# SOX – searching **sterile neutrinos** with Borexino

**Universite Libre de Bruxelles**
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(JGU Mainz & EC PRISMA)

# Motivation for sterile neutrino searches

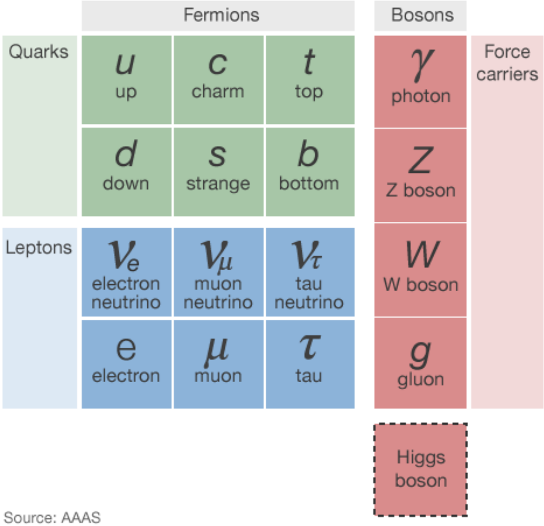
*All evidence from SM in favor of just 3 light neutrinos.*
*Why should there be more?*

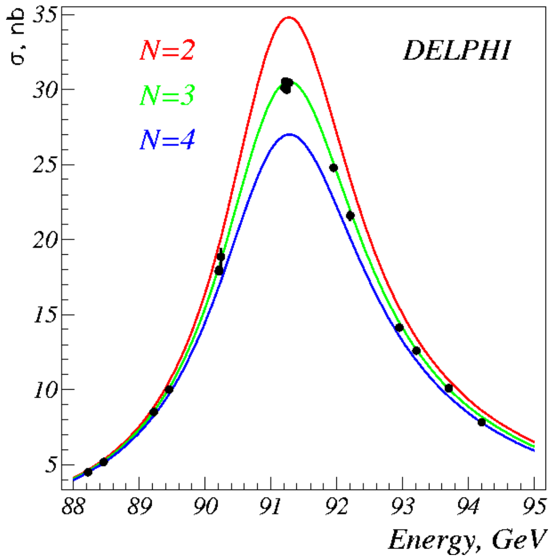
**Fundamental (from theory)**

- arguably, the most simple extension of the SM
  → addition of inactive singlet state(s)
- excellent Dark Matter candidate
- required for See-Saw mechanism
  → light active neutrino masses
  → leptogenesis for M/AM asymmetry
  → νMSM ...

**Agnostic (from experiments)**

- short-baseline oscillation anomalies (eV)
- unexplained X-ray lines:
  from keV-DM annihilation?



# Mixing of sterile and active states

- **no interactions** with SM particles, but **mixing** with active neutrinos:

*extended PMNS matrix*

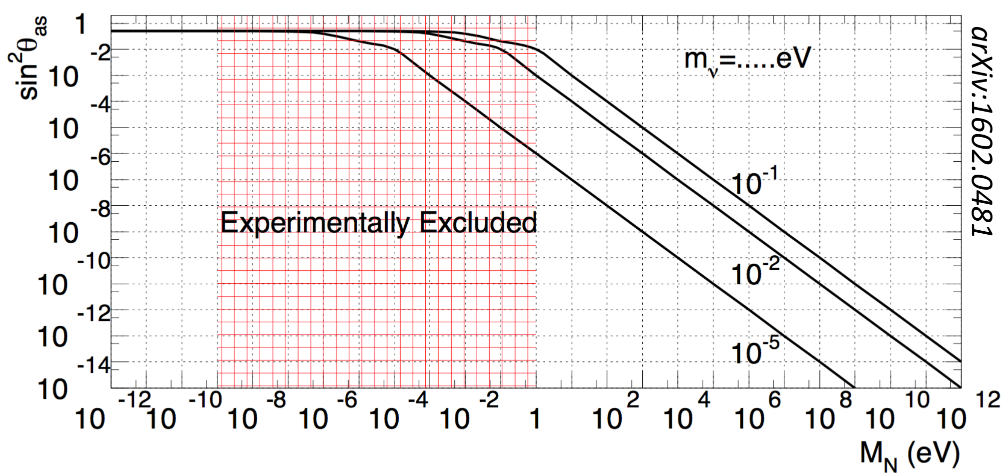
weak eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_{s1} \\ \vdots \end{pmatrix} = \begin{pmatrix} U_{11} & U_{12} & U_{13} & U_{14} & \dots \\ U_{21} & U_{22} & U_{23} & U_{24} & \dots \\ U_{31} & U_{32} & U_{33} & U_{34} & \dots \\ U_{41} & U_{42} & U_{43} & U_{44} & \dots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \vdots \end{pmatrix}$$

mass eigenstates

- in See-Saw: Natural scale for active-sterile mixing

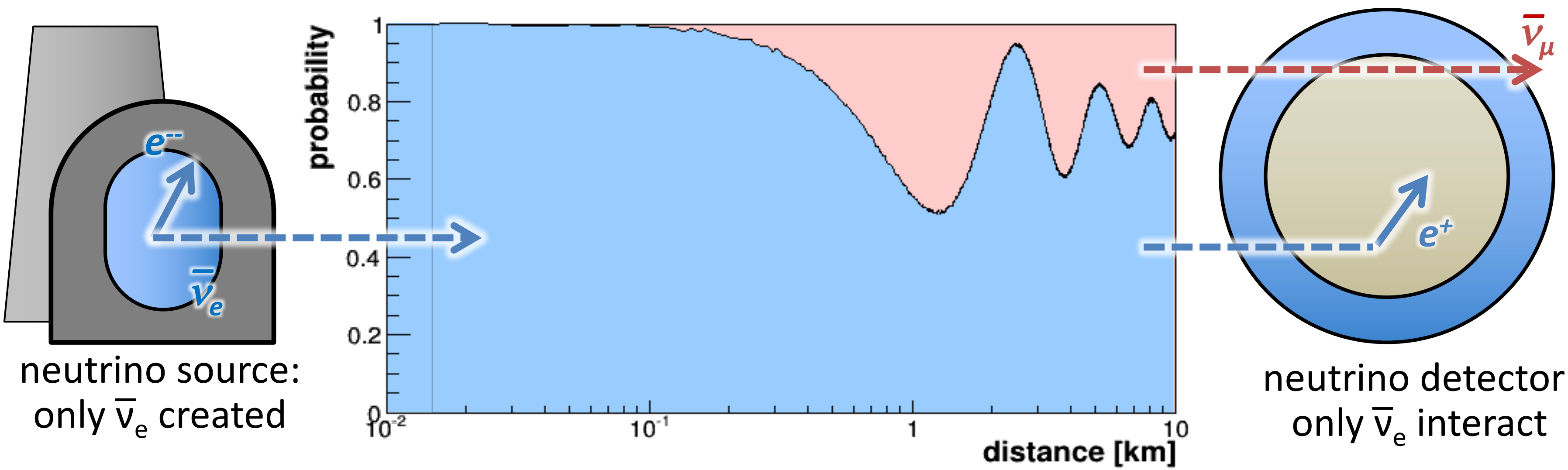
$$\Theta \sim \frac{m_{\mathrm{D}}}{M_{\mathrm{R}}}$$



# Active-to-sterile neutrino oscillations

- **Active states only:**

$$\begin{pmatrix}\nu_a\end{pmatrix} = \begin{pmatrix}U_{ai}\end{pmatrix}\begin{pmatrix}\nu_i\end{pmatrix}$$




**Survival probability:** $P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta_{12}) \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$ *distance/energy*

*oscillation amplitude*

*oscillation frequency*

- mixing angle → amplitude
- mass² difference → frequency
- neutrino energy → oscillation length

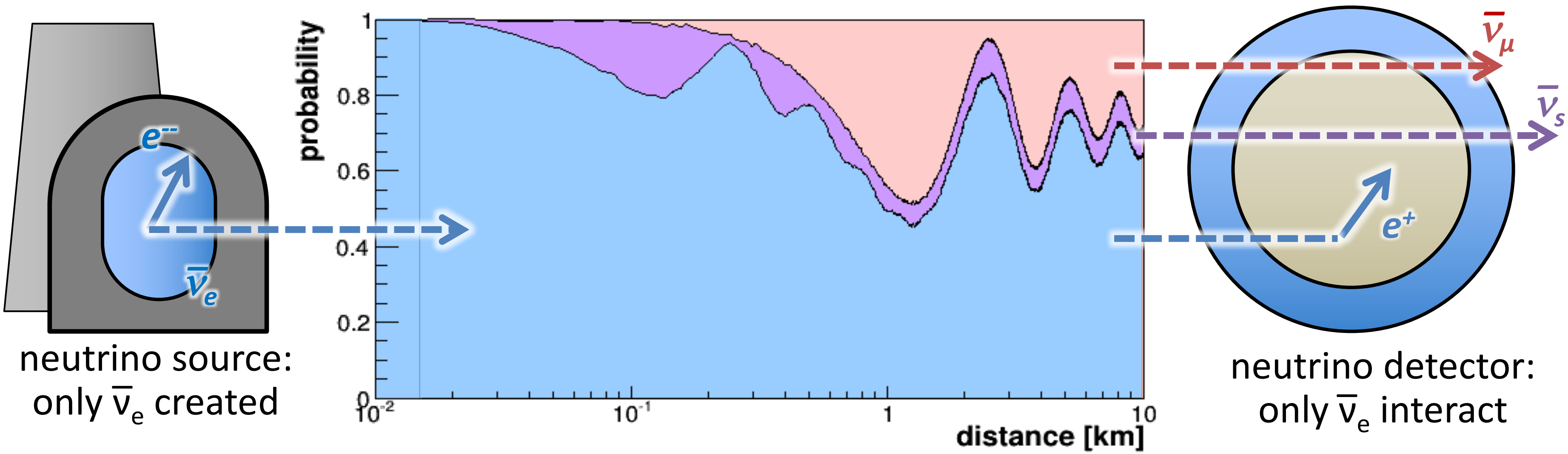
# Active-to-sterile neutrino oscillations

- **Active states only:**

$$\begin{pmatrix} \nu_a \end{pmatrix} = \begin{pmatrix} U_{ai} \end{pmatrix} \begin{pmatrix} \nu_i \end{pmatrix}$$

- **Adding sterile states**

$$\begin{pmatrix} \nu_a \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{ai} & \Theta_{aj} \\ \Theta_{si} & U_{sj} \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_j \end{pmatrix}$$



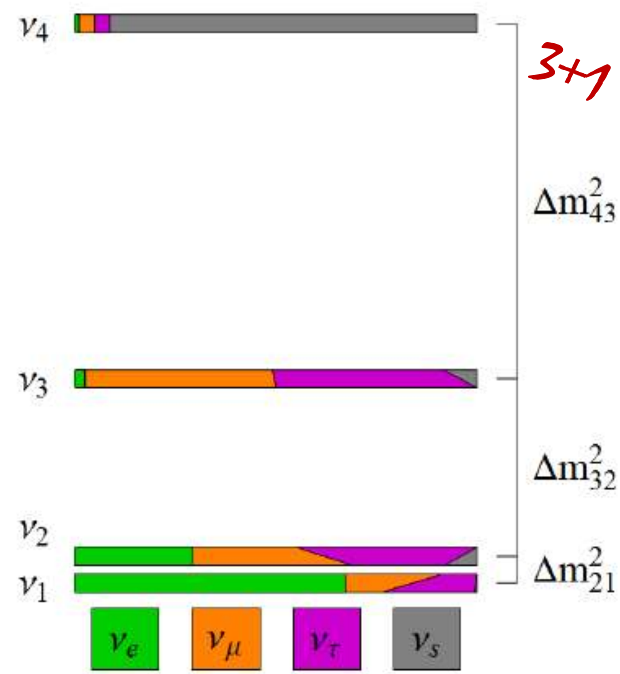

**Survival probability:** $$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta_{12}) \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

*oscillation amplitude* — *oscillation frequency* — *distance/ energy*

- mixing angle → amplitude
- mass² difference → frequency
- neutrino energy → oscillation length

# New mass states & ordering schemes

- As a necessity, new neutrino flavor states imply **new neutrino mass states**, *e.g. one further sterile state* $\nu_s$ *→ mass state* $\nu_4$




- Different mass ordering schemes might be realized:

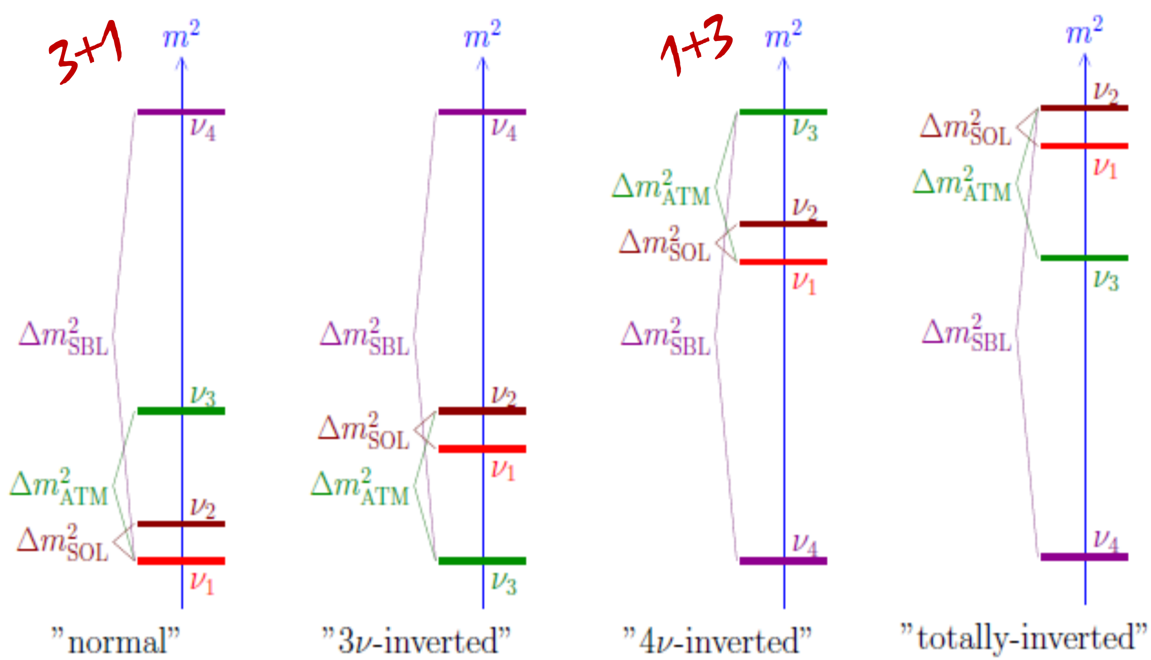



Figure 1: 3+1 four-neutrino schemes.

More complicated schemes possible:

- **3+2, 3+3** ...
- **1+3+1** etc.

# Active-sterile oscillation modes

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- Active-sterile mixing matrix → **new mixing amplitudes**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_{s1} \\ \vdots \end{pmatrix} = \begin{pmatrix} U_{11} & U_{12} & U_{13} & U_{14} & \cdots \\ U_{21} & U_{22} & U_{23} & U_{24} & \cdots \\ U_{31} & U_{32} & U_{33} & U_{34} & \cdots \\ U_{41} & U_{42} & U_{43} & U_{44} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \vdots \end{pmatrix}$$

- new masses → **new Δm² values:** $\Delta m^2_{41}, \ldots > \Delta m^2_{21}, \Delta m^2_{31}, \Delta m^2_{32}$

→ occurrence of oscillation phenomena at **new (shorter) baselines**, e.g.

