The JUNO pre-detector OSIRIS

Tobias Sterr
Eberhard Karls Universität Tübingen
Johannes Gutenberg Universität Mainz
Prisma Cluster of Excellence
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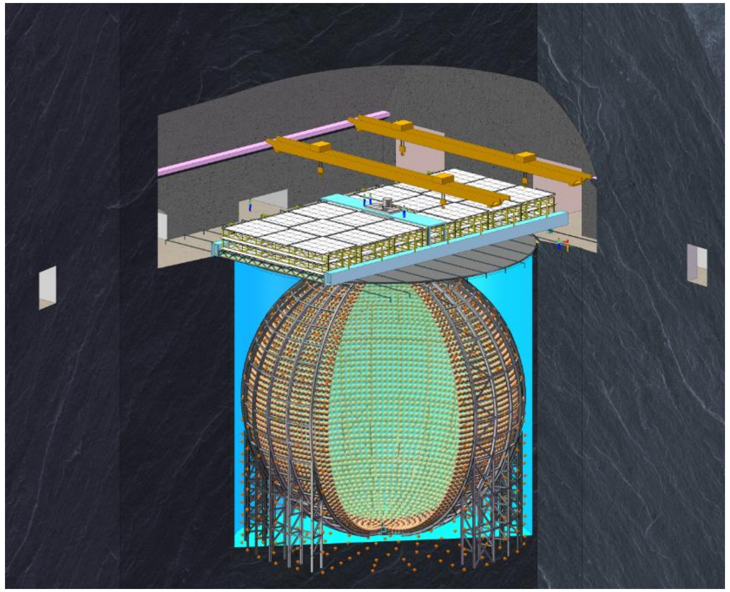
Jiangmen Underground Neutrino Observatory - JUNO

- JUNO is a medium baseline reactor neutrino experiment located in southern China
- JUNOs main goal is the determination of the neutrino mass hierarchy
  - ➢ Several other physics goals, e.g., solar neutrinos, geo neutrinos, supernova neutrinos, etc.
- The JUNO detector will feature 20 kt of liquid scintillator in spherical acrylic vessel as well as 45000 PMTs (20'' and 3'')



Top: JUNO main detector (700m rock overburden)
Bottom: JUNO location within China

Motivation – Why OSIRIS?

- OSIRIS – Online Scintillator Internal Radioactivity Investigation System
  - ➢ Radiopure detector materials are necessary to achieve sensitivity goals of JUNO
  - ➢ This leads to the radiopurity requirements set for JUNO:

Radiopurity requirements of JUNO in comparison of achieved levels of other experiments

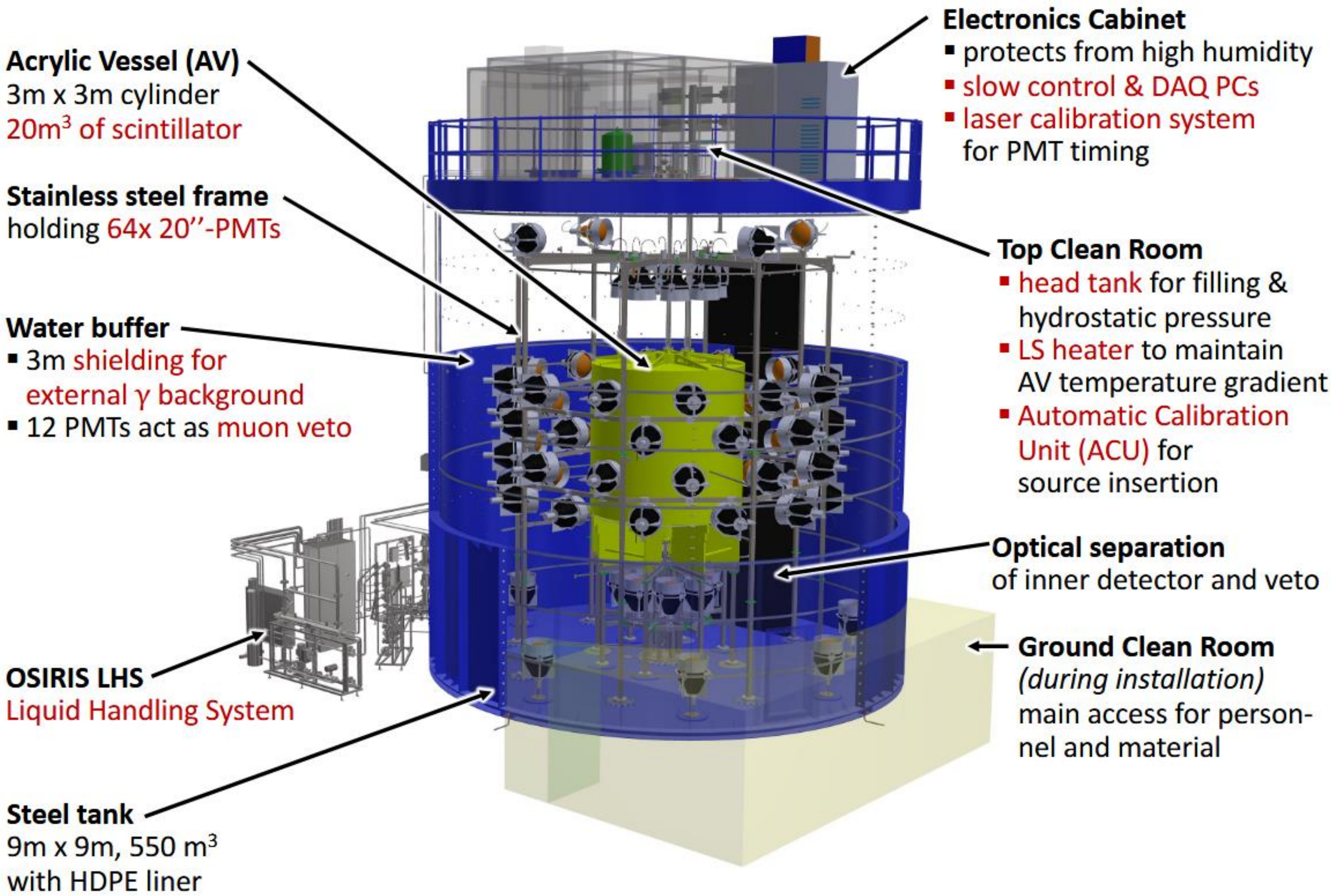
Experiment Isotope	JUNO IBD $[\frac{g}{g}]$	JUNO solar $[\frac{g}{g}]$	KamLAND $[\frac{g}{g}]$	Borexino $[\frac{g}{g}]$
^{238}U	1×10^{-15}	1×10^{-16}	$(5.0 \pm 0.2) \times 10^{-18}$	$< 1 \times 10^{-18}$
^{232}Th	1×10^{-15}	1×10^{-16}	$(1.3 \pm 0.1) \times 10^{-17}$	$< 1 \times 10^{-18}$
^{210}Po	-	5×10^{-24}	$\sim 2 \times 10^{-23}$	$< 1 \times 10^{-25}$
^{40}K	1×10^{-16}	1×10^{-17}	$(7.3 \pm 1.2) \times 10^{-17}$	$< 1 \times 10^{-19}$
^{14}C	1×10^{-17}	1×10^{-17}	-	$(2.7 \pm 0.1) \times 10^{-18}$

