SHELDON-REWIND

REfractive index **W**ith **IN**terferometric **D**evices

Measurements of the Liquid Scintillator optical properties

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University of Milan + INFN
JUNO meeting EU + AM

ENERGY AND POSITION MEASUREMENT

PMTs detected light

Total number of collected photons

Energy

Measured times of arrival

Position

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- Light yield
- Transparence
- Cherenkov contribution

Measured times of arrival

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- Fluorescence times $\boldsymbol{\tau_i}$
- Refractive index **n**
- Group velocity $\boldsymbol{v_g}$
- Emission and Absorption

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The best achievable event reconstruction is needed to fulfill the main goals of JUNO

- **Energy resolution** 3% (@1MeV) (best LS resolution ever)
- **Spatial resolution** 10cm (@1 MeV)

Best LS characterization

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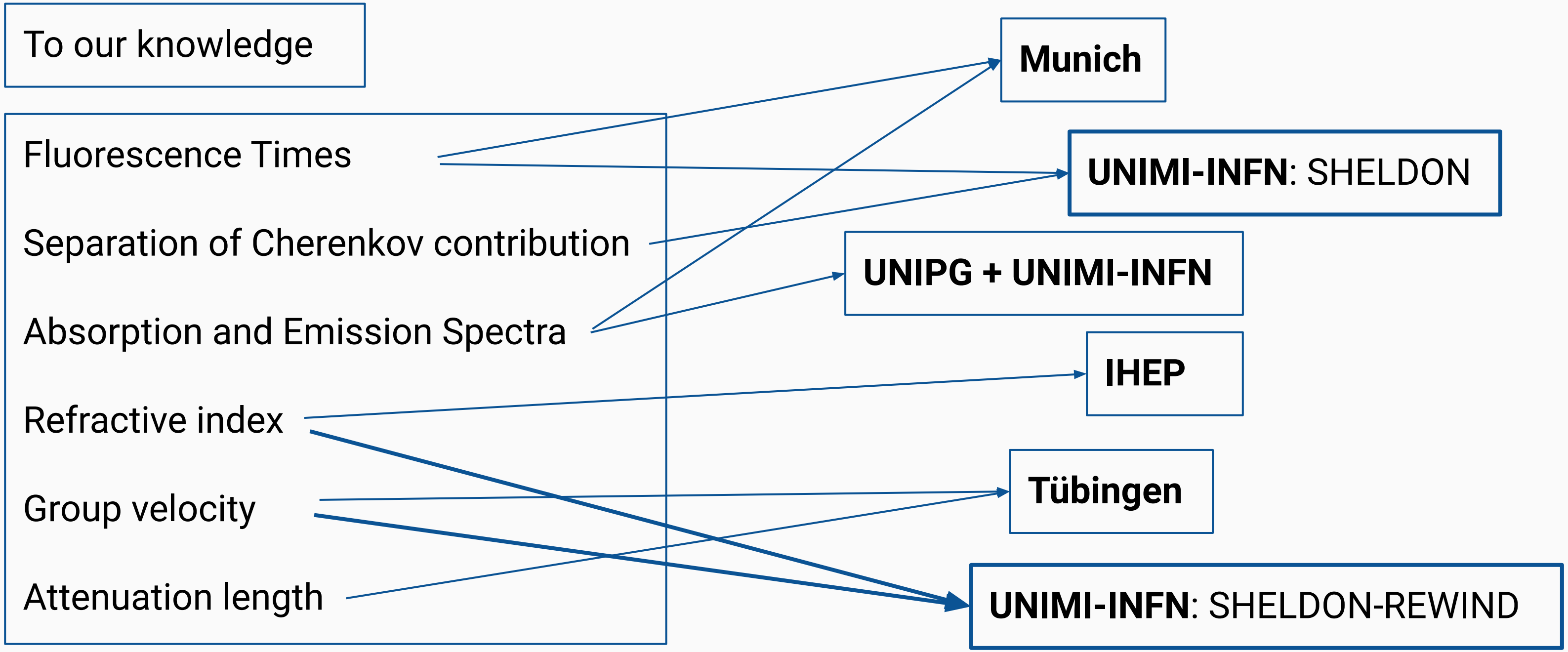
JUNO Collaboration effort

Big effort from the JUNO collaboration to collect all these information on the LS with small scale experiments



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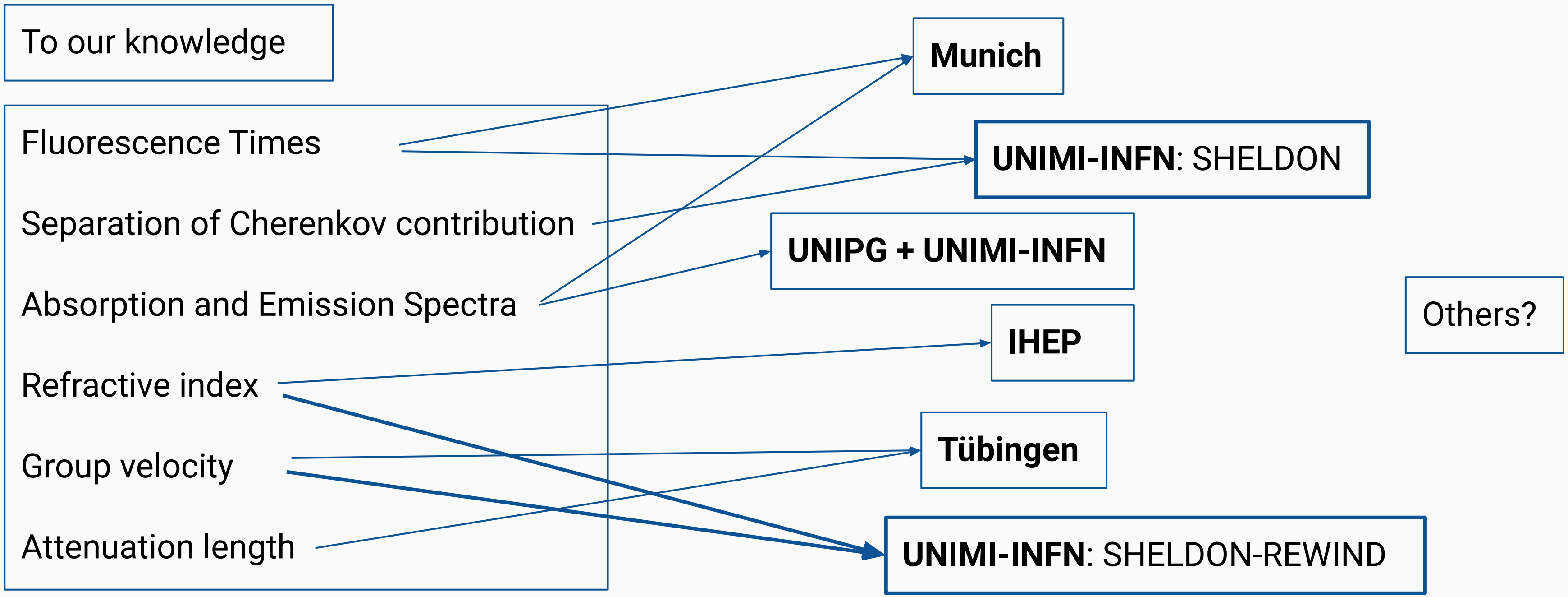

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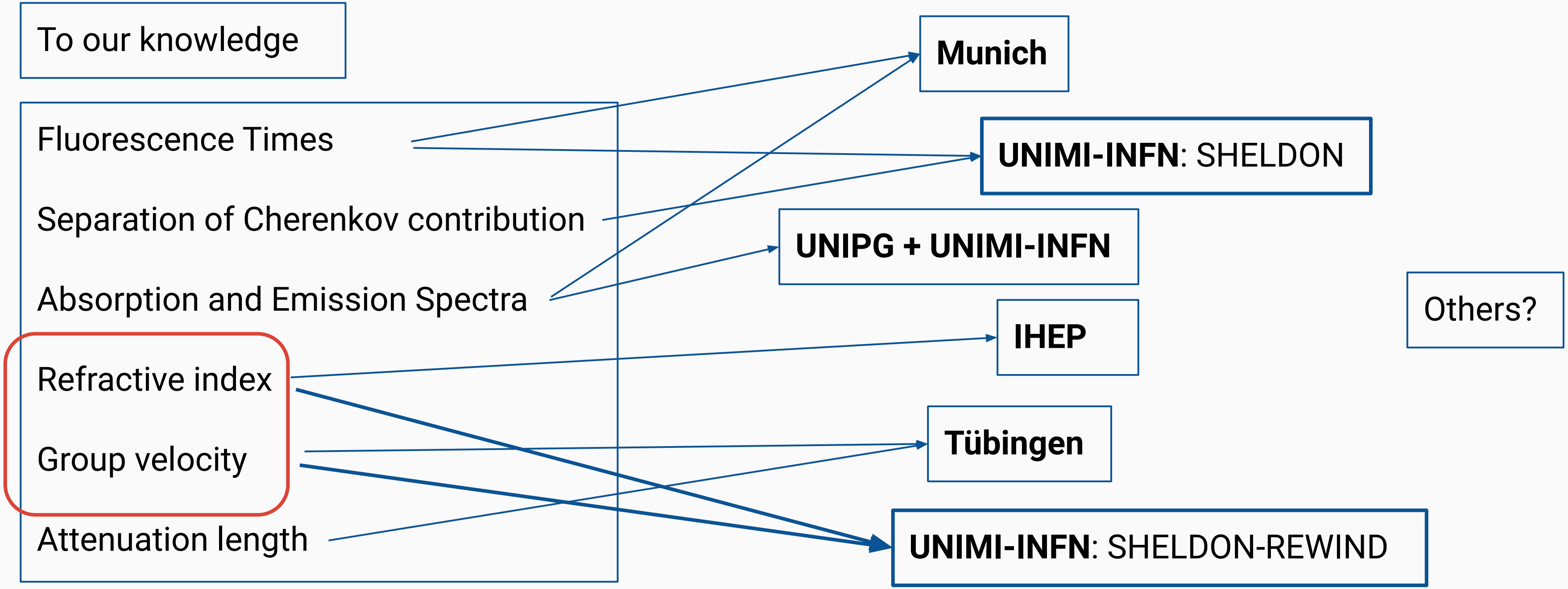

SHELDON-REWIND: REfractive index With INterferometric Devices

- Refractive Index **n**
- Group velocity $\boldsymbol{v_g}$

REFRACTIVE INDEX WITH REFRACTOMETER

n: Arrival time measurement + Cherenkov contribution

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For this measure we use a **refractometer**:

