SHELDON-REWIND
REfractive index **W**ith **IN**terferometric **D**evices
Measurements of the Liquid Scintillator optical properties

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JUNO italian meeting meeting

ENERGY AND POSITION MEASUREMENT

PMTs detected light

Total number of collected photons

Energy

Measured times of arrival

Position

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Total number of collected photons

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- Light yield
- Transparence
- Cherenkov contribution

Measured times of arrival

Position

- Fluorescence times τ_i
- Refractive index **n**
- Group velocity 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)
- **Spatial resolution** 10 cm (@1 MeV)

Best LS characterization

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SHELDON-REWIND: REfractive index With INterferometric Devices

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

Refractive index

Refractive index n

Position reconstruction

Arrival time measurements
+
processes at boundary

Energy reconstruction

Cherenkov contribution

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

Refractive index with refractometer

n: Arrival time measurement + Cherenkov contribution

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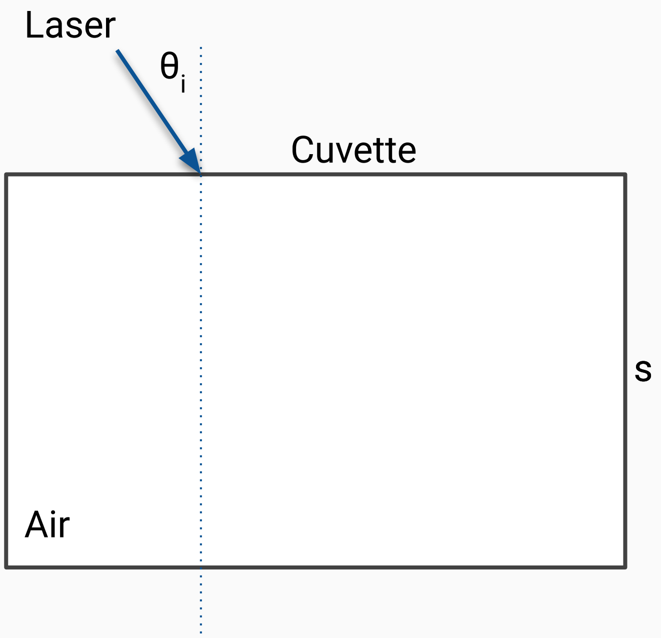
For this measurement we use a **refractometer**:

Refractive index with refractometer



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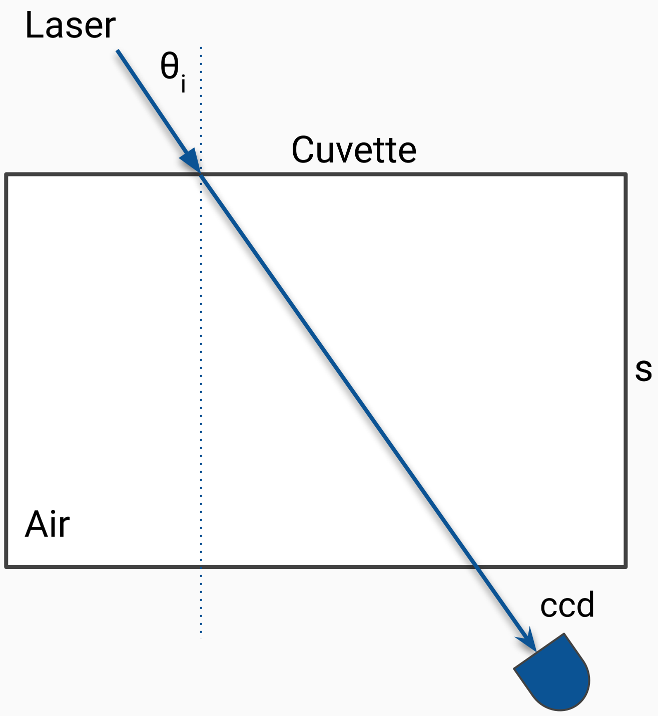