***active→sterile disappearance***

$$P(\nu_e \to \nu_s) = \sin^2 2\theta_{ee} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right); \qquad \sin^2 2\theta_{ee} = 4|U_{e4}|^2(1-|U_{e4}|^2)$$

***active→active appearance***

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{e\mu} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right); \qquad \sin^2 2\theta_{e\mu} = 4|U_{e4}|^2|U_{\mu 4}|^2$$

# Short-baseline oscillation anomalies 1/2

▶ *(Long-standing)* **electron neutrino appearance anomalies**

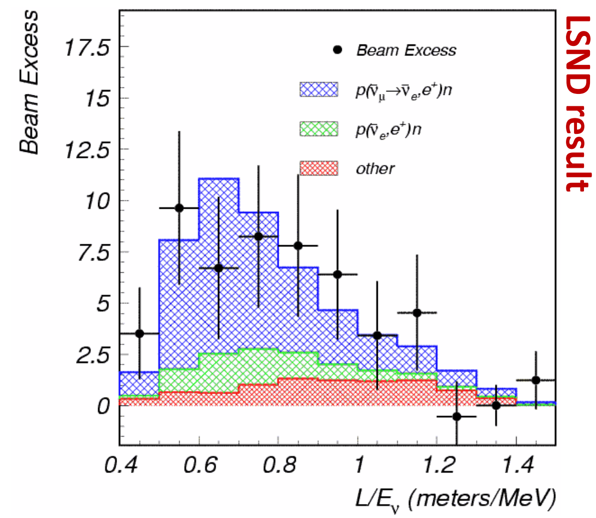
- LSND result

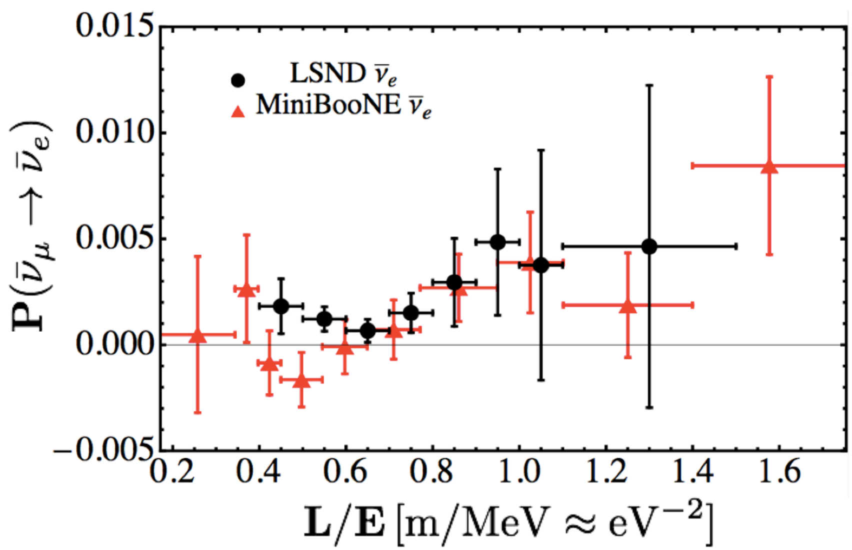
  $\nu_e$ appearance signal
  in a low-energy $\bar{\nu}_\mu$ beam
  from stopped pions

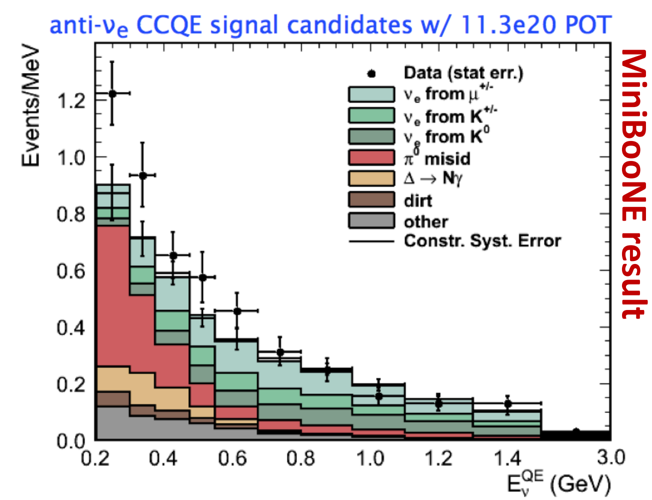
- MiniBooNE result

  $\nu_e$ appearance signal
  in a GeV $\nu_\mu/\bar{\nu}_\mu$ beam
  at similar L/E ratio

→ interpretation as **$\nu_\mu \rightarrow \nu_e$ appearance oscillations** via a **new $\Delta m^2$ on $eV^2$ scale**



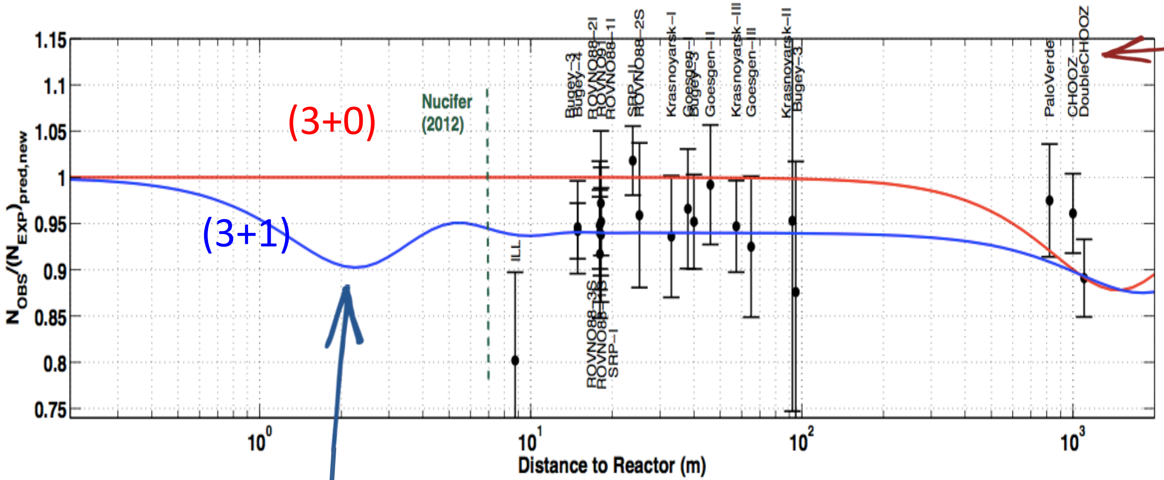



# Short-baseline oscillation anomalies 2/2

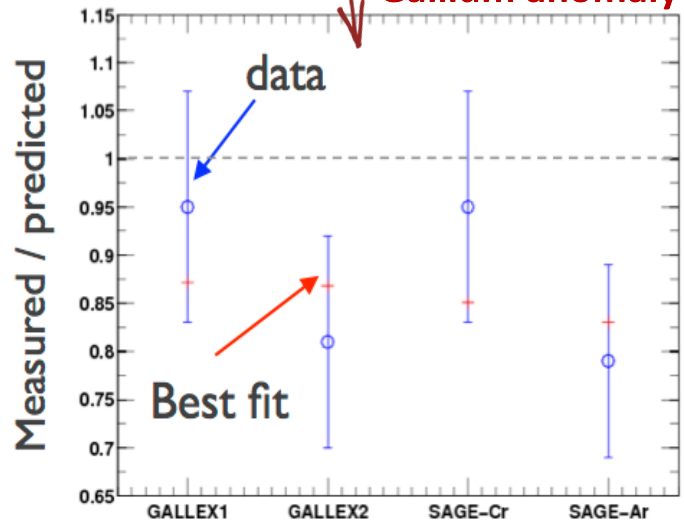
▶ *(More recent)* **electron neutrino disappearance anomalies**

**Reactor short-baseline data** vs. new rate prediction (2011)




- reactor experiments (7.3±2.3)% deficit in $\bar{\nu}_e$-rate at short distances (<100m)
- Gallium calibration data (14±5)% rate deficit close to a radioactive $\nu_e$-source

**Gallium anomaly**

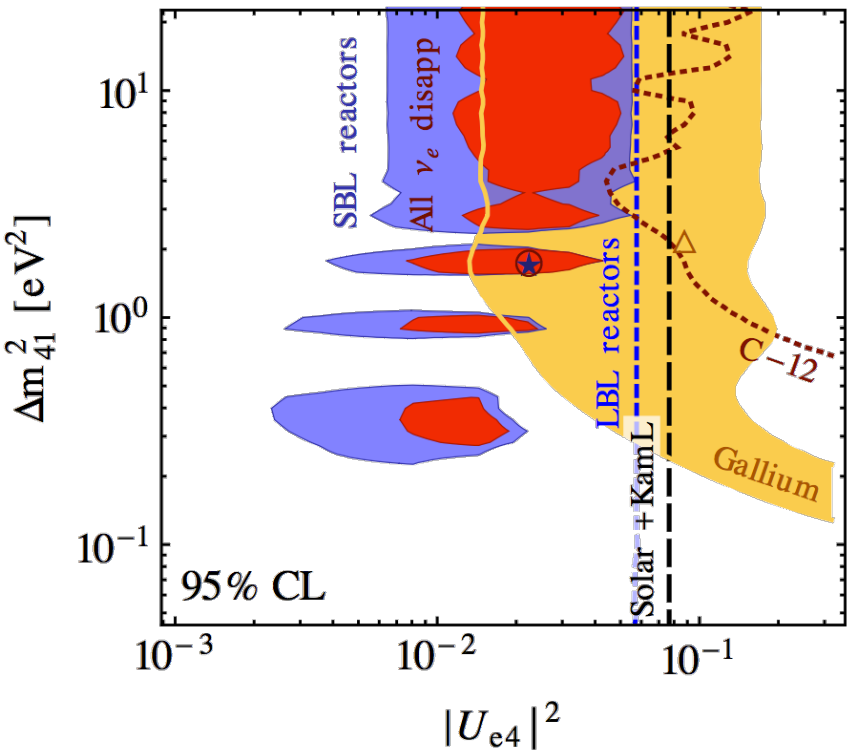



- ○ possible interpretation as **short-baseline disappearance $\nu_e \rightarrow \nu_s$**
- ○ MeV energies, oscillation length $L_{osc} \leq 10$m
  „sterile“ **$\Delta m^2_{new} \geq 1eV^2$**
- ○ Required oscillation amplitude:
  **$\sin^2 2\theta_{new} \geq 0.1$**

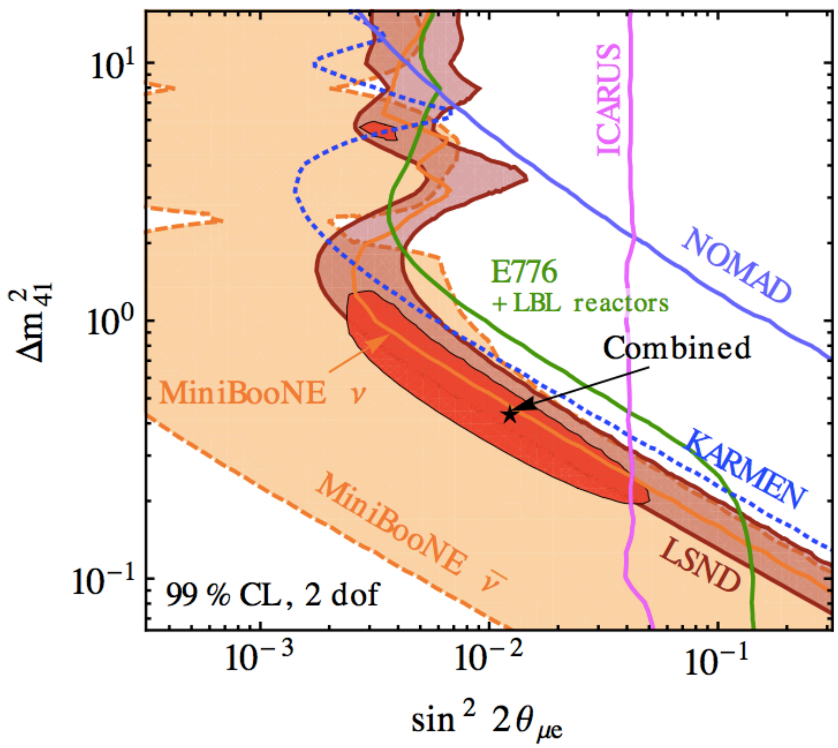
# Parameter space favored by anomalies

- All anomalies can be described by a **(3+1) scheme** adding a single eV-mass sterile neutrino

**$\nu_e \rightarrow \nu_s$ disappearance**




**$\nu_\mu \rightarrow \nu_e$ appearance**




*Kopp, Machado, Maltoni, Schwetz (2013)*

- reactor antineutrino anomaly
- gallium anomaly

- LSND
- MiniBooNE

# Results on $\nu_\mu \rightarrow \nu_s$ disappearance 1/2

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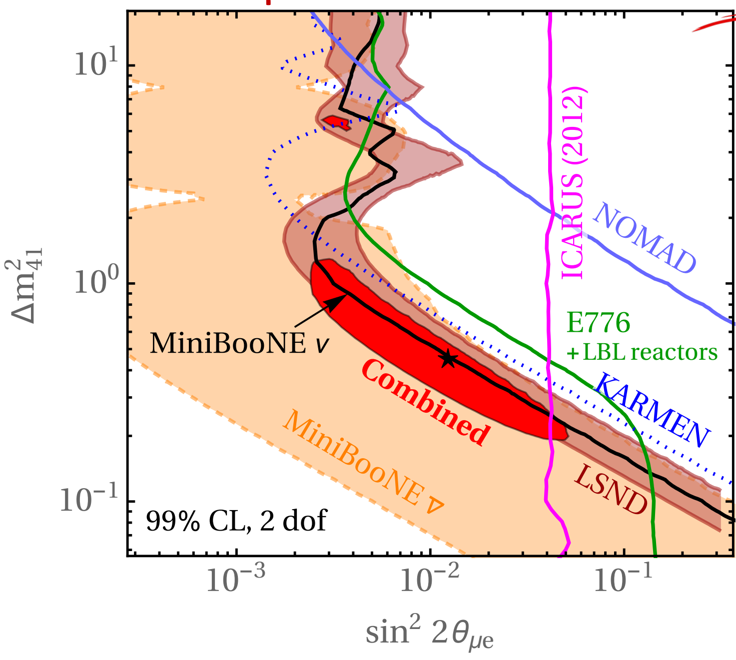
- **Note:** **Disappearance** and **appearance amplitudes** are interlinked

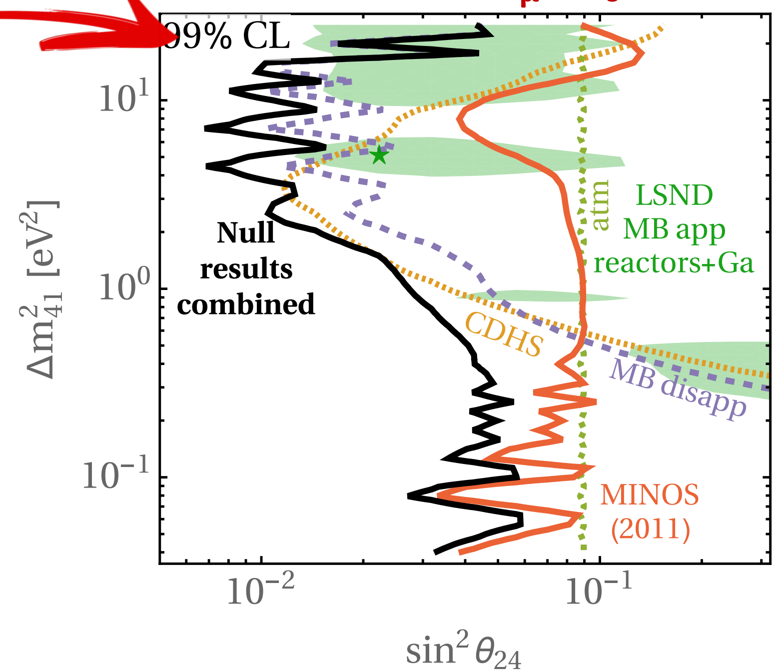
$$\sin^2\theta_{ee} = |U_{e4}|^2$$
$$\sin^2\theta_{\mu\mu} = |U_{\mu4}|^2$$
$$\longleftrightarrow$$
$$\sin^2\theta_{\mu e} = |U_{e4}| \cdot |U_{\mu4}|$$

- In 2011, already some tension between $\boldsymbol{\nu_\mu \rightarrow \nu_e}$ and $\boldsymbol{\nu_\mu \rightarrow \nu_s}$ results:

**$\nu_\mu \rightarrow \nu_e$ anomalies**



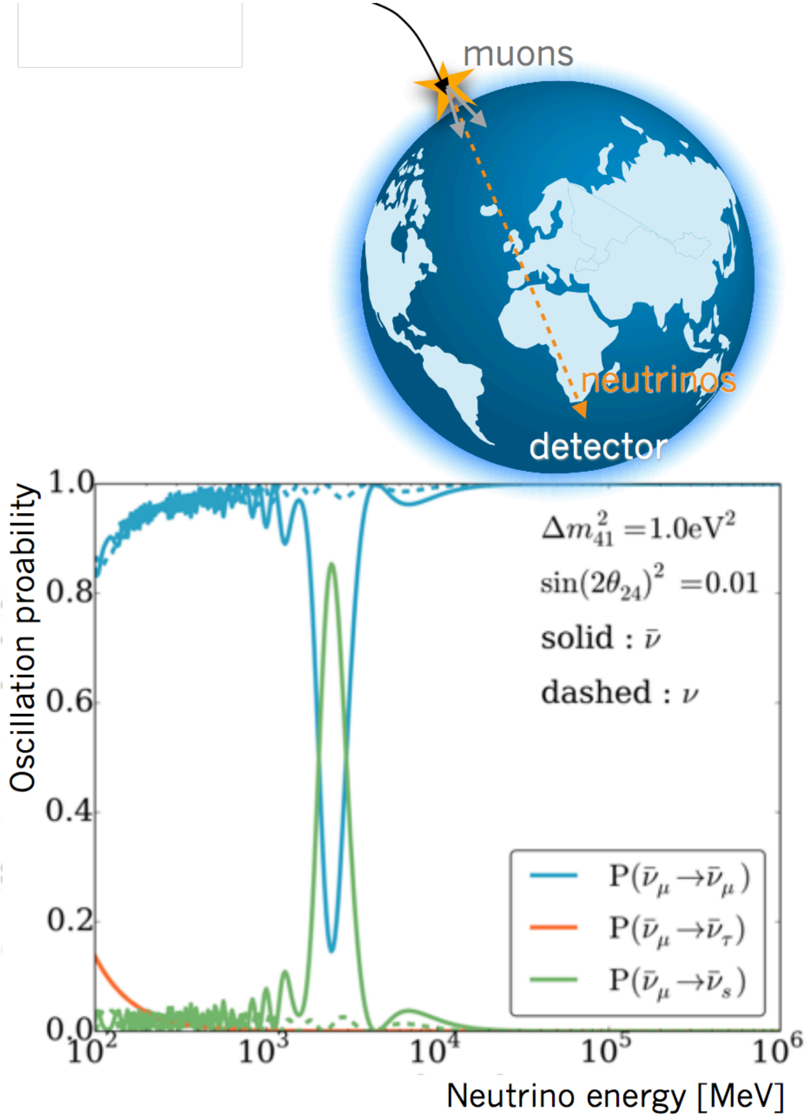

**missing $\nu_\mu \rightarrow \nu_s$**

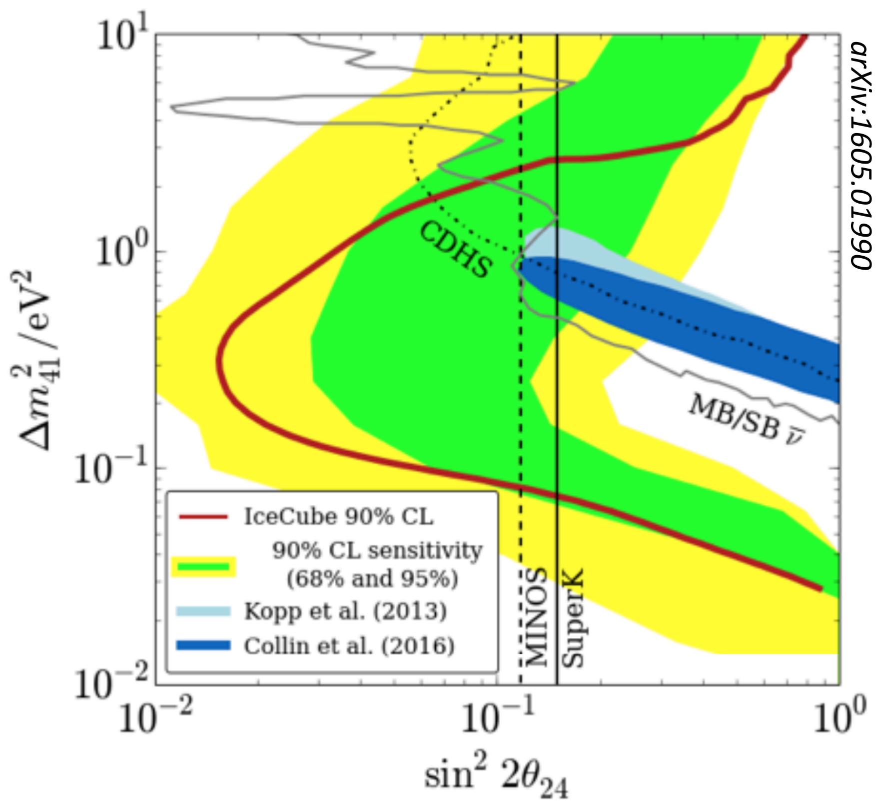



*Kopp, Machado, Maltoni, Schwetz (2013)*

# Recent IceCube result

- Probe: **Atmospheric ν's** crossing the Earth
- **matter potential** affects only active ν's
- No resonant conversion of $\nu_\mu \rightarrow \nu_s$ found at TeV energies, i.e. $\Delta m^2_{41} \sim 1\,\mathrm{eV}^2$