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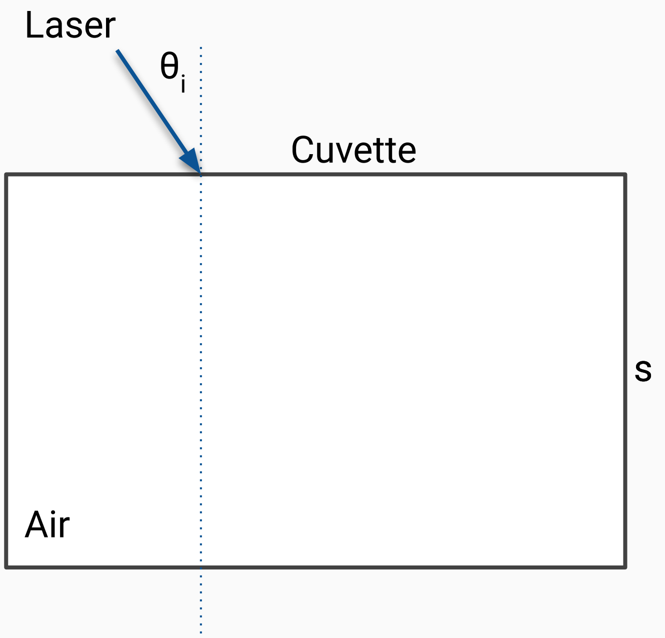

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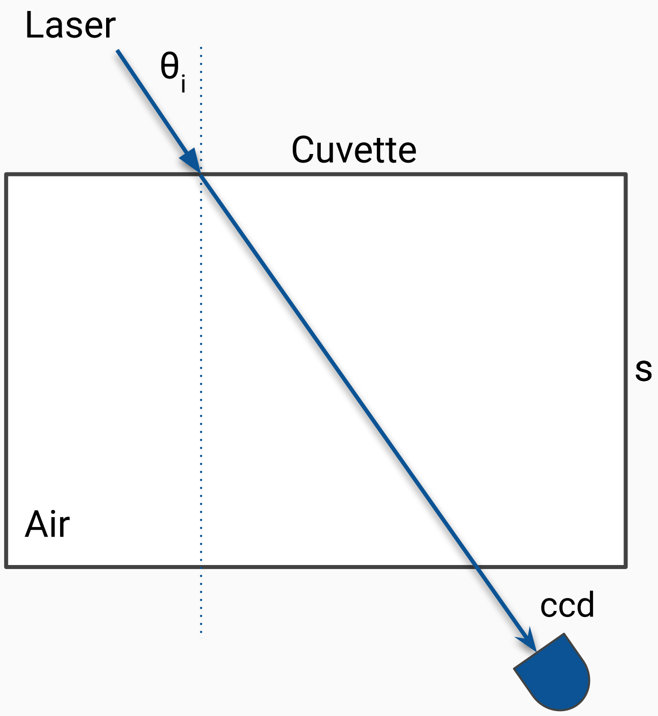

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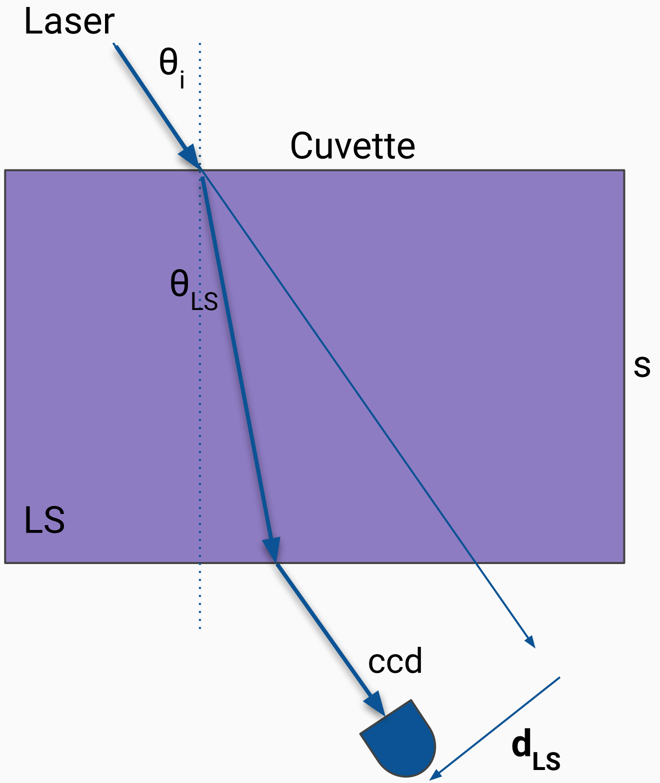
REFRACTIVE INDEX WITH REFRACTOMETER



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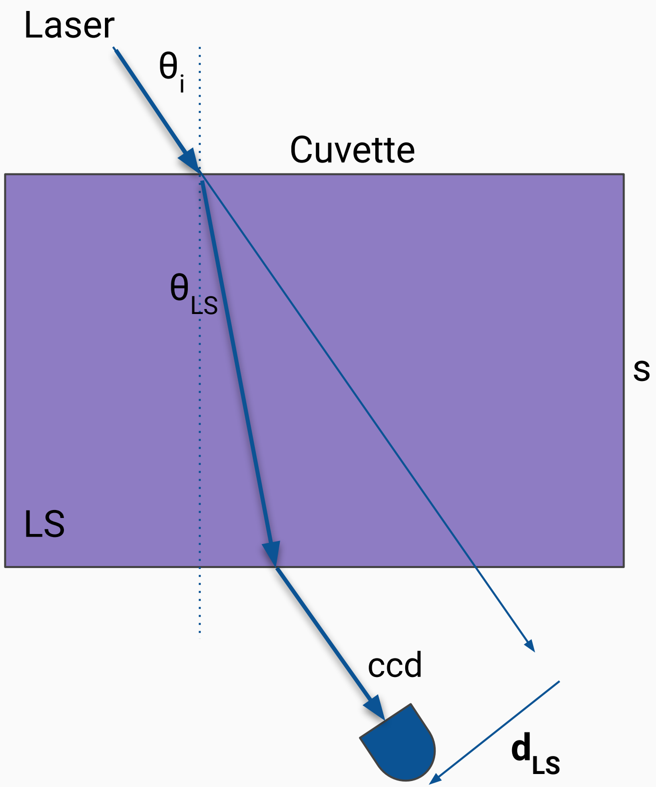

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- Different refractive angle with/without LS

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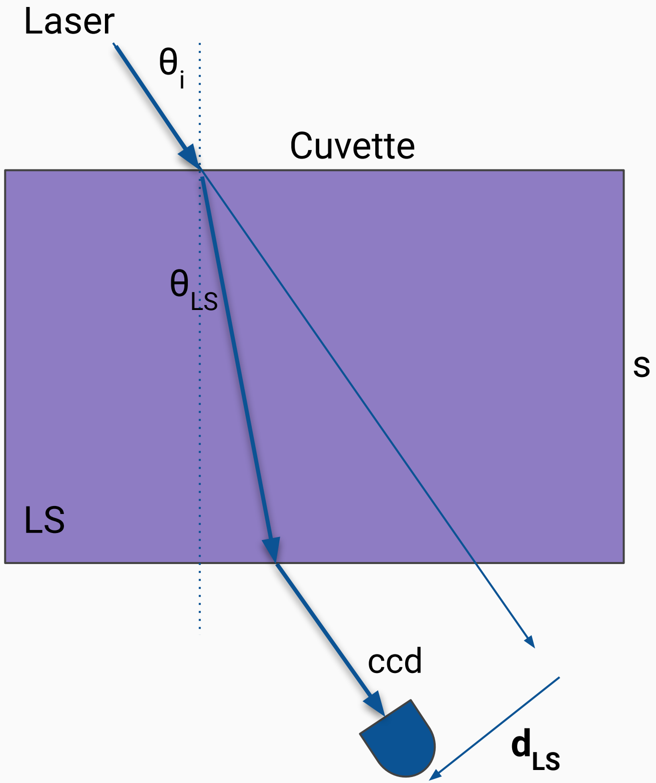

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- Measure the displacement of the beam propagation d_{LS}

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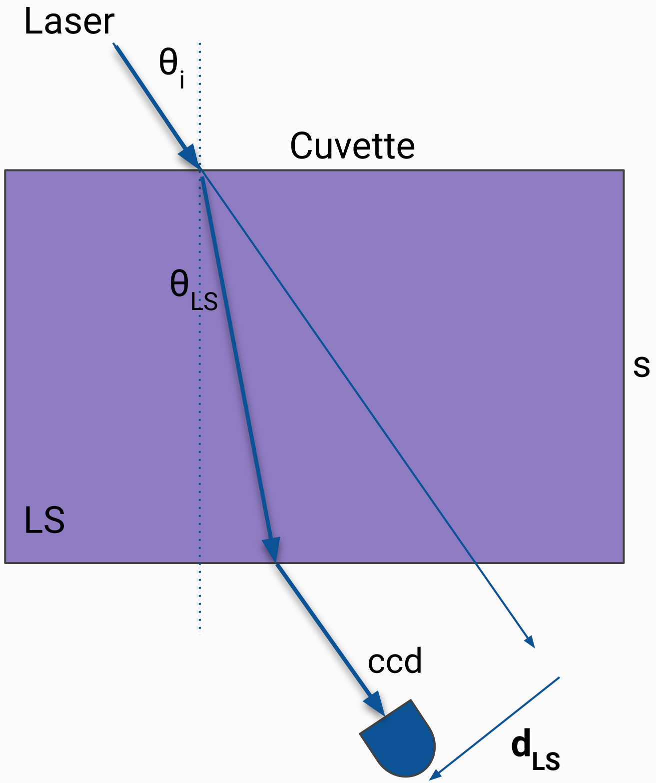

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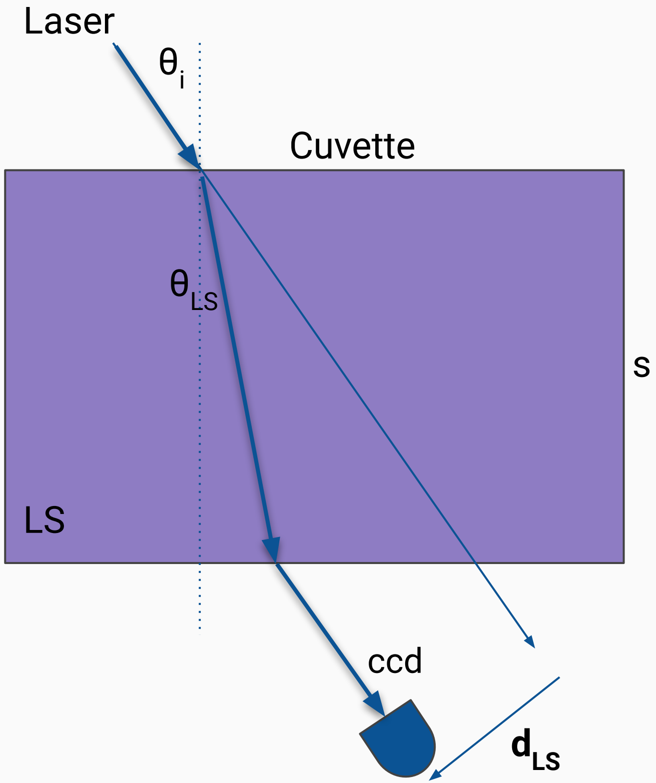
$$d_{LS} = \frac{s \sin\left[\theta_i - \arcsin\left(\frac{n_{air}}{n_{LS}} \sin\theta_i\right)\right]}{\cos\left[\arcsin\left(\frac{n_{air}}{n_{LS}} \sin\theta_i\right)\right]} \rightarrow \mathbf{n_{LS}}$$