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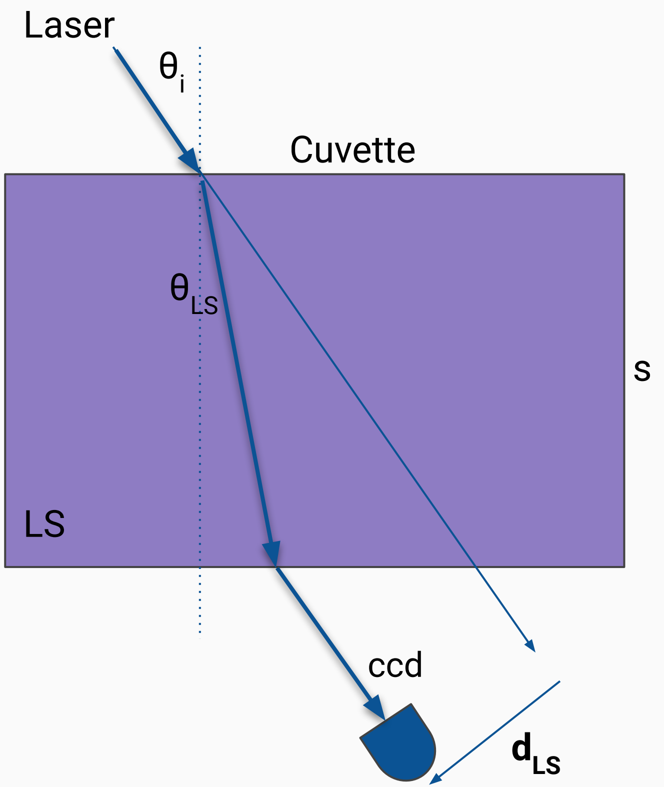

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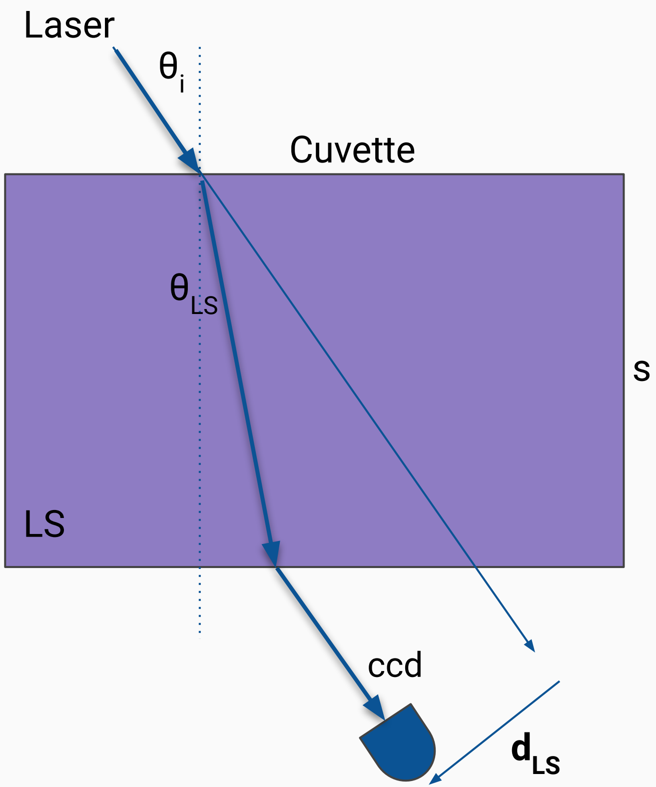

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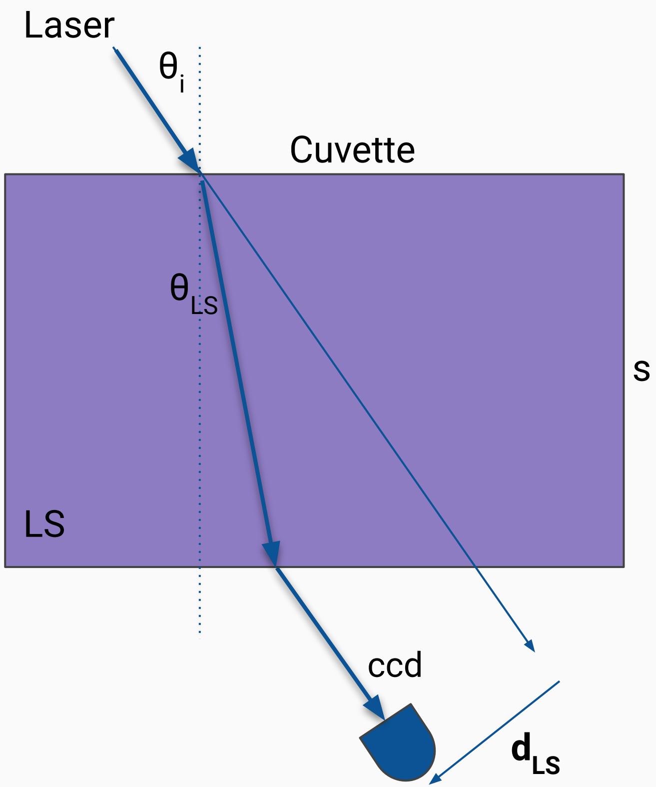

