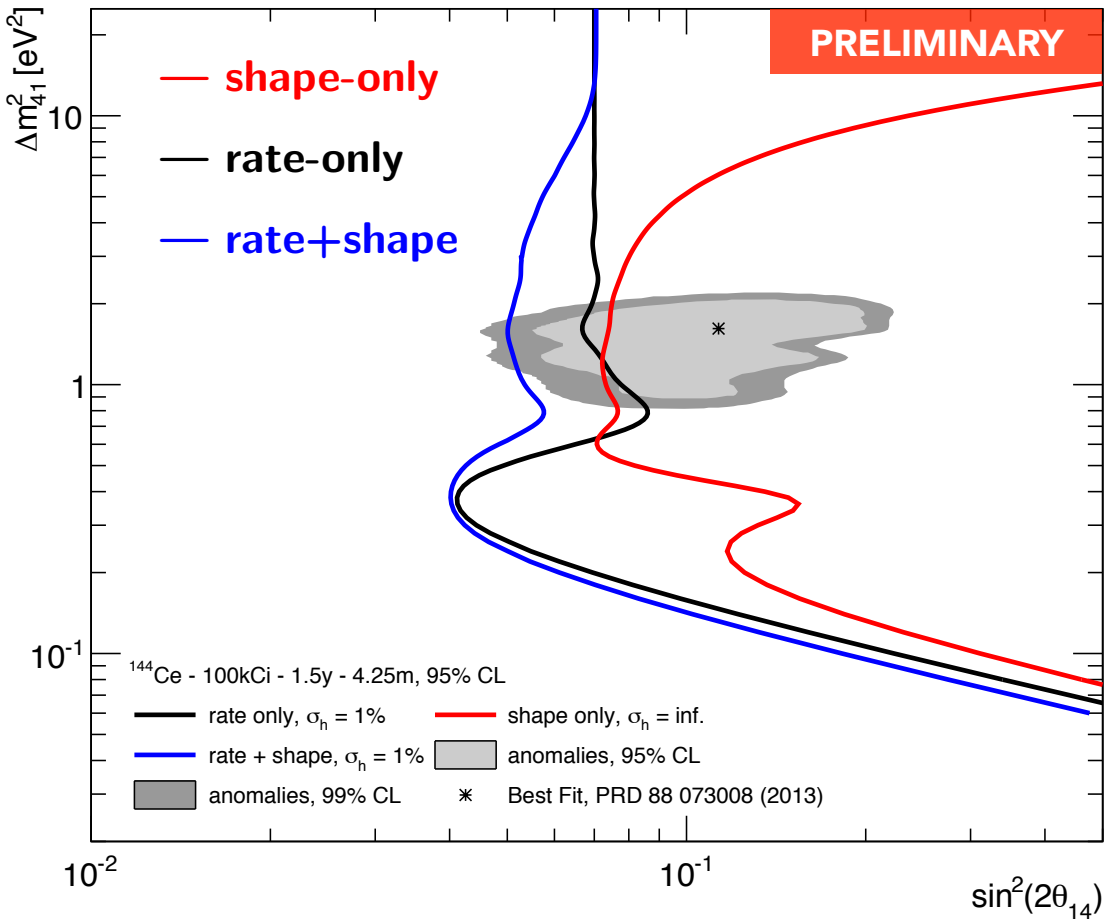
IBD count rate as a function of L/E in a (3+1) sterile neutrino model

CeSOX sensitivity

- CeSOX can potentially test most of the preferred parameter space in a really short time:

100 kCi source at 8.5 m from detector center (1% norm. uncertainty)

