MAYORANA (Multi-Aspect Young ORiented Advanced Neutrino Academy) School,
06 July 2023 Modica, Minitalks

Optical characterization of the JUNO liquid scintillator

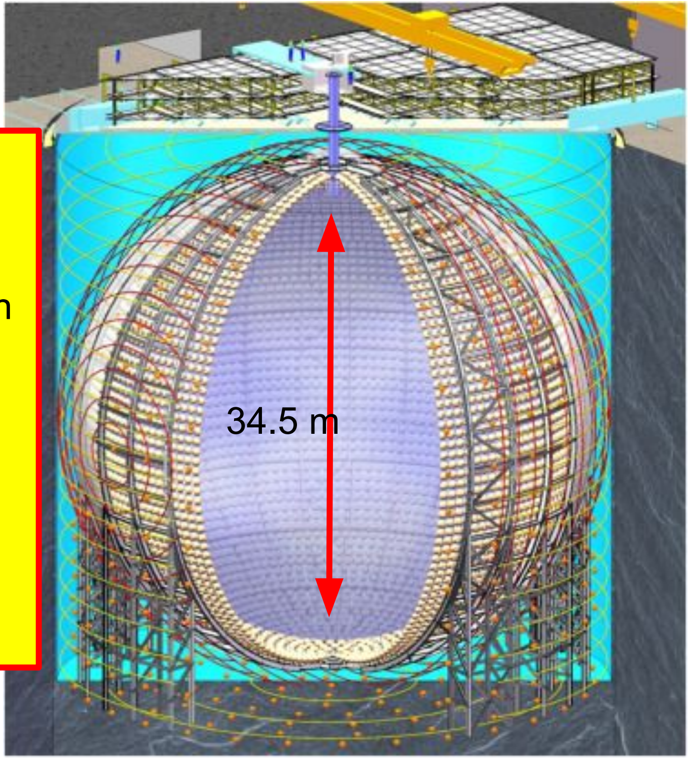
Marco Beretta
on behalf of the JUNO collaboration

Jiangmen Underground Neutrino Observatory

42 000 PMTs
~76% optical coverage

3% of energy resolution @ 1 MeV

7 cm of spatial resolution in a diameter of 3450 cm @1 MeV



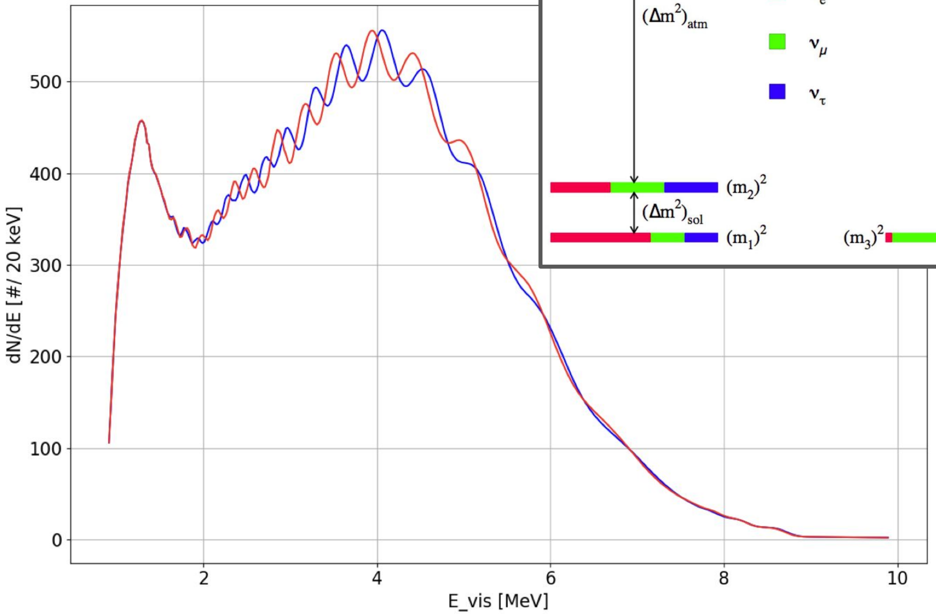
Experimental site:
China, 700 m underground, 53 km distant from two **nuclear power plants**

Detection medium:
20 kton of organic liquid scintillator

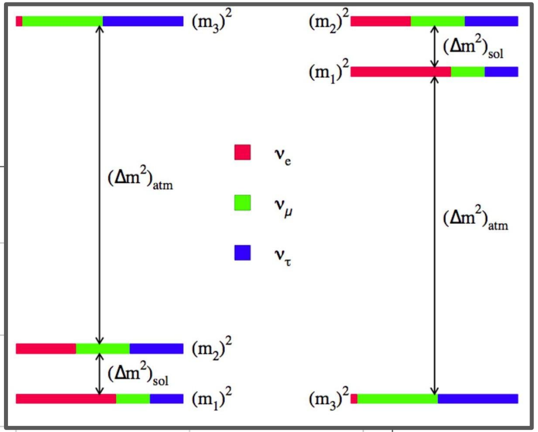
Goals:
Neutrino mass ordering
Oscillation parameters
Solar neutrino spectroscopy
Supernova neutrino burst
…

Ready for start data taking:
2024

Neutrino Mass Ordering



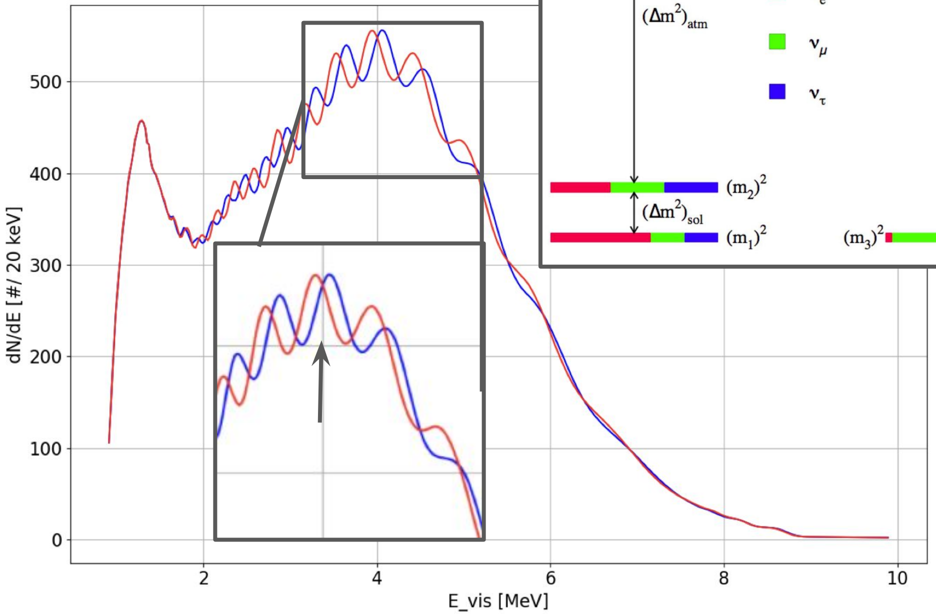
Normal **Inverted**

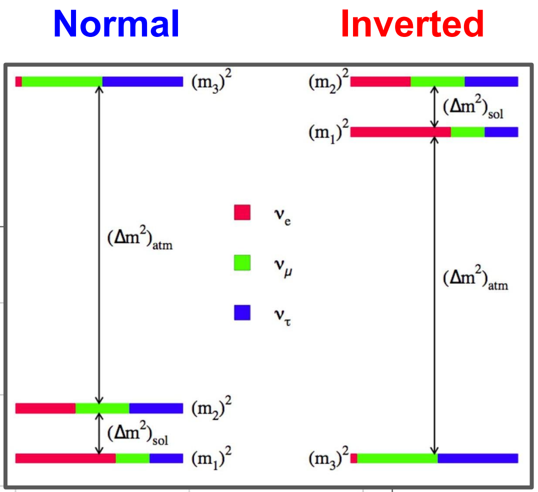


Juno will determine the neutrino mass ordering looking the anti-neutrino spectrum deriving from nuclear power plants

To determine the correct spectrum between the two cases, **Normal** or **Inverted**, having an high energy resolution 3% @ 1 MeV

Neutrino Mass Ordering

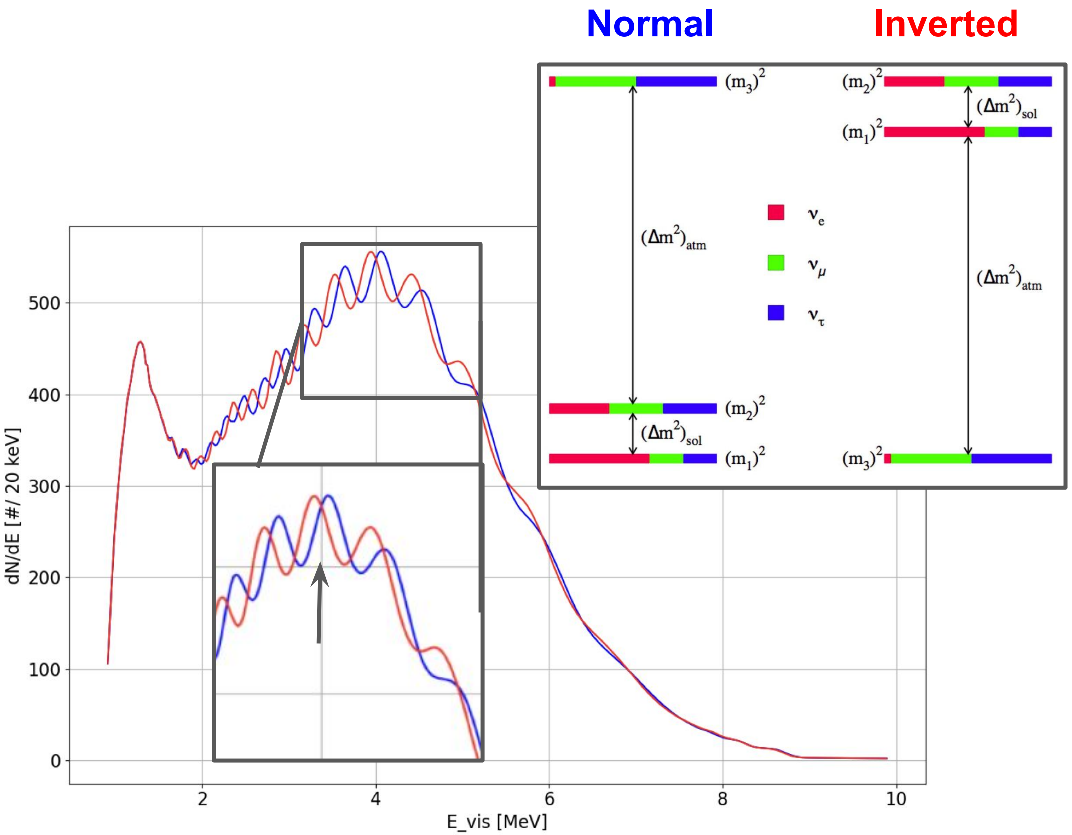




Juno will determine the neutrino mass ordering looking the anti-neutrino spectrum deriving from nuclear power plants

To determine the correct spectrum between the two cases, **Normal** or **Inverted**, having an high energy resolution 3% @ 1 MeV

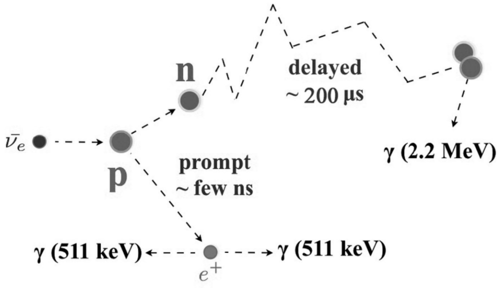
Neutrino Mass Ordering



Juno will determine the neutrino mass ordering looking the anti-neutrino spectrum deriving from nuclear power plants

To determine the correct spectrum between the two cases, **Normal** or **Inverted**, having an high energy resolution 3% @ 1 MeV

In addition the anti-neutrino events are selected through **time-position cuts** tagging the Inverse Beta Decay reaction



Introduction

- Knowing the optical parameters of the liquid scintillator in the best way possible is a crucial task for the JUNO experiment

- In Milano we have built an experimental setup called “SHELDON” to measure the **time profile** and the **Cherenkov contribution** in the liquid scintillator

- We have also built another small scale experiment called “SHELDON-REWIND” to measure **the refractive index** and **the group velocity**

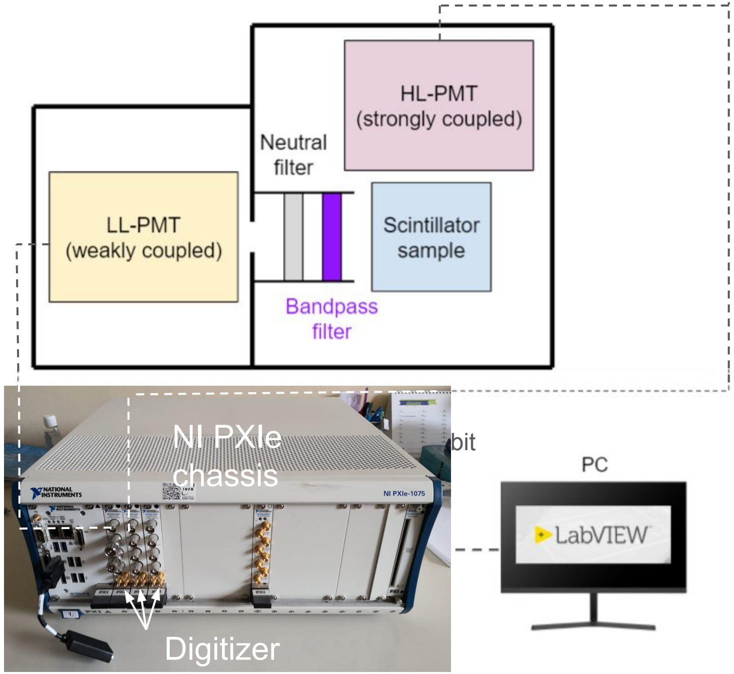
The SHELDON project: scientific goals

Separation of c**HE**renkov **L**ight for **D**irectionality **O**f **N**eutrino
@ UNIMI - Milan

Accurate measurement of fluorescence time distribution (fluorescence parameters)

Impact on the JUNO experiment:

- event reconstruction
- particle identification via PSD
- improved description of fluorescence parameters in the JUNO MC

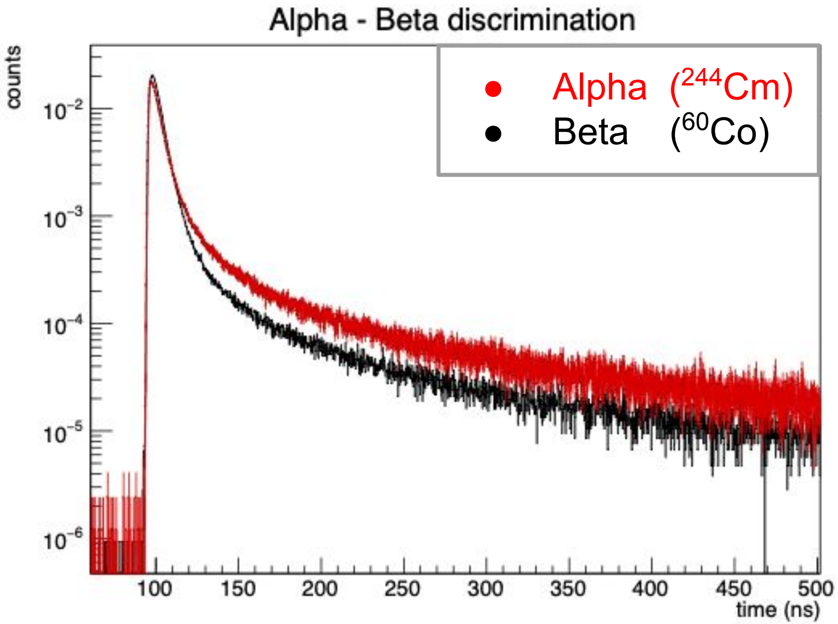


Measurement of fluorescence profile

Measurement of **fluorescence time distribution** using two different radioactive sources.