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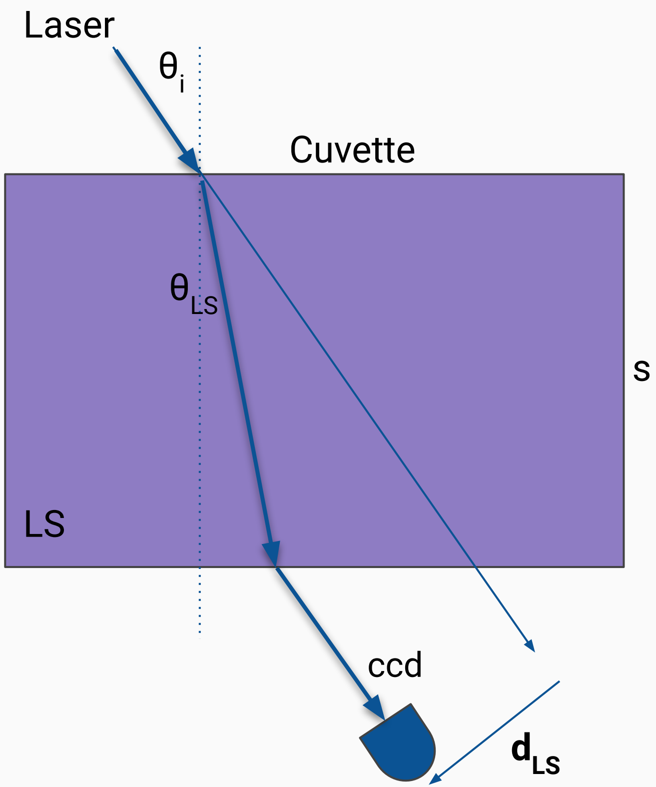

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- Different refractive angle with/without LS
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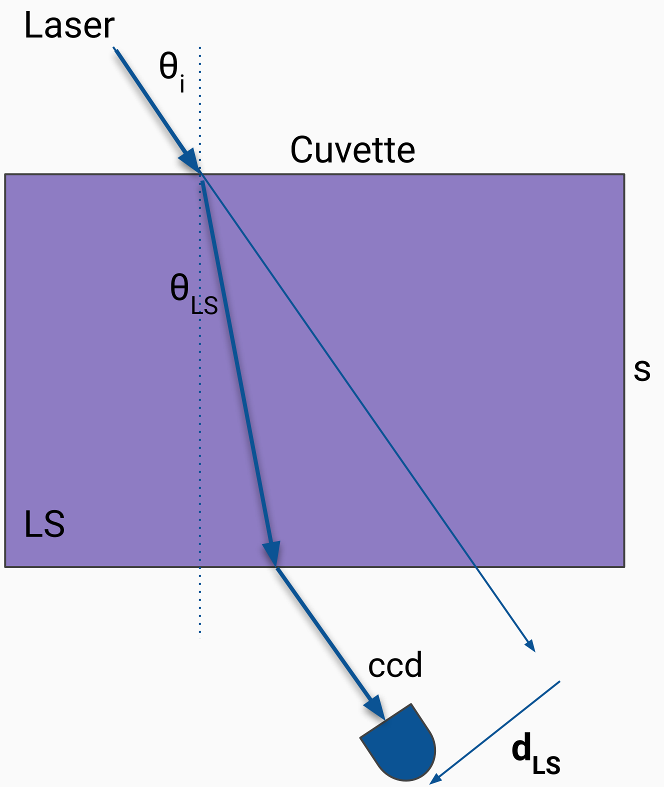
$$d_{LS} = \frac{s \sin\left[\theta_i - \arcsin\left(\frac{n_{air}}{n_{LS}} \sin\theta_i\right)\right]}{\cos\left[\arcsin\left(\frac{n_{air}}{n_{LS}} \sin\theta_i\right)\right]}$$