- ➢ Marked in red is the main focus of OSIRIS

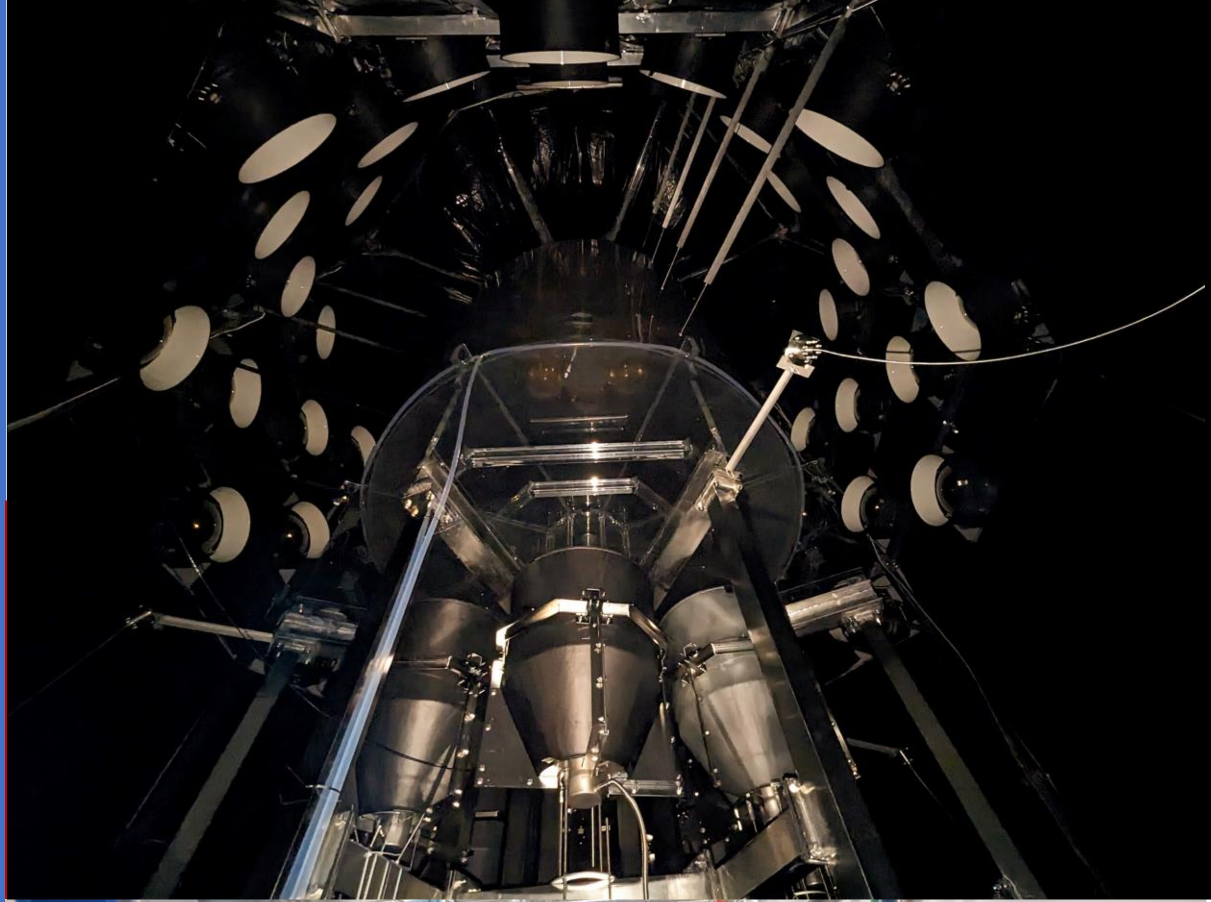
Motivation – Why OSIRIS?

- Motivation: Radioactivity Limit
  - Reactor antineutrinos:
    - ^{210}Po: Mimics inverse beta decay coincidence via ^{13}C(α,n)^{16}O reactions
    - ^{14}C: pile-up with prompt events will distort both energy scale and resolution
  - Solar neutrinos:
    - ^{238}U/^{232}Th: α and β decays will create additional background for elastic scattering on electrons
    - ^{40}K: β-decays not connected to or out of equilibrium with U/Th chains

The OSIRIS Detector



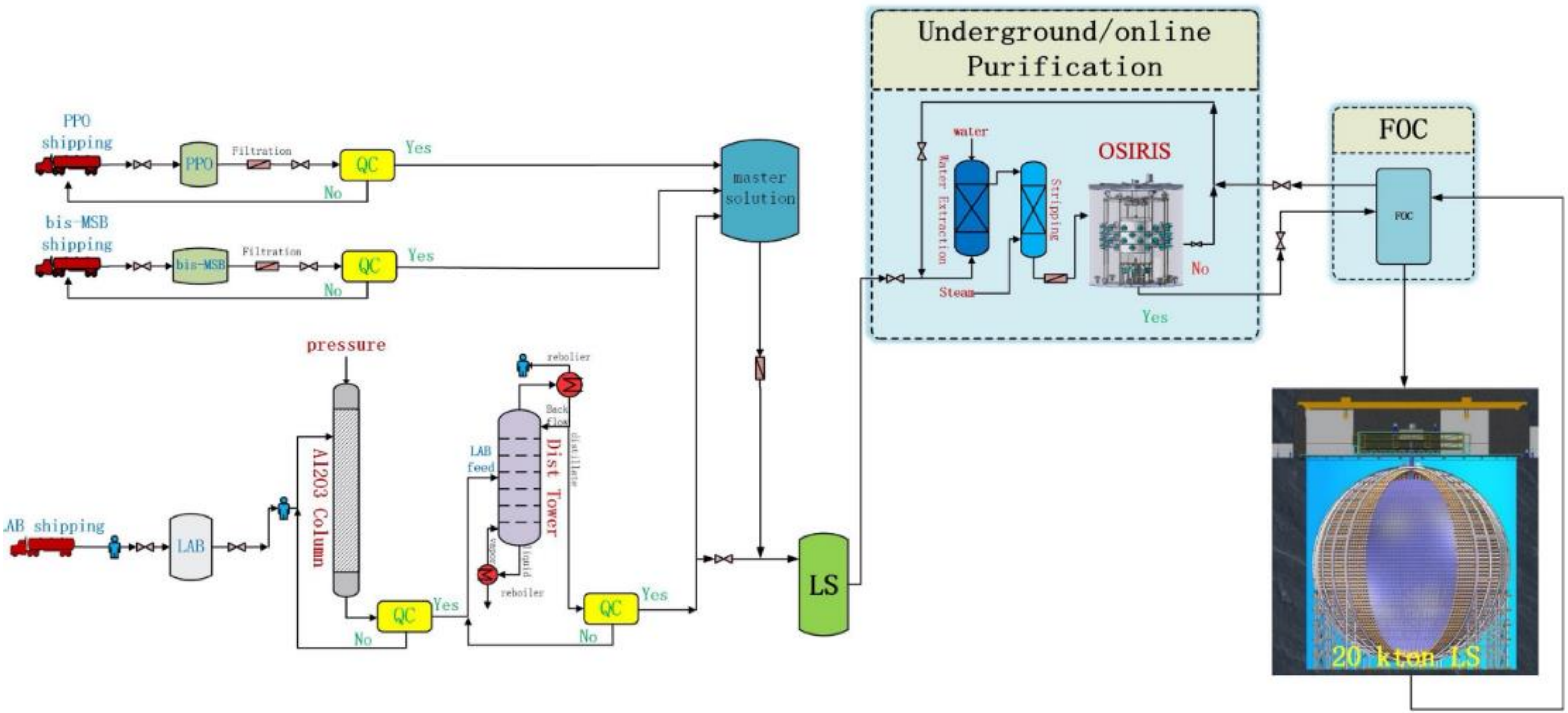
Picture by JGU Mainz Group



Top Left: Inner Volume of OSIRIS with acrylic vessel
Top Middle: PMT with shielding
Top Right: General control unit (GCU) of the PMTs
Bottom Left: Liquid handling system during construction

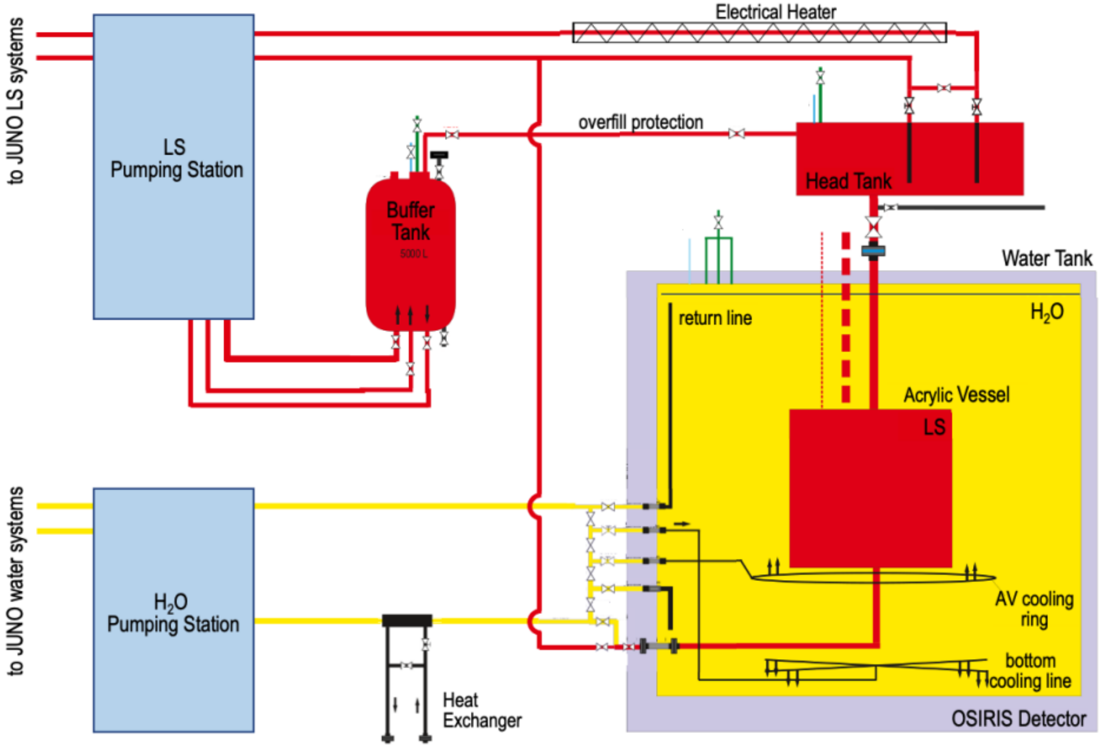
Pictures by Cornelius Vollbrecht and Tobias Sterr