# Results on $\nu_\mu \rightarrow \nu_s$ disappearance $^{2/2}$

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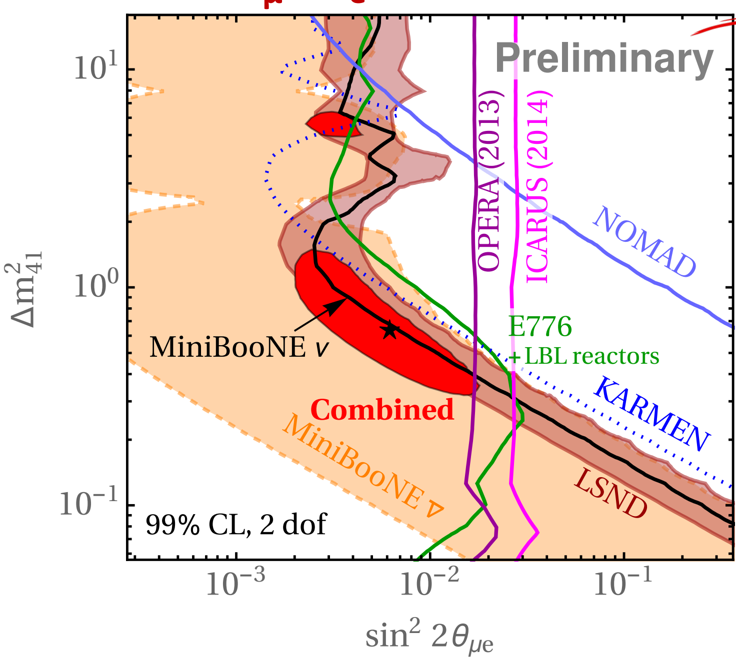
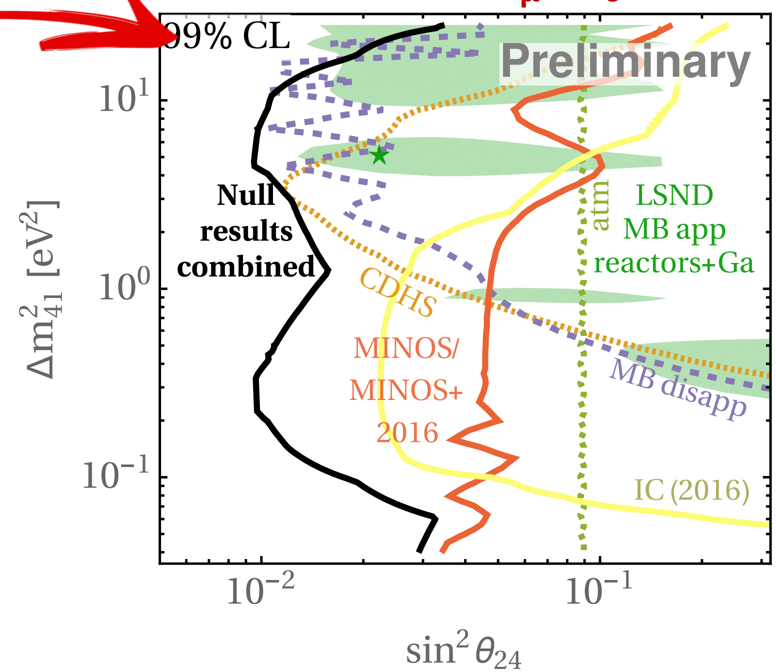
- **Note:** **Disappearance** $\sin^2\theta_{ee} = |U_{e4}|^2$, $\sin^2\theta_{\mu\mu} = |U_{\mu4}|^2$ ↔ and **appearance amplitudes** $\sin^2\theta_{\mu e} = |U_{e4}|\cdot|U_{\mu4}|$ are interlinked

- Now, new results by **MINOS+/IceCube** on $\nu_\mu \rightarrow \nu_s$ further increased the tension:

**$\nu_\mu \rightarrow \nu_e$ anomalies**



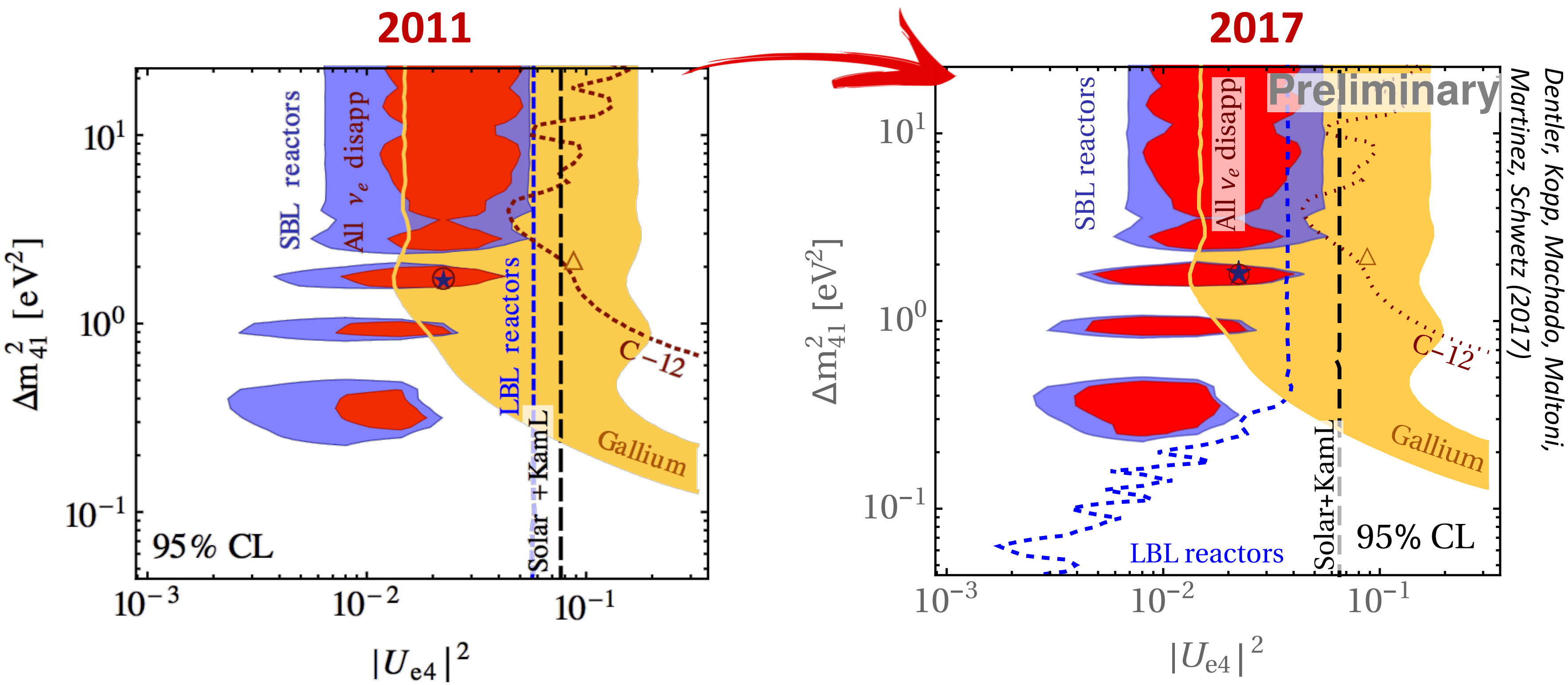

**missing $\nu_\mu \rightarrow \nu_s$**




*Dentler, Kopp, Machado, Maltoni, Martinez, Schwetz (2017)*

# The open issue: $\nu_e \rightarrow \nu_s$ disappearance

- **Note:** No oscillation data directly contradicts the reactor/Ga anomalies!

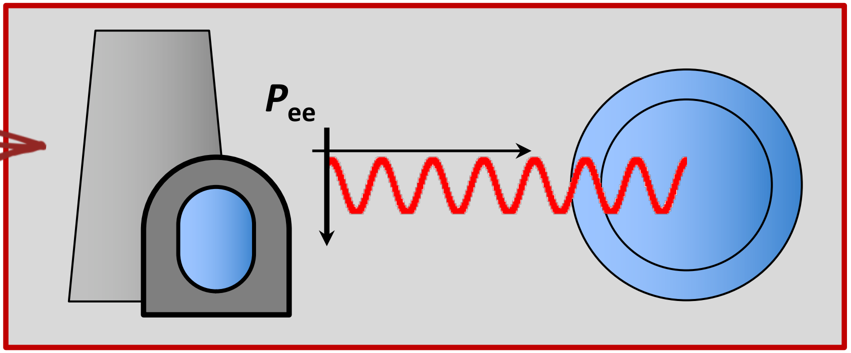



→ **need for dedicated experiments**

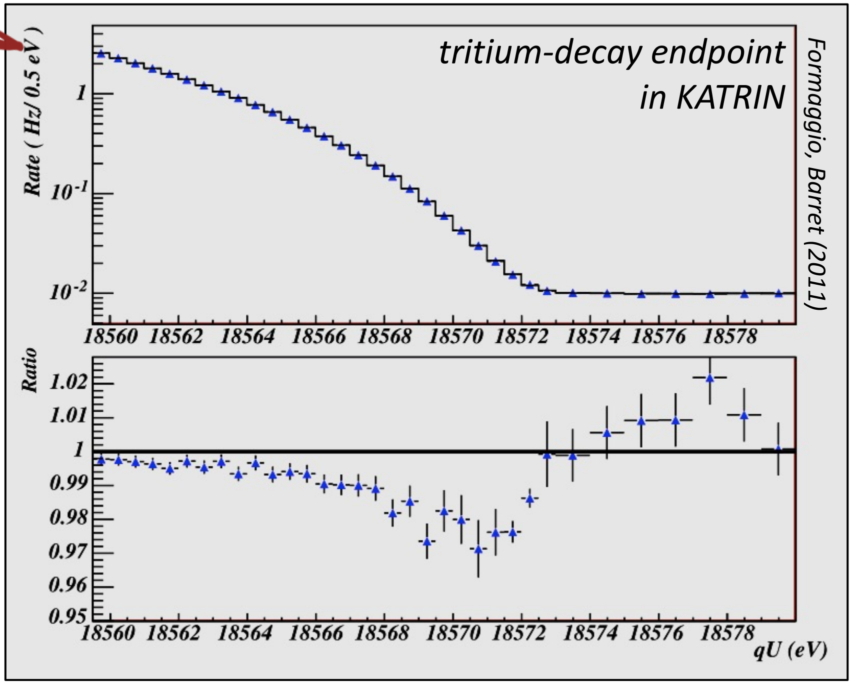
# Testing the $\nu_e$ disappearance anomalies

## New experimental approaches

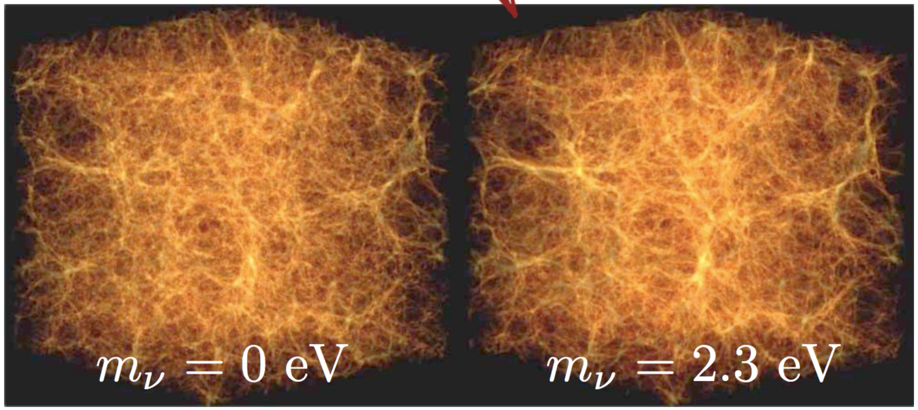
- very-short baseline experiments
  for observing $\nu_e \rightarrow \nu_s$ oscillation disappearance pattern




- β-decay ν mass experiments
  to find spectral deformation from eV-mass eigenstate $\nu_4$



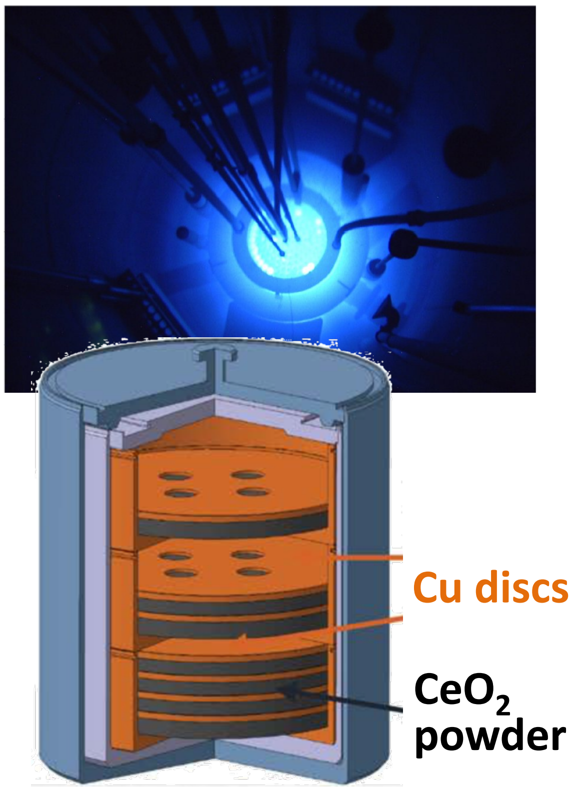

- cosmological limits on $N_{eff}$ & $\Sigma m_\nu$
  (CMB, BBN, BAO ...)



