Thermal Management and Modeling for Precision Measurements in Borexino's SOX and Solar Neutrino Spectroscopy Programs

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Borexino Thermal Monitoring & Management System

I

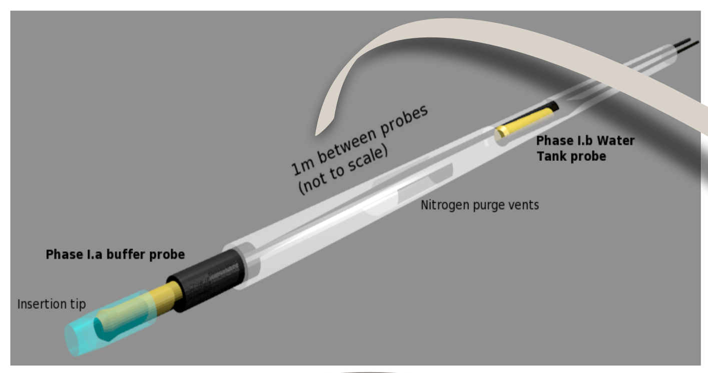
Latitudinal Temperature Probe System

HW (ref.2)

A set of 60+ **custom-calibrated, replaceable** precision temperature sensors comprise Borexino's LTPS. They provide continuous readings with a finely-spaced, **sub-0.05°C relative** precision and **absolute** accuracy (see ref.2).

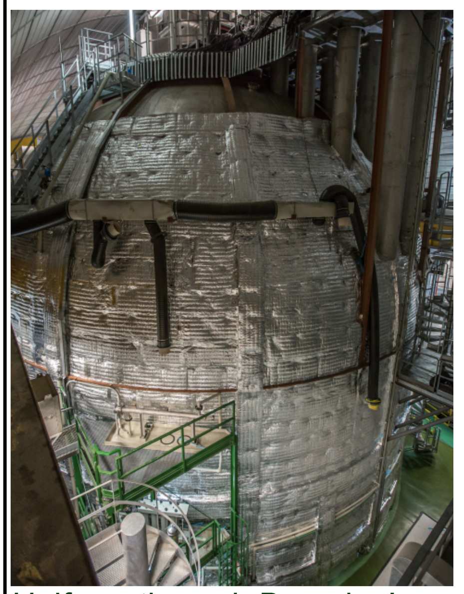
Most of them (Ph. I&II) lie on the same North-South plane, useful to contextualize data. Phase I employs existing re-entrant ports used previously for external calibrations. Their data provides anchoring points for the **CFD simulations** (*right panel*).

- Phase I.a: 14 0.5 m inside SSS (Outer Buffer), ~ ±65°, ±50°, ±25°, +7°
- Phase I.b: 14 0.5 m outside SSS (Water Tank), ~ ±65°, ±50°, ±25°, +7°
- Phase II.a: 20 Under TIS, on Water Tank walls
- Phase II.b: 6 inside SOX pit (5 ceiling, 1 ground)
- Phase III.a,.b,.c: 6 Around heating system, 1 in top Clean Room, 2 in external air



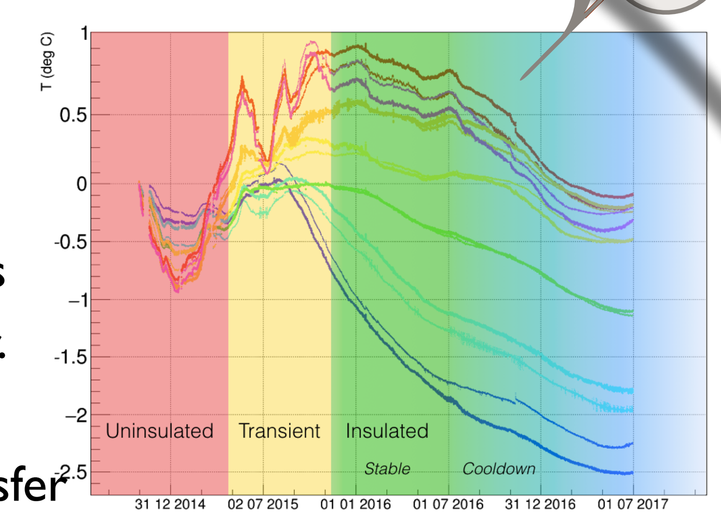
Thermal Insulation System

II



Halfway through Borexino's TIS installation, ~ mid-2015

Mineral wool layers with an aluminized exterior coating (0.3 W/m/K, **20** cm thick) thermally insulate Borexino's WT walls in contact with air. This is estimated to avoid **~60% of seasonal** heat transfer and reduces non-horizontal isotherm divergences.