REFRACTIVE INDEX WITH REFRACTOMETER



n: Arrival time measurement + Cherenkov contribution

Testing at several wavelengths

- He-Ne: 633 nm
- Ar: 514.5 nm
- Yb: 258 nm, 345 nm, 517 nm, 1035 nm

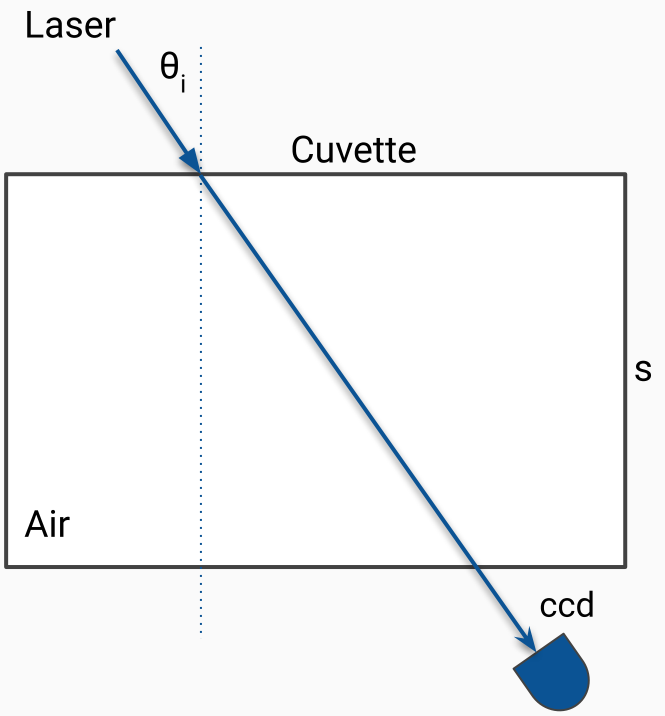
In order to get **n** as a function of wavelengths

Cherenkov radiation

$$\frac{\partial^2 N}{\partial x \partial \lambda} = \frac{2\pi\alpha}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)$$

OUR MEASUREMENT

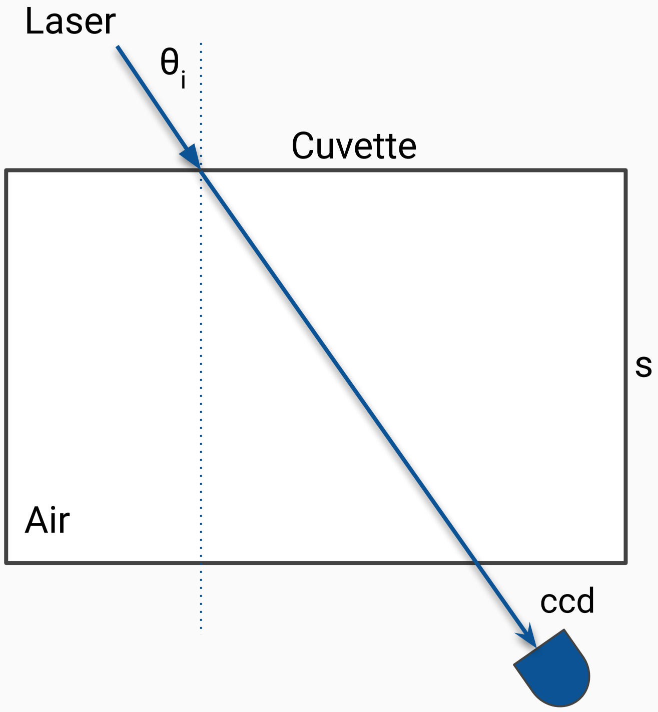
SHELDON-REWIND: REFRACTIVE INDEX WITH REFRACTOMETER



Air

Measure the position of the beam on the ccd

SHELDON-REWIND: REFRACTIVE INDEX WITH REFRACTOMETER



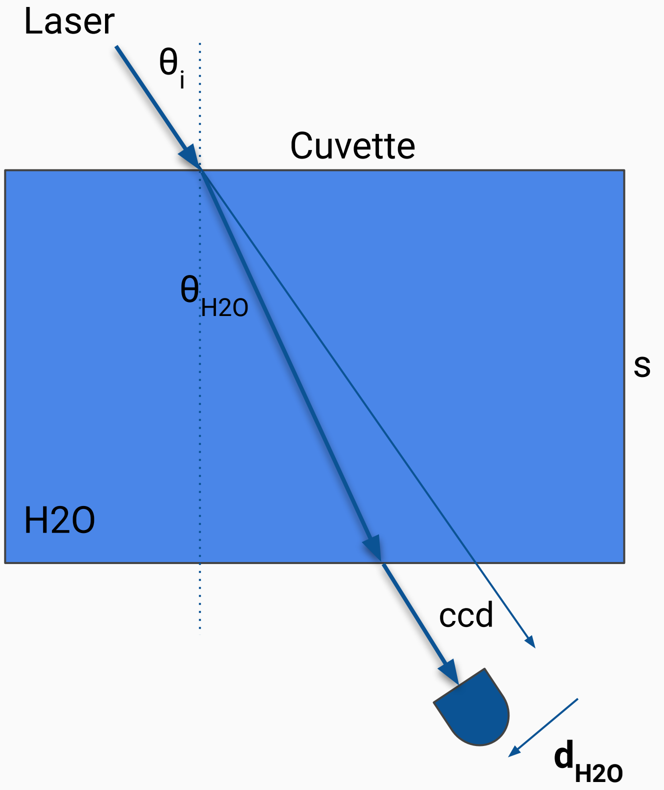
Air

Measure the position of the beam on the ccd

- Goal: need to know well θ_i
- Problem: low precision on θ_i with traditional method, such as goniometer

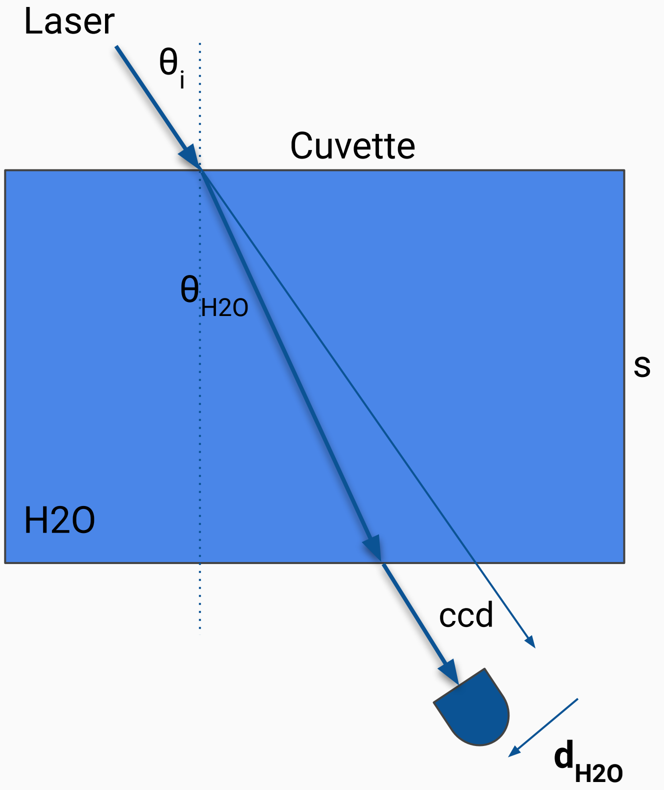
Solution: use a material with well known n

SHELDON-REWIND: REFRACTIVE INDEX WITH REFRACTOMETER



H_2O - Calibration

Measure the position of the beam on the ccd → $\mathbf{d_{H2O}}$



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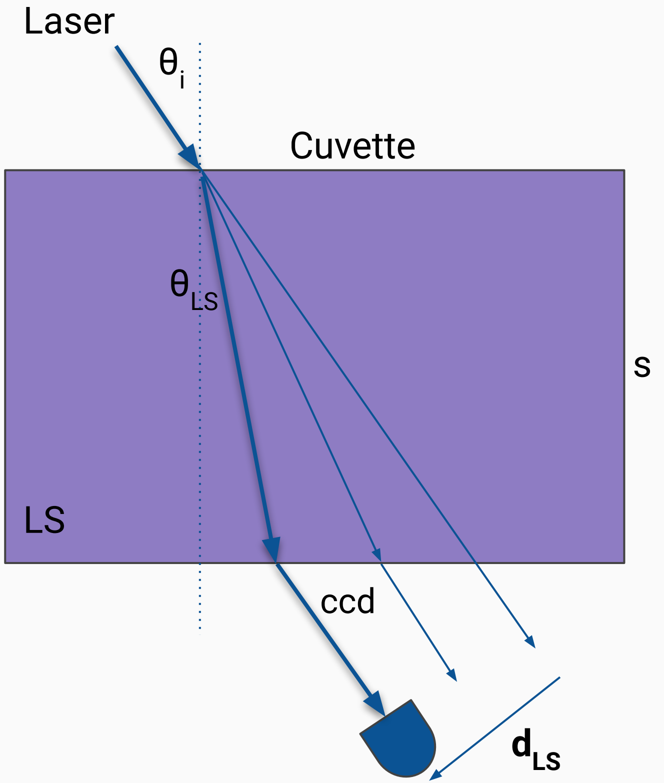
$$d_{H2O} = \frac{s \sin\left[\theta_i - \arcsin\left(\frac{n_{air}}{n_{H2O}} \sin\theta_i\right)\right]}{\cos\left[\arcsin\left(\frac{n_{air}}{n_{H2O}} \sin\theta_i\right)\right]}$$

Extract value of θ_i with higher precision

SHELDON-REWIND: REFRACTIVE INDEX WITH REFRACTOMETER



LS

Measure the position of the beam on the ccd → $\mathbf{d_{LS}}$

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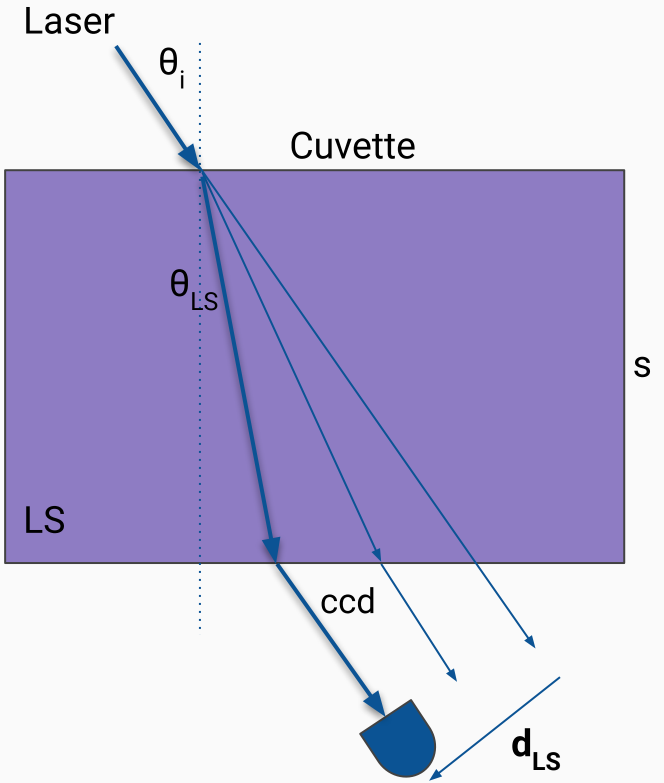