The OSIRIS Detector



The OSIRIS Detector

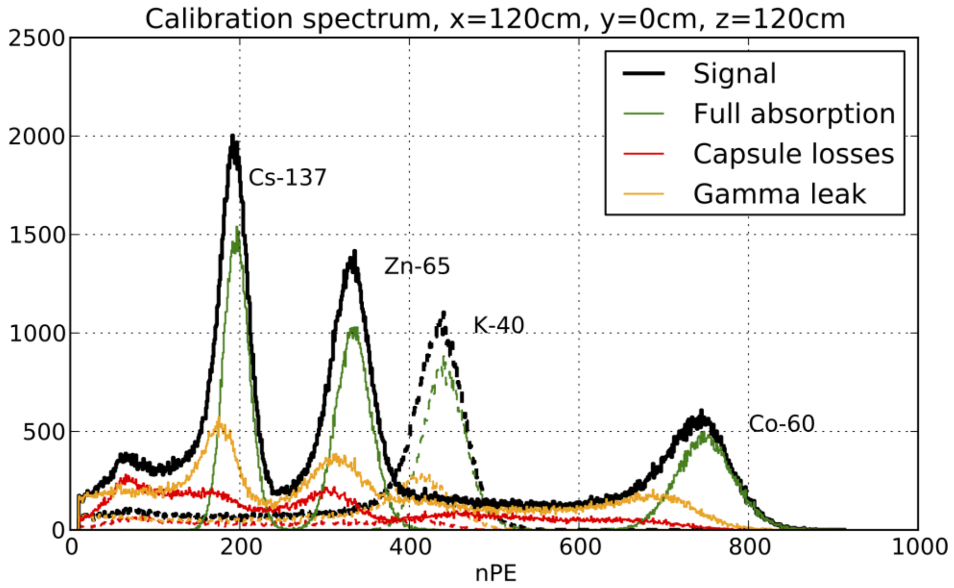
- Production and purification of liquid scintillator (LS) is performed on-site
- OSIRIS will be the last station in the LS system prior to the filling in the main detector
- Main goals of OSIRIS:
  - Support of the commissioning of the whole LS chain, including optimization of U/Th contents
  - Monitoring of the LS radiopurity during the six months long filling of the JUNO main detector
- Two possible operation modes:
  - Batch mode: Monitoring of one batch of LS for several days/weeks
  - Continuous mode: LS will constantly be filled into OSIRIS and traverse it within a day



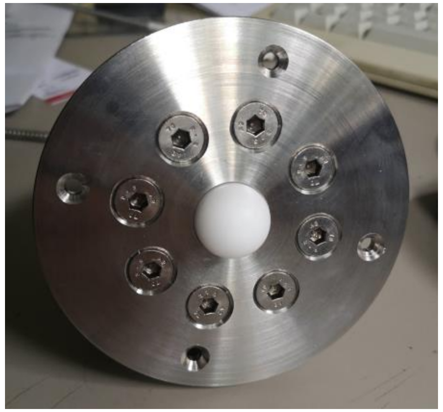
Simplified scheme of liquid handling system of OSIRIS. (**DOI** 10.1088/1742-6596/2156/1/012198)

Calibration Systems

- OSIRIS features two independent calibration systems
  - Automated Calibration Unit (ACU) inherited from Daya Bay
  - A laser calibration system developed for OSIRIS
- ACU features three calibration sources
  - Low activity ^{40}K source – will be used for long term monitoring
  - High activity source consisting of ^{137}CS, ^{65}Zn and ^{60}Co – Vertex calibration
  - Pulsed 410nm LED – Timing and charge calibration
- Laser system features 24 diffused light injection points distributed in the detector
  - Laser 420nm, ~80ps pulse width (FHWM)



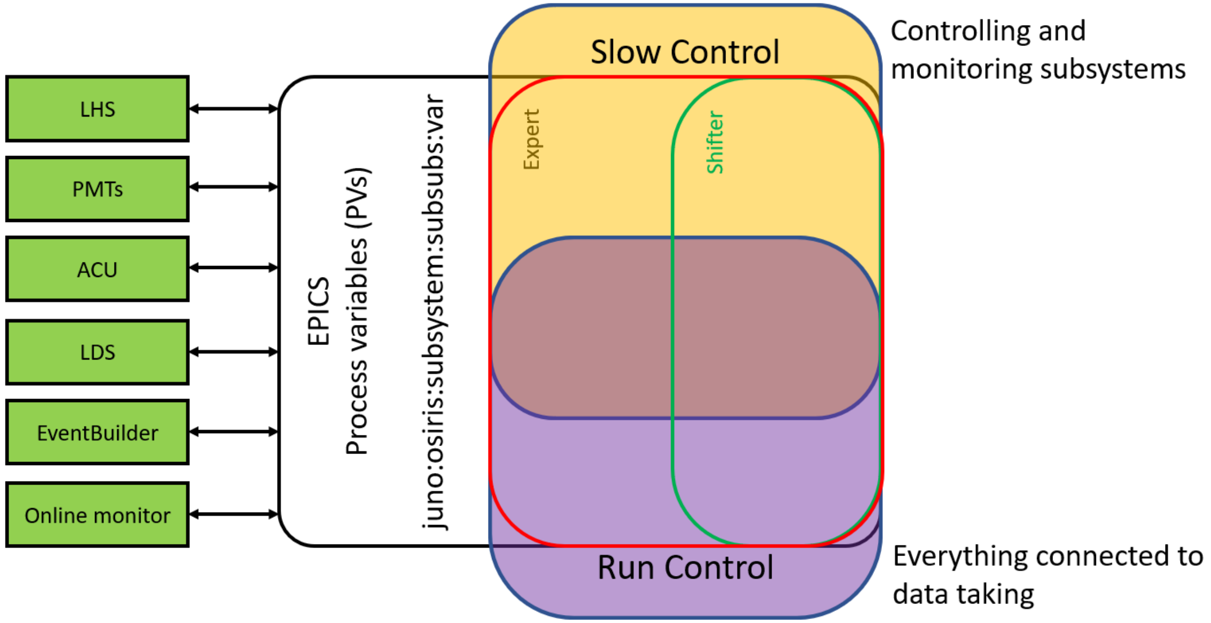
Simulated calibration spectrum of the ACU (40K and high activity source combined).