Relative **temperature behavior** in Borexino's OB from the Phase I.a LTPS, normalized to initial temperature. **TIS influence** is evident.

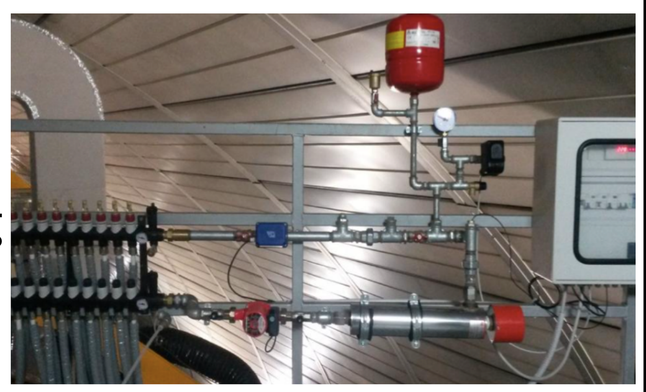
Active Gradient Stabilization System

III

AGSS heating **water coils** coupled with **insulating tape** and **copper anchors** to the WT skin, before TIS coverage

A copper-serpentine-based AGSS helps **stabilize temperatures** on Borexino's **top boundary** and, with them, its yearly vertical temperature **gradient** — which helps avoid global cooling and the largest seasonal ΔT's.

AGSS heater, circuit manifold and controller for **constant** top dome **temperature** management



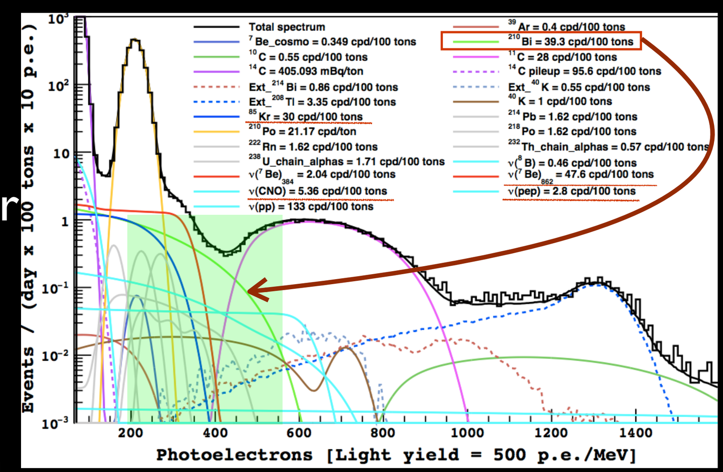
Motivation: ^{210}Bi & solar νs

Borexino's **background** levels are **unprecedentedly low**, offering extremely radiopure liquid scintillator conditions. However, determining **^{210}Bi levels** with lower uncertainties (~10%) is the key to unlocking significant precision improvements in measuring several solar ν species, especially CNO νs (see *ref. 3&4*):

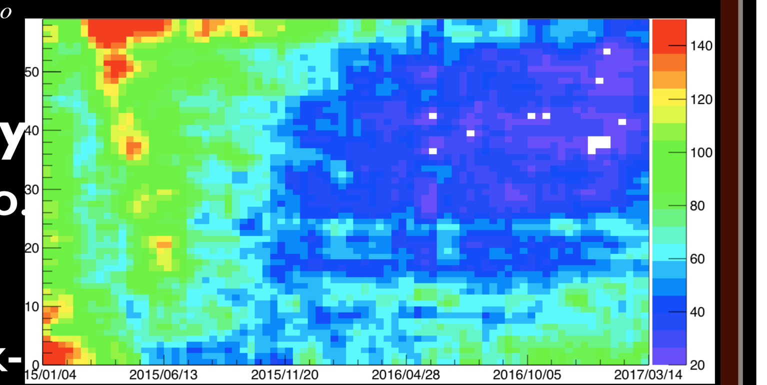
$$n_{^{210}Po}(t) = [n_{^{210}Po,0} - n_{^{210}Bi}]e^{\left(\frac{-t}{\tau_{^{210}Po}}\right)} + n_{^{210}Bi} + S_{^{210}Po}$$

Having a Compton-like signal spectrum, it can only be **tagged reliably** through its α-decaying daughter ^{210}Po.