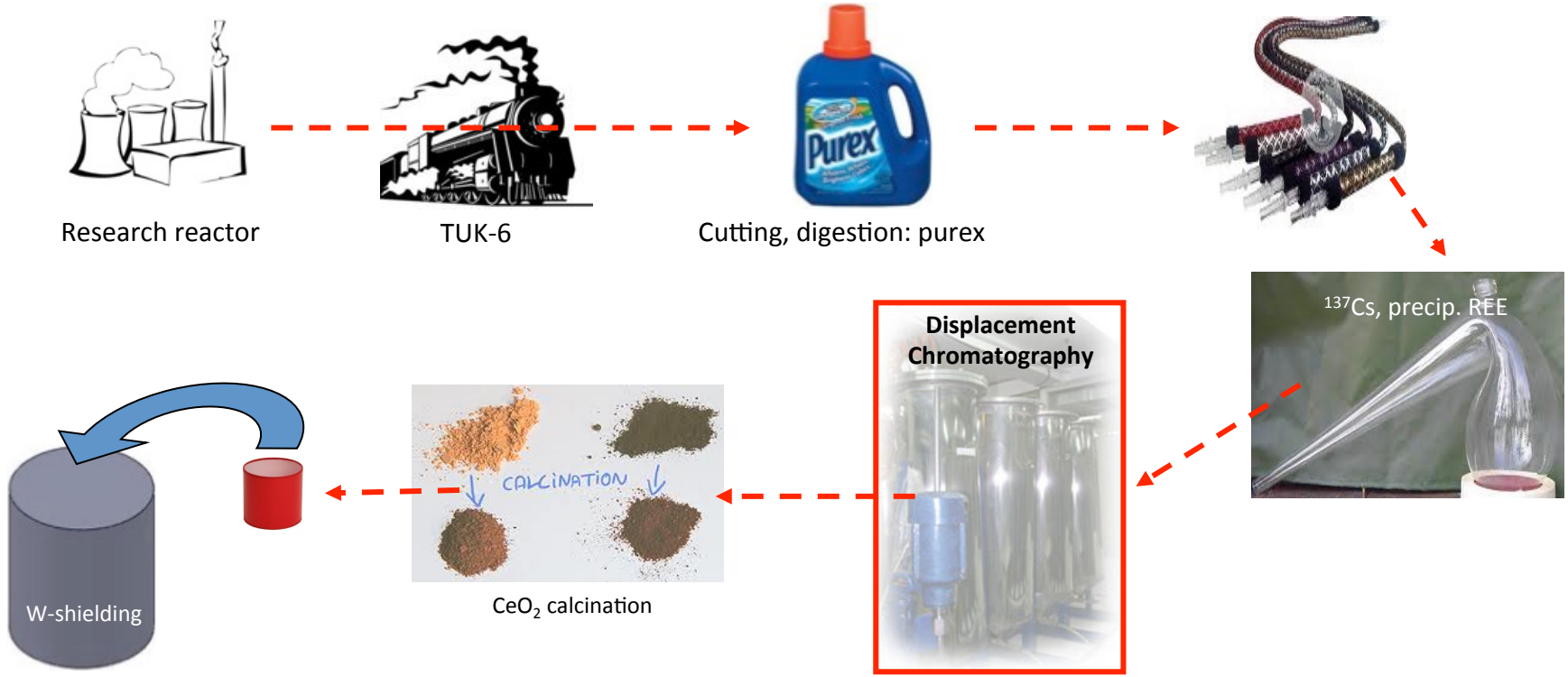


- Shape-only measurement
  - Smoking-gun signature
  - Sensitive to $\Delta m^2 \approx 0.5 - 5$ eV^2 region
  - Requires good energy and vertex resolution
  - Dominated by statistical unc.