We have measured this using the **T**ime-**C**orrelated **S**ingle **P**hoton **C**ounting technique

The two curves have different tails this **allow** to perform **alpha-beta discrimination with PSD**



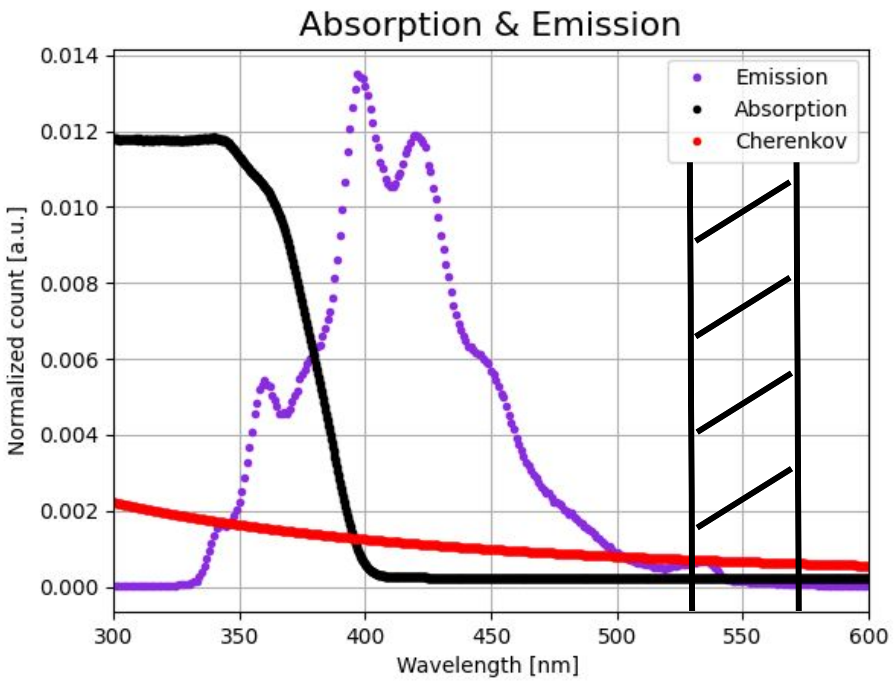
	τ_1 [ns]	τ_2 [ns]	τ_3 [ns]	τ_4 [ns]
α	4.63 ± 0.02	19.87 ± 0.41	102.0 ± 2.2	644 ± 13
e^-	4.36 ± 0.02	17.55 ± 0.51	89.16 ± 2.6	590 ± 12
	q_1 [%]	q_2 [%]	q_3 [%]	q_4 [%]
α	62.33 ± 0.31	18.66 ± 0.22	11.86 ± 0.16	7.15 ± 0.41
e^-	78.98 ± 0.29	11.07 ± 0.20	6.09 ± 0.11	3.86 ± 0.37

PRELIMINARY RESULTS

$$F_{fluo}(t) = N \sum_{d=1}^{4} \frac{q_d}{\tau_d - \tau_r} \left(e^{-t/\tau_d} - e^{-t/\tau_r} \right)$$

Cherenkov contribution

Study of the Cherenkov radiation in the JUNO LS



Impact on the JUNO experiment:

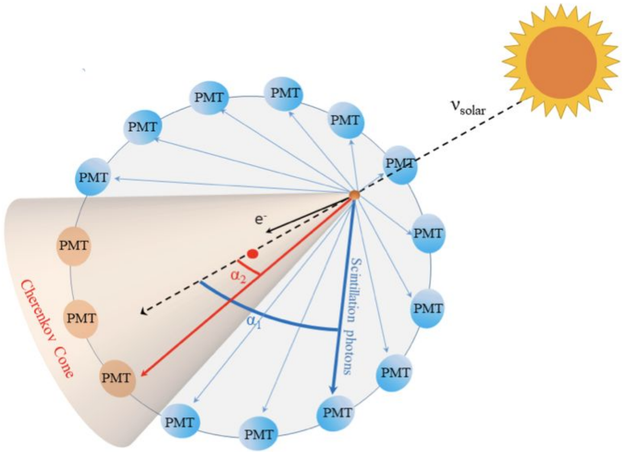
- Improved understanding of energy response
- Possible reconstruction of the direction of incident neutrino

Cherenkov contribution

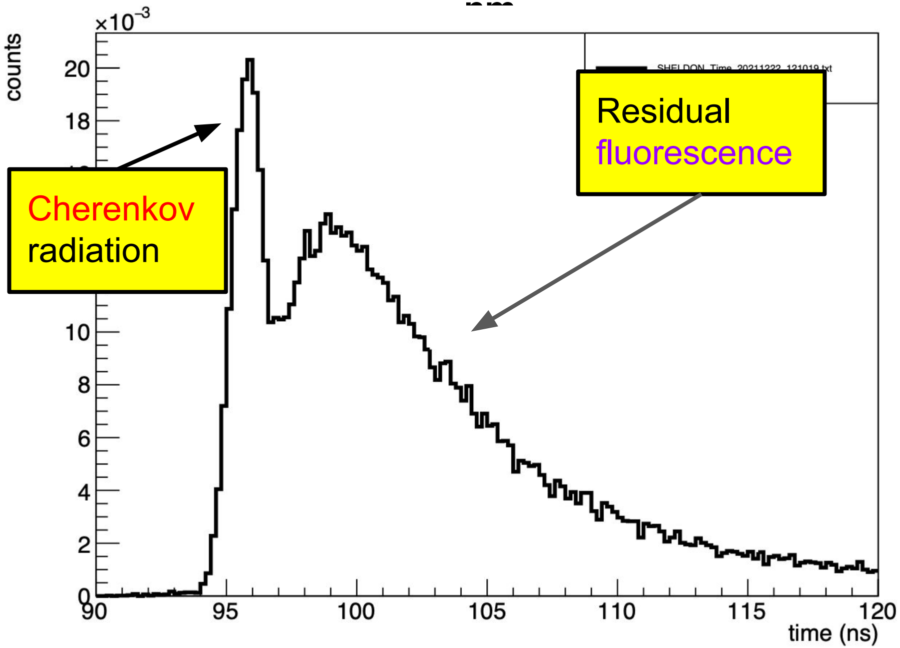
We measured the fraction of **Cherenkov light** over the total light detected at different wavelength

The **Cherenkov light** impacts on **the energy reconstruction**

Allow to **improve the signal/background ratio** for **solar neutrinos**, as demonstrated by the Borexino collaboration (cita)



Cherenkov separation in the band 530-570 nm

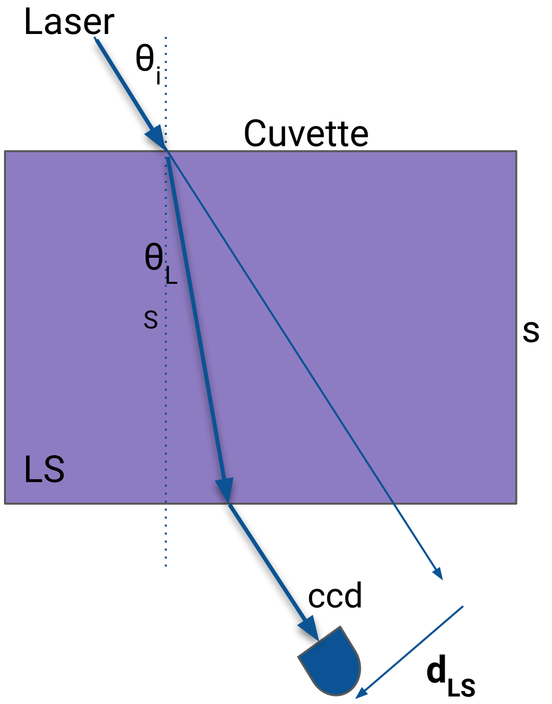


Cherenkov = 15.1 ± 0.2 %

The SHELDON-Rewind project: scientific goals

REfractive index **W**ith **IN**terferometric **D**evices
@ UNIMI - Milan

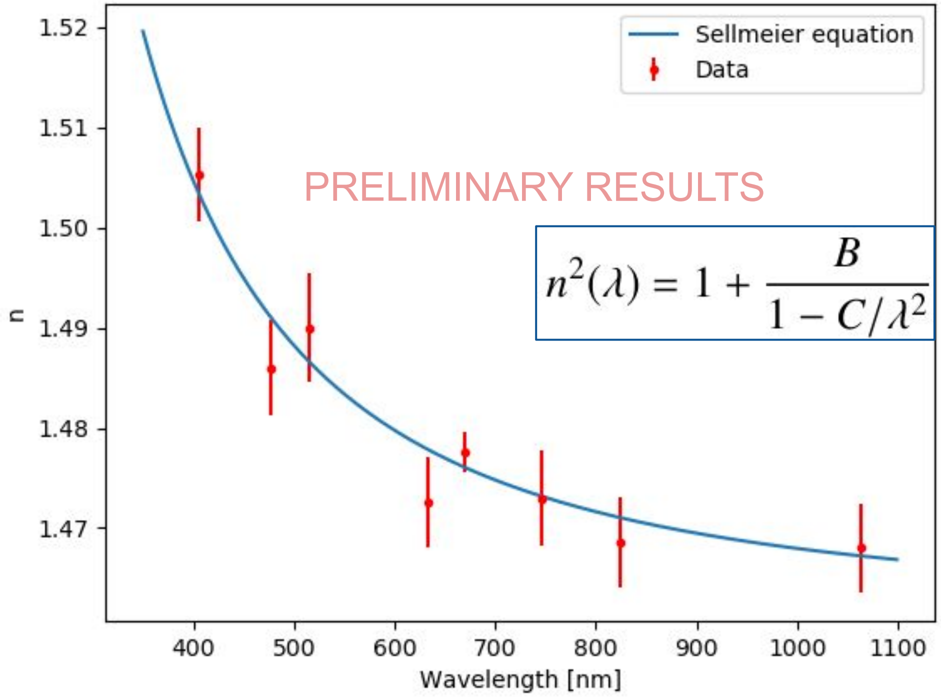
Refractive index measurement



Impact on the JUNO experiment:

- position reconstruction
- energy reconstruction

Refractive index measurement: results



$$n^2(\lambda) = 1 + \frac{B}{1 - C/\lambda^2}$$

We used a **refractometer** to perform the measurements of the refractive index

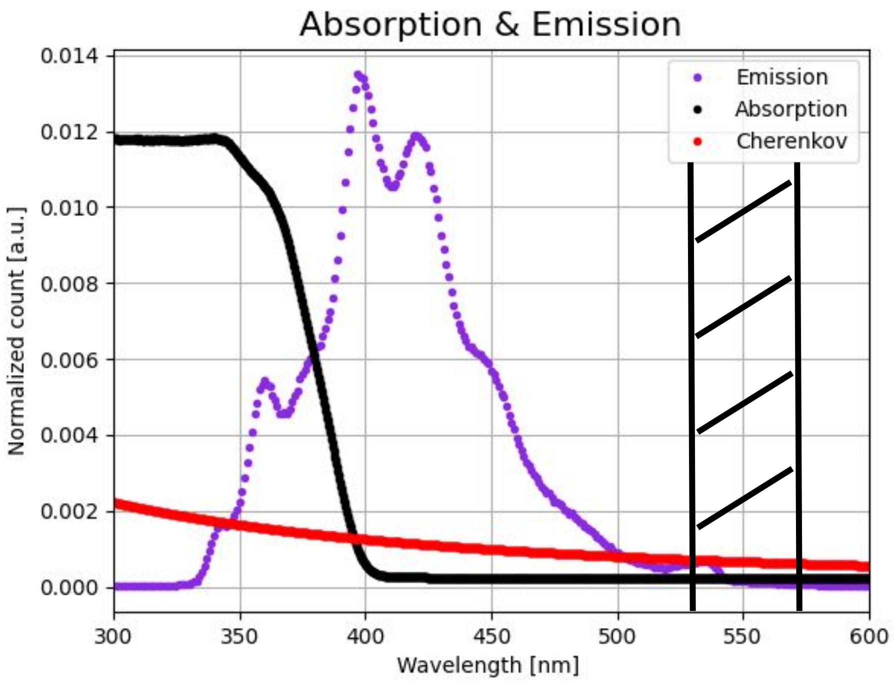
Using a laser and a CCD we can see the displacement of due to the insertion of the liquid scintillator