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↓

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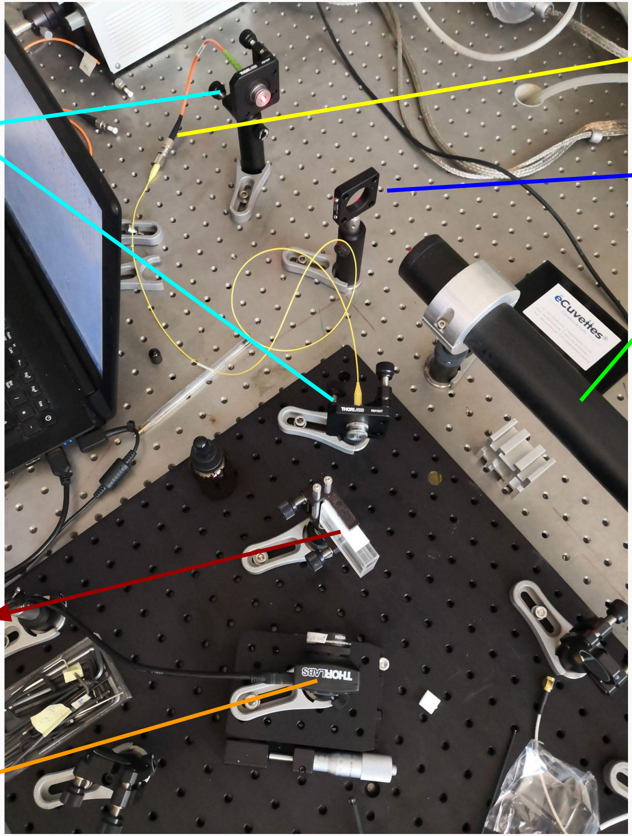

Collimators

Optical fiber

Lens

He-Ne source 633 nm

Cuvette

CCD (5.2 µm)

SHELDON-REWIND: REFRACTIVE INDEX WITH REFRACTOMETER STATUS

STATUS

SHELDON-REWIND: REFRACTIVE INDEX WITH REFRACTOMETER STATUS

Done

- The LabView acquisition code and the codes for the analysis are ready

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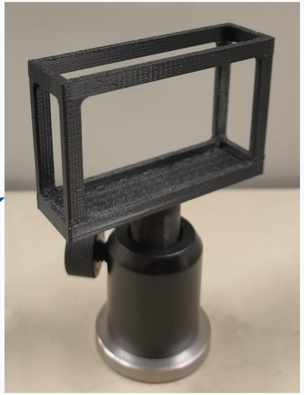

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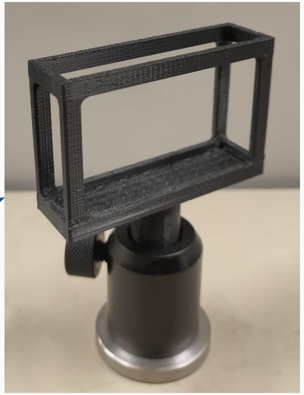

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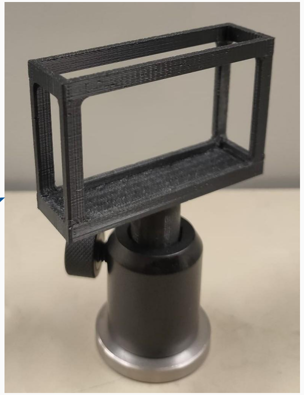

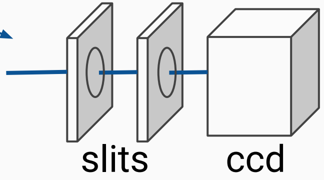

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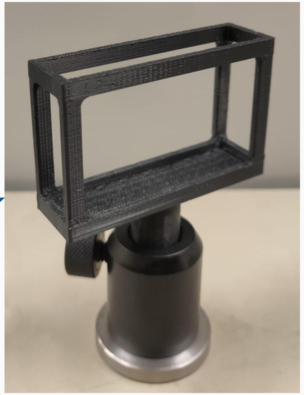

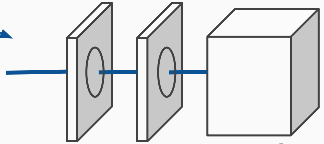

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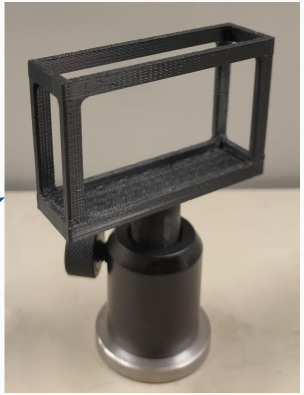

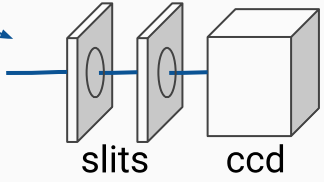

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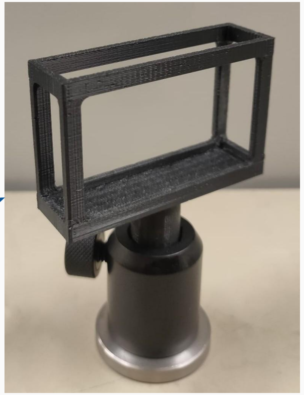
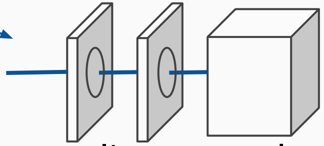
- Unable to access the laboratory (**in progress**)





SHELDON-REWIND: REFRACTIVE INDEX FIRST RESULT

Before solving the technical problems and before the maintenance works at the laboratory we made a first test measurement of the refractive index of LAB only using the He-Ne source (λ = 633 nm)

λ (nm)	633
s (cm)	0.966 ± 0.003
θ_i (rad)	0.816 ± 0.001
d_{H2O} (cm)	0.270963 ± 0.000051
d_{LAB} (cm)	0.32550 ± 0.00046

→

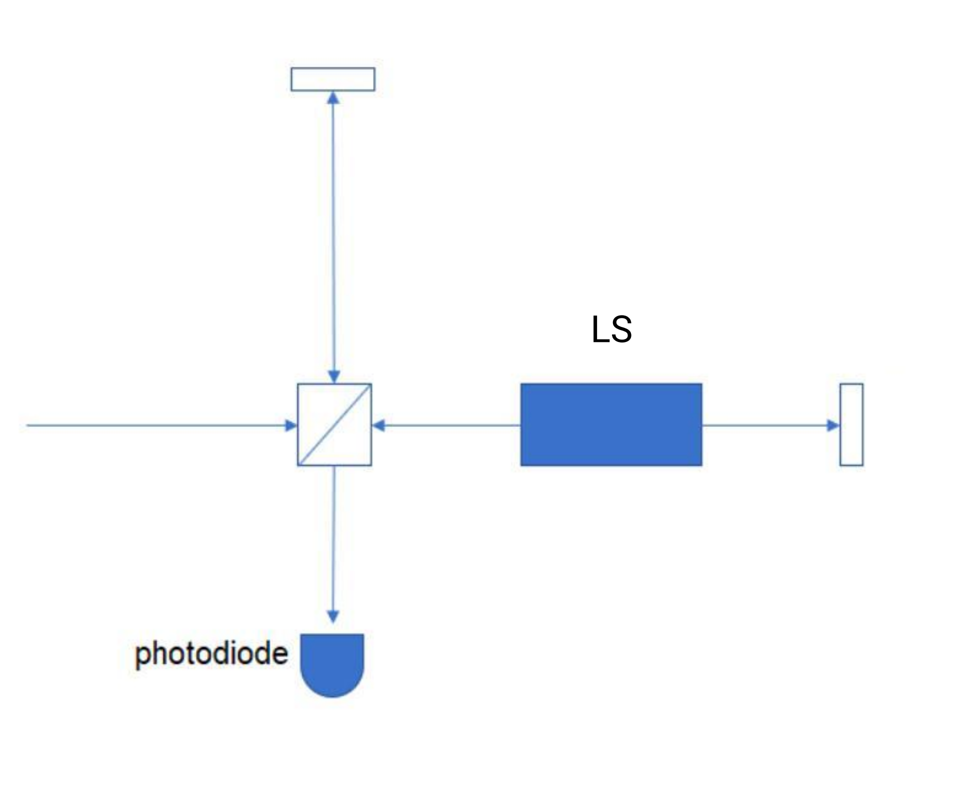
n_{LAB} = 1.481 ± 0.002

NEXT STUDIES

SHELDON-REWIND: REFRACTIVE INDEX WITH REFRACTOMETER

- We will solve the technical problems and measure again the refractive index of LAB
- We will complete our measurements for the refractive index of the LS with all the sources
- We will bring our setup to LASA (Laboratory of Accelerator and Applied Superconductivity) where there is the Yb source

SHELDON-REWIND: GROUP VELOCITY WITH INTERFEROMETER



v_g: Arrival time measurement

Testing with several wavelengths

Cuvette in one arm of interferometer with/without LS

Interference fringes displacement

→ v_g

CONCLUSION

REFRACTIVE INDEX

- The experimental setup is installed (✓)
- The acquisition and analysis codes are ready (✓)
- We did a first test measure for $\mathbf{n}_{LAB}$ (✓)
- We are taking care of the technical problems **(in progress)**
- We are waiting to access the laboratory **(in progress)**

GROUP VELOCITY

- We have to install the setup **(in progress)**
- We have to write the code for DAQ and analysis **(in progress)**

Will update you asap!