Laser diffuser capsule

Event Building and DAQ

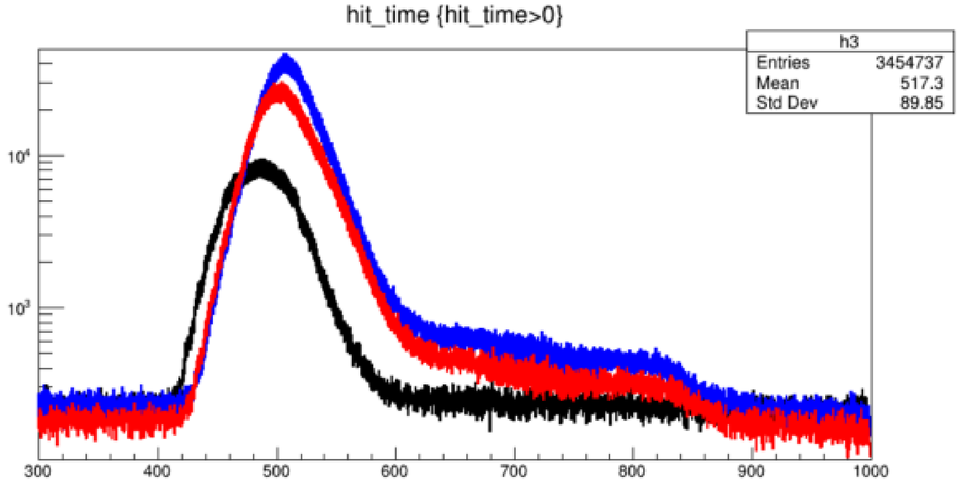
- Two step DAQ software:
  1. Event builder: Sorting and clustering PMT inputs into events
  2. Root sorter: Building root-trees of the data, minor online analysis
- DAQ features different modes:
  - ➢Standard physics mode
  - ➢Calibration mode (external trigger)
- Run and slow control of OSIRIS based on the Experimental Physics and Industrial Control System (EPICS)

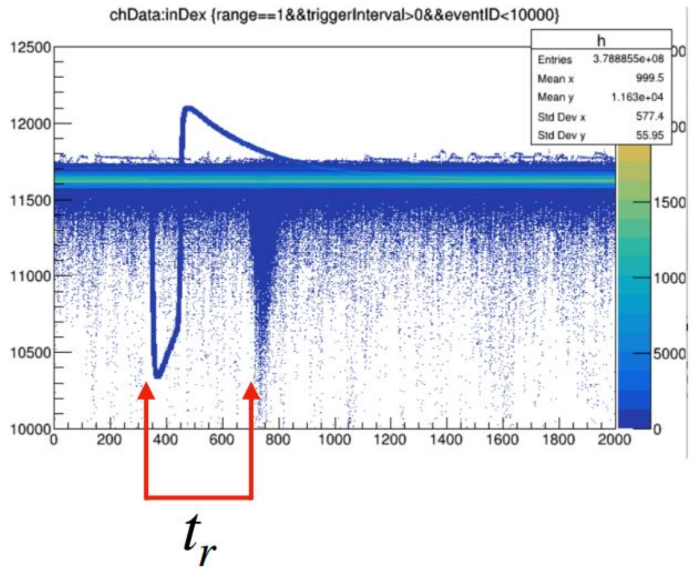


Access level scheme of the control systems of OSIRIS. Image by Kai Loo.

First Air Run Data

- First data of air runs is available
- Analysis of several detector parameters ongoing:
  - Run time measurements of the calibration systems
  - Majority trigger studies
  - Dark count threshold studies
  - Hit time studies
  - Etc.
- Final comprehensive calibration of the detector will be done after filling





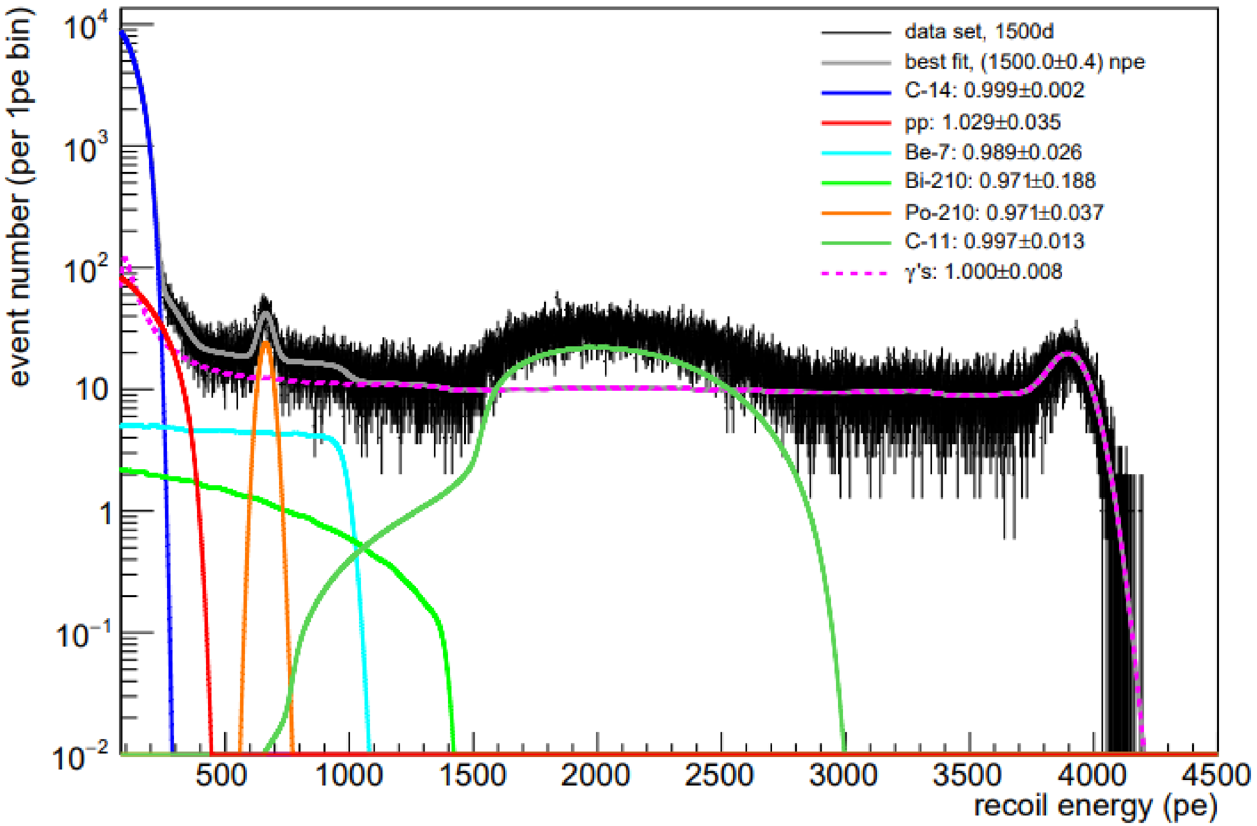
Top: Hit time study of the detector with a glass bulb filled with liquid scintillator in different heights (red and blue) vs natural radio activity (black). Left: Raw waveforms together with the trigger of the optical calibration systems. Marked is the run time between trigger and pulse at GCU.

Future OSIRIS Physics Program

- Solar proton-proton (pp) neutrinos from basic reactions of hydrogen burning
  - Hard to access because of low end point energy (but precise values given from theory)
    - Borexino pp neutrino result: ± 10%

    → OSIRIS goal: high precision of view %
  - OSIRIS upgrade could outperform JUNO and Borexino
    - Lower background and pile-up levels (^{14}C)
    - Better energy resolution
    - Possibility to use integrated directionality (CID)

See Poster #266 by Kai Loo



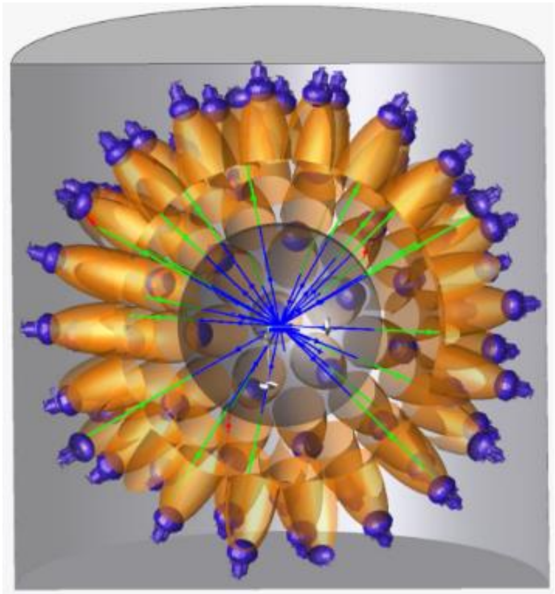
Energy spectrum and spectral fit for the proposed future pp neutrino search of OSIRIS.
(**DOI** 10.1140/epjc/s10052-022-10725-y)