- Rate + shape measurement
  - Overall sensitivity improvement with respect to shape-only analysis
  - Especially sensitive for $\Delta m^2 \geq 5$ eV^2
  - Need accurate activity measurement
    - Heat power measurement (calo.)
    - Power-to-activity conversion (β spec.)
  - Need good detection systematics
    - Energy, vertex reconstruction
    - IBD efficiency
    - …

Source production

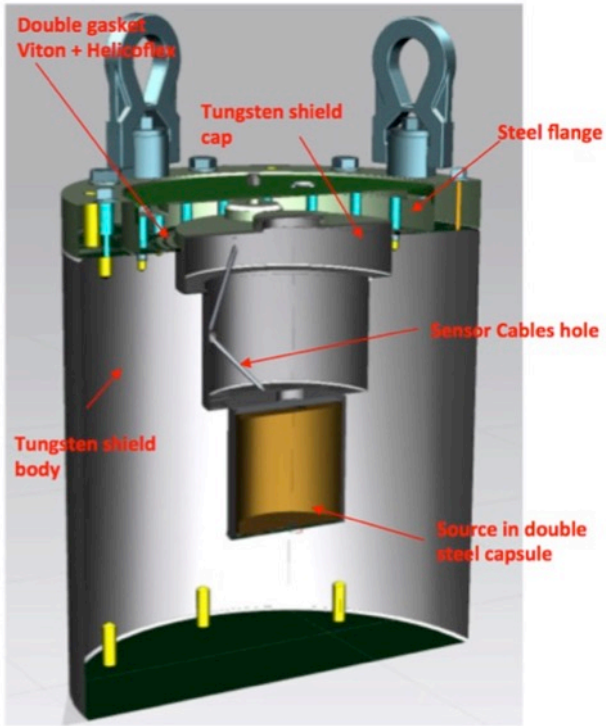
- Done @ FSUE Mayak PA (Russia)
- Source delivery between Sept. 2016 and Dec. 2016
- 9 to 12 months production process:
  1. Standard radiochemical re-processing of a few tons of SNF from research reactor:
     Purex process ⟹ lanthanides and actinides concentrate
  2. Separation of Cerium (REE complex displacement chromatography)
  3. Calcination + pressing + encapsulation: ≈ 30 g of ^{144}Ce in 5 kg of CeO_2



Source shielding

- Any gamma radiation escaping the source (reminder, activity ≈ few PBq) must be shielded
  - Biological protection
  - Avoid source-induced backgrounds in the detector

- 19-cm thick high density tungsten alloy shielding (HDTAS)
- Dimensions mostly driven by ^{144}Pr 2.185 MeV deexcitation gamma-ray (0.7% intensity).
- Manufactured at Xiamen Honglu Inc., China. Biggest tungsten shielding ever built…
- Delivery end of 2015

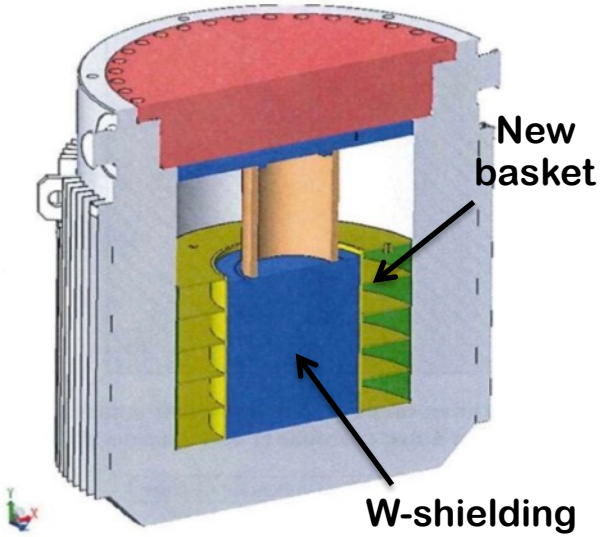


- Cylindrical shape
- H ≈ 60 cm – ϕ ≈ 60 cm
- Density ≈ 18.5 g cm^{-3}
- 2.3 tons

Aluminium mock-up

Source transport

- Transportation cask identified: MTR from Areva TN (21 tons)
- Itinerary route identified: from Mayak to LNGS through France
- Train/dedicated boat/truck: 3 weeks travel (5% activity loss)
- Source transport authorized ✔
- Expected delivery date at LNGS < Dec. 2016