Thank you for your attention

BACKUP SLIDES

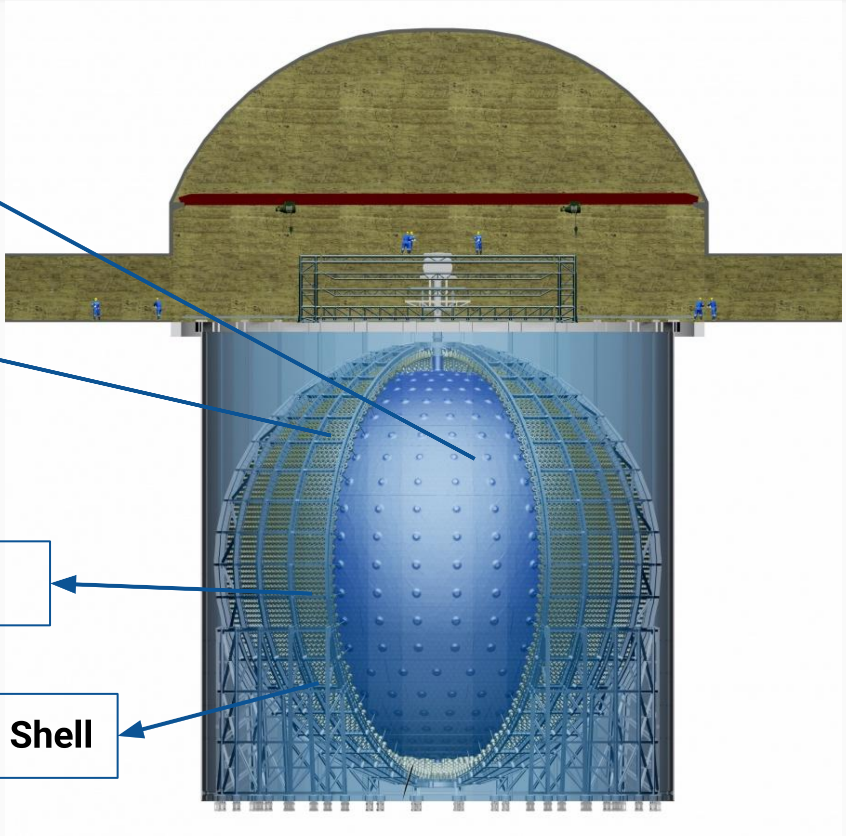
JUNO DESIGN - Central Detector

Liquid Scintillator (LS)
20 ktons

Acrylic Vessel
35.4 m diameter
265 spherical acrylic panels

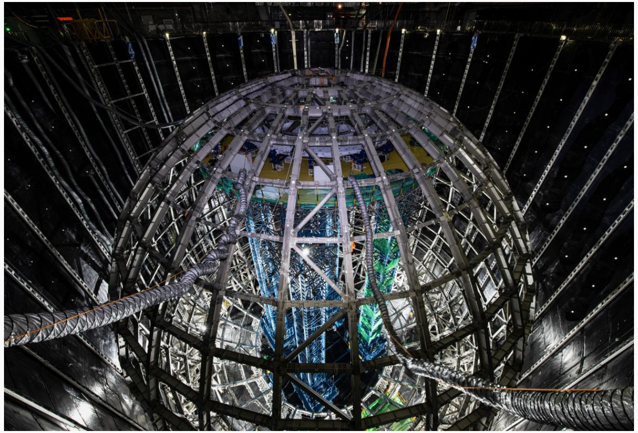
43k PMTs

Stainless Steel Shell



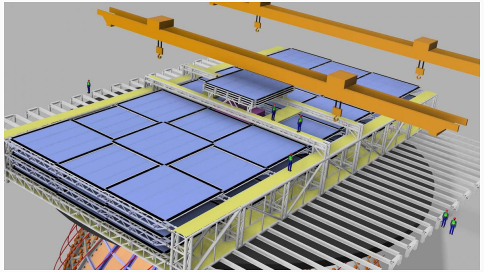
JUNO DESIGN - Support Structure

June 2022

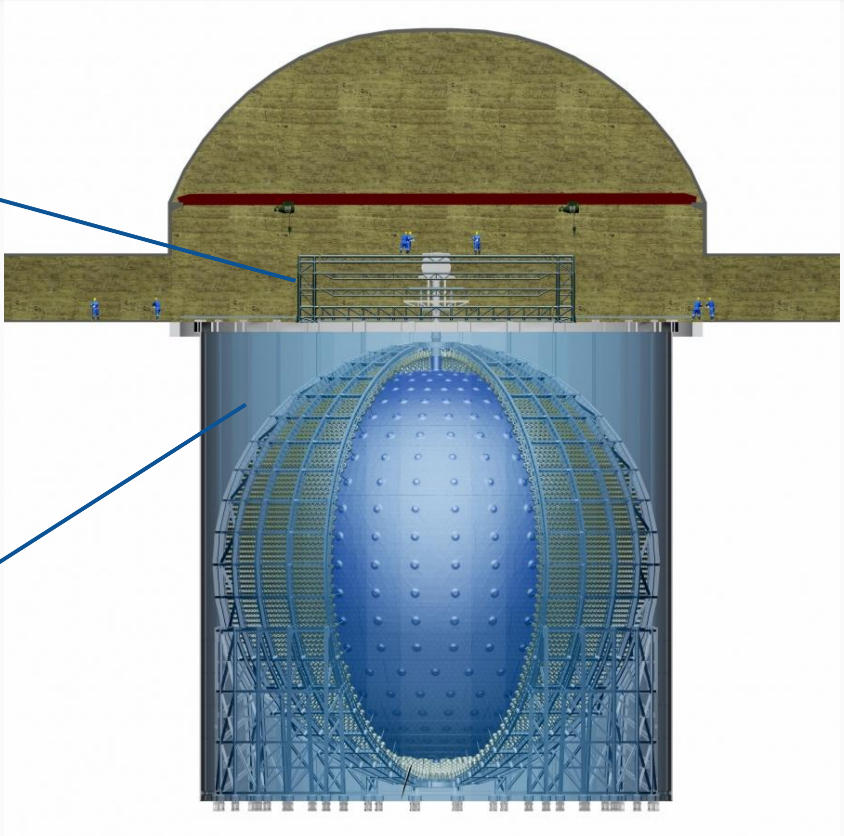


JUNO DESIGN - Veto System

Top Tracker (TT)
Plastic scintillators
Muons tracking
Cosmogenic background



Water Cherenkov Detector(WCD)
Pool to detect Cherenkov light
produced by muons

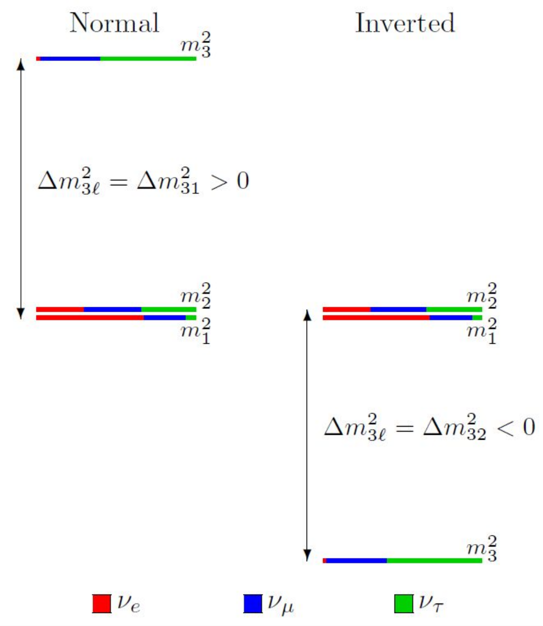


JUNO GOALS

- Neutrino Mass Ordering (**NMO**)

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U_{\mathrm{PMNS}}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

m_i = neutrino mass
$\boldsymbol{\Delta^2 m_{ij}} = m_i^2 - m_j^2$



- Neutrino Oscillations Parameters: $\boldsymbol{\theta_{12}}$, $\boldsymbol{\Delta^2 m_{21}}$, $\boldsymbol{\theta_{13}}$, $\boldsymbol{\Delta^2 m_{23}}$
- Solar Neutrino Spectroscopy
- Core-collapse Supernovae neutrinos and geoneutrinos
- Lower limit to τ_p

BACKUP

PONTECORVO-MAKI-NAKAGAWA-SAKATA mixing matrix

$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$c_{ij} \equiv \cos\theta_{ij}$$
$$s_{ij} \equiv \sin\theta_{ij}$$

What we know:

$|\Delta m^2_{3l}| \sim 2.5 \cdot 10^{-3}\ \text{eV}^2$
$\Delta m^2_{21} \sim 7.4 \cdot 10^{-5}\ \text{eV}^2$

$sin^2\theta_{12} \sim 0.3$
$sin^2\theta_{13} \sim 0.7$

What we don't know:

- Mass ordering
- Absolute values of neutrino masses (m_1, m_2, m_3)

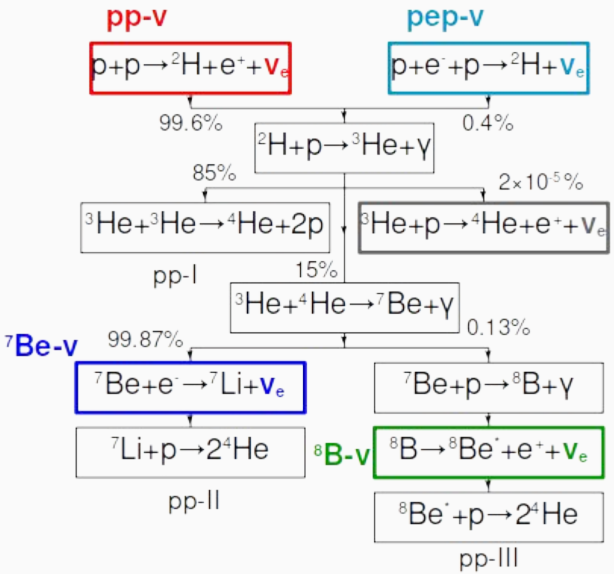
$$\begin{aligned} \mathcal{P}(\overline{\nu}_e \to \overline{\nu}_e) &= 1 - \sin^2 2\theta_{12}\, c_{13}^4 \sin^2\Delta_{21} - \sin^2 2\theta_{13} \left(c_{12}^2 \sin^2\Delta_{31} + s_{12}^2 \sin^2\Delta_{32}\right) \\ &= 1 - \sin^2 2\theta_{12} c_{13}^4 \sin^2\Delta_{21} - \frac{1}{2}\sin^2 2\theta_{13}\left(\sin^2\Delta_{31} + \sin^2\Delta_{32}\right) \\ &\quad - \frac{1}{2}\cos 2\theta_{12} \sin^2 2\theta_{13} \sin\Delta_{21}\sin(\Delta_{31} + \Delta_{32}), \end{aligned}$$

$$\Delta_{ij} \equiv \Delta m^2_{ij} L/(4E)$$

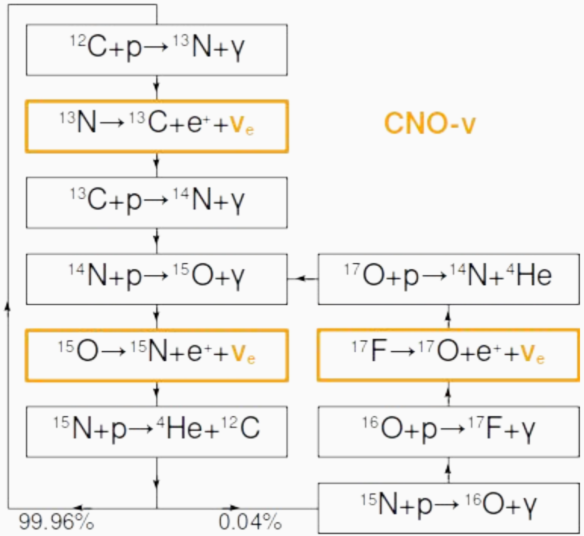
	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	$\pm$0.034 (1.3%)	$\pm$0.021 (0.8%)	$\pm$0.0047 (0.2%)	$\pm$0.0029 (0.1%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	$\pm$0.18 (2.4%)	$\pm$0.074 (1.0%)	$\pm$0.024 (0.3%)	$\pm$0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	$\pm$0.013 (4.2%)	$\pm$0.0058 (1.9%)	$\pm$0.0016 (0.5%)	$\pm$0.0010 (0.3%)
$\sin^2\theta_{13}$	0.0218	$\pm$0.0007 (3.2%)	$\pm$0.010 (47.9%)	$\pm$0.0026 (12.1%)	$\pm$0.0016 (7.3%)