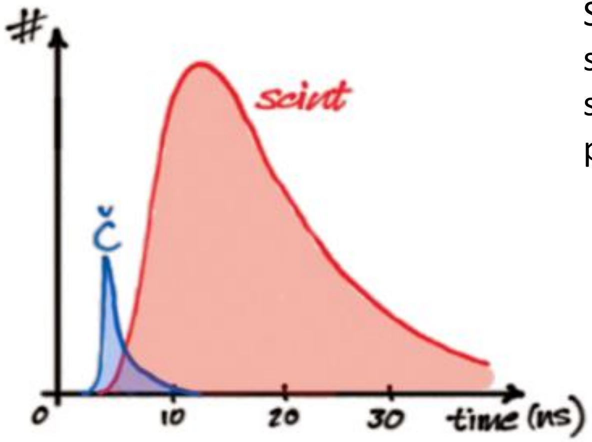
Future OSIRIS Physics Program

- Observation of $0\nu\beta\beta$ decays:
  - JUNO plans a multi-ton 2β-phase after the completion of the mass hierarchy phase
  - OSIRIS could work as a prototype to:
    - Test Te/Xe-loaded LS prepared for JUNO
    - Develop new reco techniques e.g., particle ID based on Cherenkov/scintillation ratio
    - Perform very sensitive $2\beta^+$ decay measurements with ^{78}Kr/^{124}Xe-loaded slow scintillators

Potential OSIRIS Detector Upgrade

- Both possible programs lead to similar requirements:
  - Improved background levels:
    - Additional shielding from external radioactivity (concrete/steel for ~1 m.w.e. + use of a nylon balloon)
  - Enhanced light collection:
    - Increase number of 20’’ PMTs from 76 to 132, add light concentrator (e.g., Winston cone, BooCone, etc.)
    - Increase 280 p.e./MeV → 1.500 – 2.000 p.e./MeV
  - Novel techniques for background discrimination:
    - Use Slow scintillator
    - Adjust/develop techniques for pp-directionality (CID) as well as scintillation/Cherenkov separation (ββ)



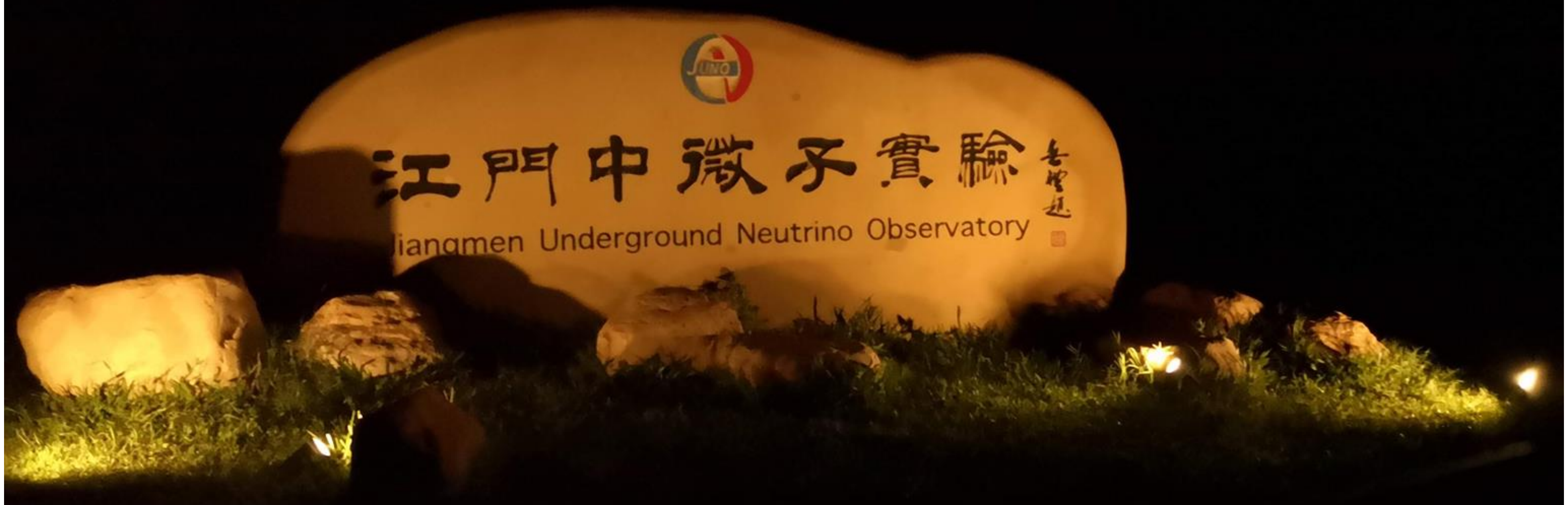


Top: OSIRIS with increase PMT count, nylon balloon and Winston cones
Bottom: Scintillation/Cherenkov separation using slow scintillator (Plot and picture by M.Wurm)

Conclusion

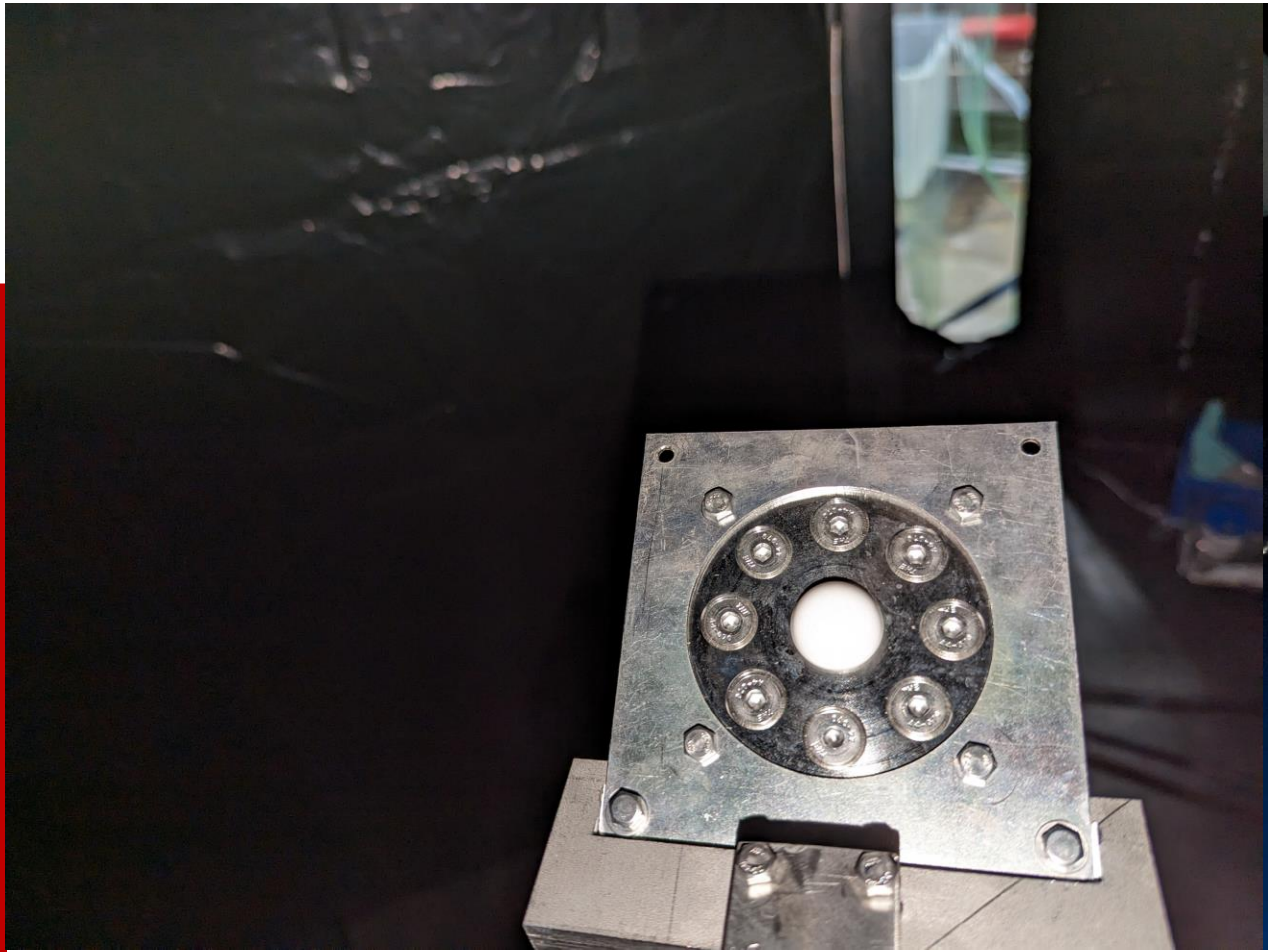
- OSIRIS is a JUNO pre-detector designed to monitor the radiopurity of the liquid scintillator during the filling phase of JUNO
  - 18t capacity
  - 76 20'' PMTs
  - Sensitivity goal $10^{-15}/10^{-16}$ g/g of Uranium and Thorium
- OSIRIS is the last step in the whole LS chain of JUNO and crucial to the quality control during filling of the JUNO main detector
- First Air run data is available
- Joint commissioning of the whole LS chain of JUNO planned to start in autumn
- Additional physics program and possible extension of the detector after the filling phase of JUNO