Calorimetric measurement

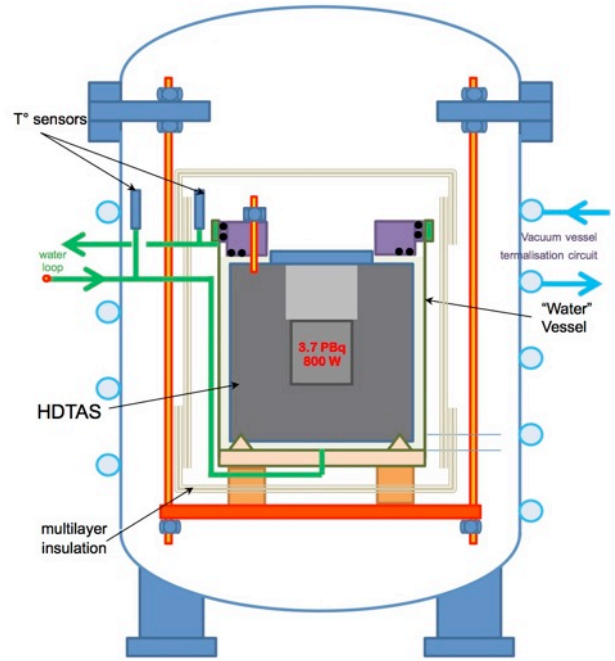
- Measure CeANG thermal power with ≤ 1.5% precision
  - P ≈ 216 W/PBq
  - 800 W @ beginning of data taking

- Measure flow and temperature in and out a water circulation loop

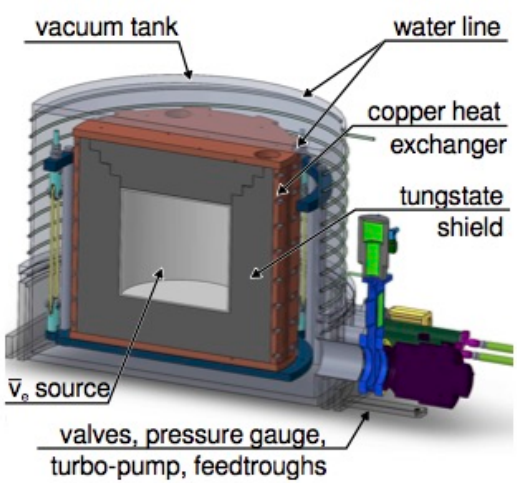
$$P_{source} = \frac{dM}{dt} \times C_p \times (T_{out} - T_{in}) + P_{leak}$$

- Calorimetric device designed to minimize leaks:
  - Conduction: suspension platform + insulation
  - Convection: vacuum vessel
  - Radiation: multilayer insulation + vacuum vessel thermalization

- Calibration with an electrical source



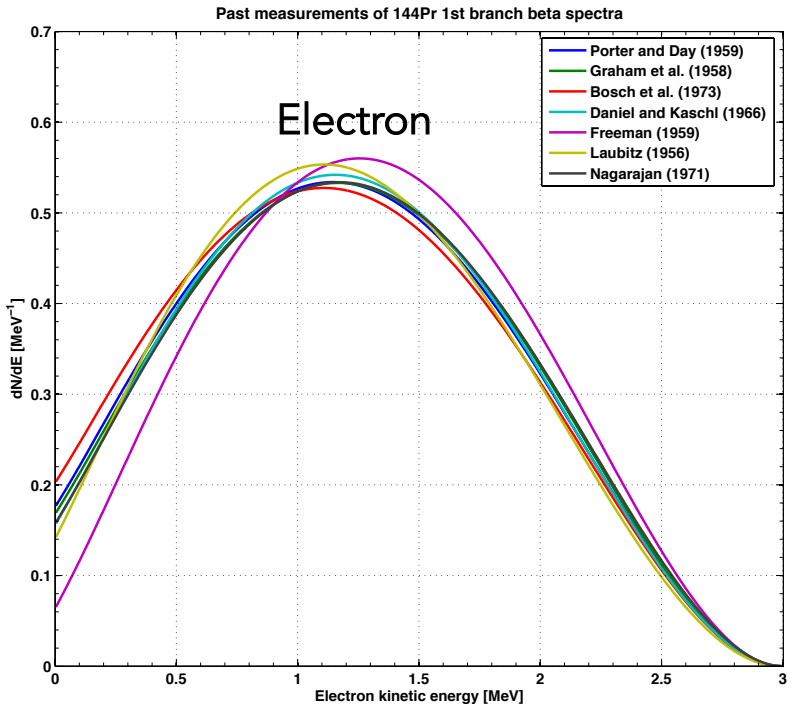
[setup @ CEA-Saclay]