# Reactor vs. Radioactive Sources

**Basic approach:**

- search for $\nu_e \rightarrow \nu_s$ **disappearance** oscillations
- Intrinsically **pure beam**: only $\nu_e$ or $\nu_e$
- **oscillometry:** oscillation waves inside the detector
- energy range: 1-10 MeV → **distance 1-10 m**
- **well-known cross-sections** at MeV energies



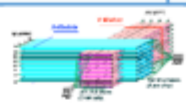
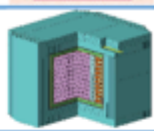
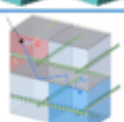
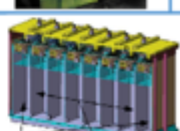

## Reactor experiments

- intense, stable source of antineutrinos
- extended reactor core → research reactor
- large intrinsic background levels

## Radioactive source

- low-background levels (nearly background-free)
- well-defined and well-localized source activity
- decaying source → limited measuring time
- bureaucratic challenge

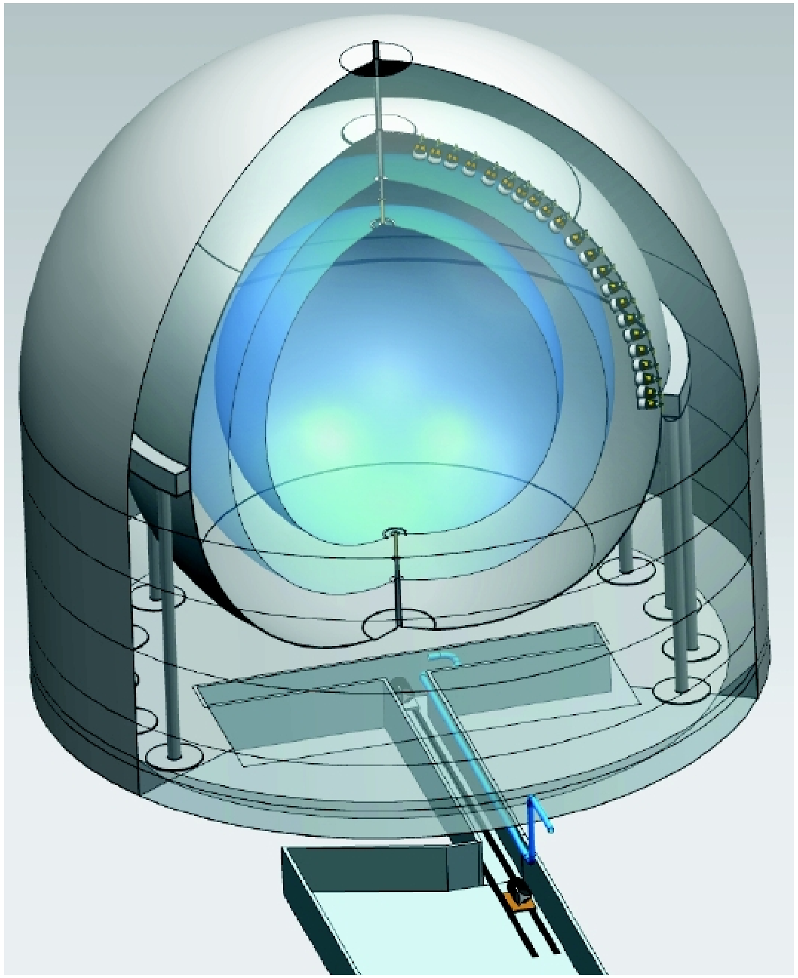
# Short-baseline reactor experiments

| 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 |

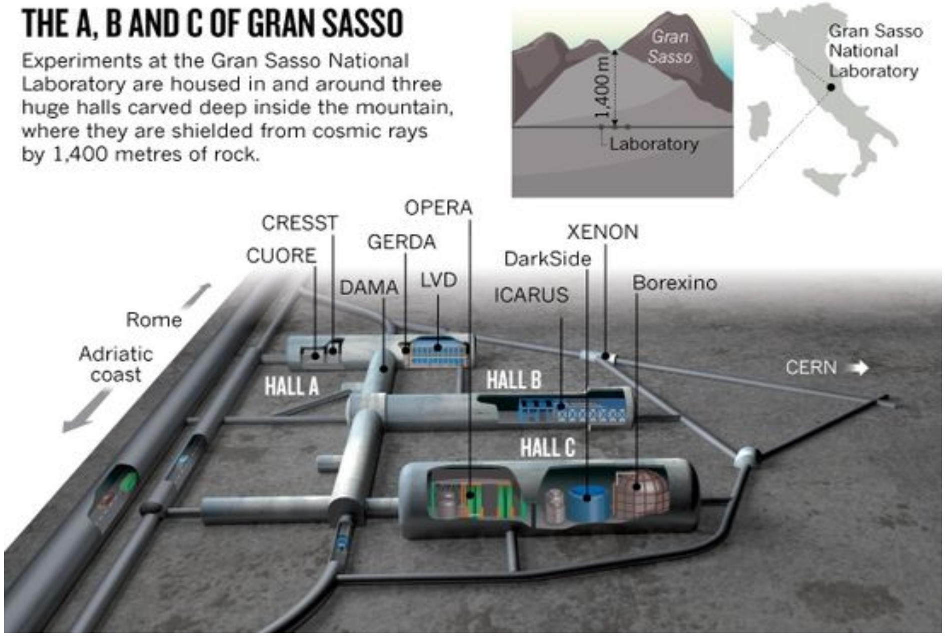
*from N. Bowden's talk at Nu16*

# Short-baseline source experiment: SOX

## Schematic of Borexino



**Start:** May 2007




## Borexino @ Gran Sasso Laboratories

- low-energy solar neutrino experiment
- organic liquid-scintillator detector
- since 2007: $^{7}$Be, pep, pp, geo-neutrinos
- ultra-low background conditions:
  - rock shielding: 1.4 km
  - intrinsic radiopurity: $10^{-18}$ g/g U/Th

# Short-baseline source experiment: SOX

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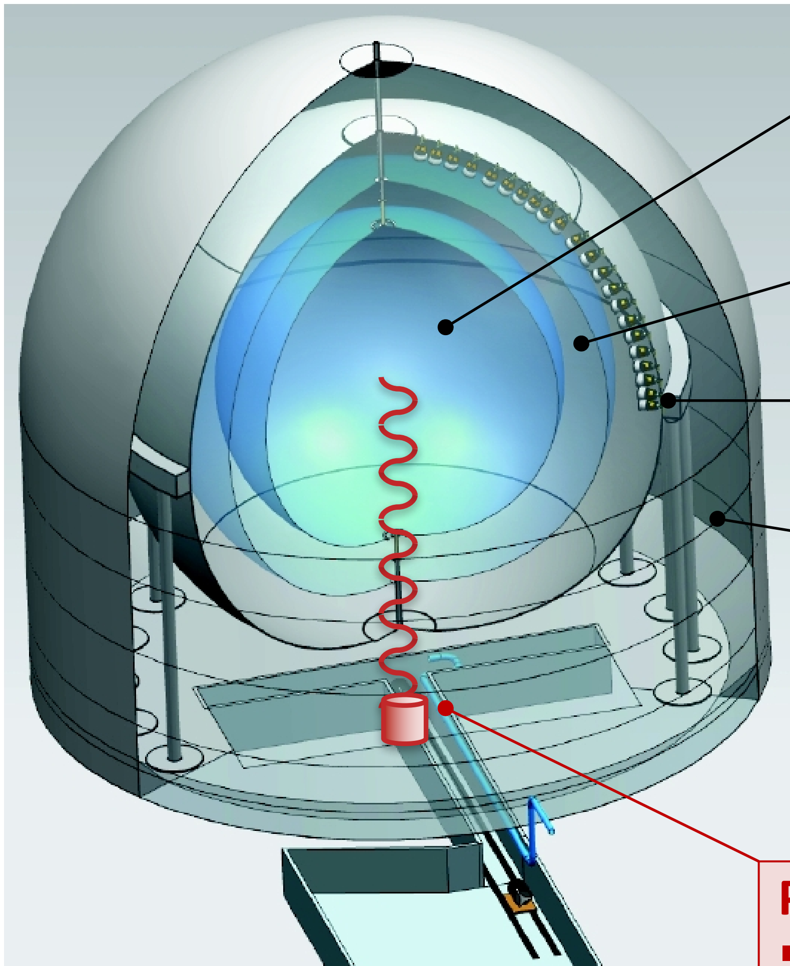
**Schematic of Borexino**



**neutrino target**
- diameter: 8.5 m
- pseudocumene+PPO: 300 tons

**buffer volume**
- shielding from external radioactivity

**steel sphere with 2212 PMTs**
- diameter: 13.7 m

**water Cherenkov muon veto**

**Pit for neutrino source**
- 8.5m from center

**Start:** Spring 2018 – duration: 1.5 yrs

# SOX Pit below Borexino

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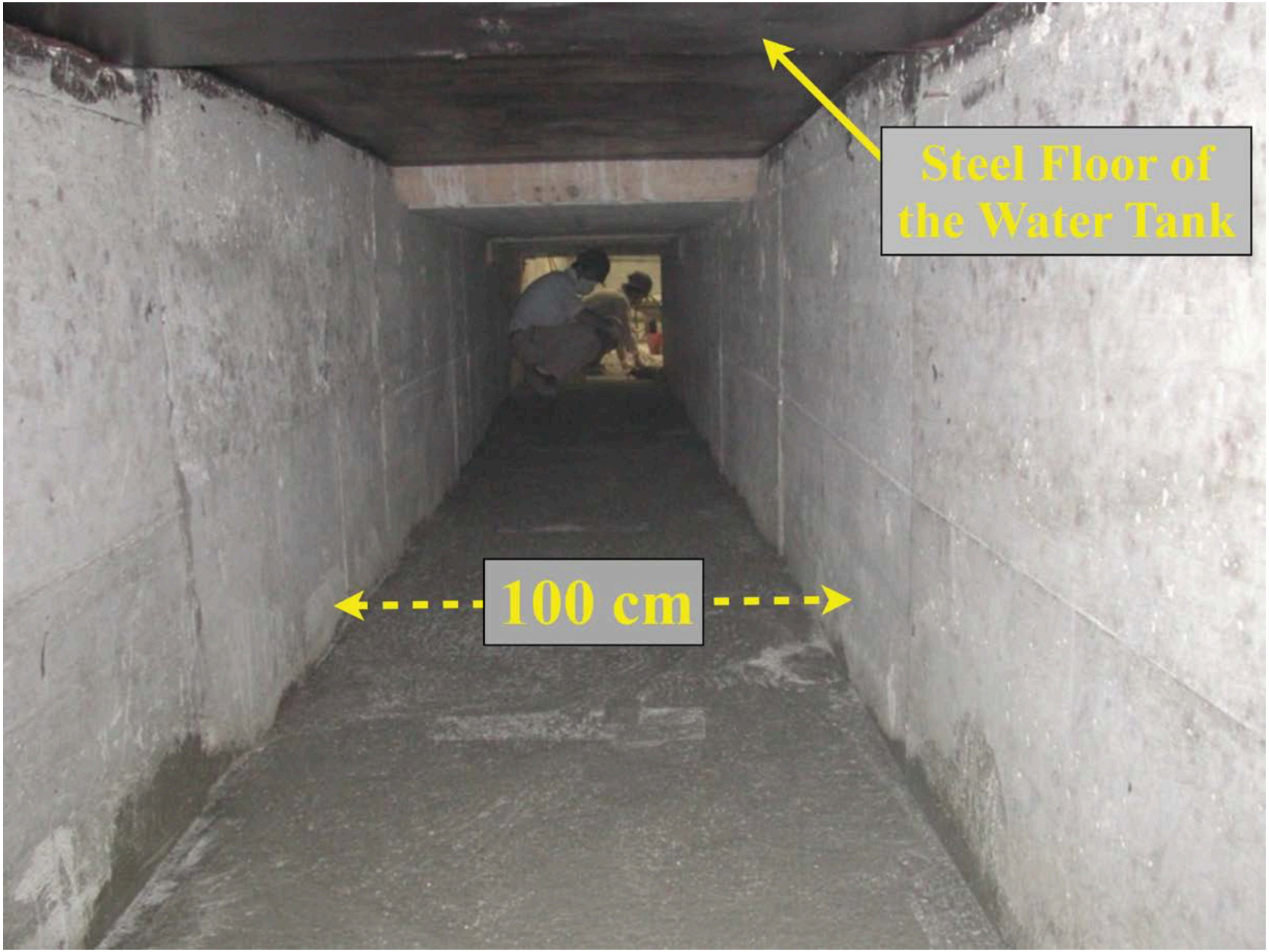

# Antineutrino source: $^{144}Ce/^{144}Pr$

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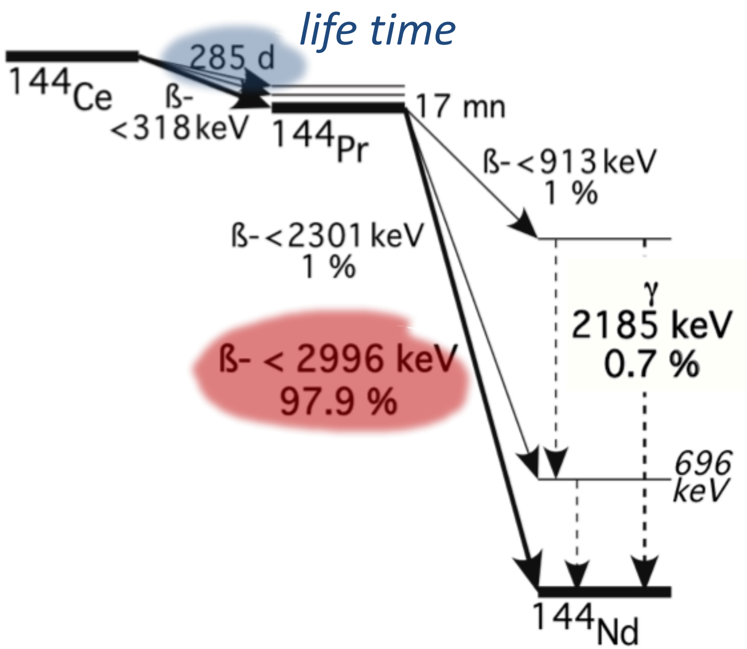
## $^{144}Ce$-$^{144}Pr$ decay scheme



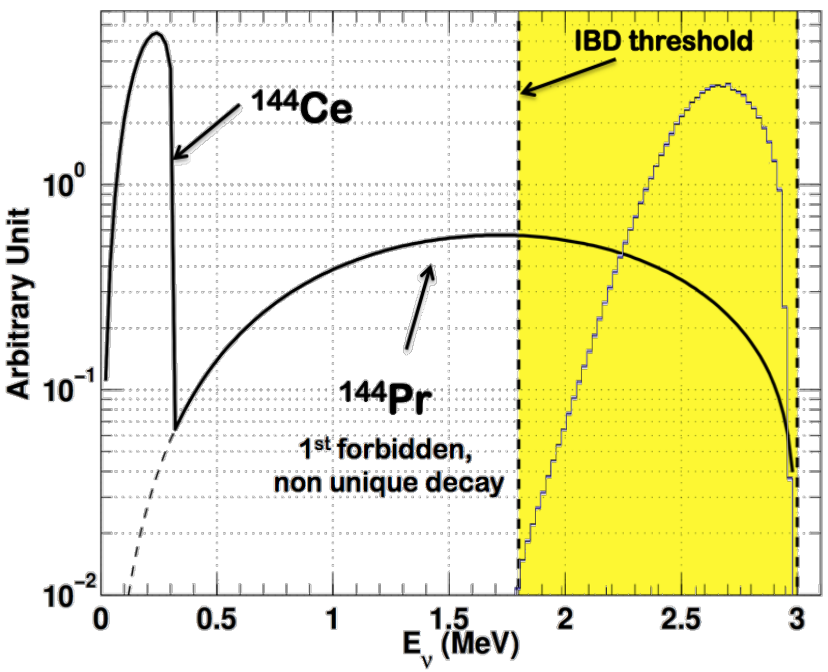

**Initial activity:** 100-150 kCi
4-6 PBq

heat power: 0.9 – 1.3 kW

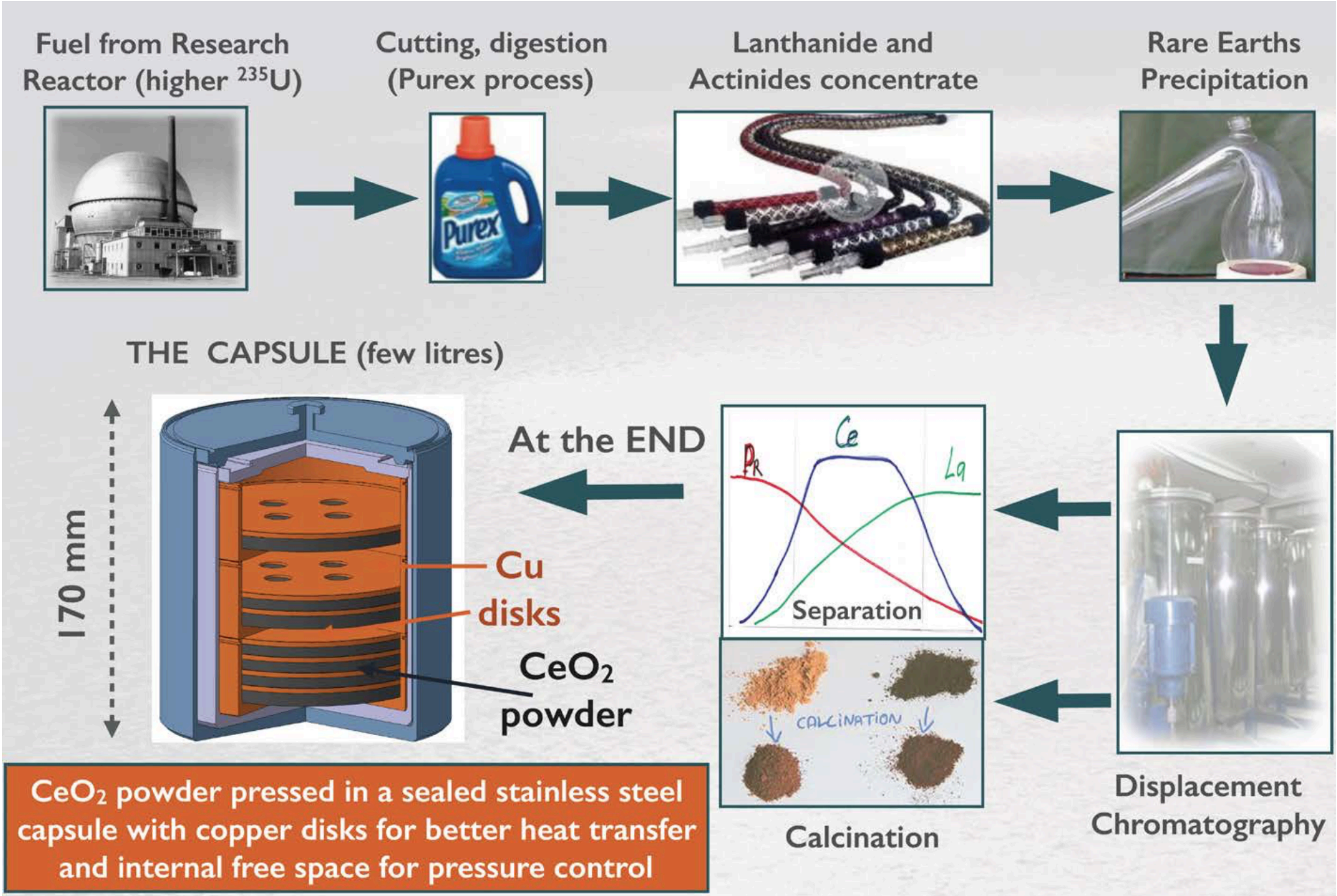
**Inverse Beta Decay (IBD) cross section:**

$$\sigma_{\mathrm{IBD}} \approx 9.5 \cdot 10^{-45}\,\mathrm{cm}^2 \left(E - 1.8\,\mathrm{MeV}\right)^2$$