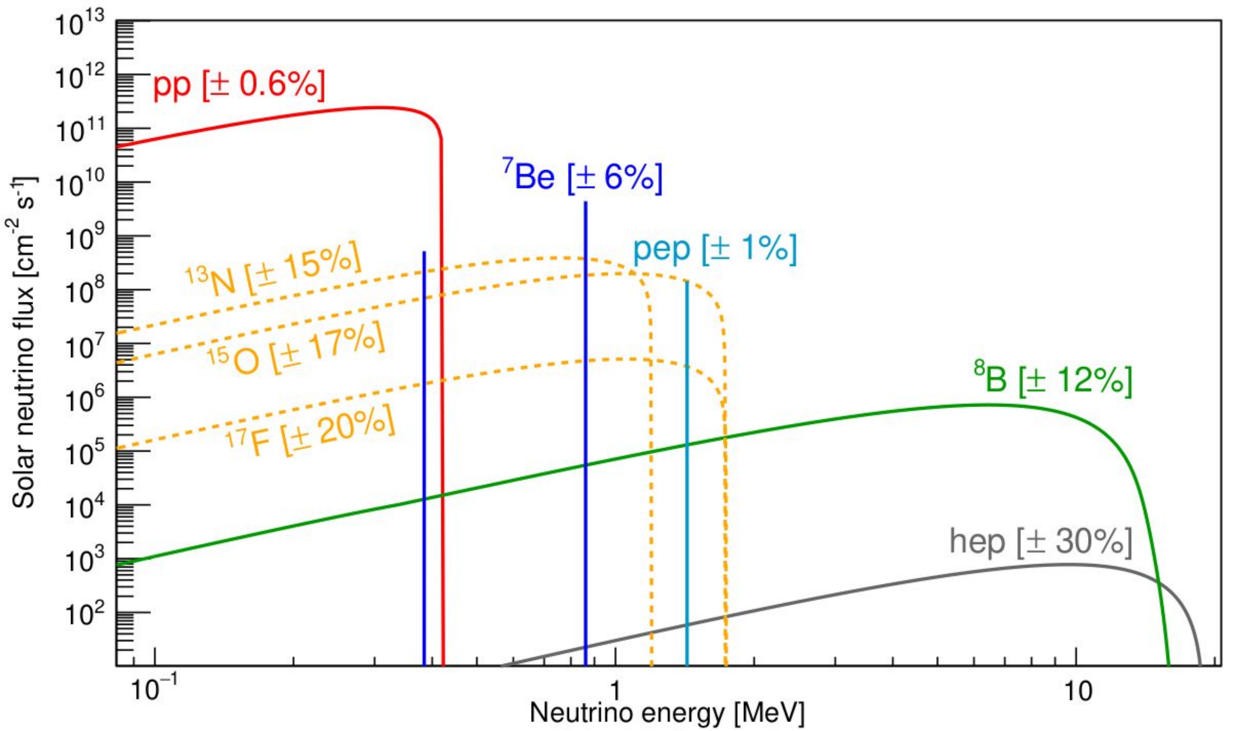
SOLAR NEUTRINOS

Proton-proton chain



CNO cycle




pp [± 0.6%]
^{7}Be [± 6%]
pep [± 1%]
^{13}N [± 15%]
^{15}O [± 17%]
^{17}F [± 20%]
^{8}B [± 12%]
hep [± 30%]
Solar neutrino flux [cm^{-2} s^{-1}]
Neutrino energy [MeV]
10^{-1}
1
10
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}

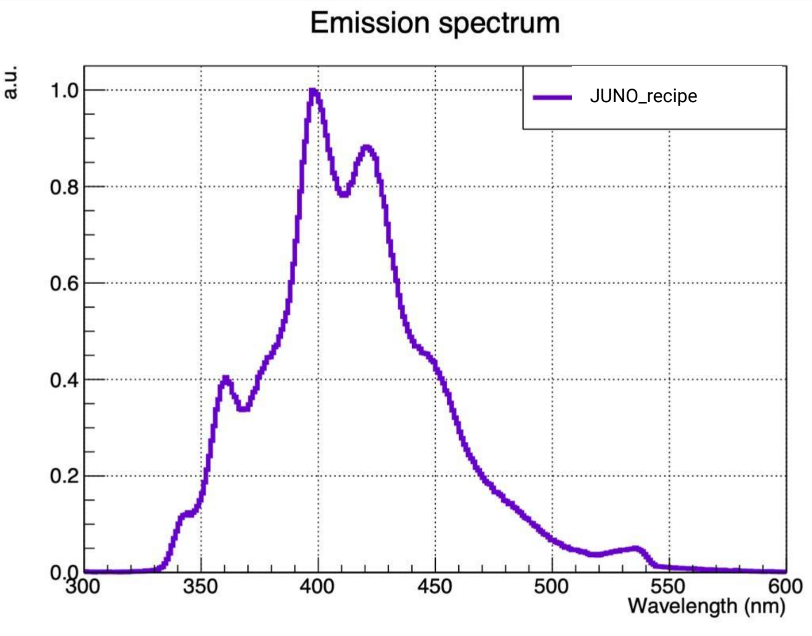
LIQUID SCINTILLATOR

Recipe: LAB + 2.5 g/l PPO + 3 mg/l bis-MSB

Charged particle passes through the LS → its molecules get excited
Transition from excited levels to the ground state

Typical **τ**: few ns to few μs
Light-yield: 10^4 ph/MeV

Fluorescence light emission



NEUTRINO INTERACTIONS

Antineutrinos

Inverse Beta Decay (IBD)