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

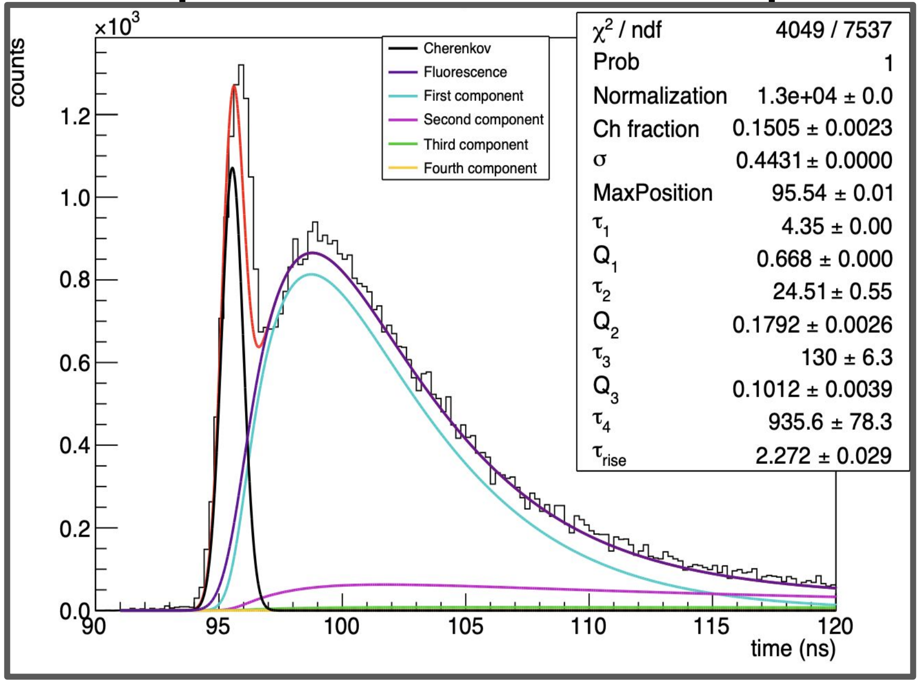
Thank you for the attention

JUNO Liquid Scintillator

Cherenkov contribution



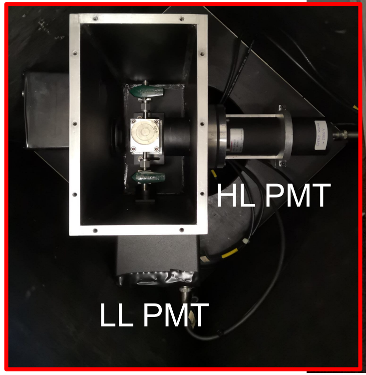
530 - 570 nm



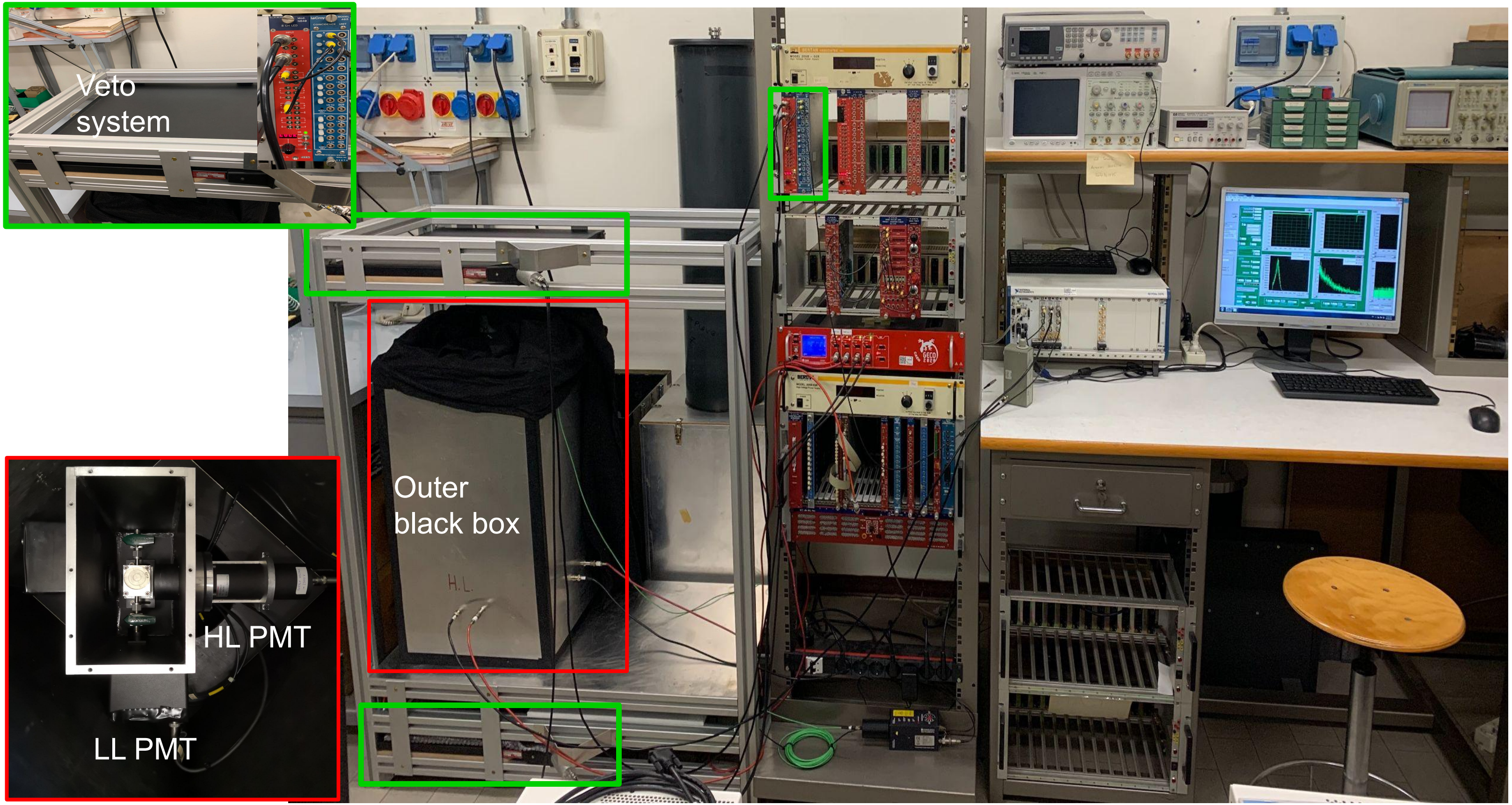
Cherenkov = 15.1 ± 0.2 %

SHELDON experimental setup

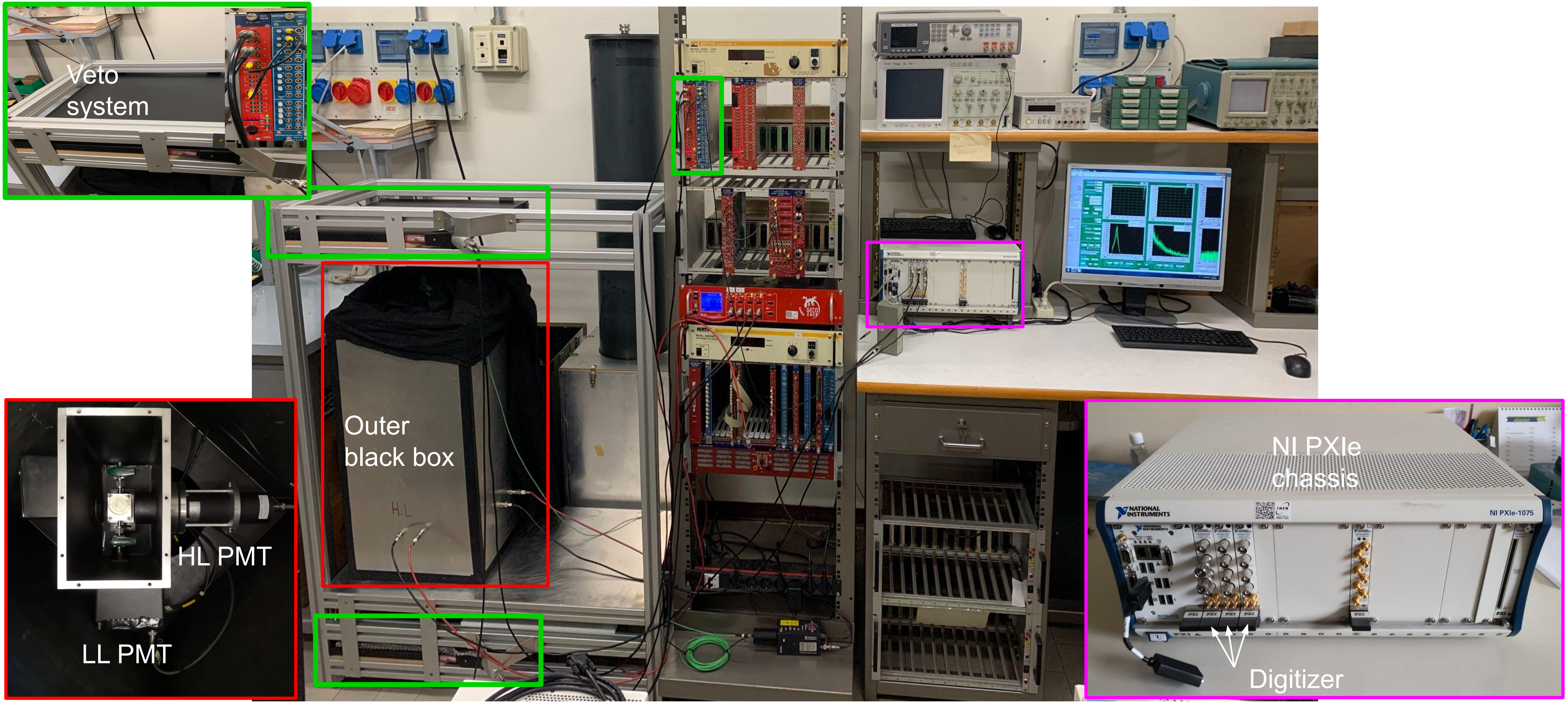
SHELDON experimental setup



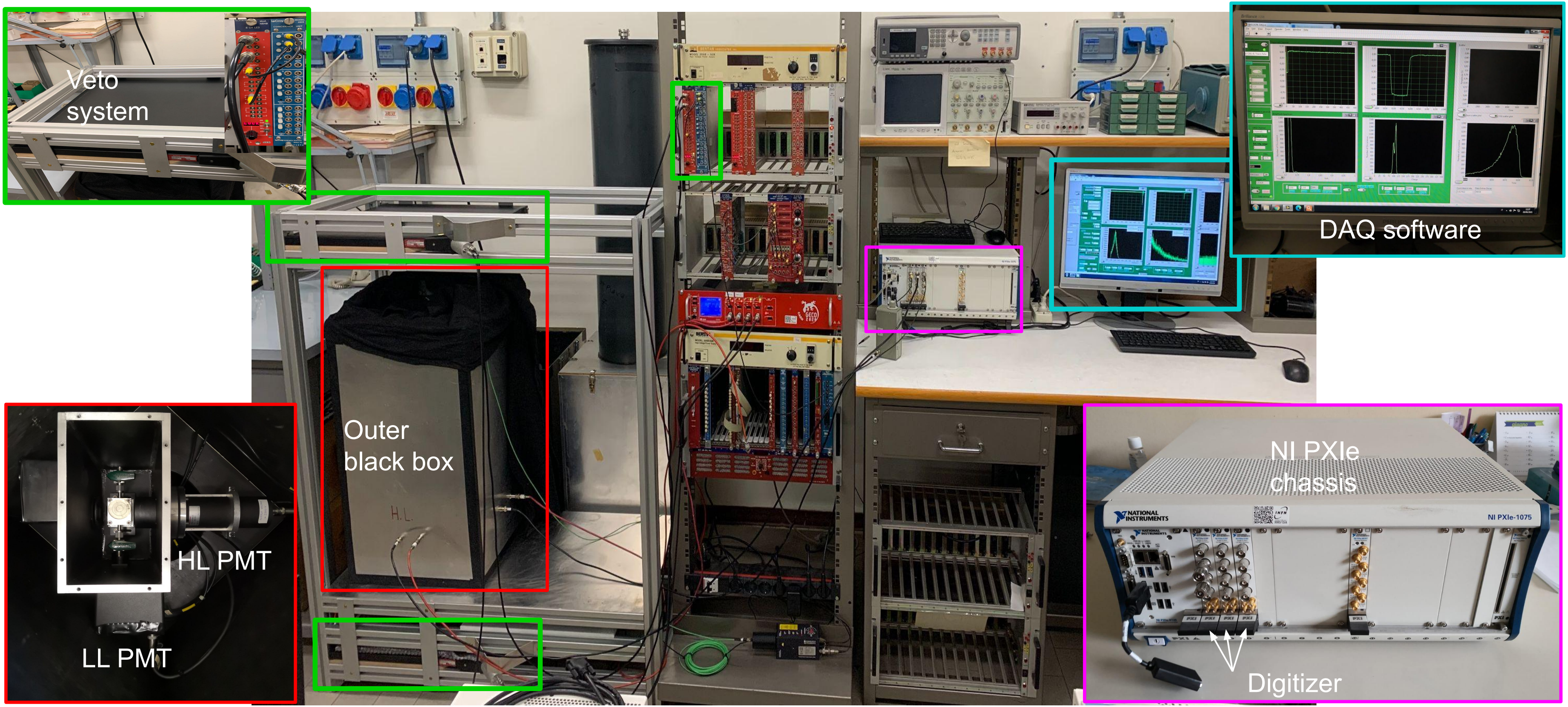
SHELDON experimental setup



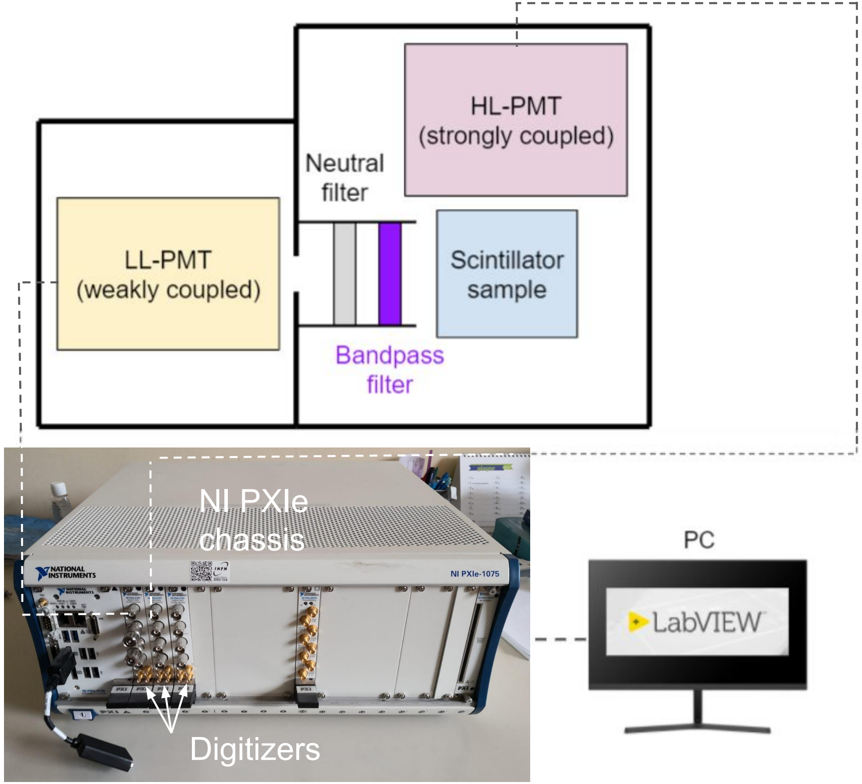
SHELDON experimental setup



SHELDON experimental setup



SHELDON experimental setup



Components of the setup:

JUNO LS sample (degassed with N_2)

2 PMTs, one weakly coupled

Neutral or Bandpass filter

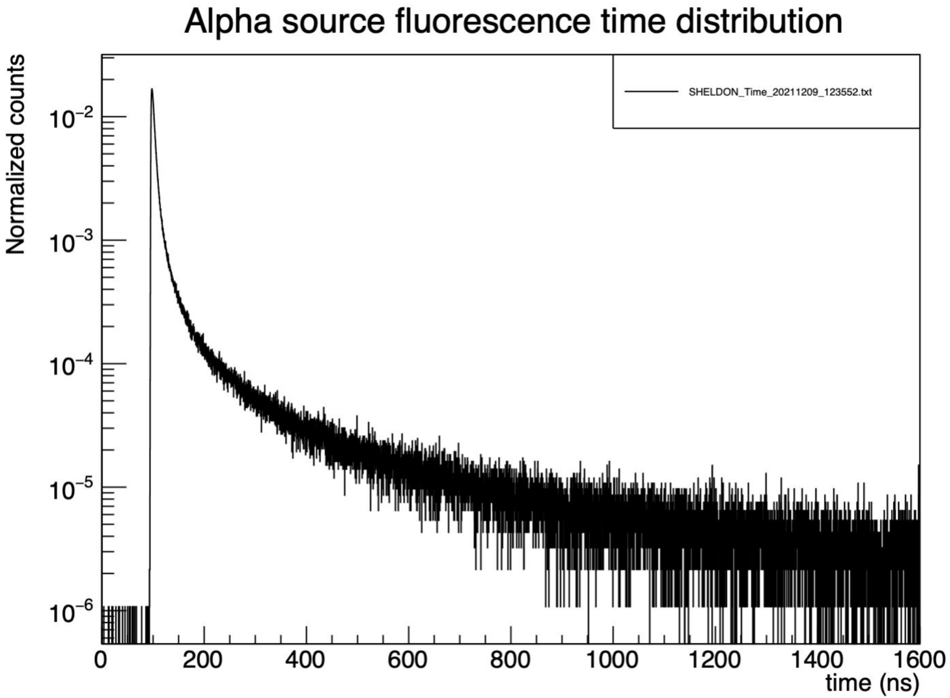
2 Digitizers (5 GS/s each)

LabVIEW DAQ software

Technique:

Time-**C**orrelated **S**ingle **P**hoton **C**ounting

Measurement of fluorescence

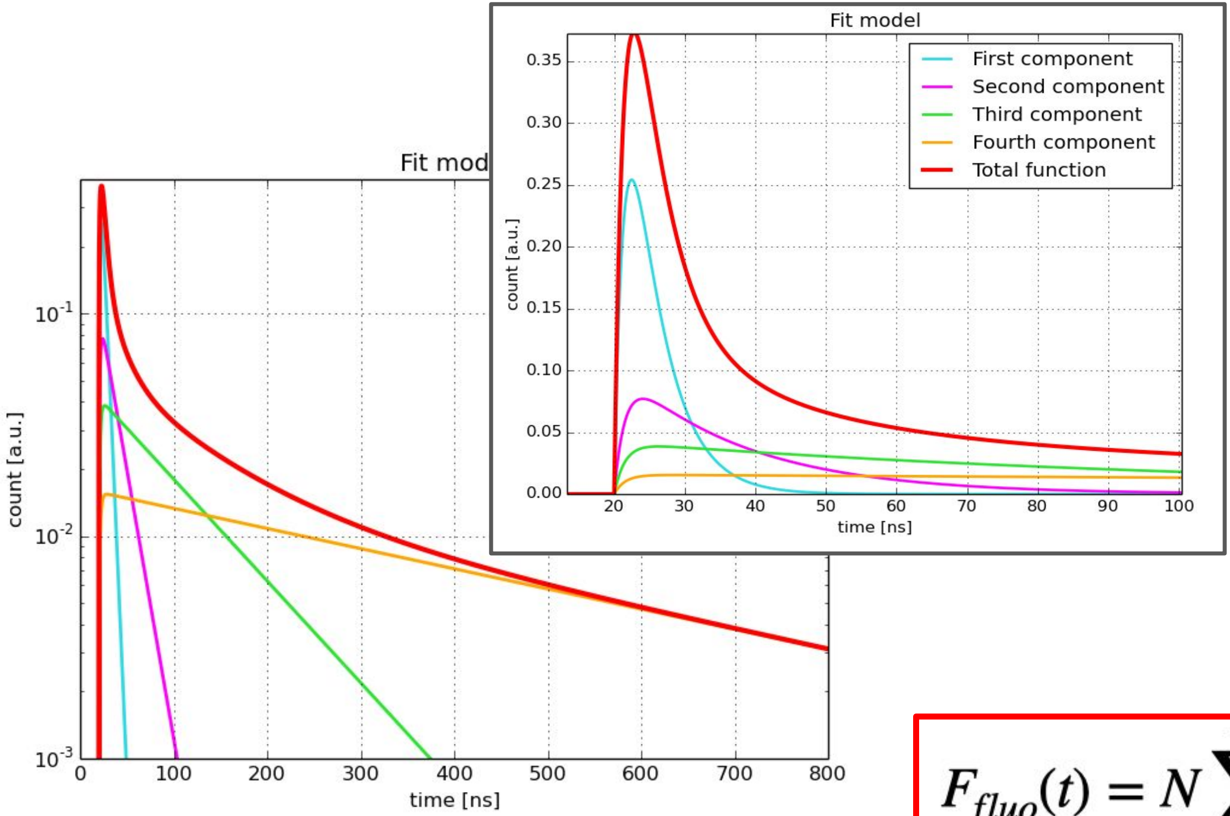


Fluorescence time distribution obtained using an alpha source

The duration of the data acquisition is 10 days to obtain 10^6 events

The light emission is **not** a prompt emission

Fit model: four exponential decay



To describe the fluorescence time profile **4 components** are needed

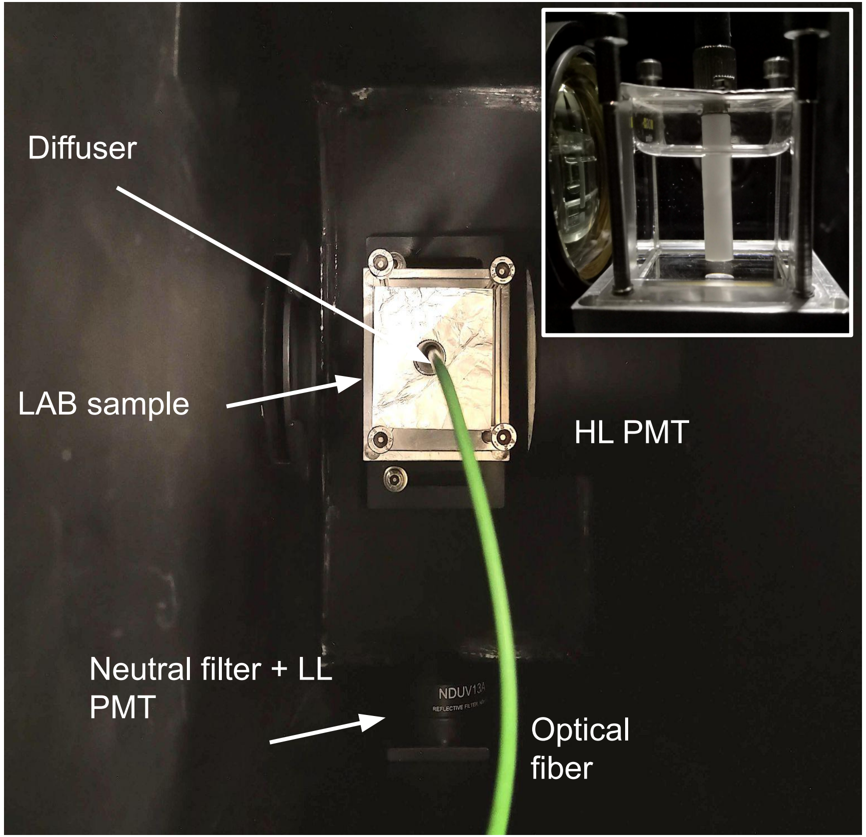
The fourth becomes dominant starting from **~300 ns**

Our DAQ time window is **1600 ns**

This model needs to be **convolved** with the **detector response**

$$F_{fluo}(t) = N \sum_{d=1}^{4} \frac{q_d}{\tau_d - \tau_r} \left(e^{-t/\tau_d} - e^{-t/\tau_r} \right)$$

Impulse response function

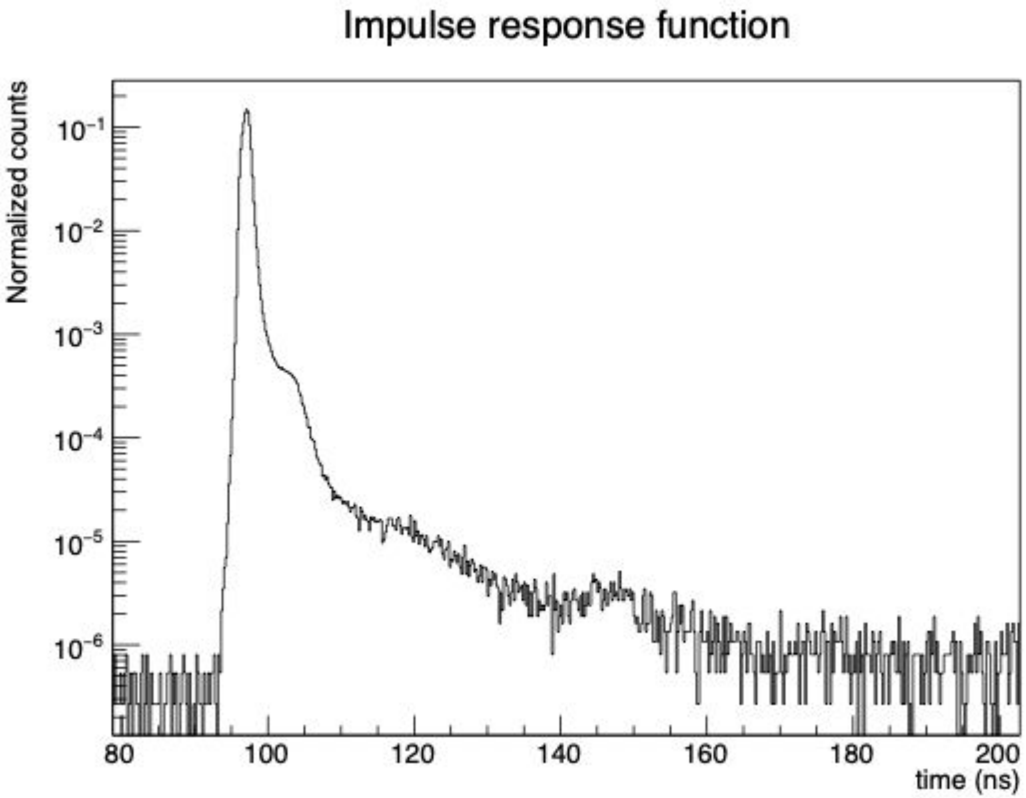


We used a **laser at 405 nm** to characterize the detector response

The laser beam goes to a **diffuser immersed** in **LAB**

We wanted to emulate all the effect in the experimental setup, like reflections

Impulse response function



We used a **laser at 405 nm** to characterize the detector response

The laser beam goes to a **diffuser immersed** in **LAB**

We wanted to emulate all the effect in the experimental setup, like reflections

Mainly **Gaussian** with some secondary effects (visible in log-scale only) that we take into account in the fit

Fluorescence in SNiPER

Particles	Fast(ns)/ Ratio	Slow(ns)/ Ratio	Slower(ns)/ Ratio	Slowest(ns)/ Ratio
γ, e^+, e^-	4.6/70.7%	15.1/20.5%	76.1/6.0%	397/2.8%
n, p^+	4.5/61.4%	15.7/23.2%	76.2/9.0%	367/6.4%
α	4.345/49.82%	17.64/27.39%	89.045/14.67%	544.48/8.12%

Talk of Yaoguang Wang “Detector simulation status” 18/07/2022

Fluorescence in SNiPER

Provided by the Munich group as preliminary results

Particles	Fast(ns)/ Ratio	Slow(ns)/ Ratio	Slower(ns)/ Ratio	Slowest(ns)/ Ratio
γ, e^+, e^-	4.6/70.7%	15.1/20.5%	76.1/6.0%	397/2.8%
n, p^+	4.5/61.4%	15.7/23.2%	76.2/9.0%	367/6.4%
α	4.345/49.82%	17.64/27.39%	89.045/14.67%	544.48/8.12%

Talk of Yaoguang Wang “Detector simulation status” 18/07/2022

Fluorescence in SNiPER

Provided by the Munich group as preliminary results

Particles	Fast(ns)/ Ratio	Slow(ns)/ Ratio	Slower(ns)/ Ratio	Slowest(ns)/ Ratio
γ, e^+, e^-	4.6/70.7%	15.1/20.5%	76.1/6.0%	397/2.8%
n, p^+	4.5/61.4%	15.7/23.2%	76.2/9.0%	367/6.4%
α	4.345/49.82%	17.64/27.39%	89.045/14.67%	544.48/8.12%

Talk of Yaoguang Wang “Detector simulation status” 18/07/2022

We still don’t know the source of this parameters

Fluorescence in SNiPER: compare

Particles	Fast(ns)/ Ratio	Slow(ns)/ Ratio	Slower(ns)/ Ratio	Slowest(ns)/ Ratio
e^-	4.36/78.98%	17.55/11.07%	89.16/6.09%	590/3.86%
α	4.63/62.33%	19.87/18.66%	102.0/11.86%	644/7.15%
α	4.345/49.82%	17.64/27.39%	89.045/14.67%	544.48/8.12%

PRELIMINARY RESULTS

We still don't know the source

Fluorescence in SNiPER: compare

Provided by the Munich group as preliminary results

Particles	Fast(ns)/ Ratio	Slow(ns)/ Ratio	Slower(ns)/ Ratio	Slowest(ns)/ Ratio
γ, e^+, e^-	4.6/70.7%	15.1/20.5%	76.1/6.0%	397/2.8%
e^-	4.36/78.98%	17.55/11.07%	89.16/6.09%	590/3.86%
α	4.63/62.33%	19.87/18.66%	102.0/11.86%	644/7.15%

PRELIMINARY RESULTS

SHELDON: conclusion

- **We are studying the systematics** of our measurements, checking the results on different solvents (from two different producers HELM, SASOL or from mixtures made in different time by different persons and so on..) **So far we are not seeing big systematic effects**

- I have brought back **from China a sample of the LAB** which will be actually used in JUNO. **We will perform the measurement also on this**

- After these final checks, we think the **results are mature to be put officially on SNIPER**

- The Munich group is also performing a similar measurement (on the same samples that we use): we will compare our results with their when it is available

The SHELDON-Rewind project: scientific goals

REfractive index **W**ith **IN**terferometric **D**evices
@ UNIMI - Milan

Refractive index measurement

Group velocity measurement

The SHELDON-Rewind project: scientific goals

REfractive index **W**ith **IN**terferometric **D**evices
@ UNIMI - Milan

Refractive index measurement

Group velocity measurement

Impact on the JUNO experiment:

- position reconstruction
- energy reconstruction

The SHELDON-Rewind project: scientific goals

REfractive index **W**ith **IN**terferometric **D**evices
@ UNIMI - Milan

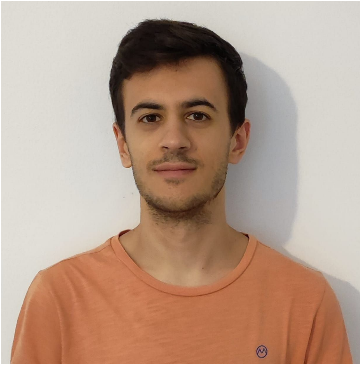
Refractive index measurement

Group velocity measurement

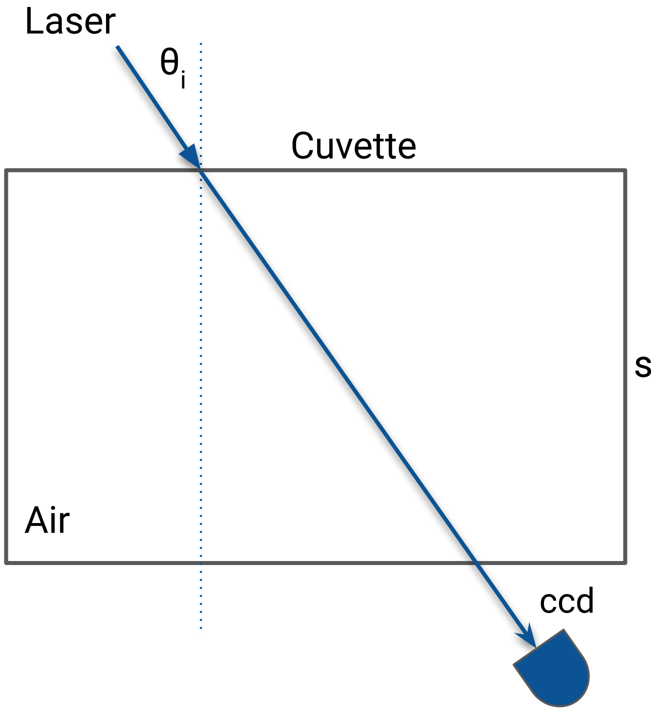
Impact on the JUNO experiment:

- position reconstruction
- energy reconstruction

This was the main goal of the Master's Thesis of **Gioele Reina**, who completed his studies at the beginning of April.