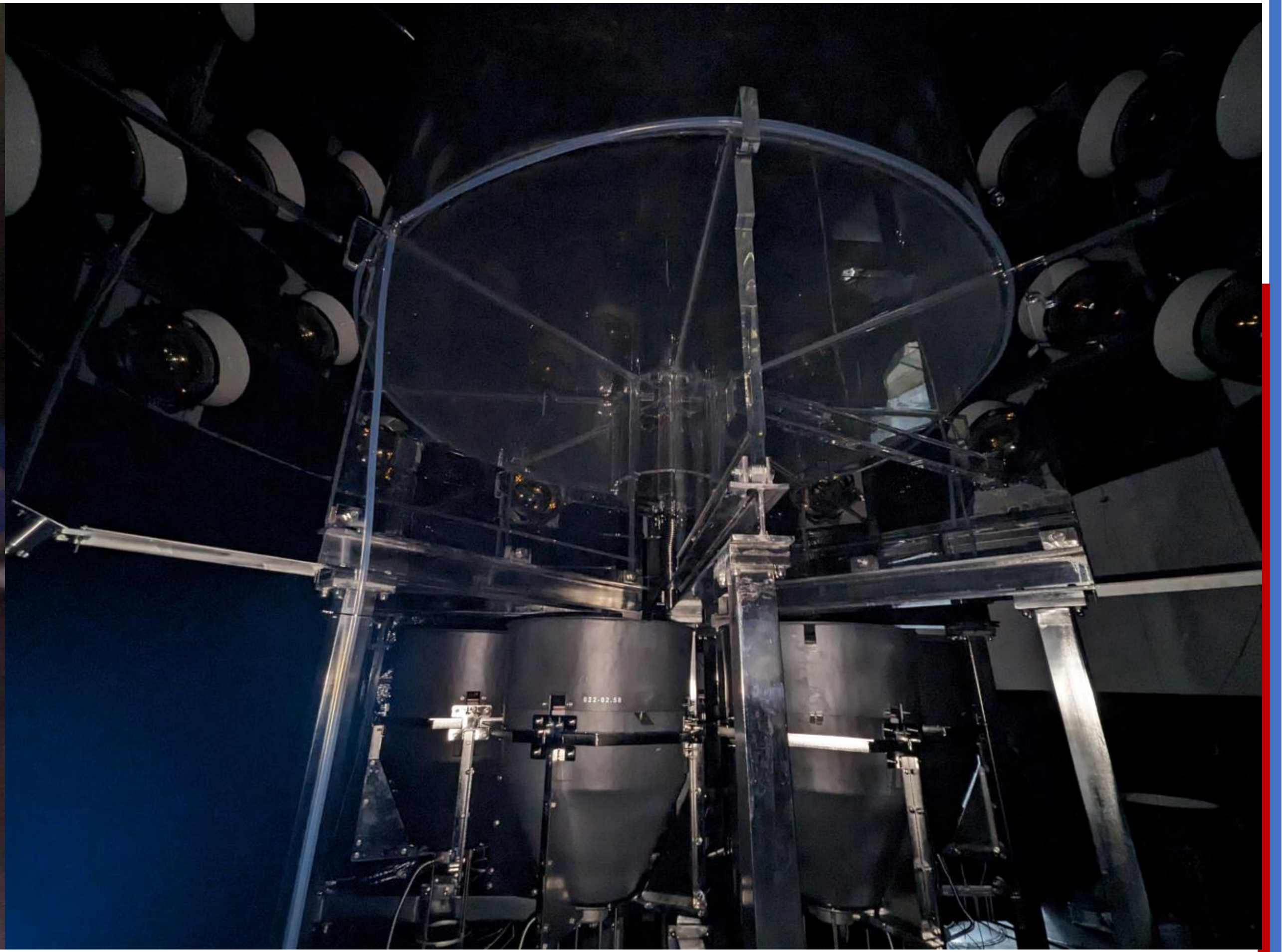
Thank you for your attention



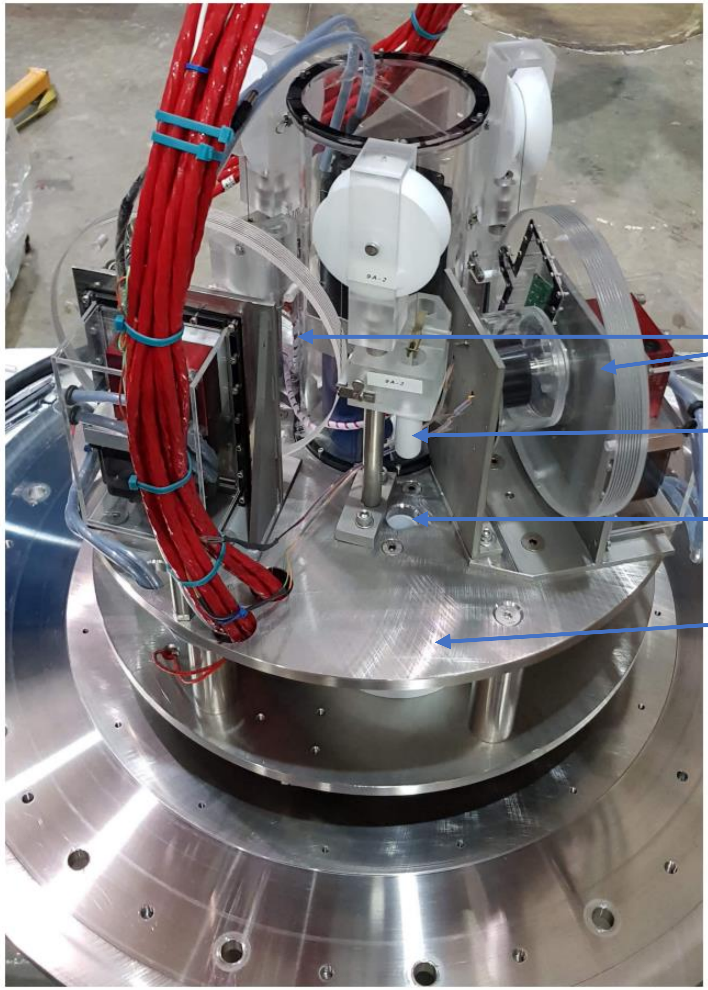
Contact:
Tobias Sterr
Tobias-Richard.Sterr@uni-tuebingen.de
Auf der Morgenstelle 14
72076 Tübingen, Germany

BACKUP



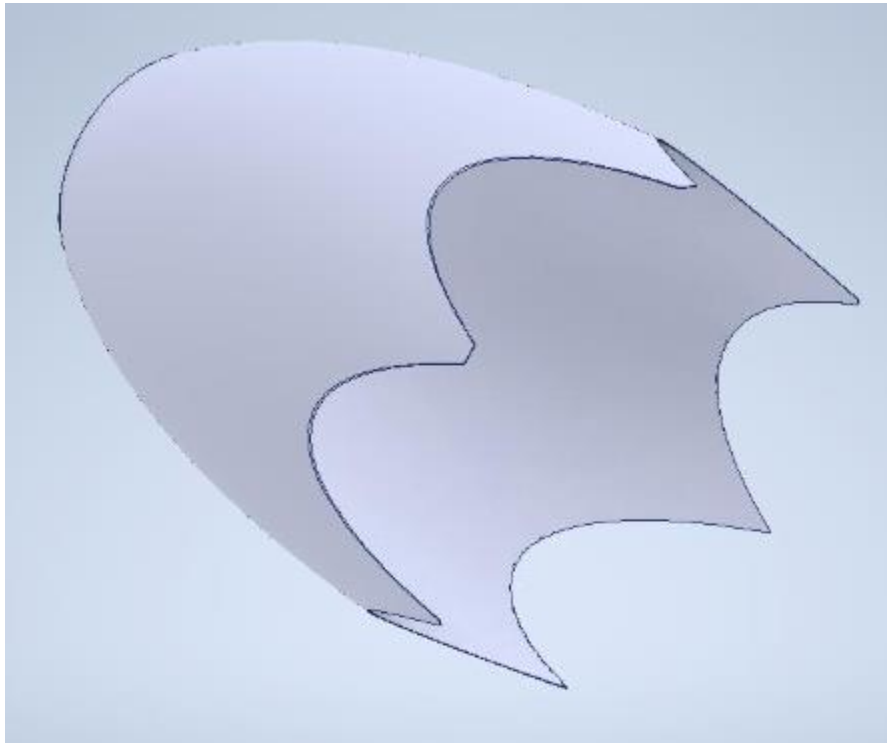


ACU - Hardware



ACU without the mounted bell jar.