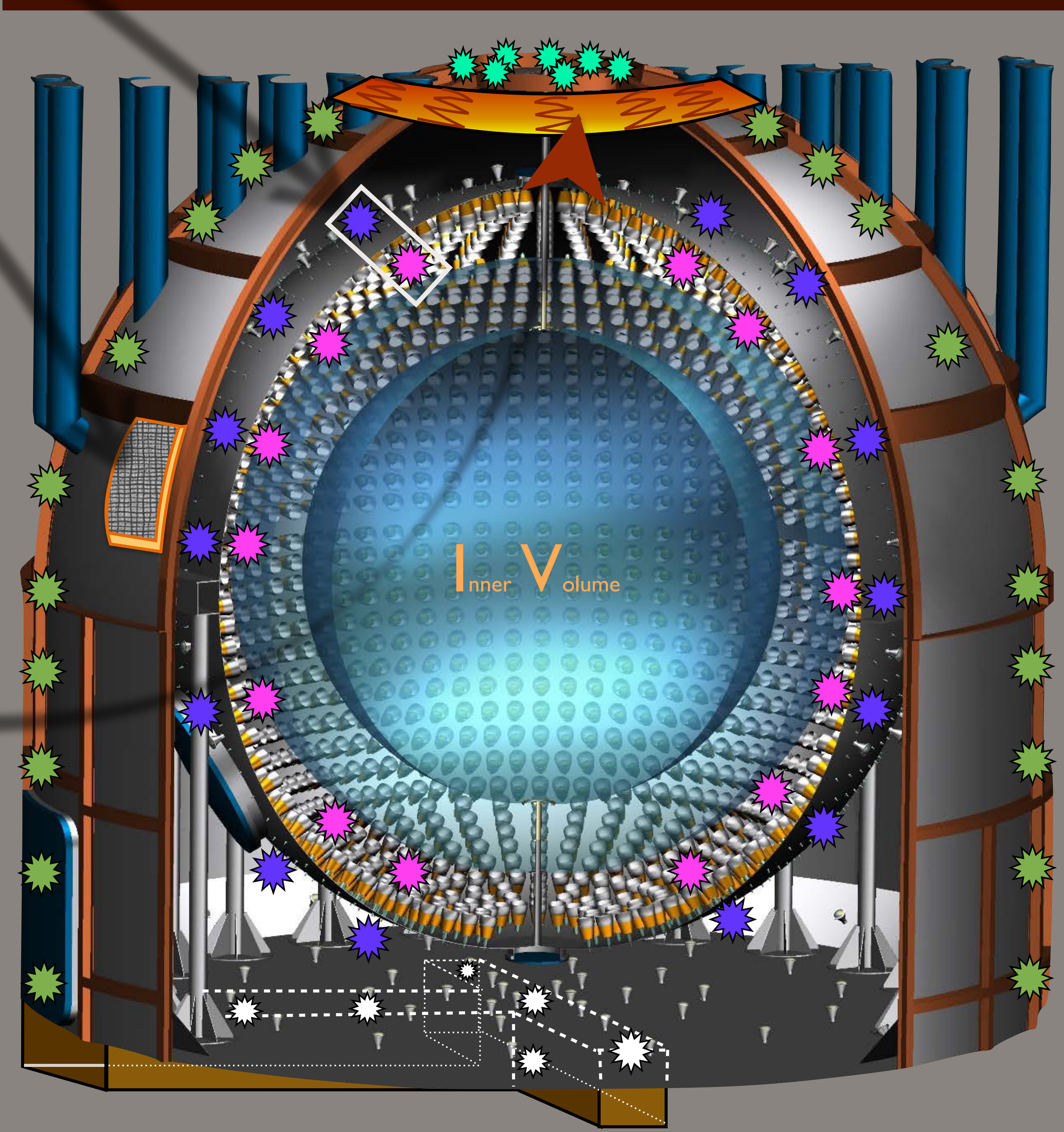
Low rates and temporal instabilities compatible with **vessel-to-IV** background **migrations**, correlated with ΔT's, have prevented this so far.



Simulation of **Borexino's spectrum** with all relevant signal and background species in the RoI. The prominent **^{210}Po peak** has been reduced to <0.7 counts/(day·ton) since 2016



Regional estimates of **^{210}Po concentration** in 52 spherical sub-volumes, from the top to the bottom of a r_S=3m FV (2013-2017 timeframe, **ref.3**)



Computational Fluid Dynamics

SW (ref.1)

Fluid dynamics in the Inner Volume cannot be directly measured but are key to better understand background movements. Likewise, the mechanism behind ^{210}Bi-Po shifts was not well characterized and difficult to predict.