## β-spectrum & cross-section



# $^{144}$Ce source production

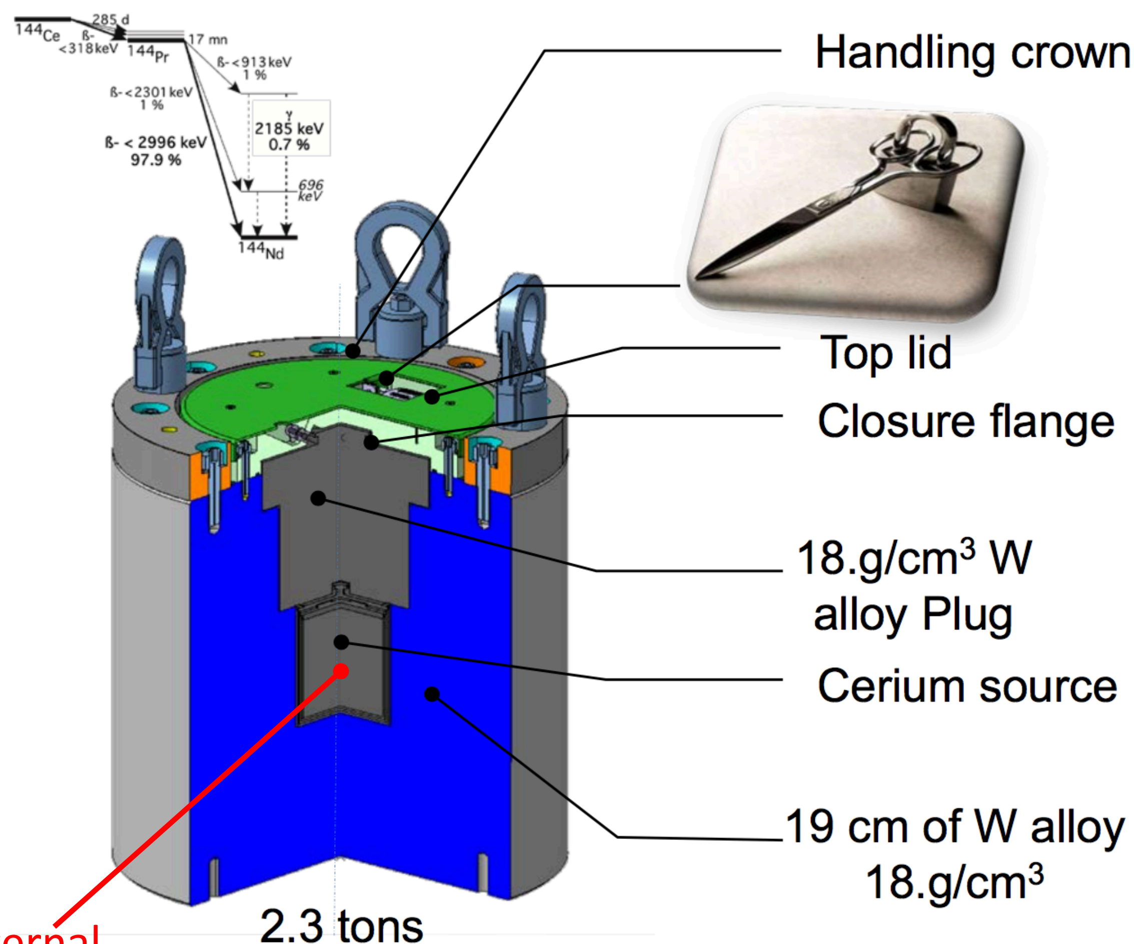


# Source transport

3 weeks of transport

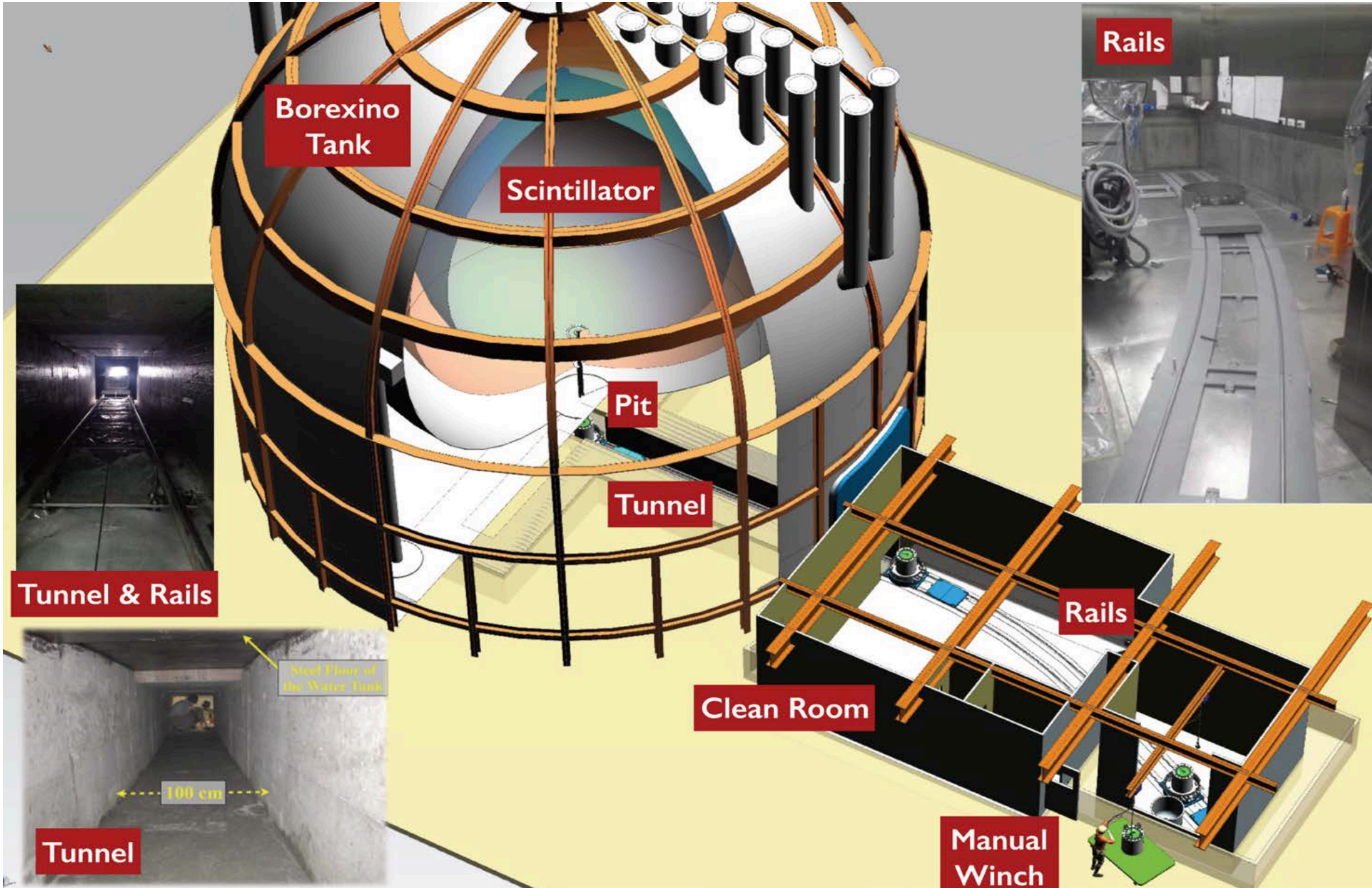
# Tungsten shielding

**Source shielding:** reduces 4PBq to 200Bq surface activity

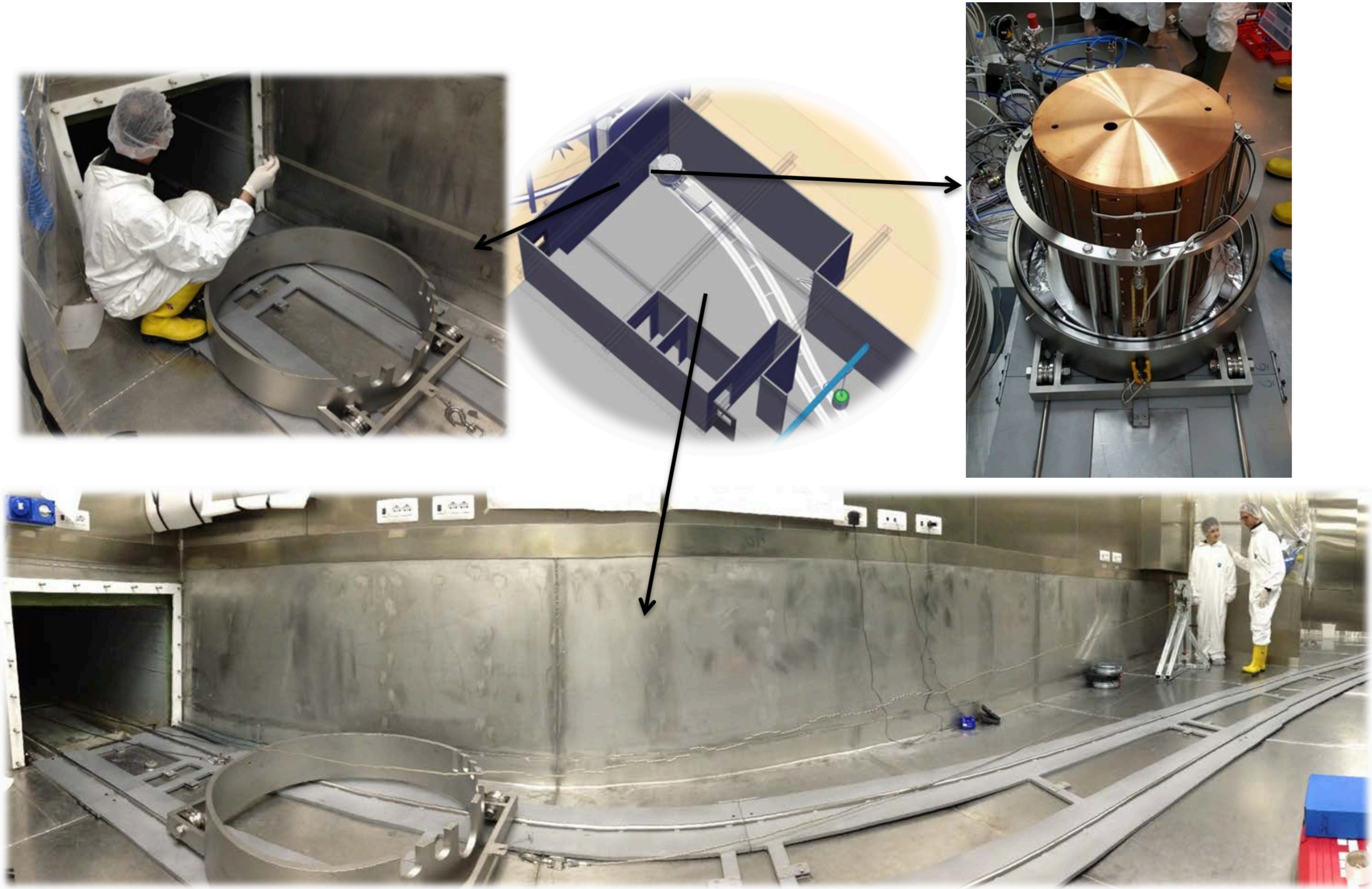



internal temperature: ~500°C

# SOX experimental layout



# SOX source insertion system



# Antineutrino detection in Borexino

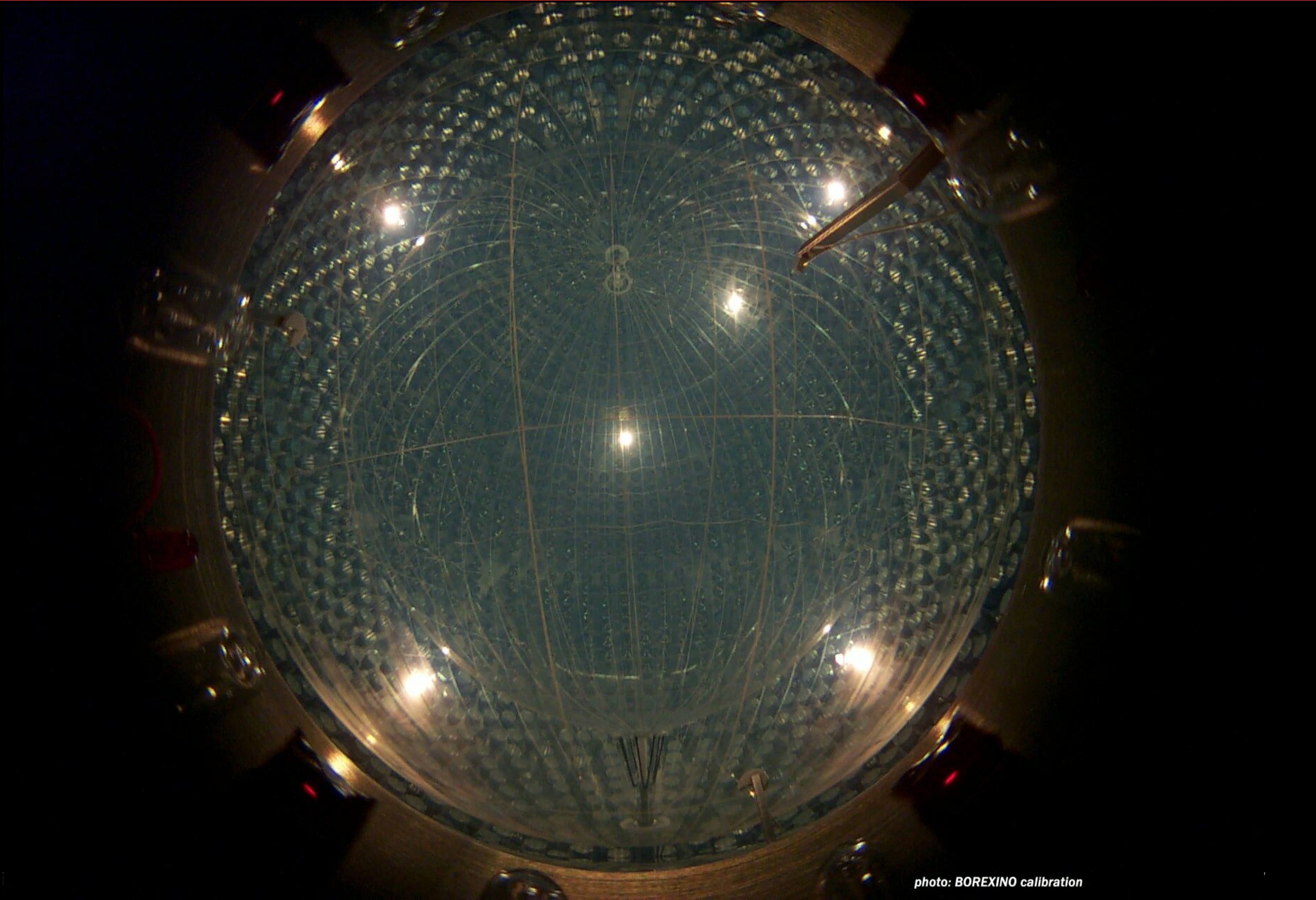


photo: BOREXINO calibration

# Antineutrino detection

**Threshold:**

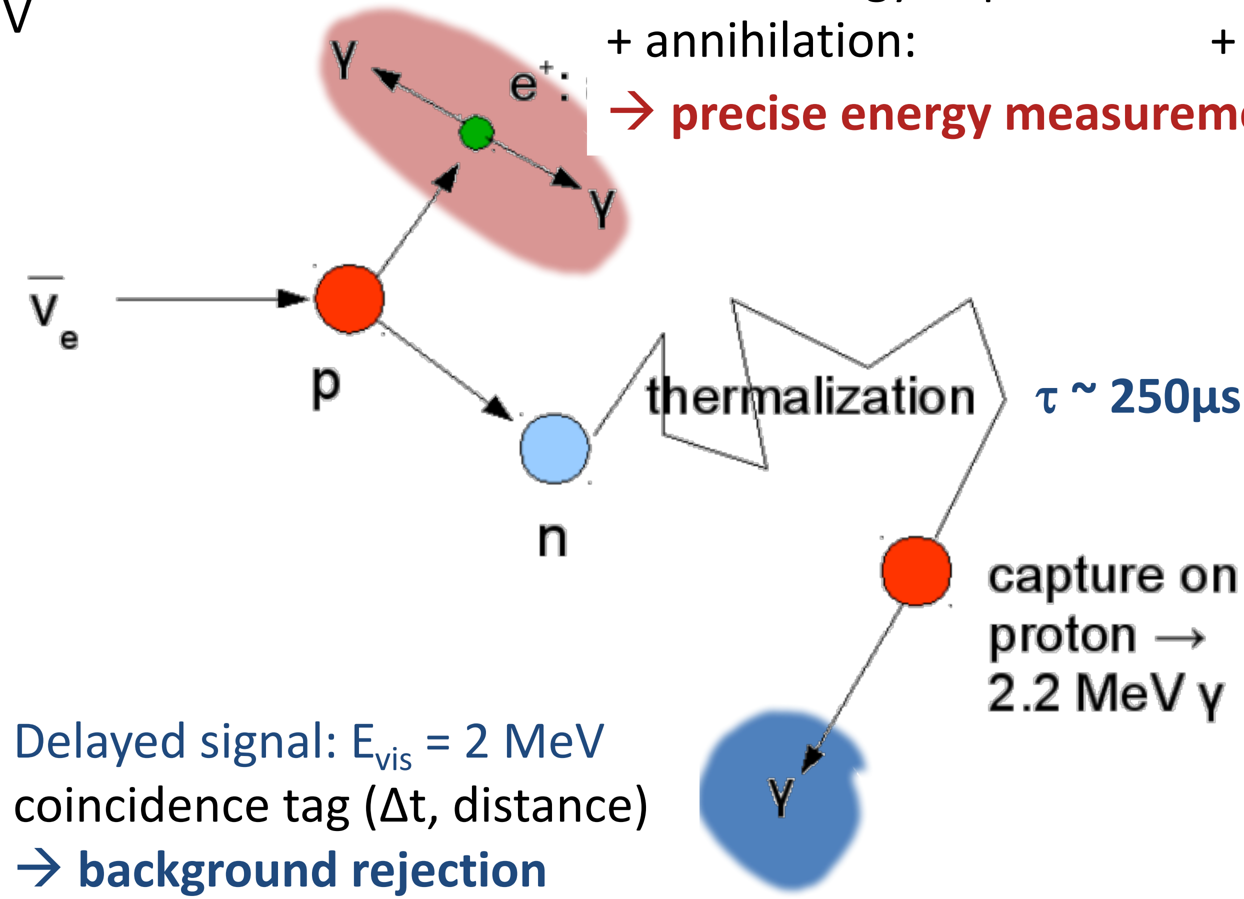
$Q = m(n)+m(e^+)-m(p)$
$\quad = 1.8$ MeV