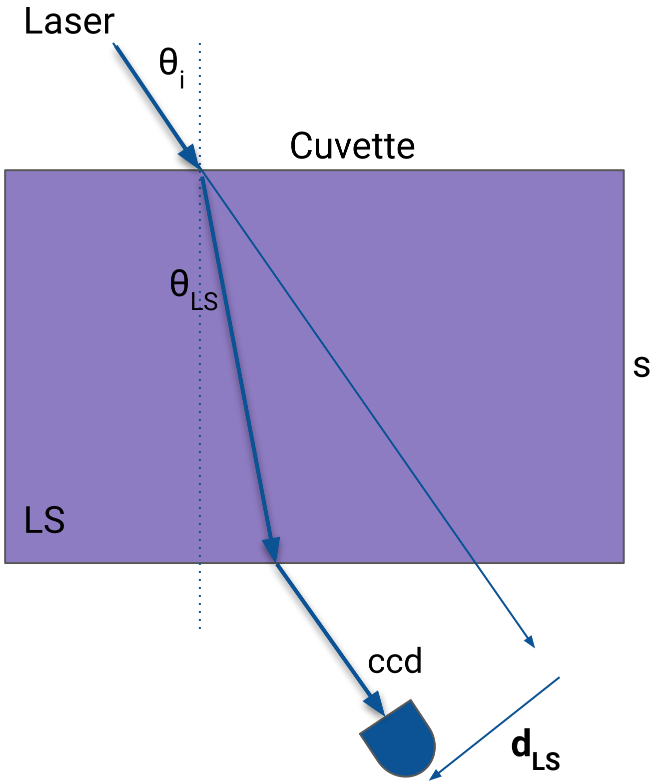
Refractive index measurement



We used a **refractometer** to perform the measurements of the refractive index

Using a laser and a CCD we can see the displacement of due to the insertion of the liquid scintillator

Refractive index measurement

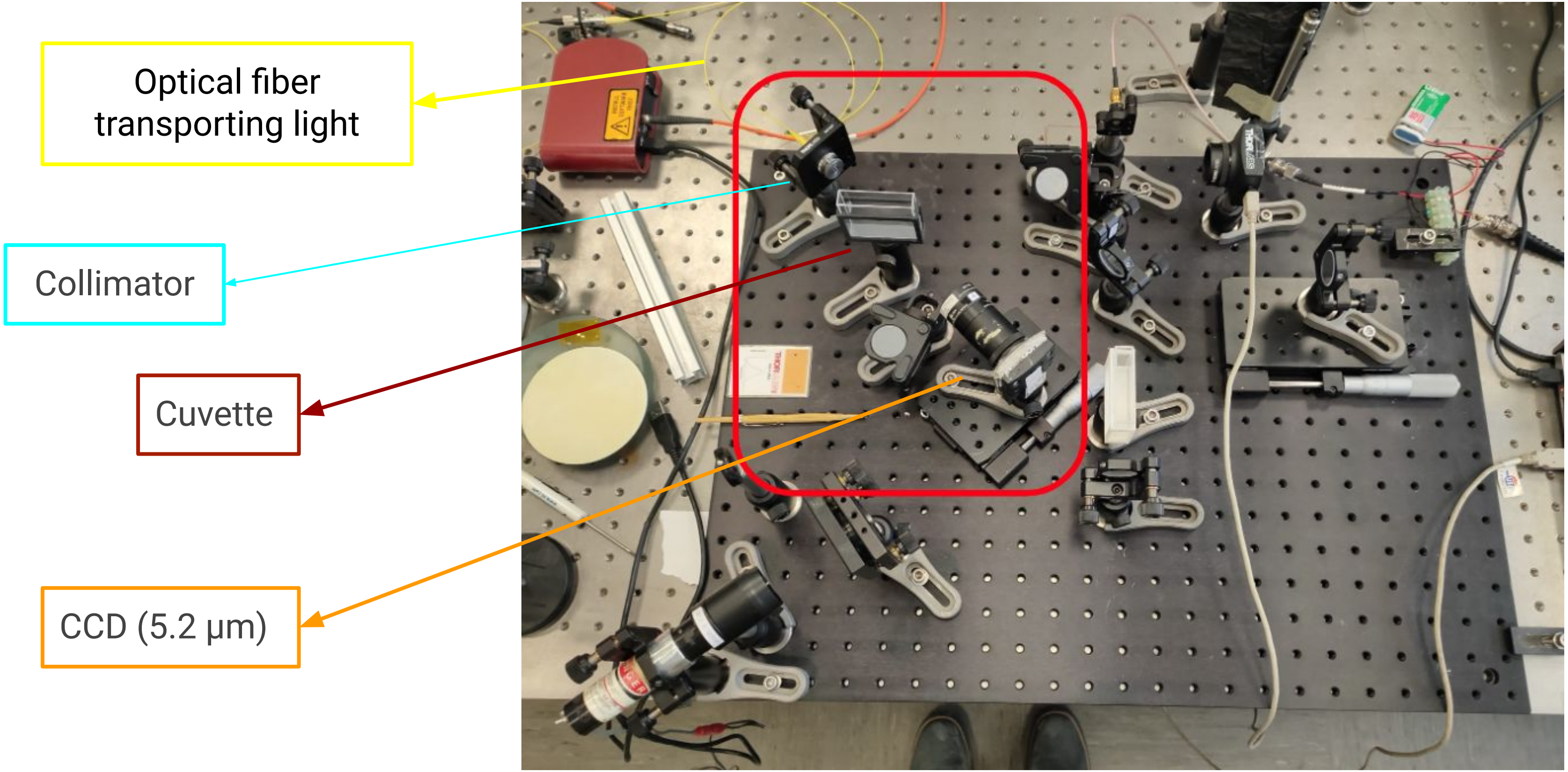


We used a **refractometer** to perform the measurements of the refractive index

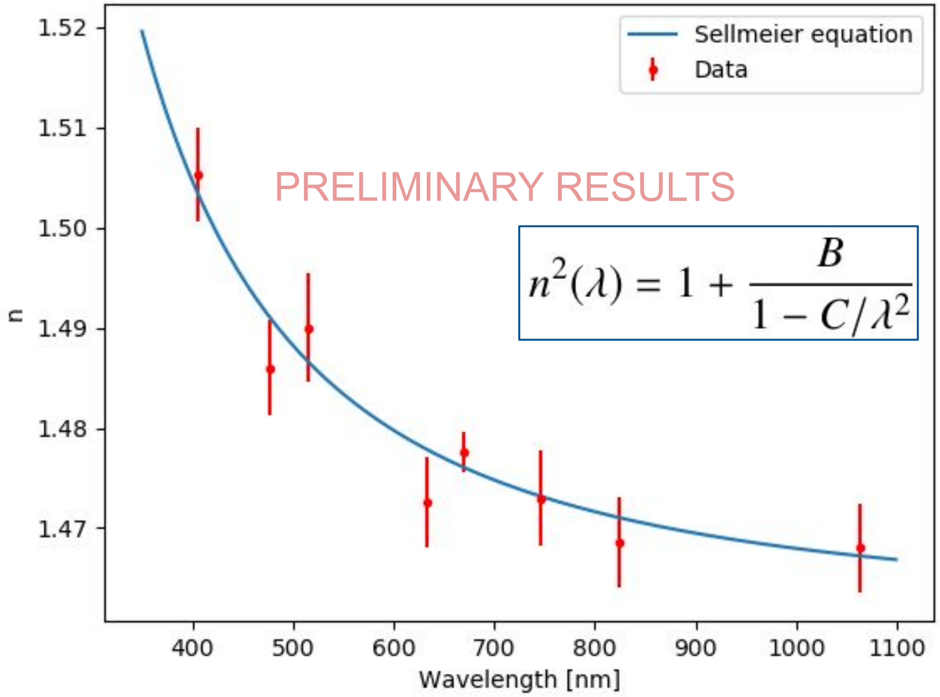
Using a laser and a CCD we can see the displacement of due to the insertion of the liquid scintillator

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

Refractive index measurement: setup



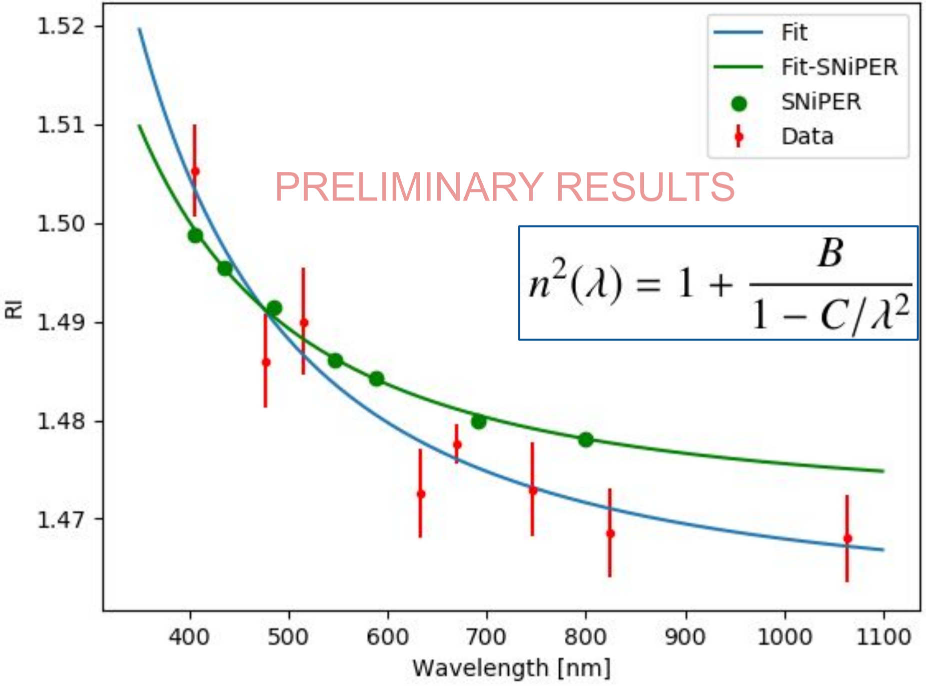
Refractive index measurement: results



Wavelength (nm)	Refractive index
405.5	1.505 ± 0.007
476.5	1.486 ± 0.007
514.5	1.49 ± 0.008
633	1.473 ± 0.007
670	1.478 ± 0.003
745.7	1.473 ± 0.007
823.5	1.469 ± 0.007
1064	1.468 ± 0.007

PRELIMINARY RESULTS

Refractive index measurement: results

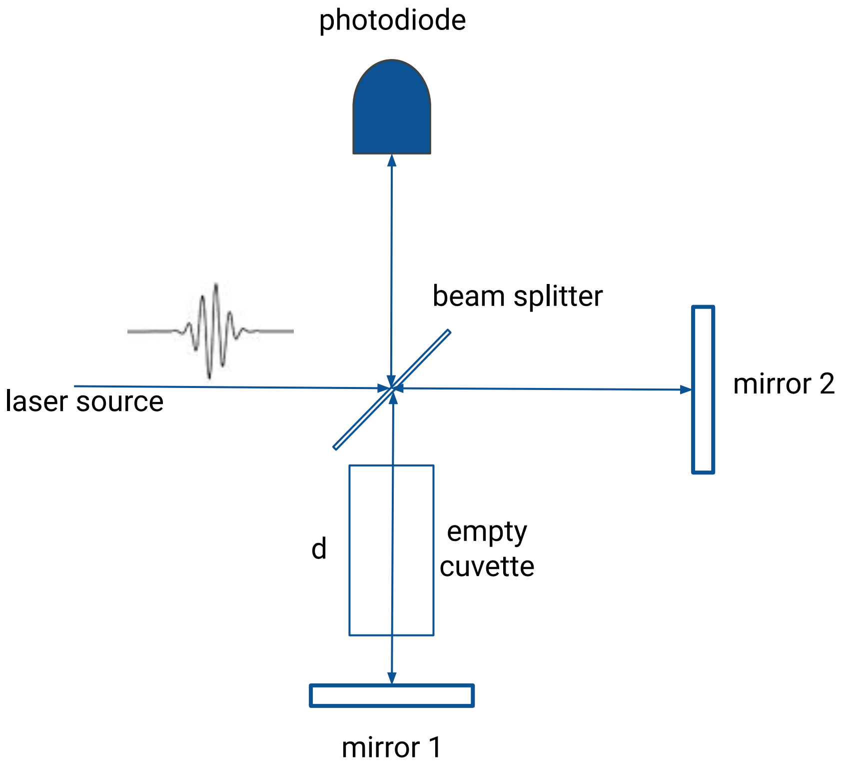


We compared our results with the SNiPER parameter

We found a difference in the shape but we do not know the SNiPER errors

We know that a Chinese group is going to measure the refractive index using another method

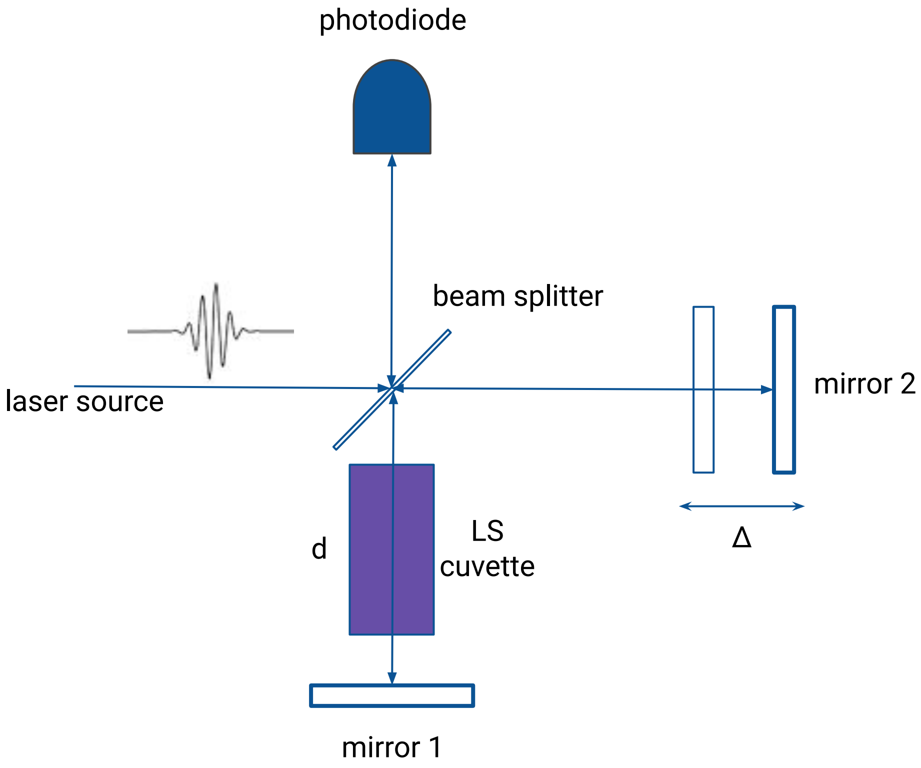
Group velocity measurement



We used a **interferometer** to perform the measurements of the group velocity

We have only one laser with the optimal characteristics to perform this measurement

Group velocity measurement



We used a **interferometer** to perform the measurements of the group velocity

We have only one laser with the optimal characteristics to perform this measurement

Inserting the LS and moving a mirror we can measure the group velocity in the liquid scintillator

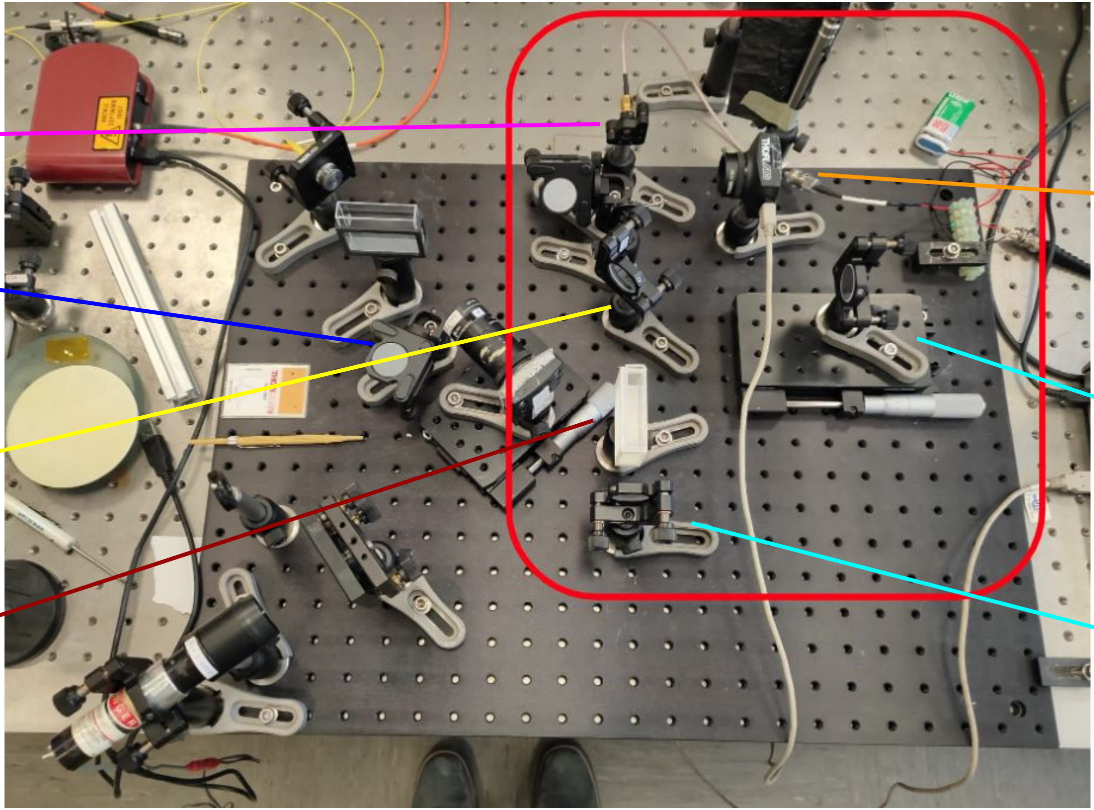
Group velocity measurement: setup

Photodiode

Flipping mirrors

Beam splitter

Cuvette

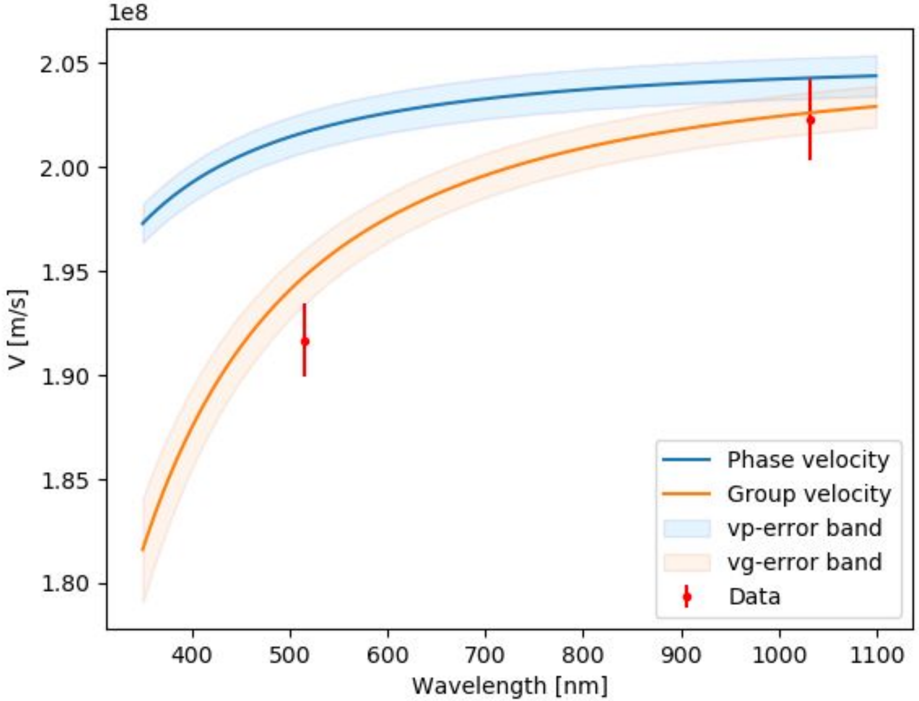


CCD (5.2 μm)