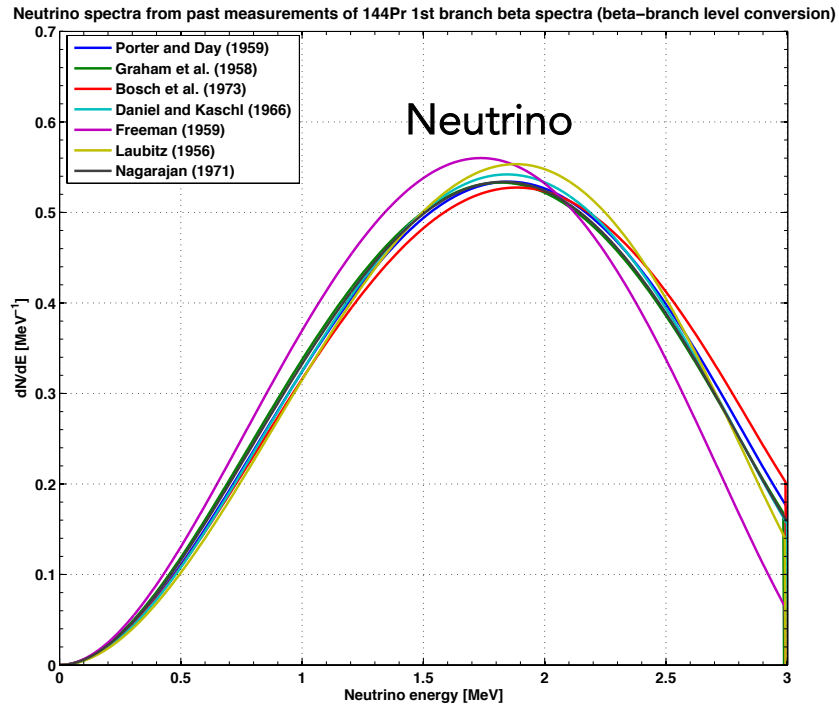


[setup @ TUM/Genova]

^{144}Pr $\bar{\nu}_e$ energy spectrum: β spectroscopy

- Both source heat power and expected IBD interaction rate in Borexino depends on CeANG β/ν_e spectrum
- ^{144}Ce and ^{144}Pr beta spectra both present non-unique forbidden transitions, for which spectral shape is uncertain at the few % level
- Furthermore, past β spectrum measurements don't agree well: up to 10-15% differences, which makes 10% uncertainty in the predicted IBD rate
- Need for a new β spectrum measurement to reach < 1% uncertainty on IBD rate