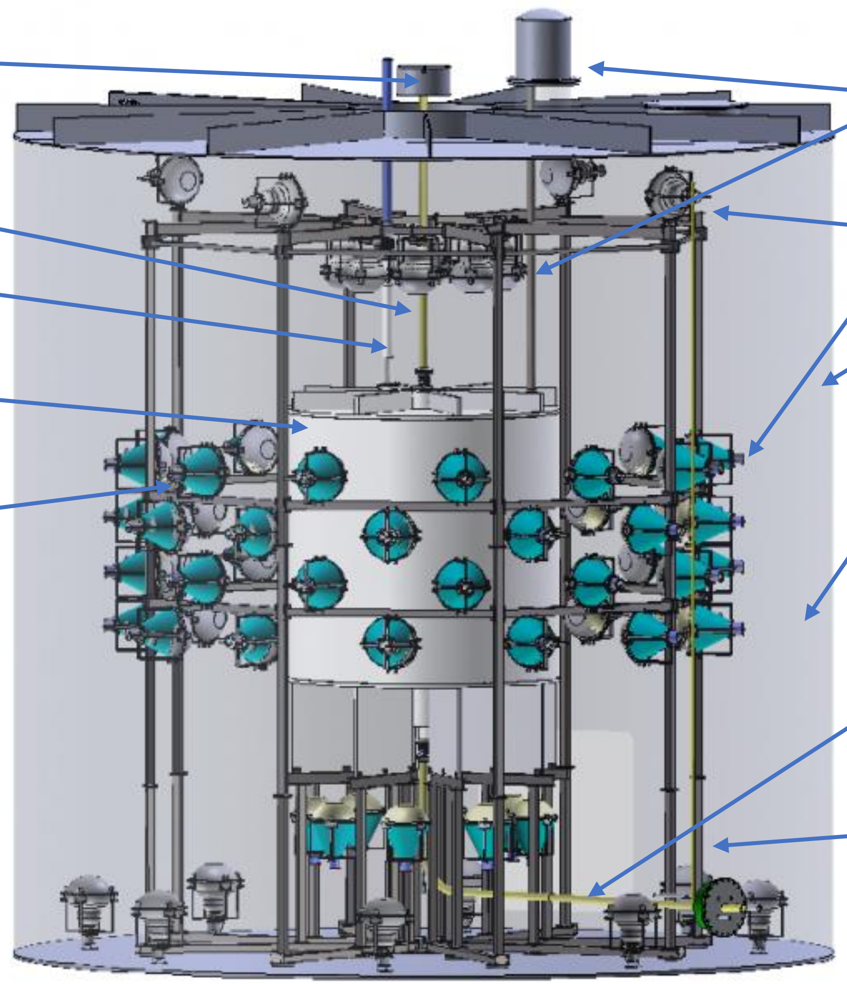
BooCone



Motivation – Why OSIRIS?

- JUNO is an experiment, dedicated to measure the neutrino mass hierarchy
  - Radiopure detector materials are necessary to achieve sensitivity goals of JUNO
  - Signals the mimic inverse beta decay (IBD) events, need to be reduce as far as possible
  - Thorium and Uranium chain elements in the liquid scintillator (LS) need to be $\leq 10^{-15}$ g/g (IBD physics) and $\leq 10^{-16}$ g/g for solar neutrino detection
- Purification chain of the LS include distillation, column chromatography, water extraction and steam stripping
- Final stage is the verification in the Online Scintillator Internal Radioactivity Investigation System (OSIRIS)
  - Search for impurities is based on fast coincidence decays of ^{214}Bi-^{214}Po/^{212}Bi-^{212}Po

The OSIRIS Detector

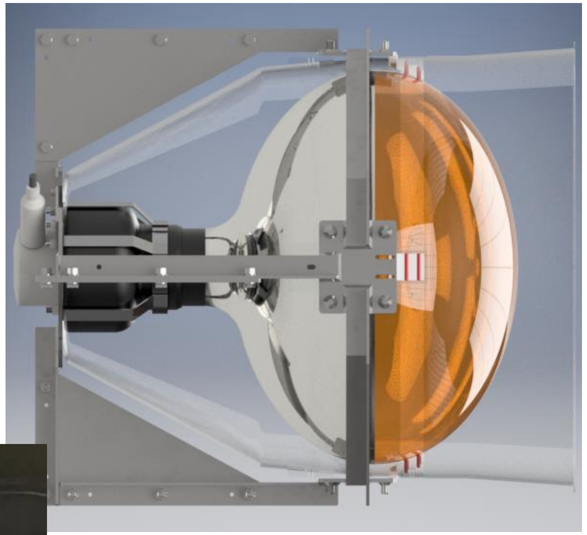


For clarity reasons not visible in this picture:

- Optical separation of inner and outer volume
- Under water electronics of the PMTs

The PMTs of OSIRIS

- PMTs of OSIRIS are "standard" JUNO tubes
  - Housing is changed to fit the needs of OSIRIS
- 76 PMTs in total (64 in the inner volume, 12 in the veto)
- Three PMTs are connect to one General Control Unit (GCU)
  - GCU contains all necessary electronics to create ready-to-use waveforms (see next slide)
  - 25+1 GCUs in total



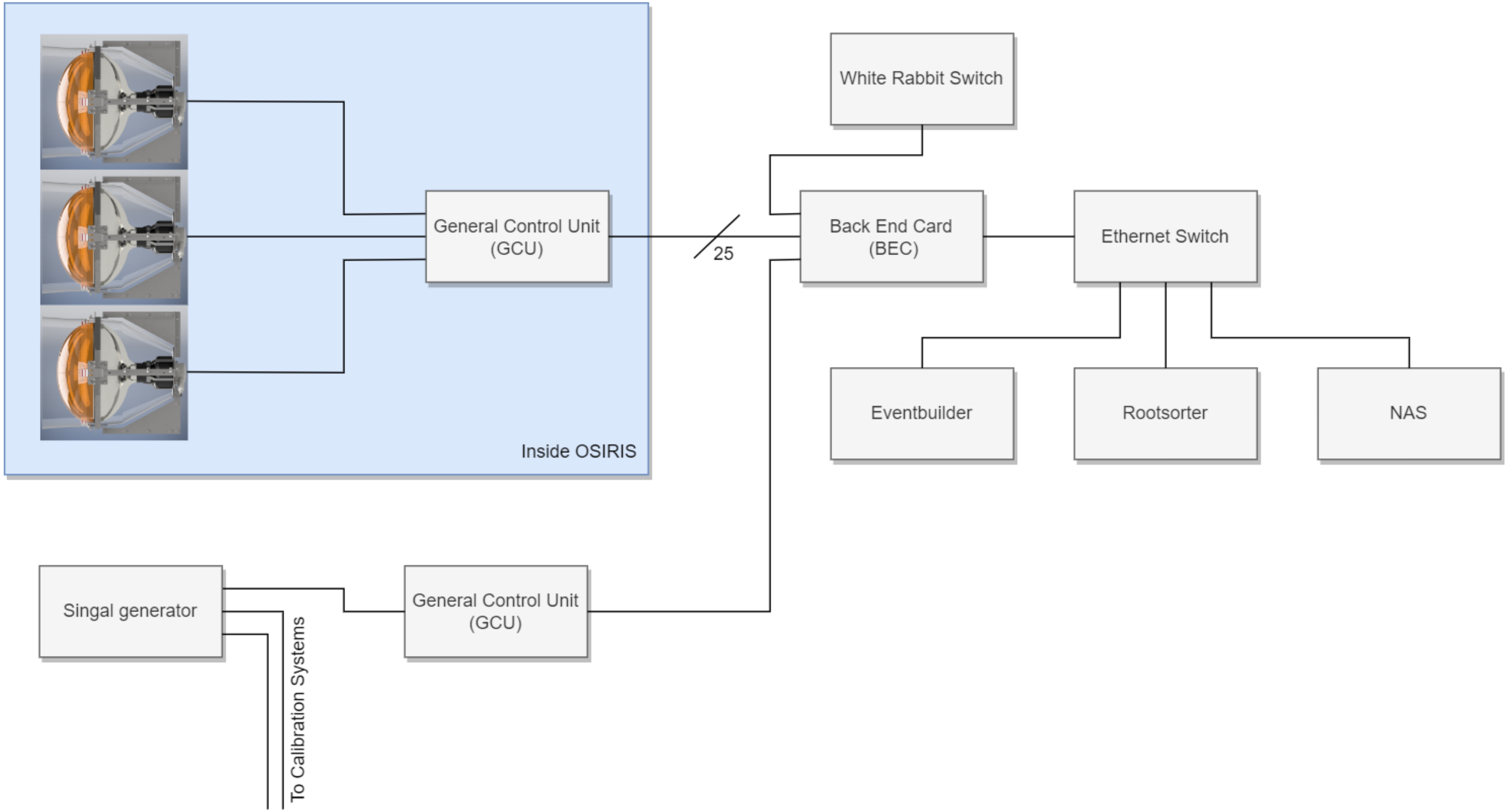
CAD and picture of the final assembly of the JUNO/OSIRIS PMTs. Picture by Yatian Pei, CAD by Cornelius Vollbrecht.