Mirror 2
+
Sliding plate

Mirror 1

Group velocity measurement: results



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

Refractive index from the previous fit result

Wavelength (nm)	Group velocity (c)
516	0.6394 ± 0.006
1032	0.6748 ± 0.007

SHELDON-Rewind: conclusion

- We will try to measure the refractive index and the group velocity at **two new wavelength 405 nm and 343 nm**

- **Our measurements** of the group velocity and the refractive index **are compatible** with each other

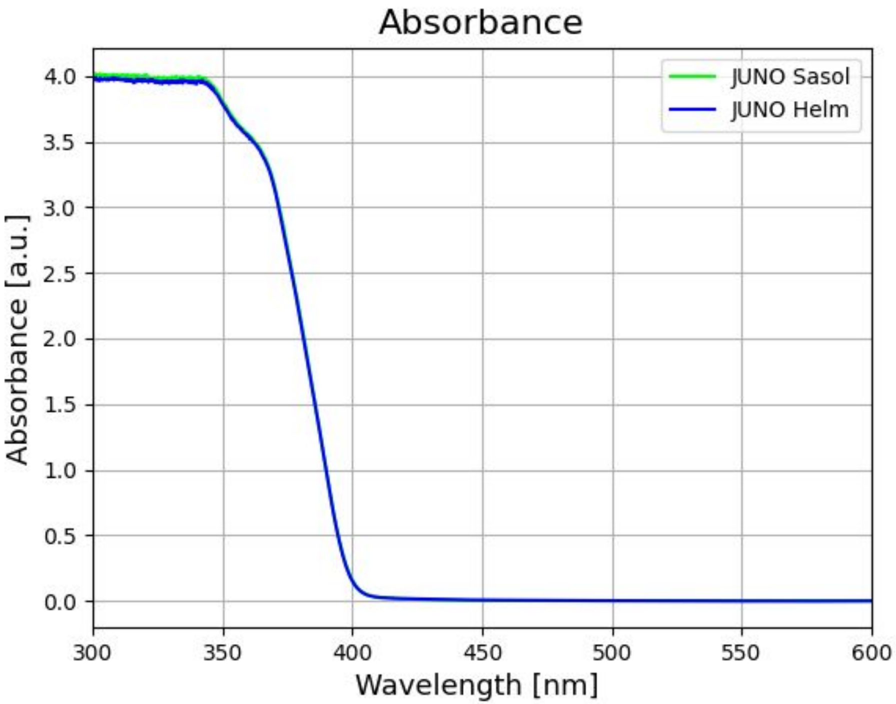
- We have made **contact with the Chinese group** that is about to start doing similar refractive index measurements

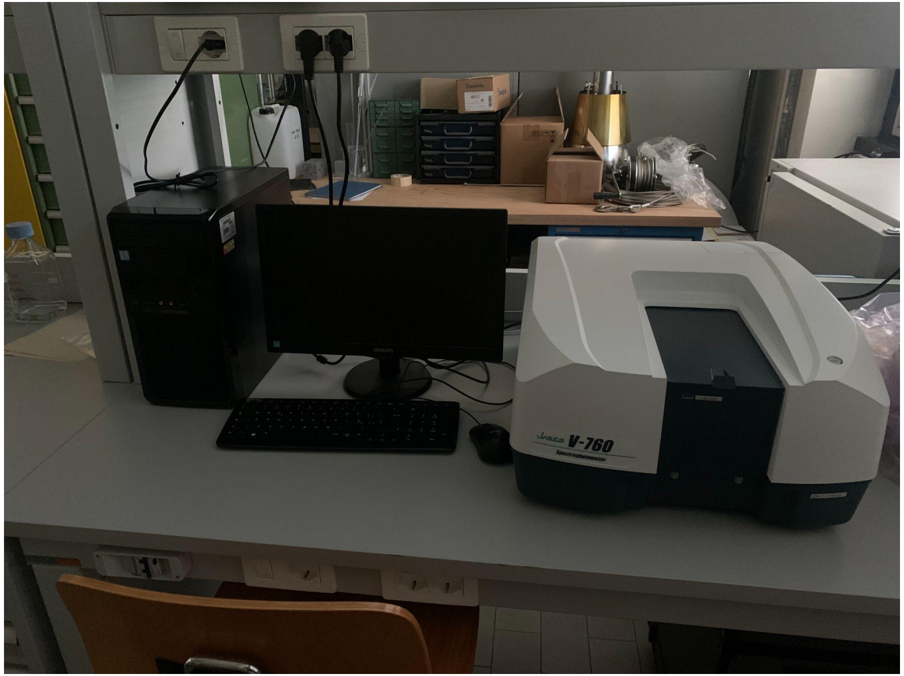
- After cross-checking with the Chinese group, we want to put the **new refractive index values into SNiPER**

Thank you for the attention

Backup

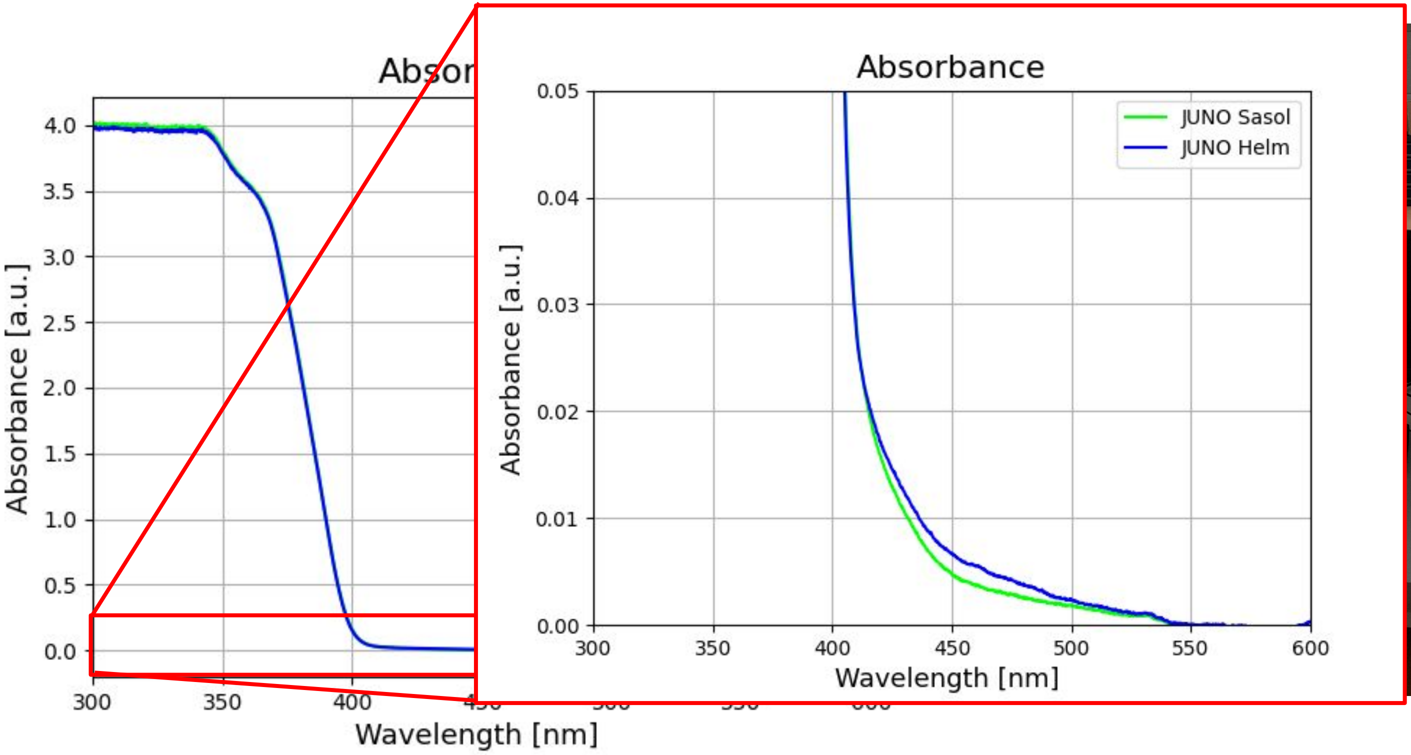
Absorbance





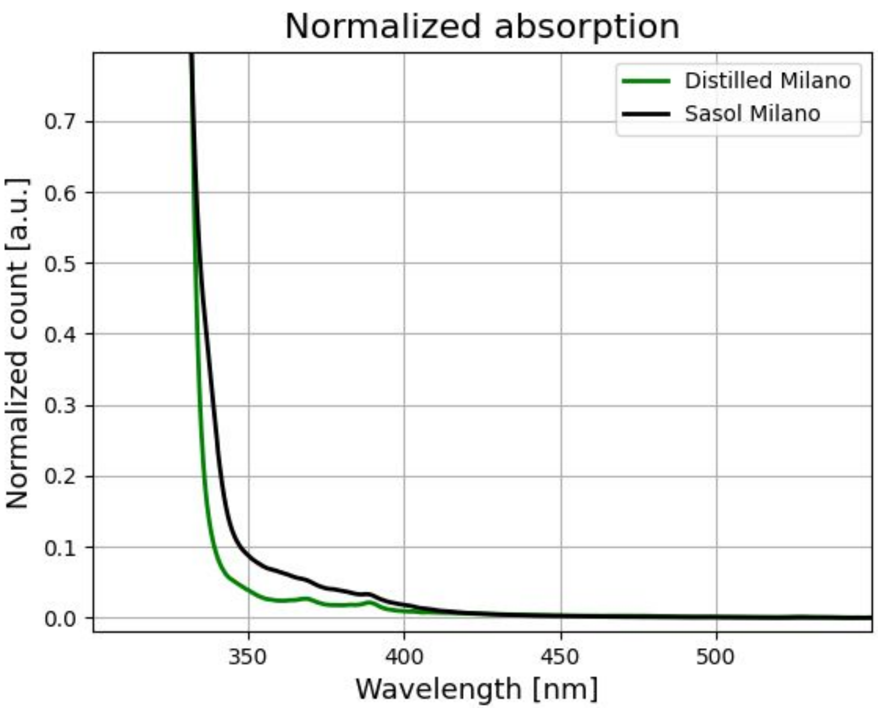
Measured using a spectrophotometer in Milan

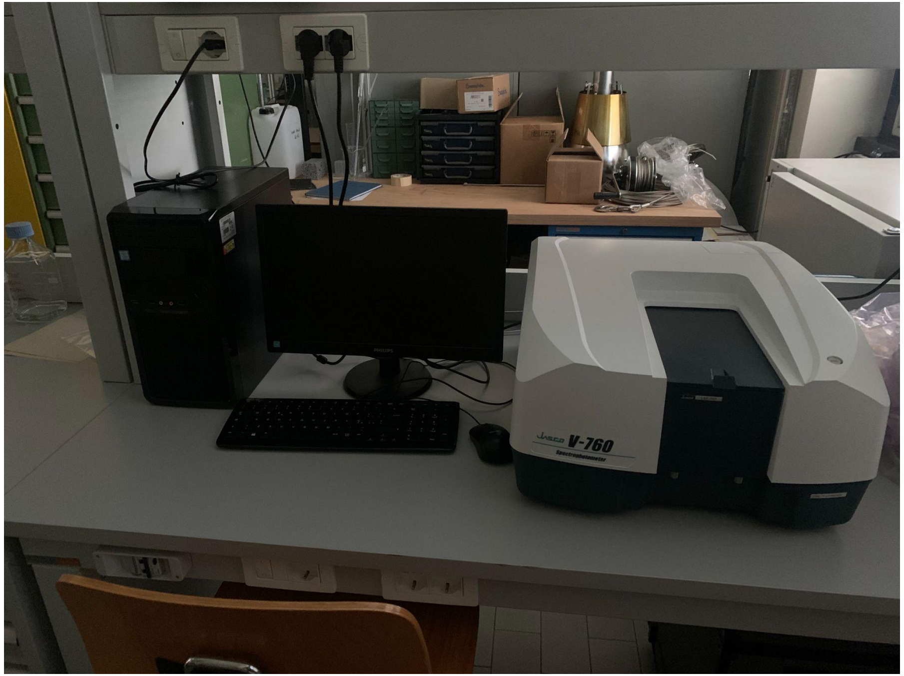
Absorbance



Measured using a spectrophotometer in Milan

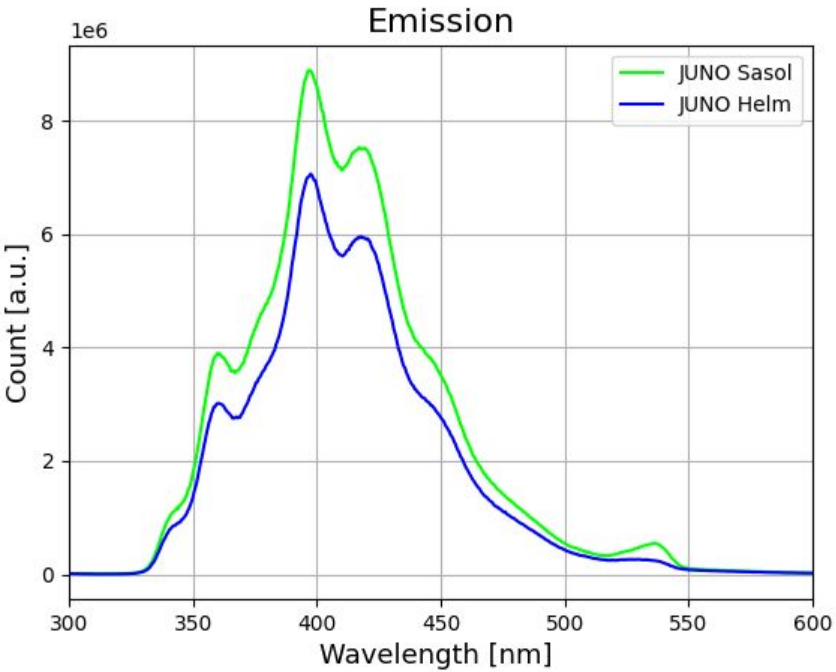
Absorbance: LAB compare





Measured using a spectrophotometer in Milan

Emission spectrum

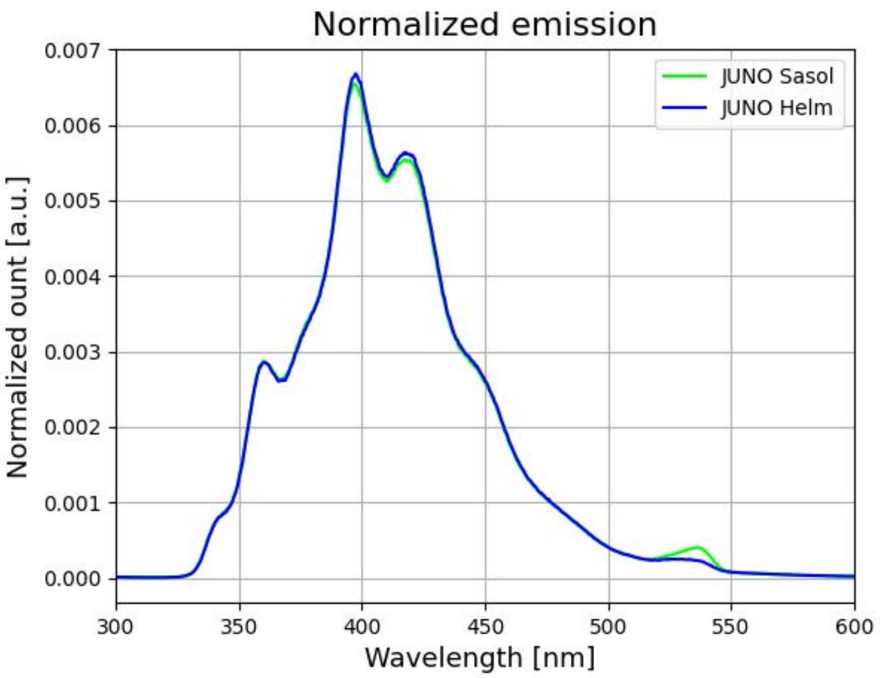


JUNO LS mixtures produce, in Perugia, using Sasol LAB and Helm LAB have:

- **Different light yield**

Measured @ Università degli Studi di Perugia
thanks to: Fausto, Aldo e Catia

Emission spectrum



JUNO LS recipe: LAB + 2.5 g/L PPO + 3.0 mg/L bis-MSB

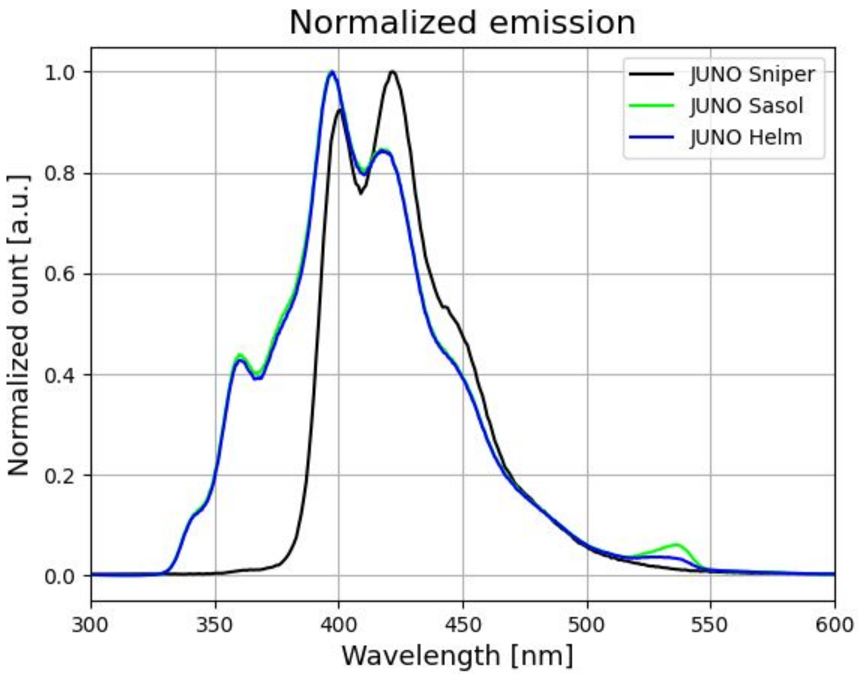
JUNO LS mixtures produce, in Perugia, using Sasol LAB and Helm LAB have:

- **Different light yield**

but

- **Similar shape**

Emission spectrum



JUNO LS recipe:	LAB + 2.5 g/L PPO + 3.0 mg/L bis-MSB
DB LS recipe:	LAB + 3.0 g/L PPO + 15 mg/L bis-MSB

JUNO LS mixtures produce, in Perugia, using Sasol LAB and Helm LAB have:

- **Different light yield**

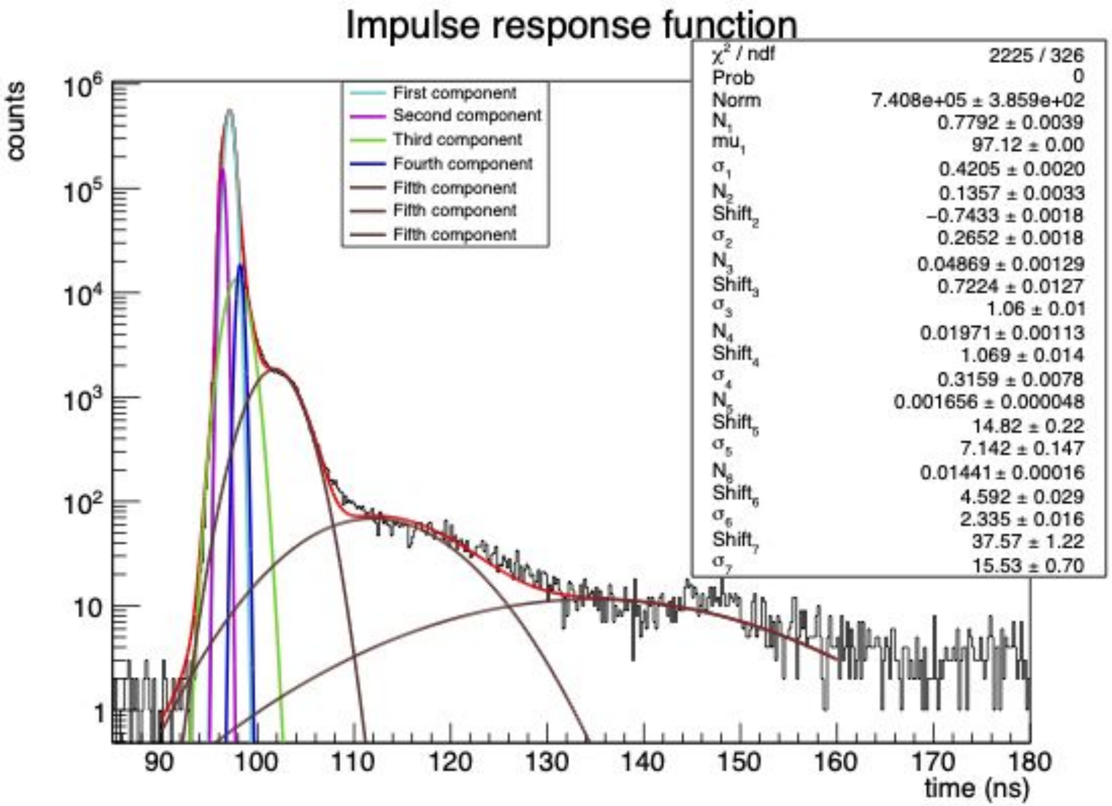
but

- **Similar shape**

Both have different shape comparing to SNiPER spectrum

→ **inherited from DayaBay**

Impulse response function: modeling



We used a **laser at 405 nm** to characterize the detector response

The laser beam goes to a **diffuser immersed** in **LAB**

We wanted to emulate all the effect in the experimental setup, like reflections

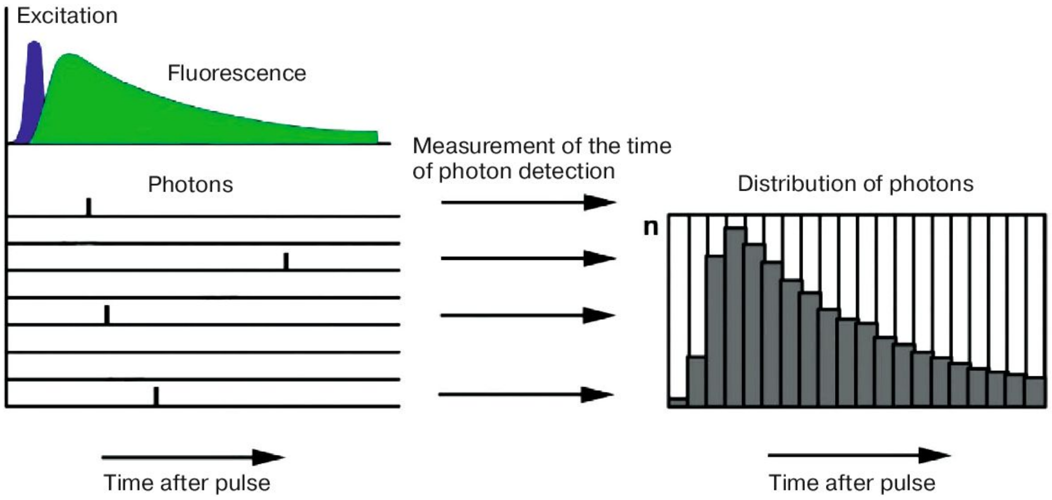
Mainly **Gaussian** with some secondary effects (visible in log-scale only) that we take into account in the fit

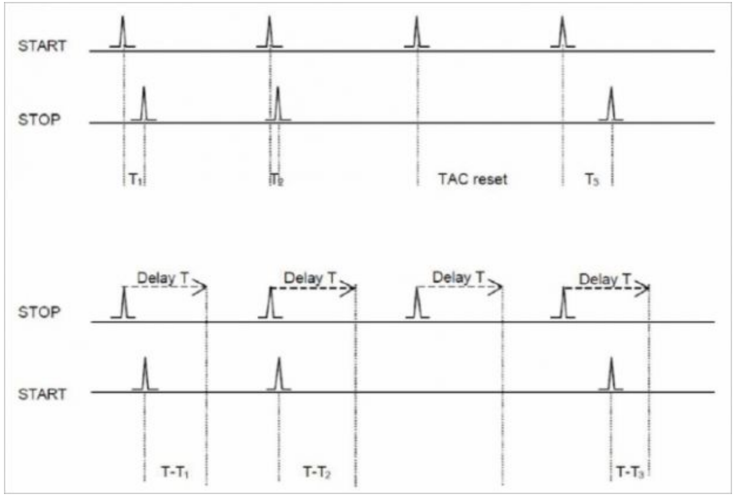
TCSPC

Time-correlated single photon counting (TCSPC) is a technique to measure the fluorescence decay time.

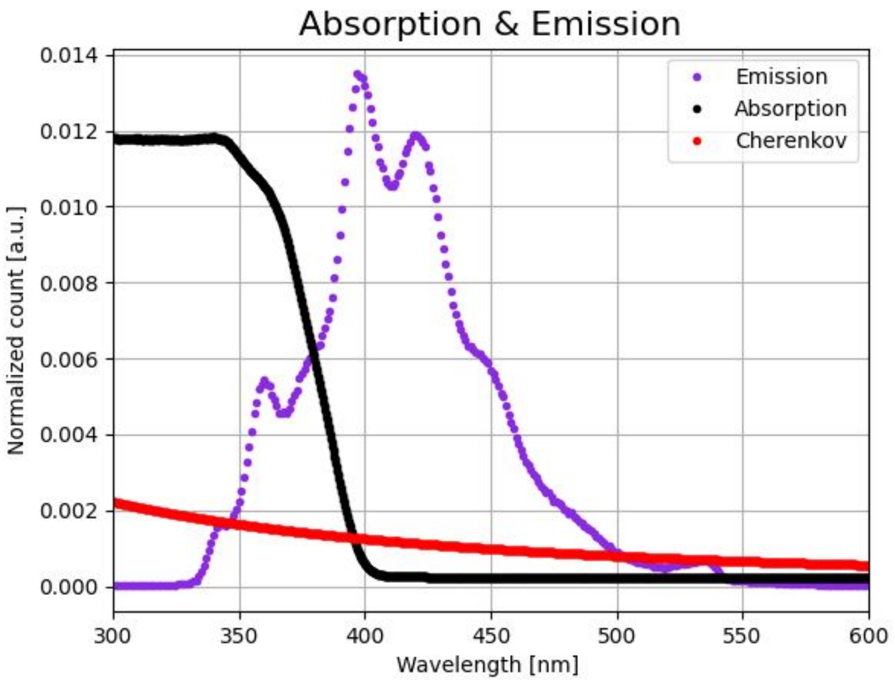
Under certain hypothesis ($R_{sp} << R_{tr}$), the time of arrival of the photons w.r.t. to the trigger reproduces the fluorescence time distribution.

In our application, one PMT provides the START signal (trigger) and the other PMT gives the STOP signal.





Cherenkov contribution



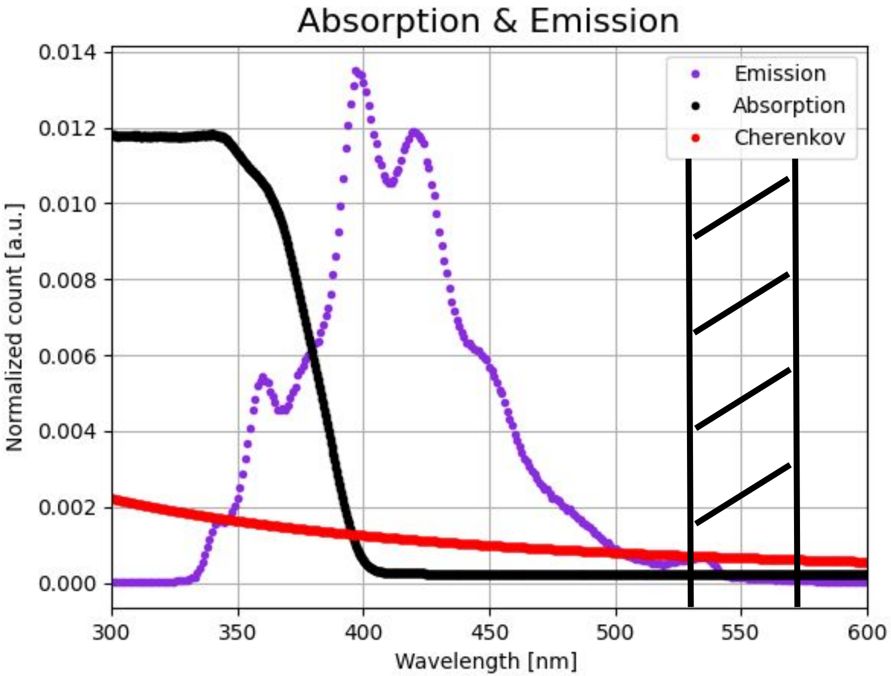
Cherenkov light can be separated from scintillation light thanks to its spectral features.