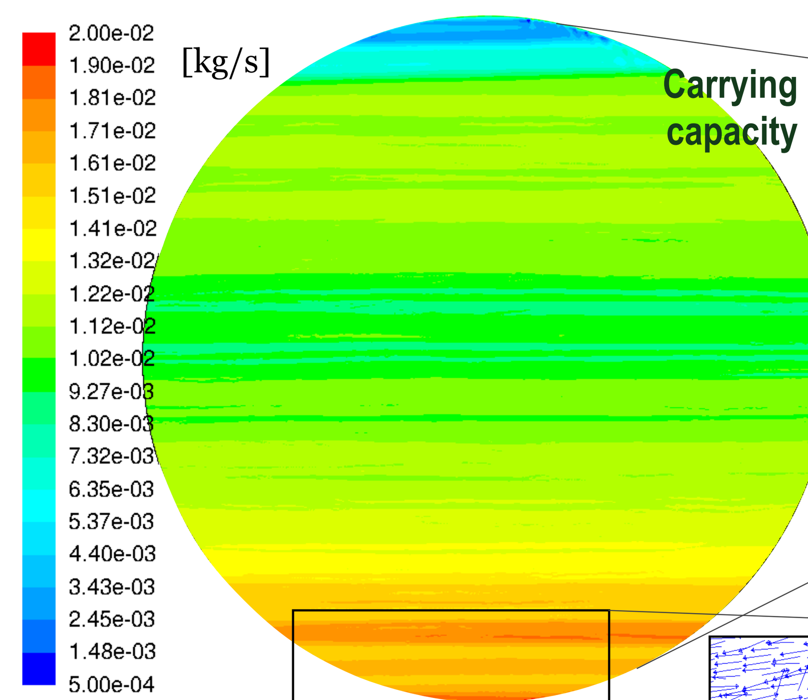
2D/3D CFD models were **fed LTPS data** as **boundary conditions** in order to :

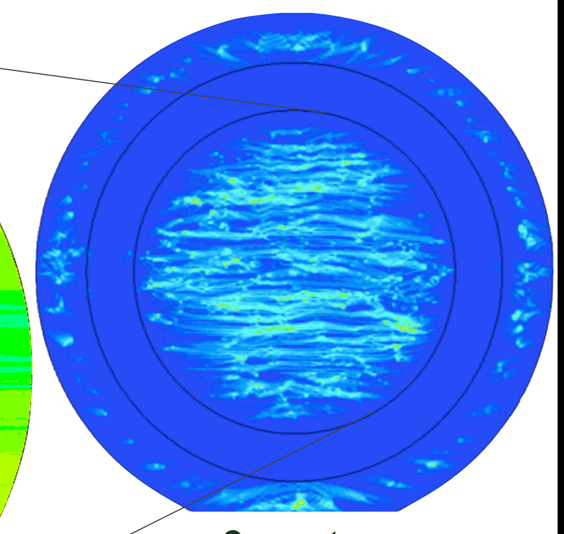
- Determine **conduction-dominated** phenomena over the whole detector (*long-term cooldown, seasonal changes, structural heatpaths, TIS effects on the boundaries, lower limits for power exchange budgeting…*)
- Explore **AGSS** influence and ideal operational range
- **Benchmark** simulated **convection** conditions with:
  √ representative literature scenarios (*similar Rayleigh number as Borexino's*)
  √ thermal transport Borexino model (*bounded by Phase I.b data, checked against Phase I.a temperatures at the same positions, see left panel*)
- Determine leading **mechanisms in fluid transport** inside Borexino's IV with a detailed convective model bounded by projected Inner Vessel temperatures

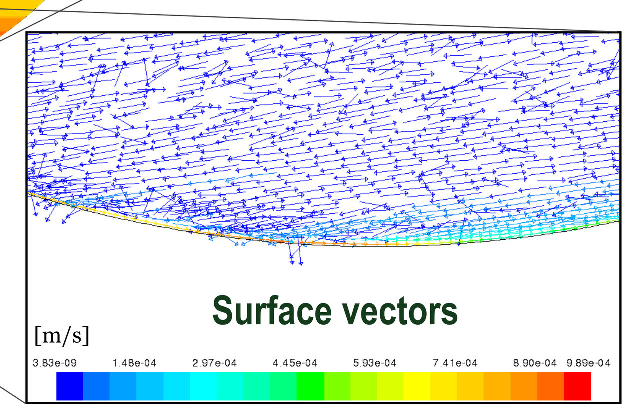
FINDINGS

- **Horizontal (global) transport phenomena**
- **Consistent "speed vs $^{Po}\tau_{1/2}$" relationship**
- **North-South ΔT asymmetries dominate flow**
- **Increased top-bottom gradient limits extent of vertical movement**

(see more in ref. 1)







Surface vectors

Challenges to this approach mainly arise, ironically, from **Borexino's pseudo-stable** fluid condition. Temporal and spatial granularity in the model have to be identified in order to minimize "numerical noise", especially over the **long timescales** (>months) being considered.

Current work aims to fully clarify fluid-dynamics' role in ^{210}Po migration, and even forecast probable background distributions, by **quantitatively relating both data**. Studies relevant for SOX's unique detector configuration are also foreseen.

Acknowledgements & References

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