Prompt signal: $E_{vis}$ = 1 – 3 MeV

Kinetic energy of positron: $E(\nu) - Q$

+ annihilation: $+ 2m(e^{\pm})$

→ **precise energy measurement**




Delayed signal: $E_{vis}$ = 2 MeV

coincidence tag (Δt, distance)

→ **background rejection**

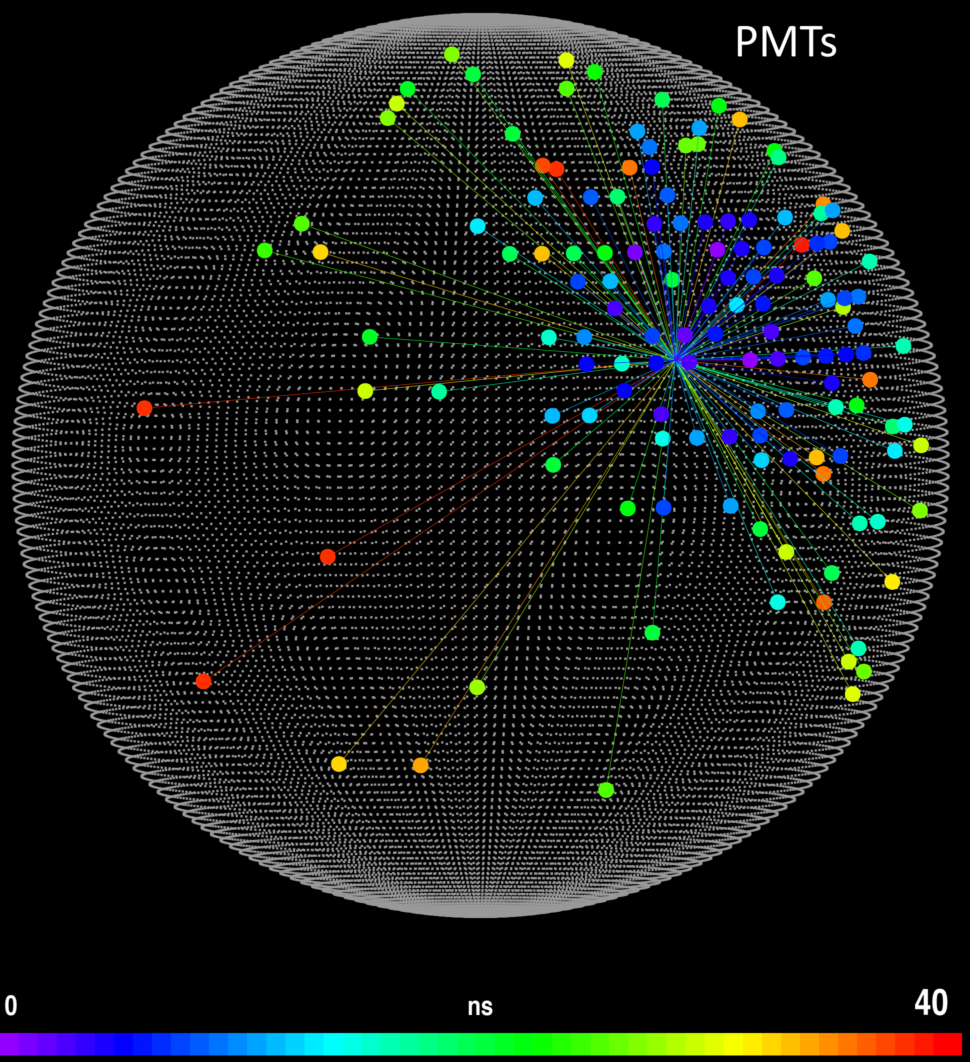
# Event reconstruction in Borexino

- **Scintillator light yield:**
  ~10k photons per MeV
  → 5% detected by PMTs

- **Energy resolution**
  ~500 p.e. per MeV
  **→ ΔE/E ~ 5% @ 1 MeV**

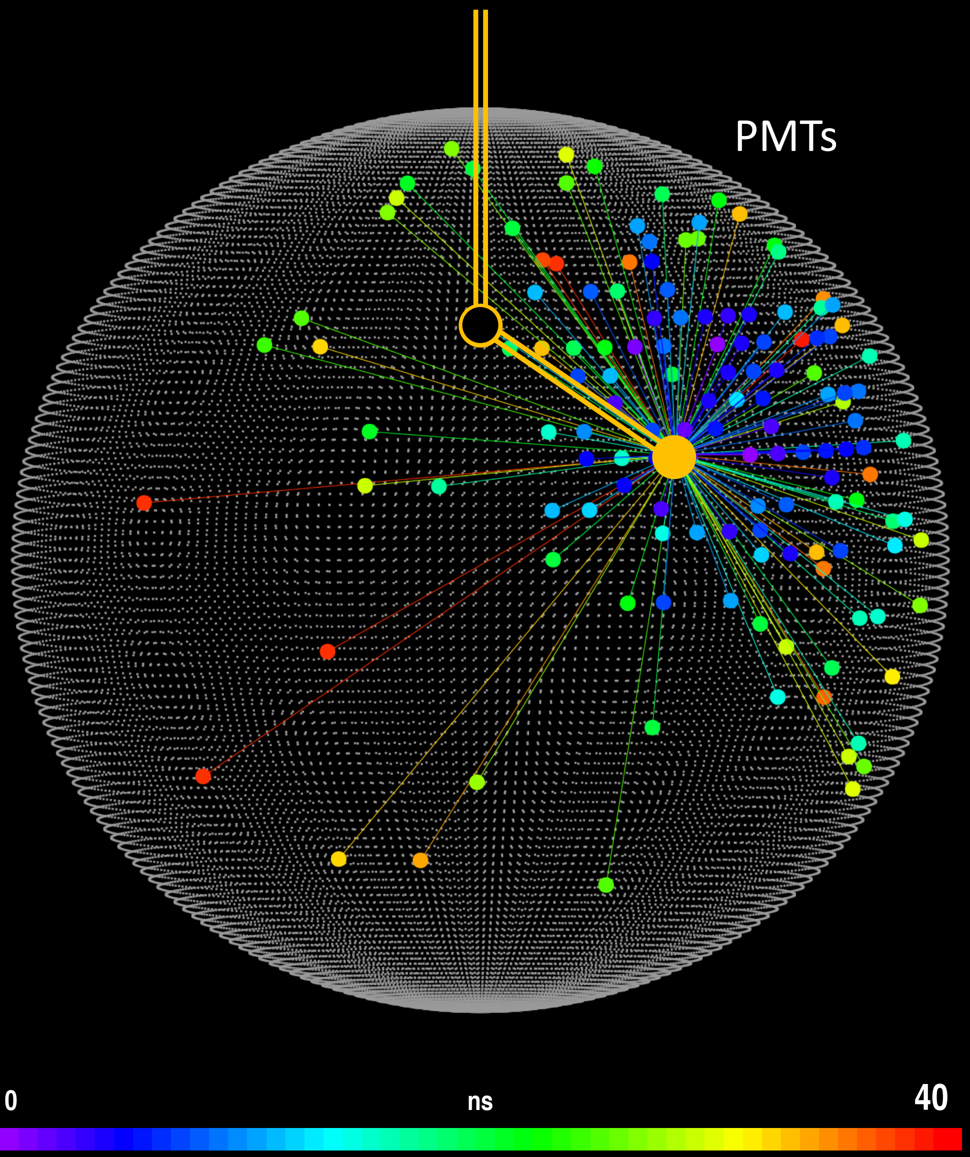
- **Energy threshold**
  instrumental: ~50 keV
  solar analysis: **~150 keV**

- **Spatial reconstruction**
  from photon time-of-flight
  **→ Δx ~ 10 cm @ 1 MeV**

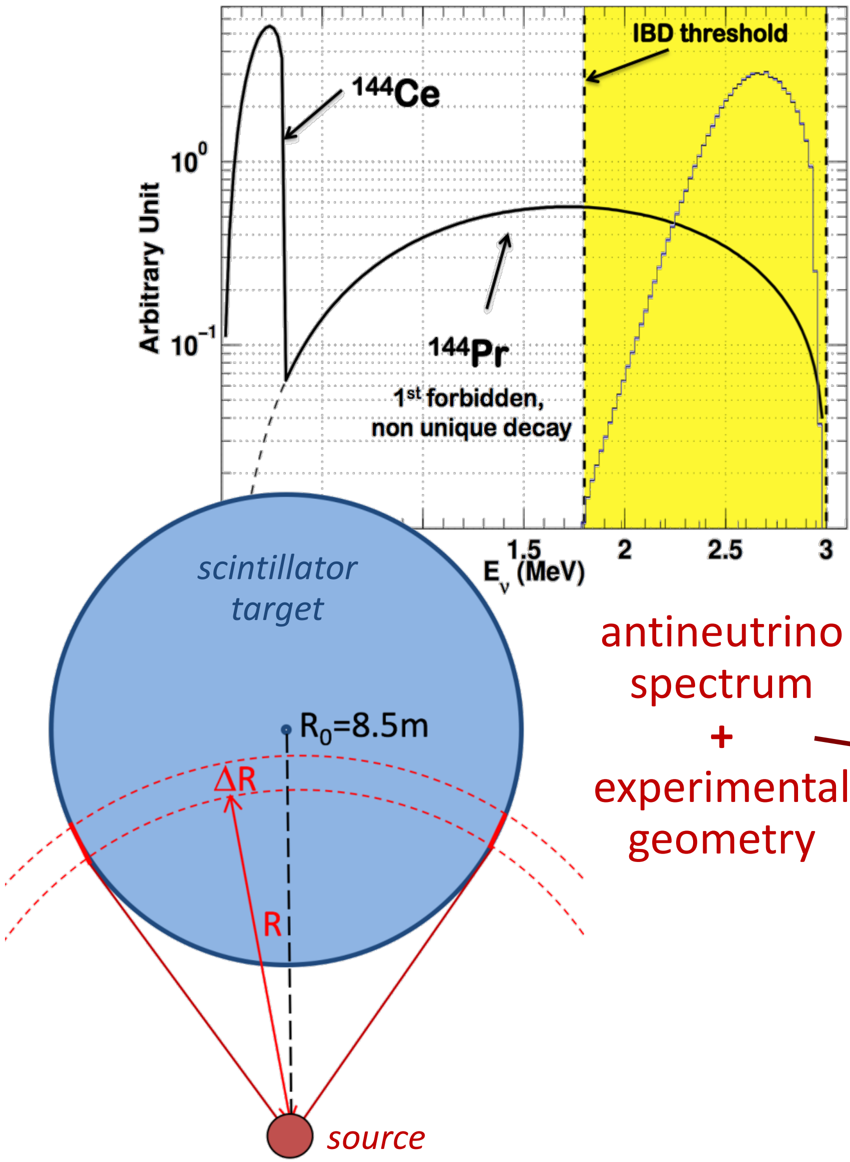


# Event reconstruction in Borexino

- **Scintillator light yield:**
  ~10k photons per MeV
  → 5% detected by PMTs
- **Energy resolution**
  ~500 p.e. per MeV
  → **ΔE/E ~ 5% @ 1 MeV**
- **Energy threshold**
  instrumental: ~50 keV
  solar analysis: **~150 keV**
- **Spatial reconstruction**
  from photon time-of-flight
  → **Δx ~ 10 cm @ 1 MeV**
- **Calibration campaign** with sources inside IV planned for autumn.

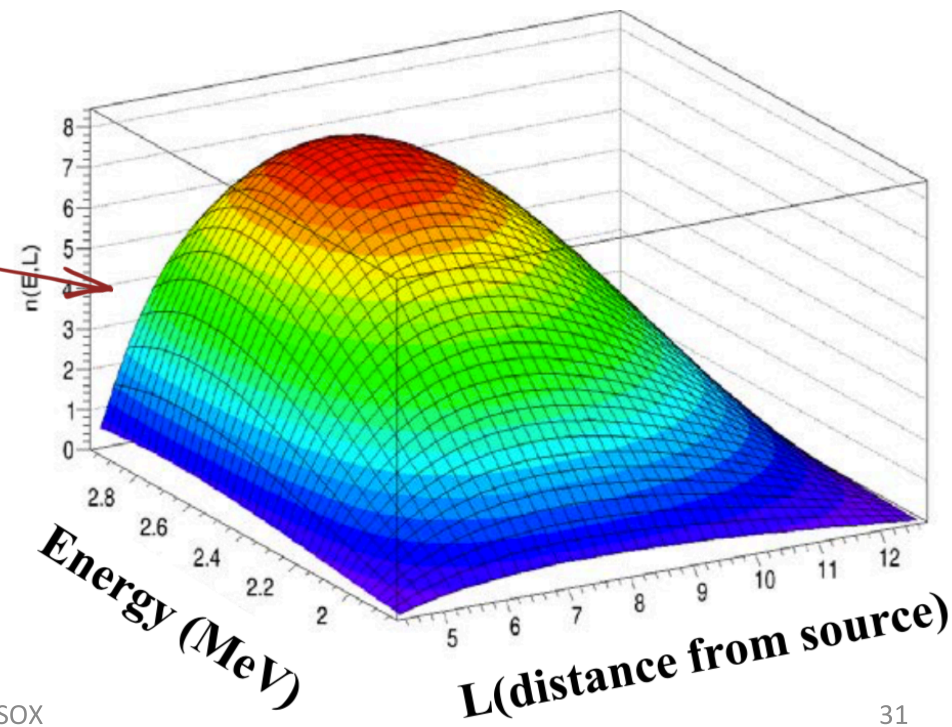


# Expected antineutrino signal

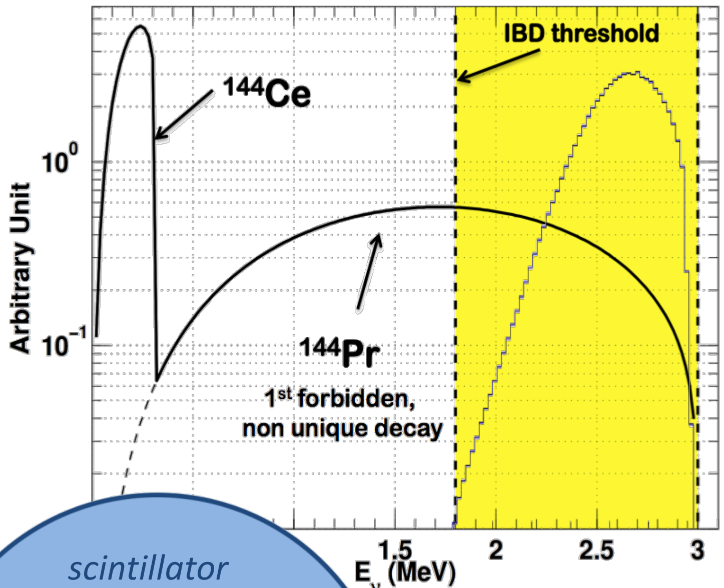


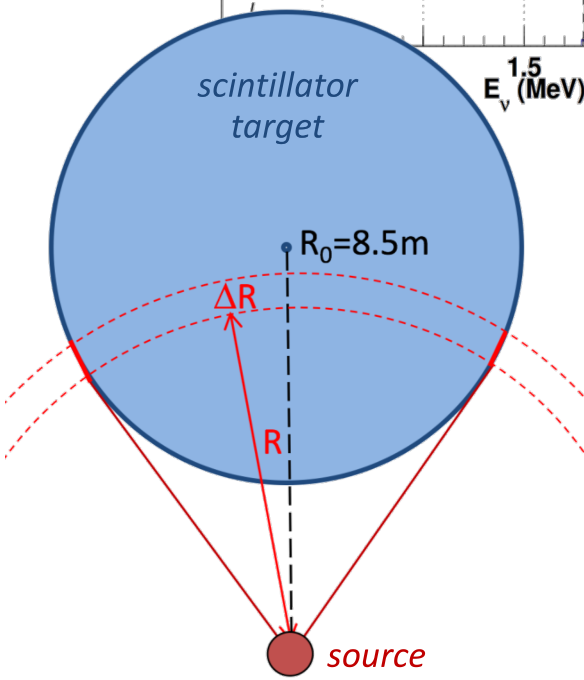

antineutrino spectrum
+
experimental geometry

**L-E distribution**
without oscillations



# Expected antineutrino signal



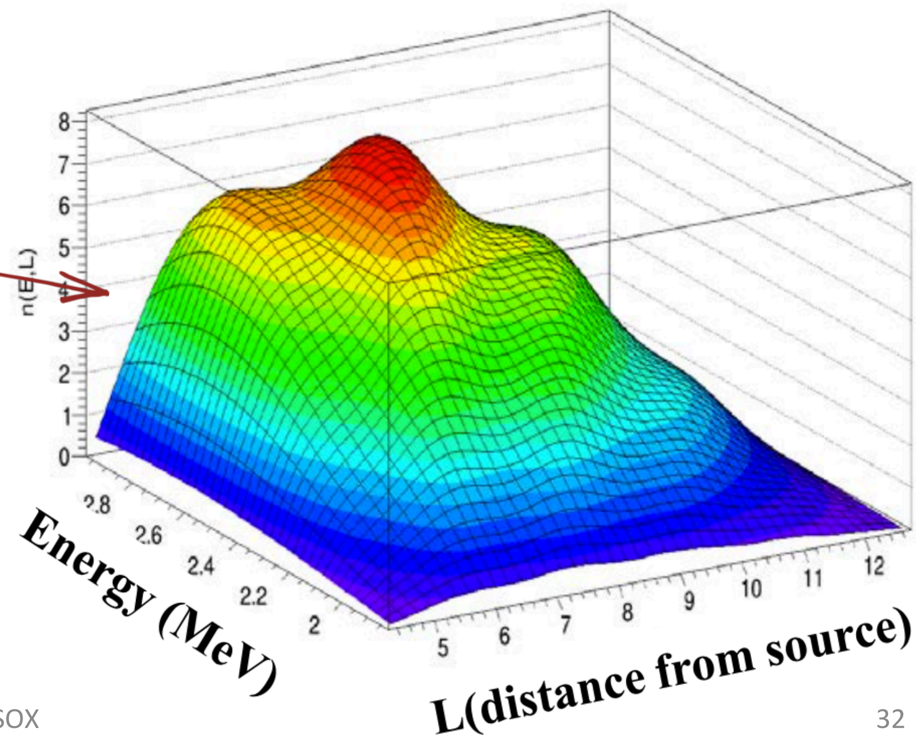

**signature of disappearance oscillations**

- rate deficit (source activity)
- oscillation waves (statistics: $10^4$ IBDs)