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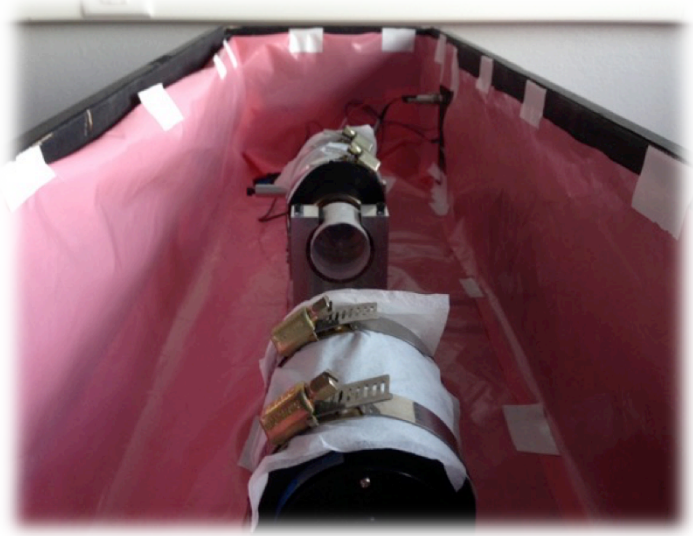
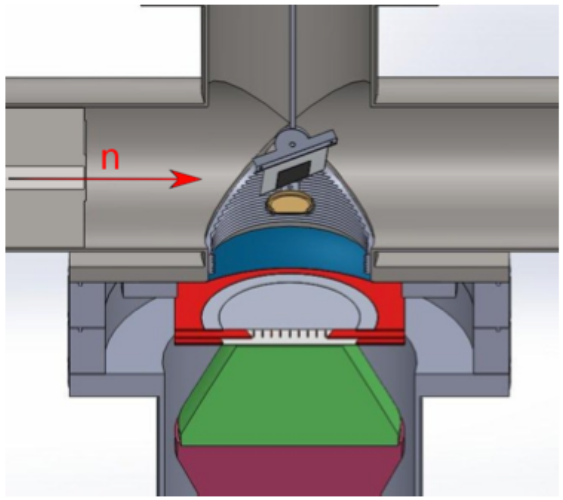
- ^{144}Ce and ^{144}Pr beta spectra both present non-unique forbidden transitions, for which spectral shape is uncertain at the few % level
- Furthermore, past β spectrum measurements don't agree well: up to 10-15% differences, which makes 10% uncertainty in the predicted IBD rate
- Two measurements on-going at Saclay, on $Ce(NO_3)_3$ samples received from PA Mayak:

CEA spectrometer (under development)



TUM spectrometer (PRL. 112, 122501)



- Chemical separation of ^{144}Ce and ^{144}Pr envisaged, to measure separately their corresponding spectra
- Other measurement techniques under consideration: Si-detector, magnetic spectrometer, …