The PMTs of OSIRIS

- Each GCU contains
  - A slow control configurator (Spartan6)
  - ADC plugins connected to the command-and-control SoC (Kintex7)
  - Three HV modules
  - POE and I/O interfaces
  - 2Gb of DDR3 memory + firmware flash
  - clock and synchronization hardware
- Control is included in the slow control of OSIRIS

Insides of a GCU as used in OSIRIS. Visible are debugging connections (cables) as well as HV modules (aluminum covers). Image by ULB Brussels.

The PMTs of OSIRIS

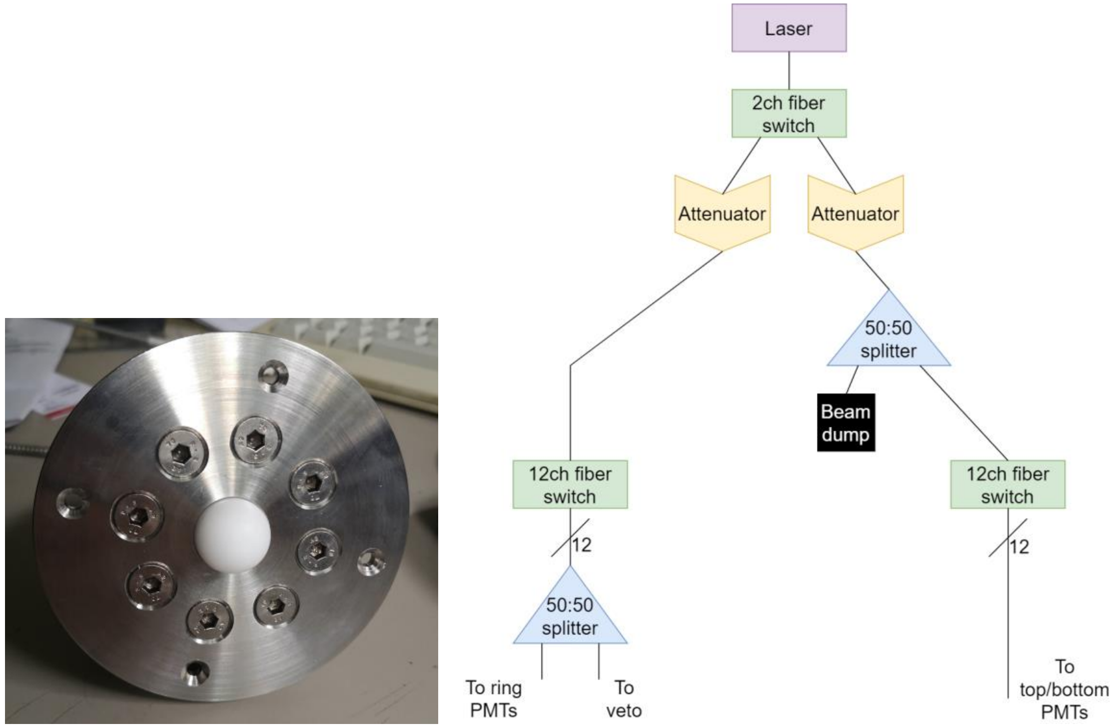


The OSIRIS Detector

- Two possible operation modes:
  - ➢Batch mode: Monitoring of one batch of LS for several days/weeks
  - ➢Continuous mode: LS will constantly be filled into OSIRIS and traverse it within a day
- All parts of OSIRIS have been installed
- Currently, commissioning is ongoing
- Main filling phase of JUNO will start in early 2024
  - ➢Will take four to six months
- An additional physics program is planned for OSIRIS after its main purpose has been fulfilled

Calibration Systems

- Laser calibration system (LCS) consists of three parts:
  - ➢420 ps Laser (80ps FHWM @ 50% tuning)
  - ➢Light distribution system
  - ➢26 diffuser capsules distributed in the detector
- System will be used to do timing and charge calibration
- Design goals:
  - ➢Light intensity μ=0.01 p.e. per pulse
- LCS will be used to calibrate the system on a weekly basis



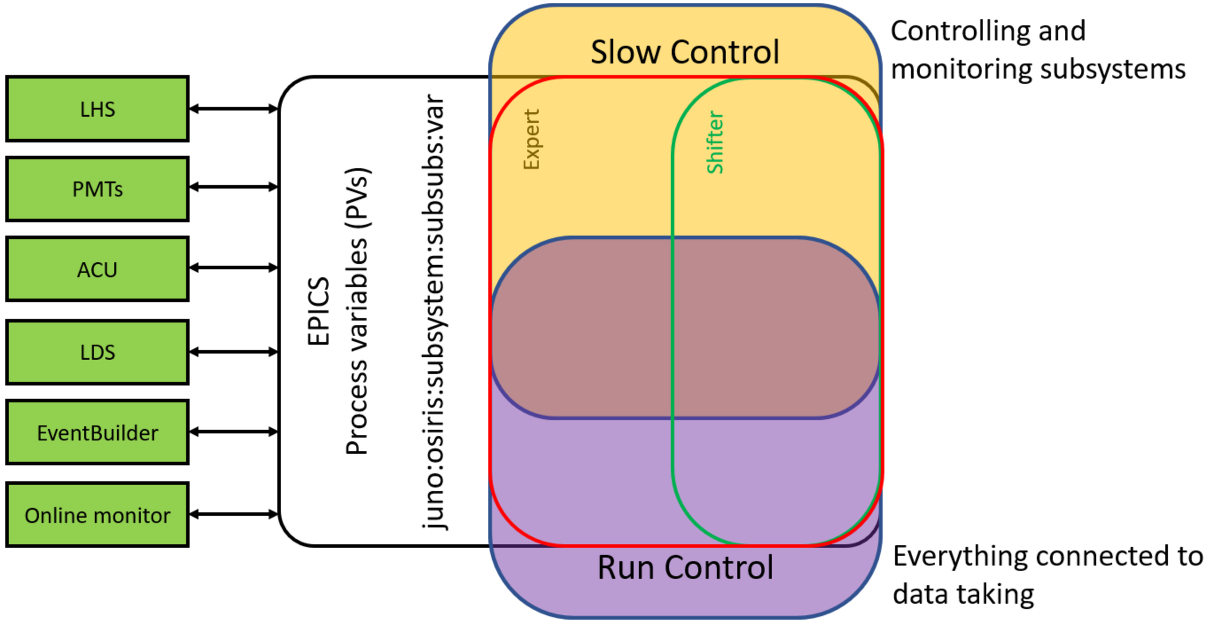
Diffuser capsule and light routing scheme of the light distribution system.

Event Building and DAQ

- Two step DAQ software:
  1. Event builder: Sorting and clustering PMT inputs into events
  2. Root sorter: Building root-trees of the data, minor online analysis
- Both parts run on individual machines
- DAQ features different modes:
  - Standard physics mode
  - Calibration mode
    - Physics triggered source calibration mode
    - External triggered optical calibration mode
- Maximum data rate: 500Hz (each channel)

Slow and Run Control

- Including some extensions:
  - EPICS State Notation Language (SNL) to define run control state machines
  - EPICS Control System Studio (CSS) to create slow control GUIs
  - EPICS Archiver Appliance for slow control storage
- Both systems include two level access
- All hardware of OSIRIS can be controlled and monitored via EPICS



Access level scheme of the control systems of OSIRIS. Image by Kai Loo.

Schedule

- August/September 2023: Finishing air runs
- September/October 2023: Filling of OSIRIS
- October/November 2023: Joint commissioning of the whole LS chain of JUNO
- Early 2024: Start of JUNO filling