antineutrino spectrum
+
experimental geometry

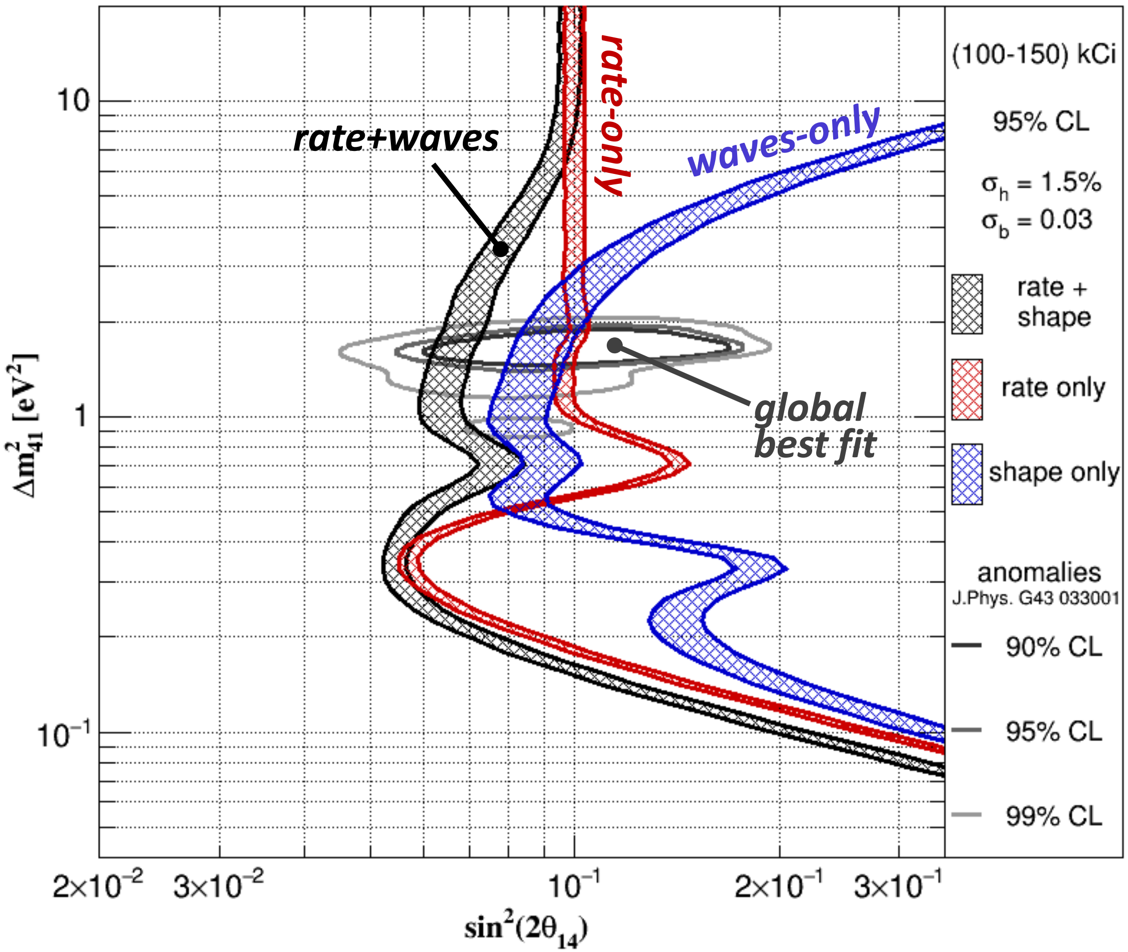
**L-E distribution**

with oscillations: $\sin^2 2\theta=0.14$, $\Delta m^2=2.5eV^2$



# Expected sensitivity vs. rate

$$P(\nu_e \to \nu_s) = 1 - \sin^2(2\theta_{14})\sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$




**Experimental parameters**

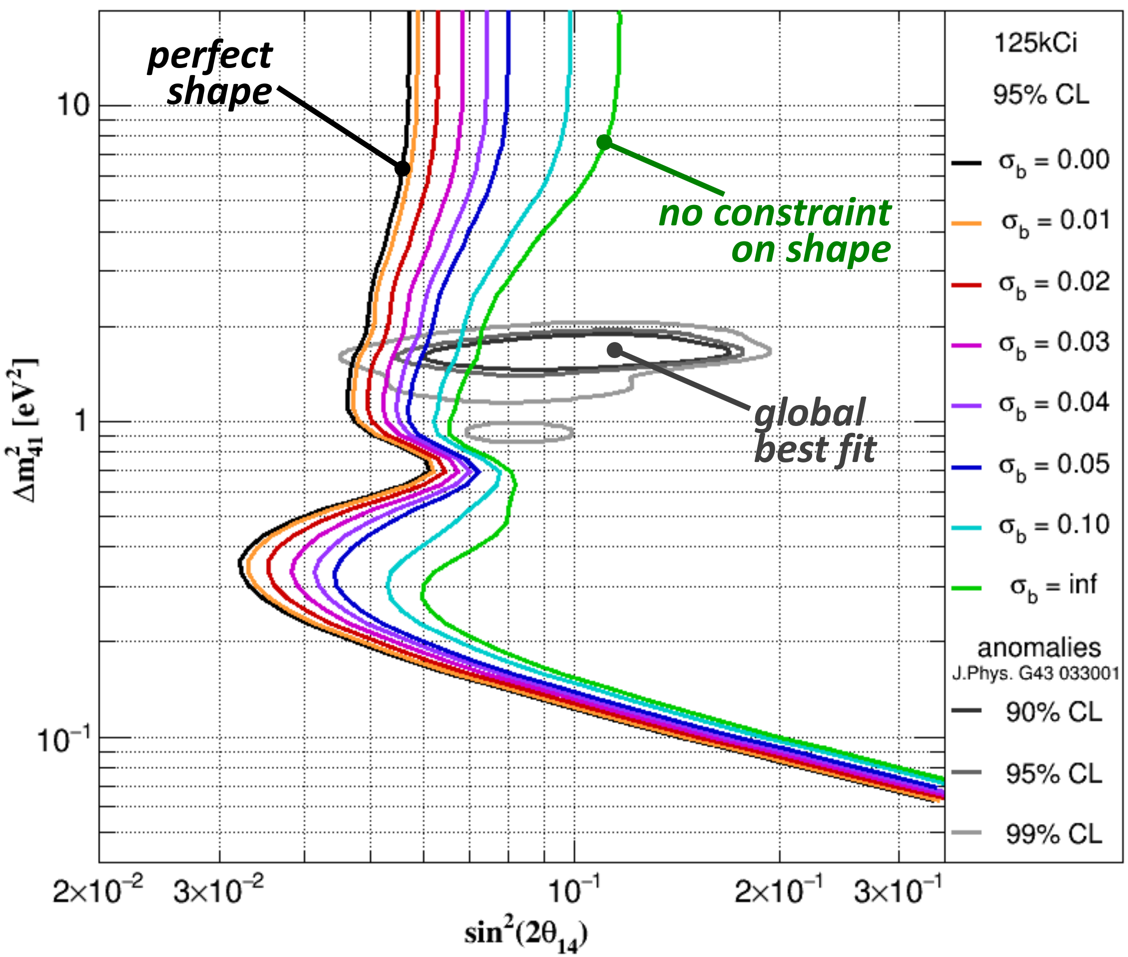
- **activity: 100→150 kCi**
- exposure: 1.5 yrs
- fiducial radius: 4 m
- uncertainties
  - on activity: 1%
  - on fiducial volume: 1%
  - on spectral shape *b*: 3%
- no background

→ maximum sensitivity for oscillation waves in region of the anomalies

# Expected sensitivity vs. spectral shape

$^{144}$Pr β-spectrum with **shape correction factor**:

$$\frac{dN}{dE} = \sum_i BR_i \cdot S_{\beta i}(E) \cdot C(E) \text{ with } C(E) = 1 + b \cdot m_e/E$$




**Experimental parameters**

- activity: 125 kCi
- exposure: 1.5 yrs
- fiducial radius: 4 m
- uncertainties
  - on activity: 1%
  - on fiducial volume: 1%
  - **on spectral shape *b*: 0%→∞**
- no background

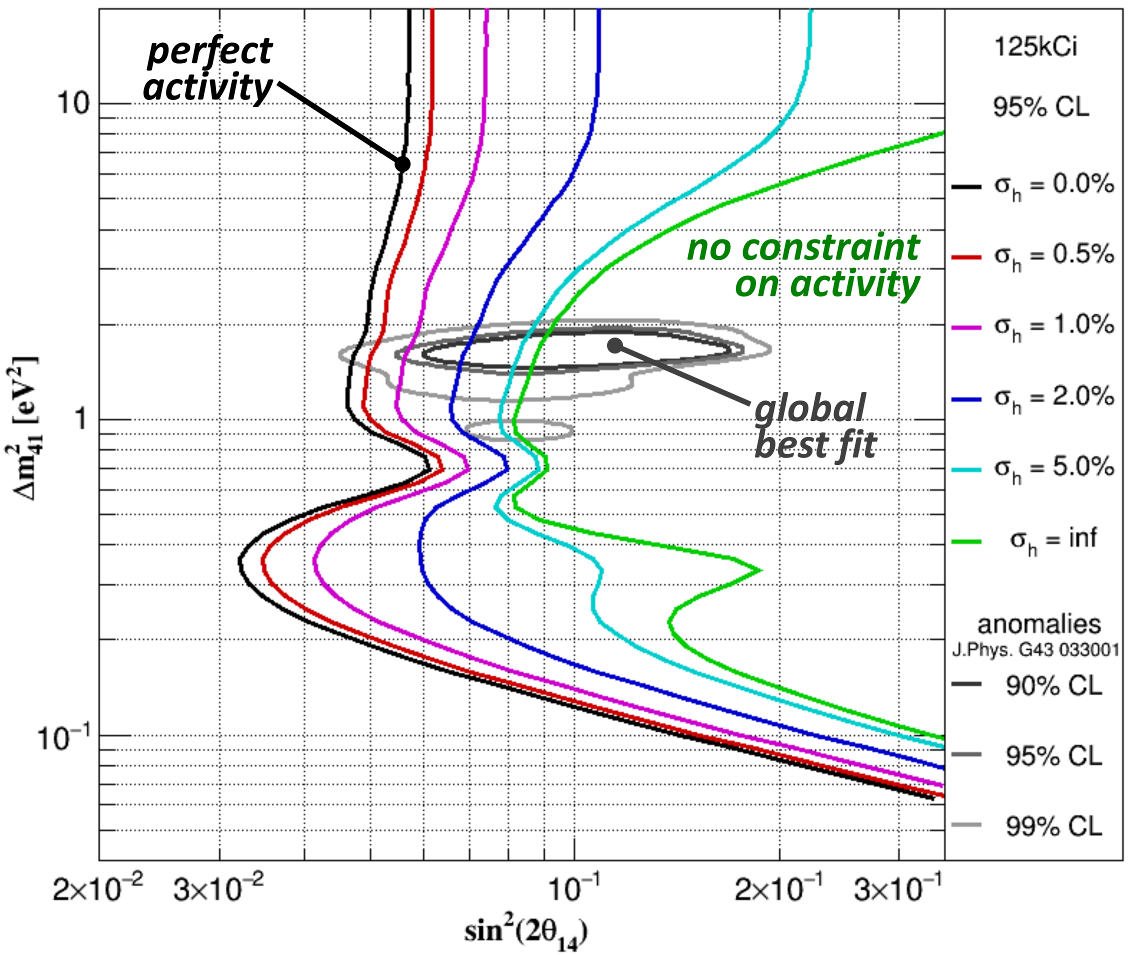
→ maximum sensitivity for oscillation waves in region of the anomalies

→ shape uncertainty matters but is under control

# Expected sensitivity vs. spectral shape

JG|U

**Activity** closely linked to heat power released by β-decays → **expected event rate**




**Experimental parameters**

- activity: 125 kCi
- exposure: 1.5 yrs
- fiducial radius: 4 m
- uncertainties
  - **- on activity: 0%→∞**
  - - on fiducial volume: 1%
  - - on spectral shape *b*: 3%
- no background

→ maximum sensitivity for oscillation waves in region of the anomalies

→ shape uncertainty matters but is under control

→ error on activity matters! better 5% needed for gain over wave-only analysis

# Source heat power measurement

*Mounting mock-up source in TUM/Genova calorimeter*

**Two calorimeters** for independent measurements of **thermal power** (~1%)

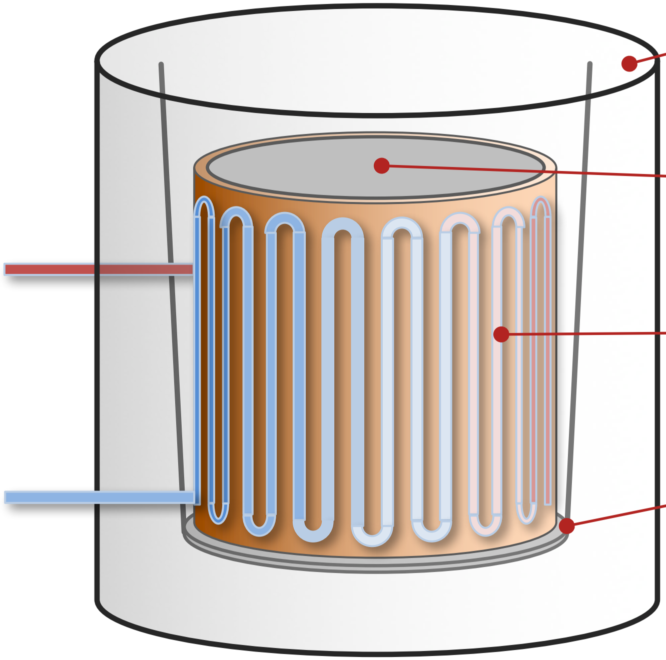
- **Calorimeter inside SOX-Pit**
  German groups/Genova
- **Calorimeter outside PIT/in Mayak**
  CEA Saclay