The JUNO LS emission spectrum has a maximum at 400 nm

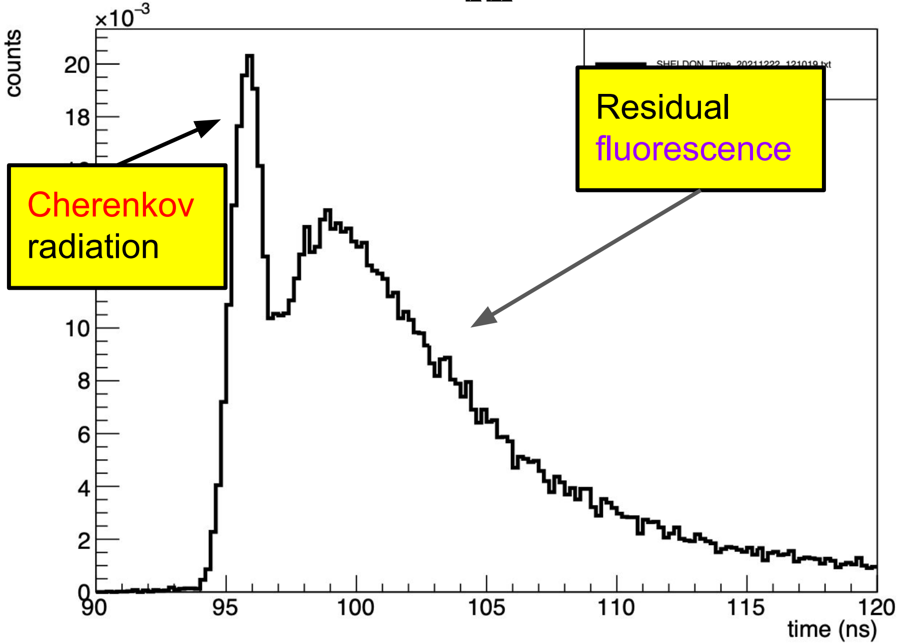
The **Cherenkov spectrum** (not to scale) decreases as $1/\lambda^2$ and extends above the scintillation spectrum.

Using appropriate optical filters it is possible to select the light in a **desired wavelength interval**, separating scintillation and Cherenkov light.

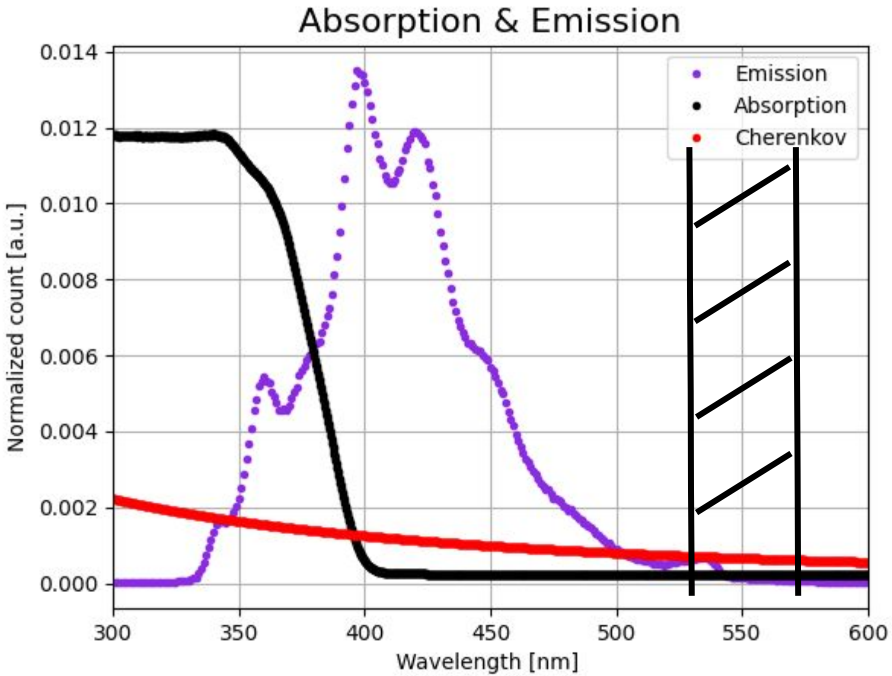
Cherenkov contribution



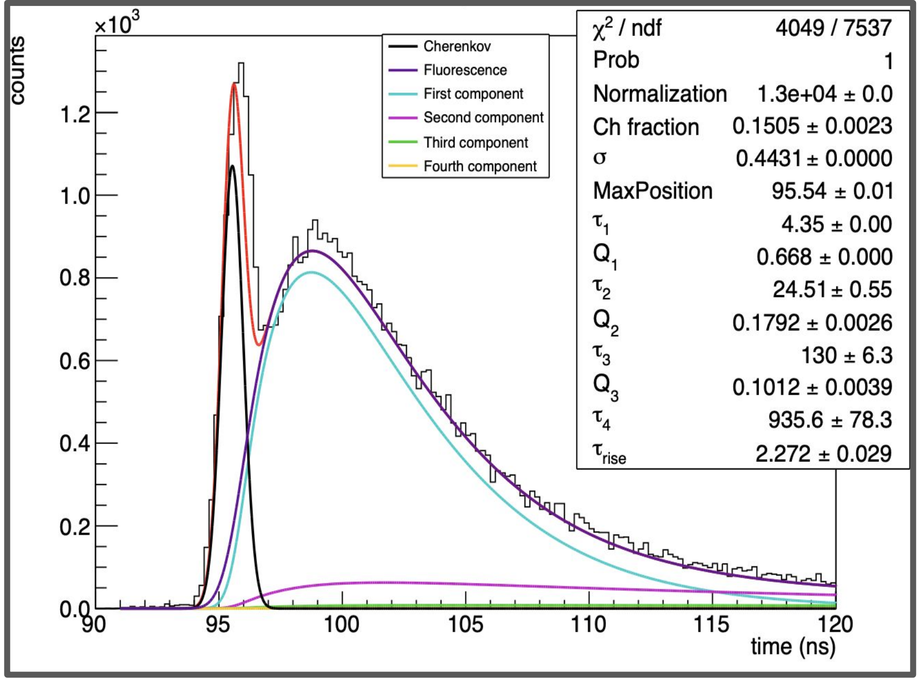
Cherenkov separation in the band 530-570



Cherenkov contribution



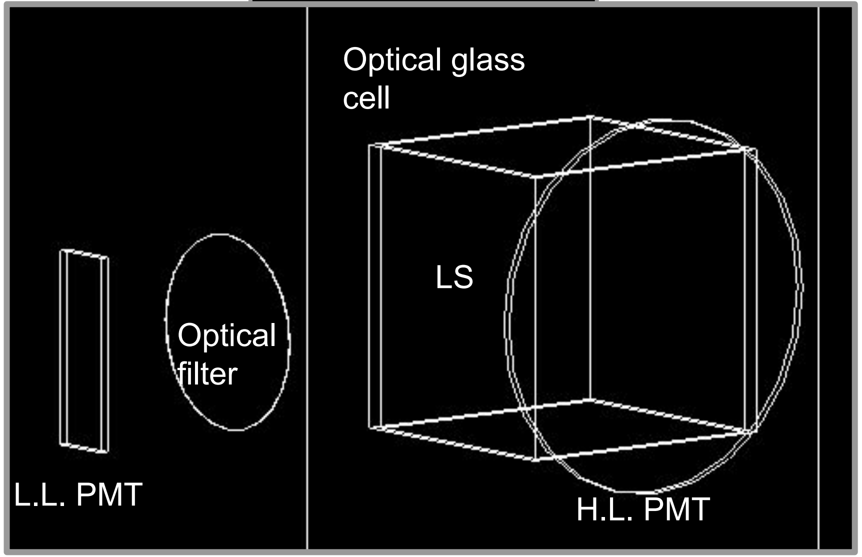
550 - 40 nm



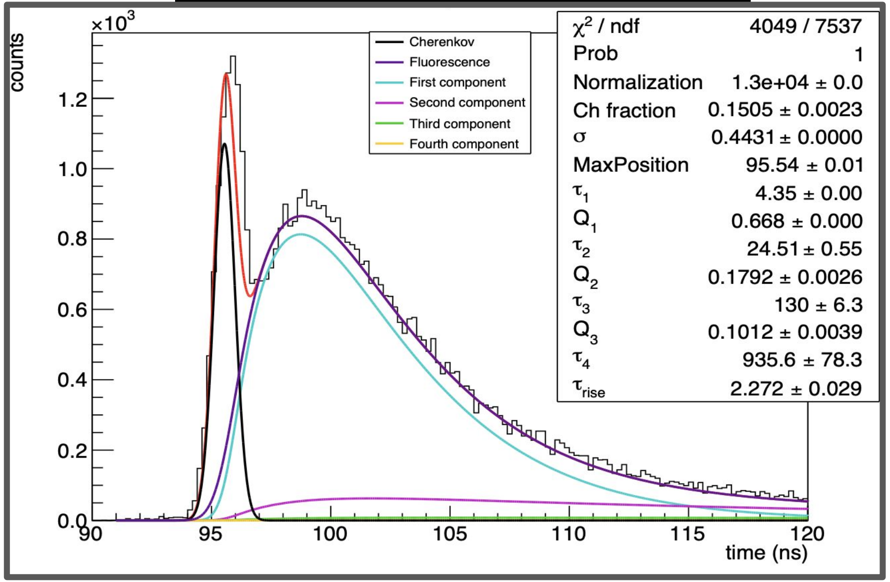
Cherenkov = 15.1 ± 0.2 %

Cherenkov contribution

Geant4 simulation



550 - 40 nm



We will measure the Cherenkov contribution in the JUNO LS comparing real data with simulations

SHELDON-Rewind: Laser sources

Testing at several wavelengths

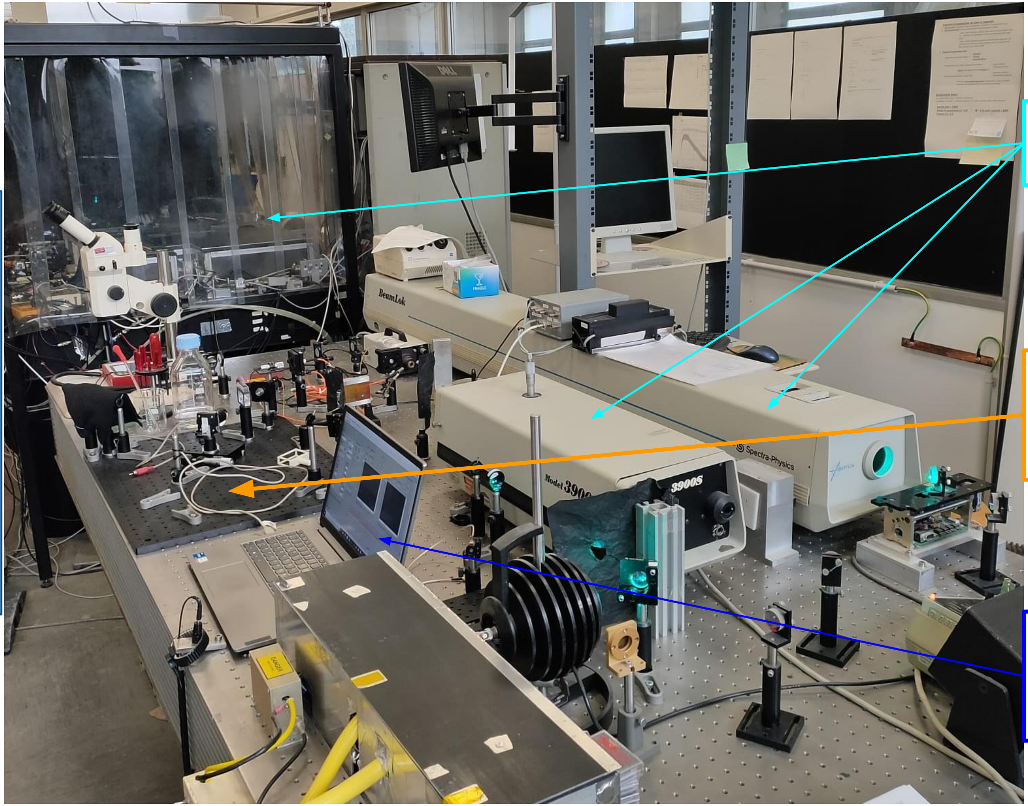
He-Ne: 633 nm

Ar: 476 nm, 514.5 nm

Diode: 405 nm, 670 nm

Yb: 345 nm, 516 nm, 1032 nm

Nd:YAG: 1064 nm

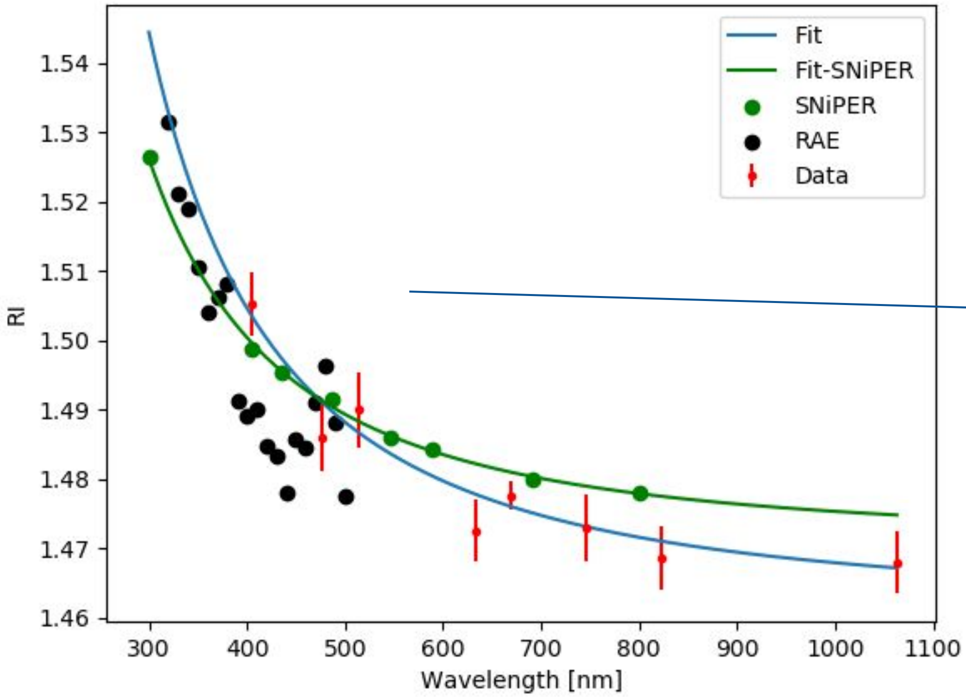


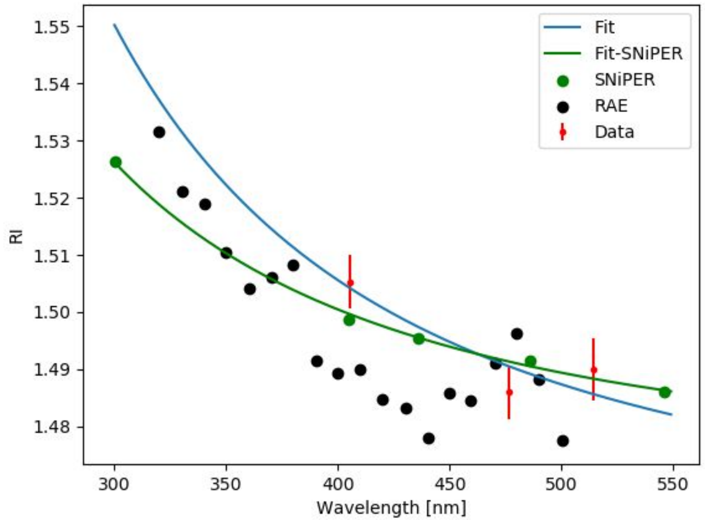
Lasers

REWIND optical breadboard

DAQ LabVIEW code

Refractive index: SNiPER compare





	τ_1 [ns]	τ_2 [ns]	τ_3 [ns]	τ_4 [ns]	q_1 [%]	q_2 [%]	q_3 [%]	q_4 [%]
α	4.63 ± 0.02	19.87 ± 0.41	102.0 ± 2.2	644 ± 13	62.33 ± 0.31	18.66 ± 0.22	11.86 ± 0.16	7.15 ± 0.41
e^-	4.36 ± 0.02	17.55 ± 0.51	89.16 ± 2.6	590 ± 12	78.98 ± 0.29	11.07 ± 0.20	6.09 ± 0.11	3.86 ± 0.37

PRELIMINARY RESULTS