$\bar{\nu}_e + p \longrightarrow e^+ + n$

few ns prompt

$e^+ + e^- \longrightarrow 2\gamma$ *(511 KeV)*

200 μs delayed

$n + p \longrightarrow \gamma$ *(2.2 MeV)*

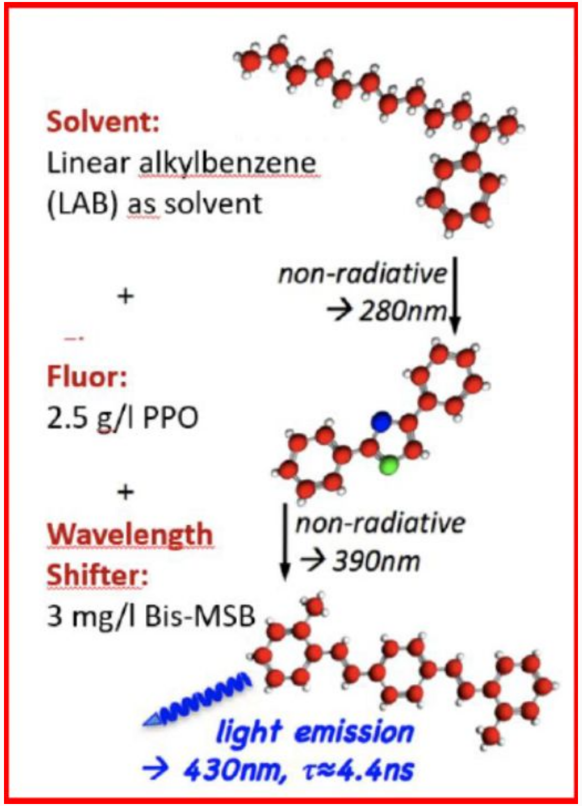
Neutrinos

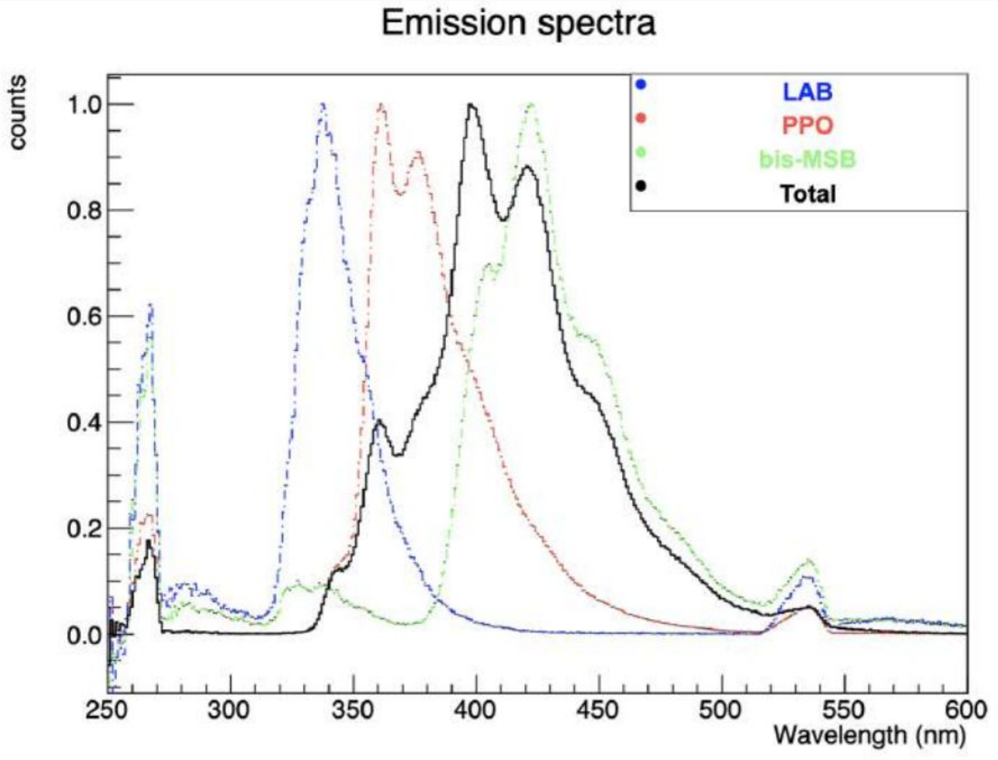
Elastic Scattering

$\nu + e^- \longrightarrow \nu + e^-$

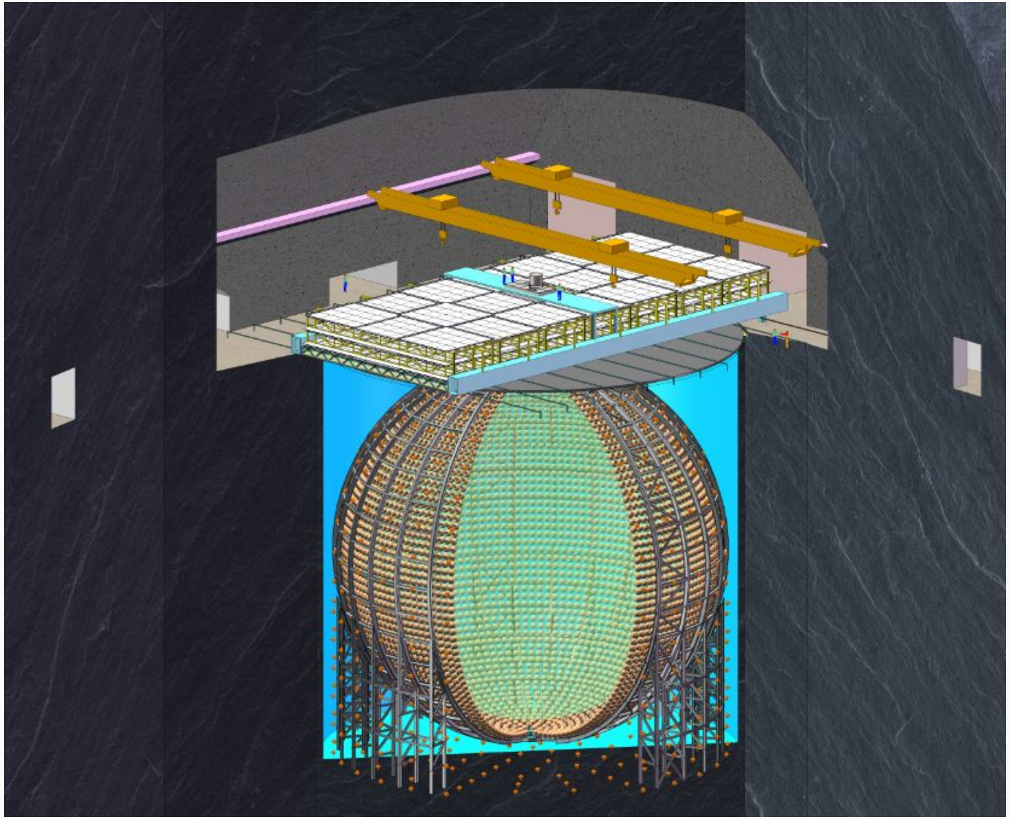
Detection of light by PMTs

LIQUID SCINTILLATOR - EMISSION SPECTRA



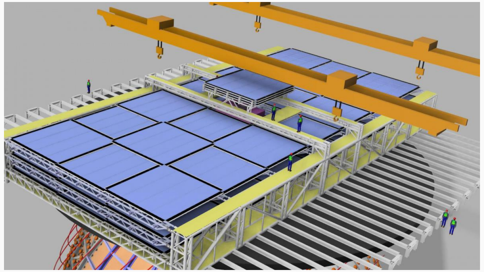


BACKUP



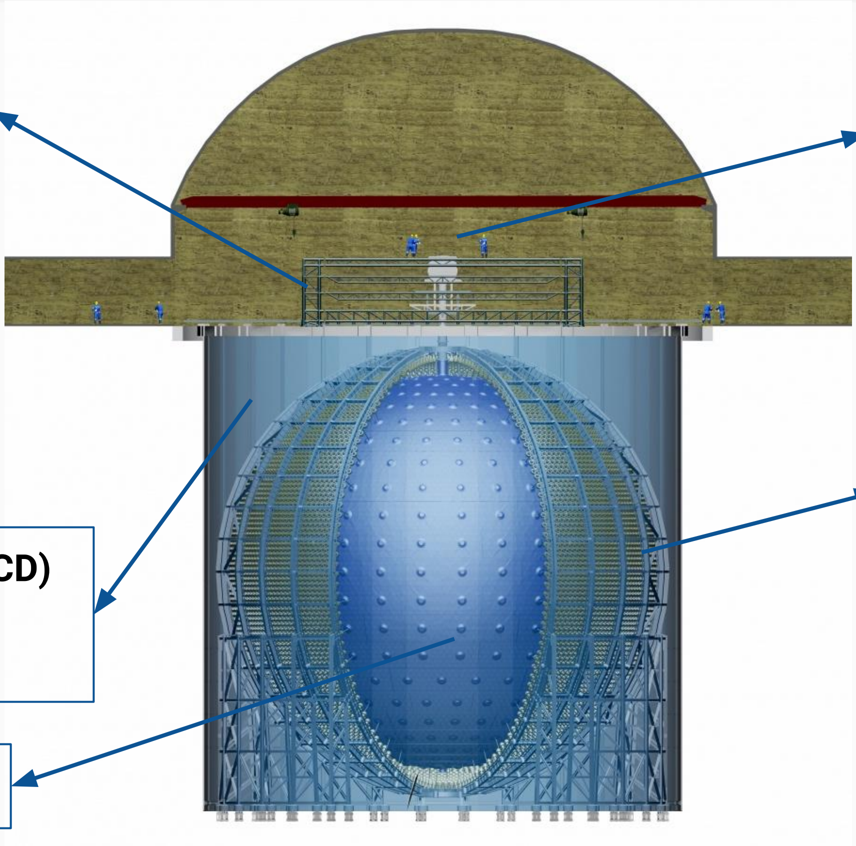
JUNO DESIGN

Top Tracker (TT)
Plastic scintillators
Muons tracking
Cosmogenic background



Water Cherenkov Detector(WCD)
Pool to detect Cherenkov light
produced by muons

Central Detector(CD)

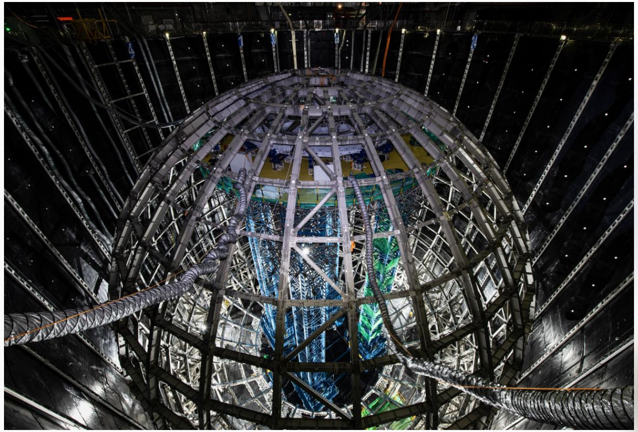


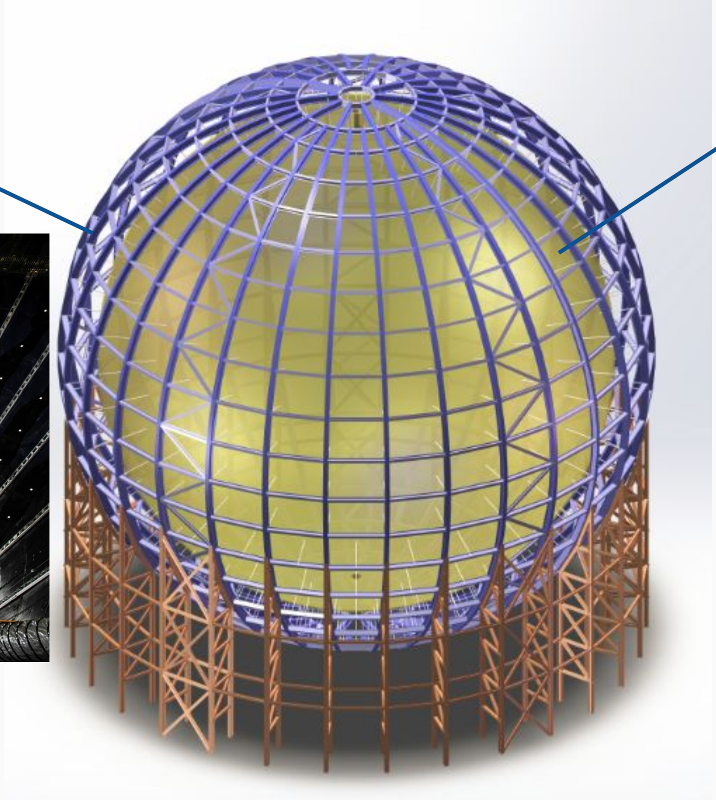
Calibration House
Study detector response
Correct energy non-linearity
and spatial non-uniformity
Several radioactive sources

PMTs
42k internal
2400 external

CENTRAL DETECTOR

Stainless Steel Shell
40.1 m diameter of structure





Acrylic Vessel
35.4 m diameter
265 spherical acrylic panels

NEUTRINO DETECTION

Inverse Beta Decay (IBD)

$\bar{\nu} + p \longrightarrow e^+ + n$

few ns

$e^+ + e^- \longrightarrow 2\gamma$ *(511 KeV)*

prompt signal

200 μs

$n + p \longrightarrow \gamma$ *(2.2 MeV)*

delayed signal

Elastic Scattering

$\nu + e^-(p) \longrightarrow \nu + e^-(p)$

Fluorescence

Cherenkov
(if e^- and possible)

Interaction with ^{12}C

$\nu + {}^{12}C \longrightarrow \nu + {}^{12}C^*$
$\nu_e + {}^{12}C \longrightarrow e^- + {}^{12}N$
$\nu_e + {}^{12}C \longrightarrow e^+ + {}^{12}B$

Fluorescence

Cherenkov
(if possible)