## Measurement strategy

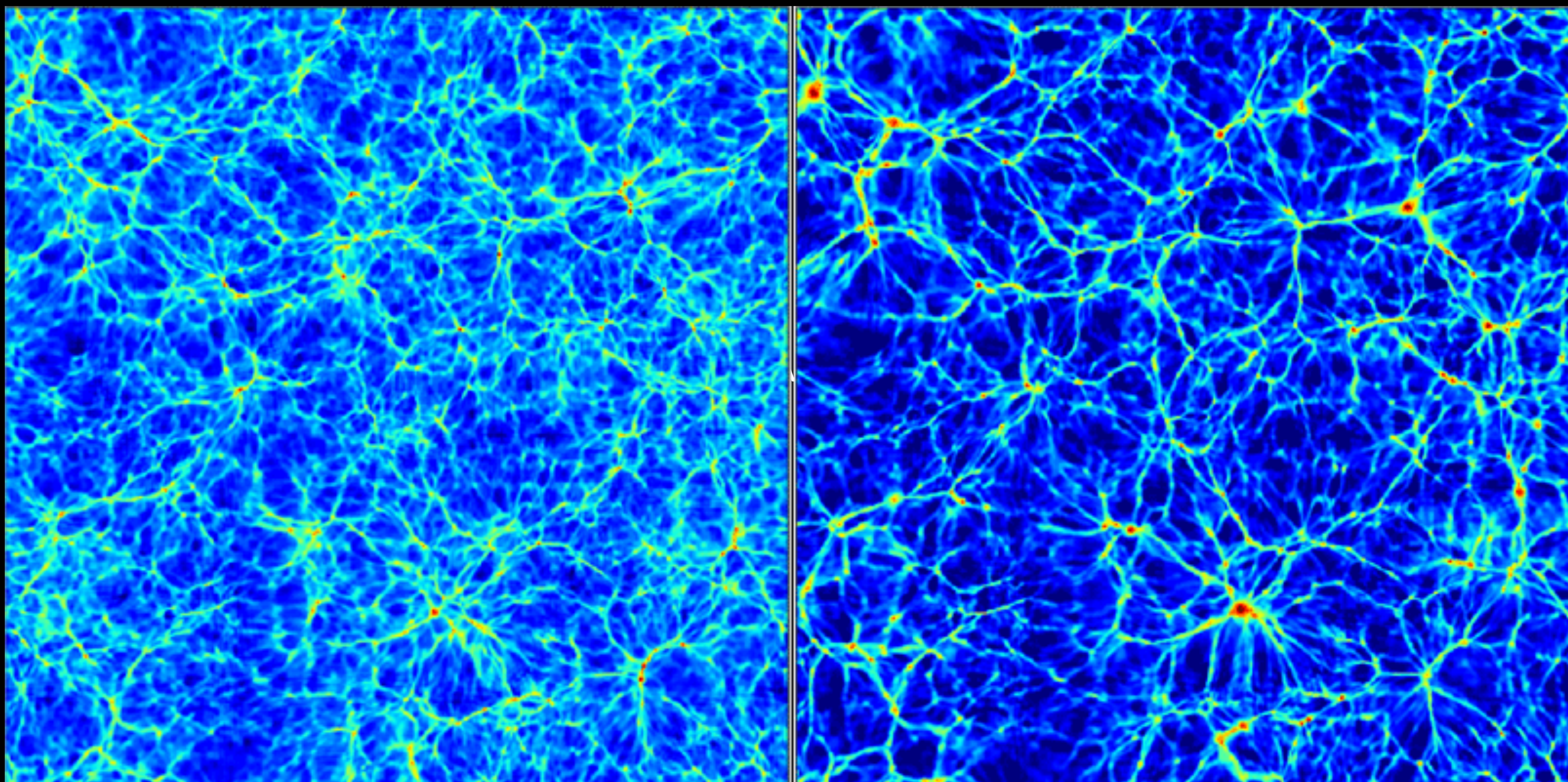
- insulate source from surroundings
- circulate water through loop around W shielding
- measure mass flow $\Phi$ and temperature increase $\Delta T$

$$P = \Phi \cdot C_{H_2O} \cdot \Delta T + P_{loss}$$

- sub-% accuracy reached in test measurements



# Complementary information on sterile neutrinos



$m_\nu = 0$ $m_\nu = 1.9$ eV

# Effect of steriles on β-decay spectra

JG|U

**Measuring the electron neutrino mass**

- Effect of mass is a shift of the endpoint/spectral deformation
- Effective mass is incoherent sum

$$m^2(\nu_e) := \sum |U_{ei}^2| m^2(\nu_i)$$

- 3 known mass eigenstates could in principle be resolved but mass differences very small

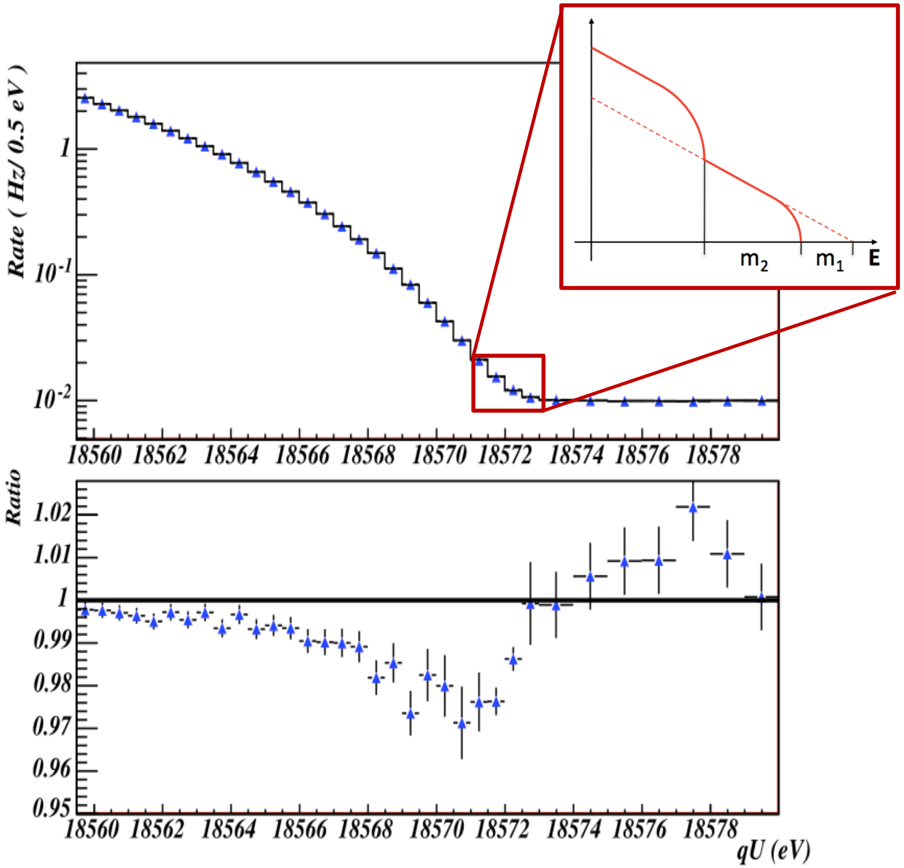
$$\Delta m_{31} < 50 \text{ meV}$$

- **sterile mass splitting** much larger

$\Delta m_{41} \sim 1\text{eV}$ *for light steriles*

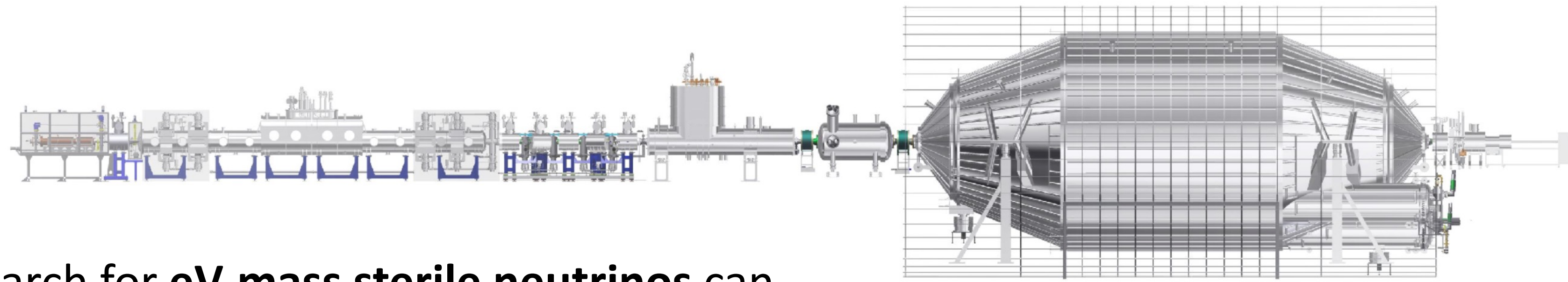
- Size of effect depends on $\nu_4$ admixture to $\nu_e$ flavor state: $|U_{e4}|^2$

**→ observable in upcoming experiments?**

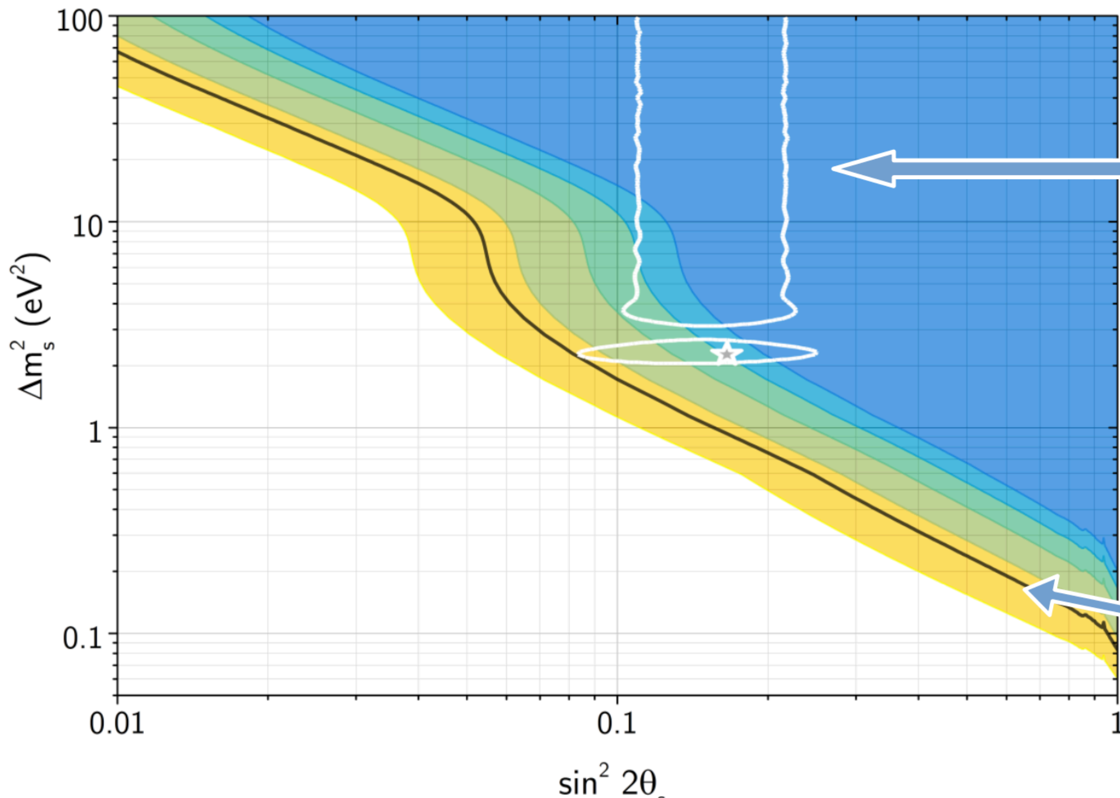



*J. A. Formaggio, J. Barret, PLB 706 (2011) 68*
*Spectral deformation of tritium decay spectrum*
*(3-year measurement in KATRIN)*
*Sterile ν parameters: $\Delta m^2 = 2$ eV$^2$, $|U_s|^2 = 0.067$*

# eV-mass sterile neutrinos in KATRIN



- search for **eV-mass sterile neutrinos** can be performed based on regular setup




reactor anomaly combined fit 90% C.L.

K. N. Abazajian et al. 2012

exclusion curve confidence levels

- KATRIN 5σ
- KATRIN 4σ
- KATRIN 3σ
- KATRIN 95%
- KATRIN 90%
- KATRIN 68%

*talk by K. Valerius @ PhysStat-ν 16*

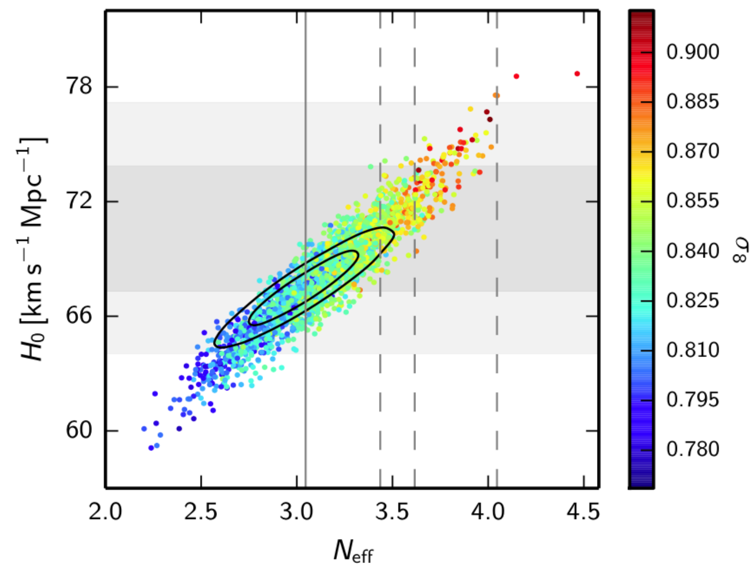
# Constraints on light sterile neutrinos

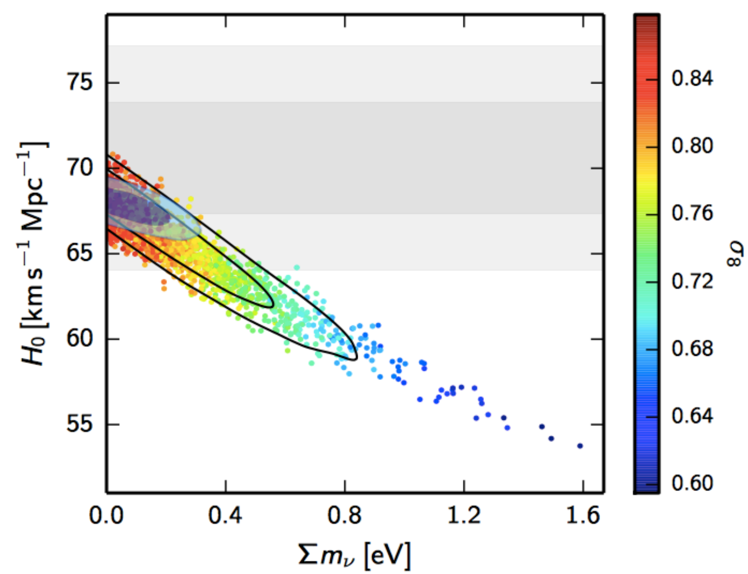
- Cosmological observations able to place stringent bounds on the **number $N_{eff}$** and **mass sum $\Sigma m_\nu$** of light (i.e. thermalizing) sterile neutrinos

- Most important observables
  - Cosmic Microwave Background
  - Big Bang Nucleosynthesis
  - Large-scale structure

- Bounds from PLANCK (+BAO):
  - $N_{eff} = 2.99 \pm 0.20$
  - $\Sigma m_\nu < 0.49$ (0.17) eV (95% C.L.)

- These limits can be avoided by introducing additional physics, e.g. sterile neutrino self-interactions
  Dasgupta, Kopp [arXiv:1310.6337]

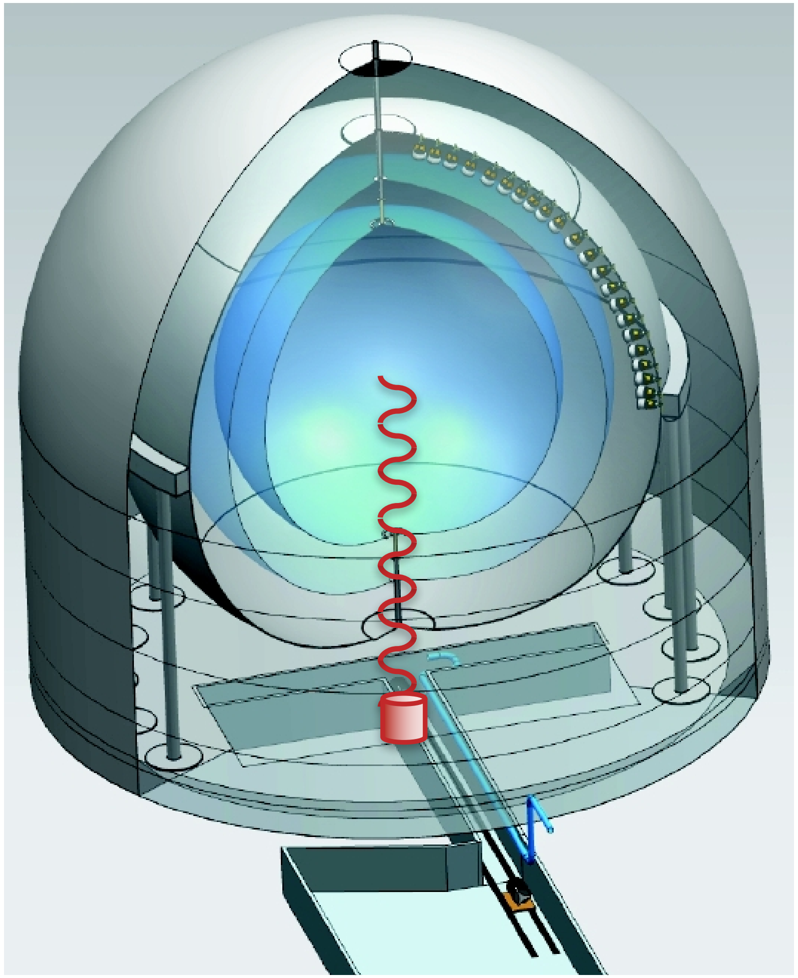


# Conclusions

**SOX is getting ready:**

- Contract with Mayak for the $^{144}Ce$ source has been signed.
- Experimental site is ready (Borexino, clean room ...)
- Tungsten shield has arrived at LNGS.
- Source calorimeters are in commissioning phase.
- Summer: Complete test of procedures with mock-up source.
- Autumn: Calibration run with radioactive source inside the target.



**Start of data taking in early 2018.**

- Most of statistics acquired in ½ year
  → stay tuned for first results

# Thank you for listening!

JG|U

## Borexino and SOX Collaborations

Università degli Studi di Milano

INFN

LNGS

Princeton University

cea

National Research Center "Kurchatov Institute"

St. Petersburg Nuclear Physics Inst.

Technische Universität München

Gran Sasso Science Institute – Center for Advanced Studies, Istituto Nazionale di Fisica Nucleare

Jagiellonian University in Kraków

Jülich Forschungszentrum

Virginia Tech

Johannes Gutenberg Universität Mainz

UHH

Politecnico Milano 1863

НИИЯФ МГУ

Joint Institute for Nuclear Research

Università degli Studi di Genova

Eberhard Karls Universität Tübingen

University of Hawai'i

Università degli Studi di Ferrara

The University of California – UCLA

Technische Universität Dresden

APC

Studium Generale Civitatis Perusii

University of Massachusetts Amherst 1863

# Backup slides