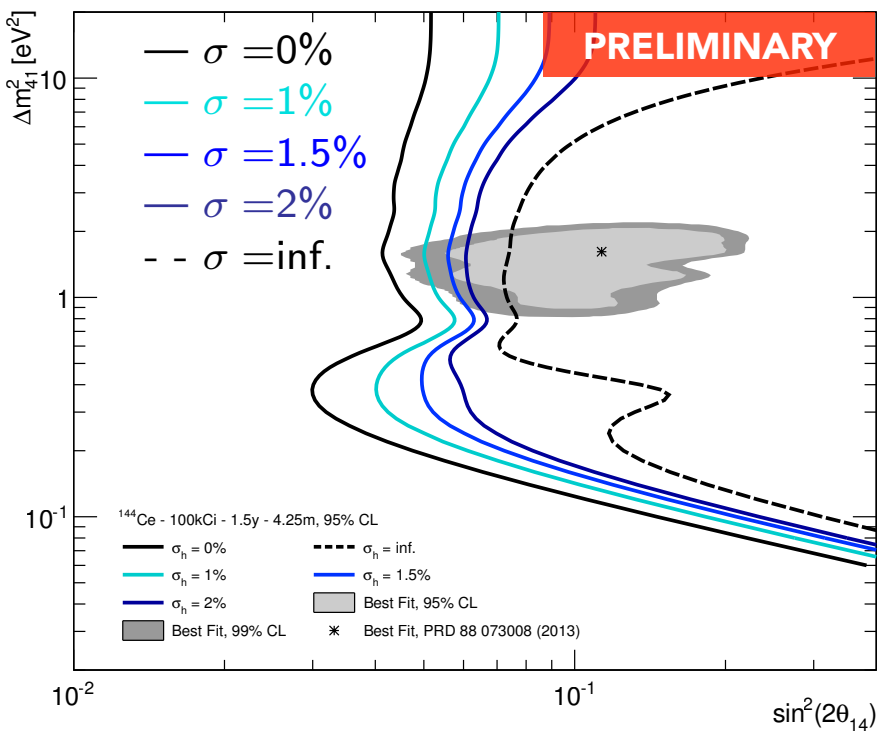
Impact of source related systematics

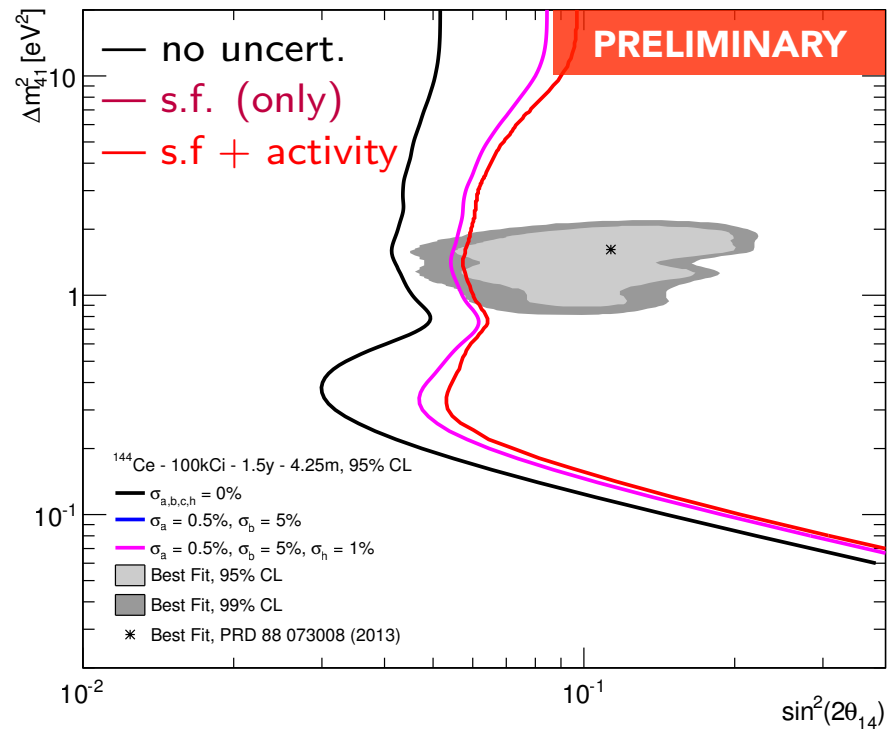
Heat power measurement

- Necessary for rate+shape analysis
- Target precision: 1% (calorimetry)

β spectrum shape

- Conversion from power to activity
- Necessary for rate+shape analysis
- Target precision: O(5%)





Conclusion

- SOX will test the Gallium and reactor anomalies and search for $\bar{\nu}_e/\nu_e$ very short baseline oscillations

- First SOX phase, namely CeSOX, is soon to be started:
  - Source production nearly started: delivery by Sept. 2016
  - Source shielding in production: delivery by end of 2015
  - Transport solution frozen and authorized: source arrival at LNGS < Dec. 2016

- CeANG characterization on-going. Goal: benefit from an additional rate information for ν_s search and make sure source impurities are kept to sufficiently low levels
  - Calorimetry
  - β spectrometry
  - γ, α and ICP-MS/AES spectrometry (not covered in this talk)

  see [J. Gaffiot et al. (2015)] for full discussion about technical details related to source production

- Intense detector calibration campaign to achieve detection systematics at the 1-2 % level

- Future measurement with ^{51}Cr under consideration (very relevant in case of a positive signal)

THANK YOU !