Detection of light by PMTs

ENERGY MEASUREMENT

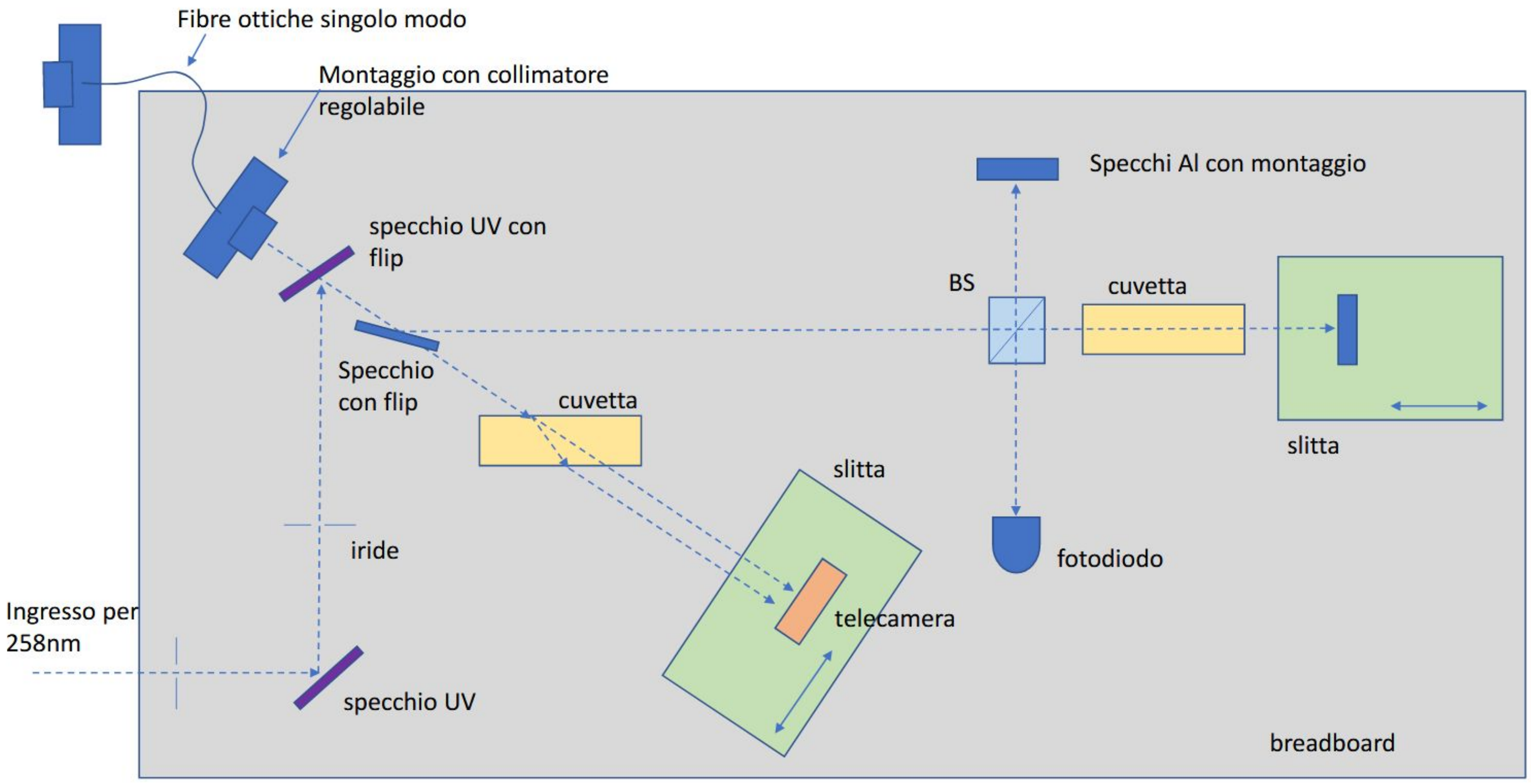
Scintillation light

$$\frac{dL}{dx} = S\frac{\frac{dE}{dx}}{1 + kB\frac{dE}{dx}}$$

Cherenkov radiation

$$\frac{\partial^2 E}{\partial x\,\partial \omega} = \frac{q^2}{4\pi}\mu(\omega)\omega\left(1 - \frac{c^2}{v^2 n^2(\omega)}\right)$$

SHELDON - REWIND

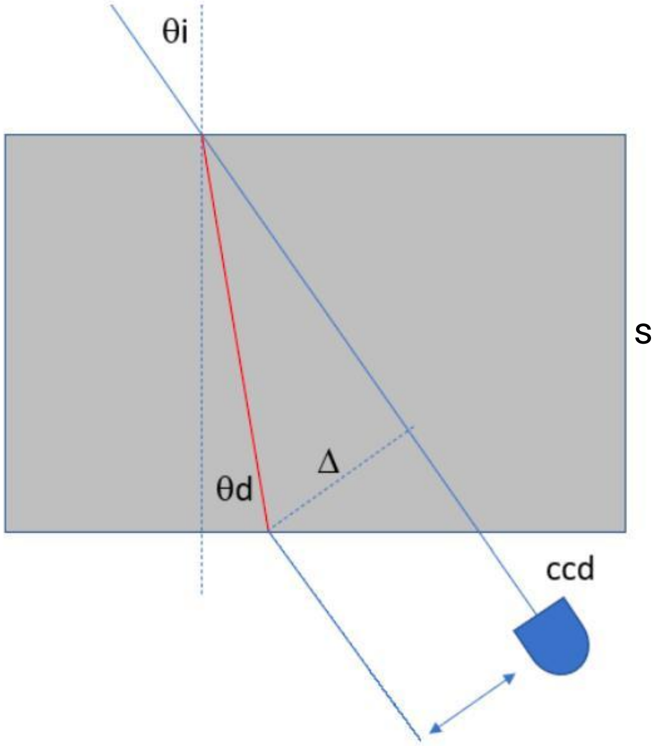


SHELDON - REWIND: GROUP VELOCITY WITH INTERFEROMETER

Useful link to check known refractive index of several material as a function of temperature, pression, wavelength, humidity and so on:

refractiveindex.info

SHELDON-REWIND: REFRACTIVE INDEX WITH REFRACTOMETER



n: Time measurement + Cherenkov contribution

Testing at several wavelengths

- He-Ne: 633 nm
- Ar: 514.5 nm
- Yb: 258 nm, 345 nm, 517 nm, 1035 nm

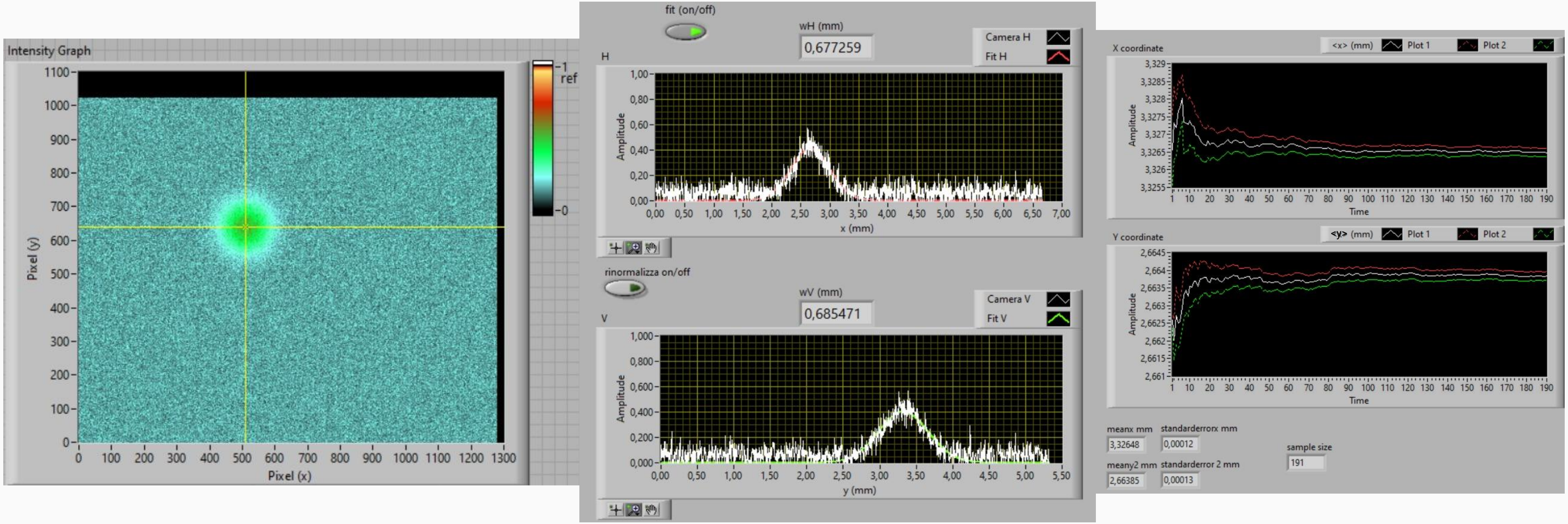
Different refractive angle with/without LS

Beam propagation displacement

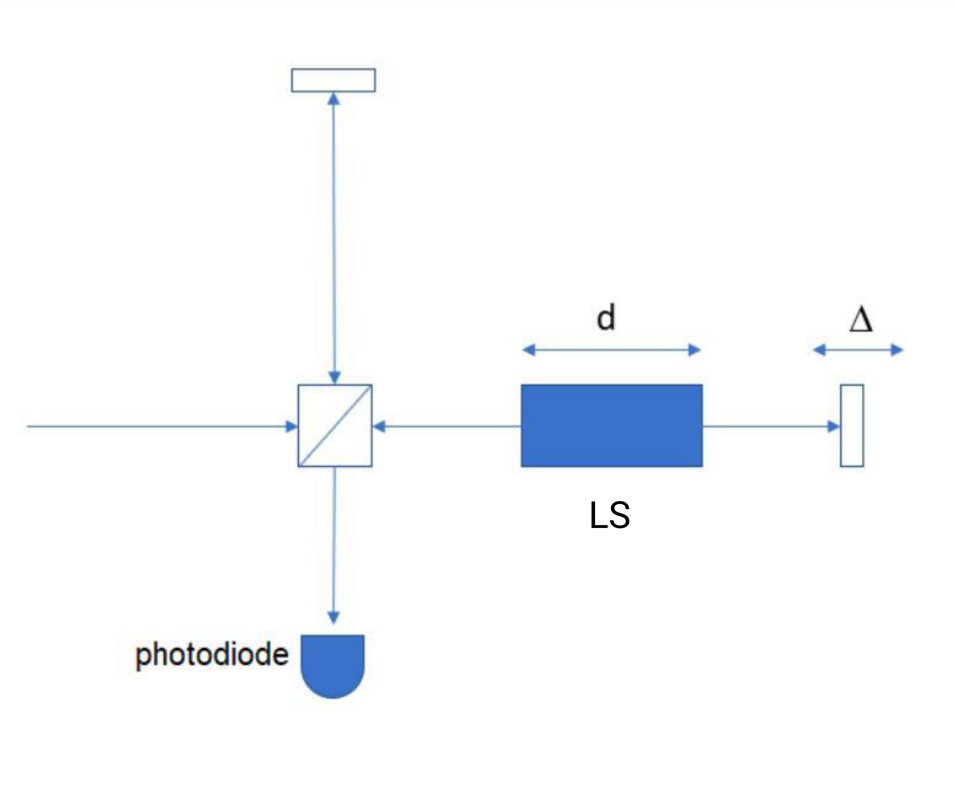
↓

n

SHELDON-REWIND: REFRACTIVE INDEX WITH REFRACTOMETER LabView



SHELDON - REWIND: GROUP VELOCITY WITH INTERFEROMETER



$$v_g = \frac{c}{n_g}$$

$$n_g(\lambda) = n(1 - \frac{\lambda}{n}\frac{dn}{d\lambda})^{-1}$$

$$dn_g = d + \Delta$$

$$n_g = 1 + \frac{\Delta}{d}$$