→ $\mathbf{n_{LS}}$

Refractive index with refractometer



n: Arrival time measurement + Cherenkov contribution

Testing at several wavelengths

From 405 nm to 1064 nm

Get **n** as a function of wavelengths

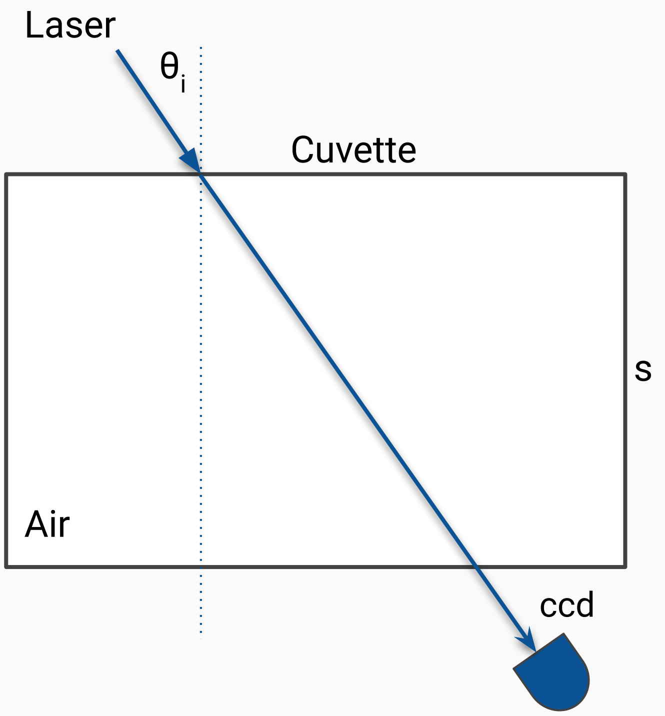
Cherenkov radiation

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

REWIND: Refractive index with refractometer

OUR MEASUREMENT

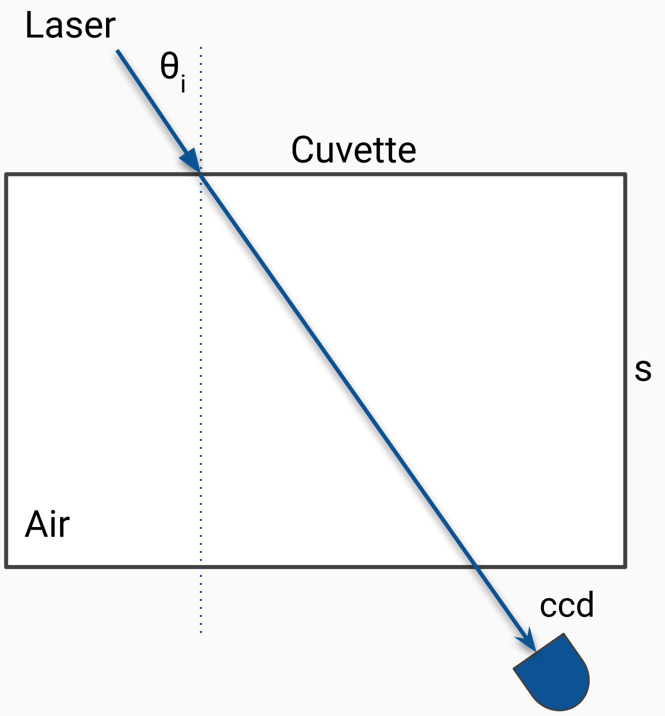
REWIND: Refractive index with refractometer



Air

Measure the position of the beam on the ccd

REWIND: Refractive index with refractometer



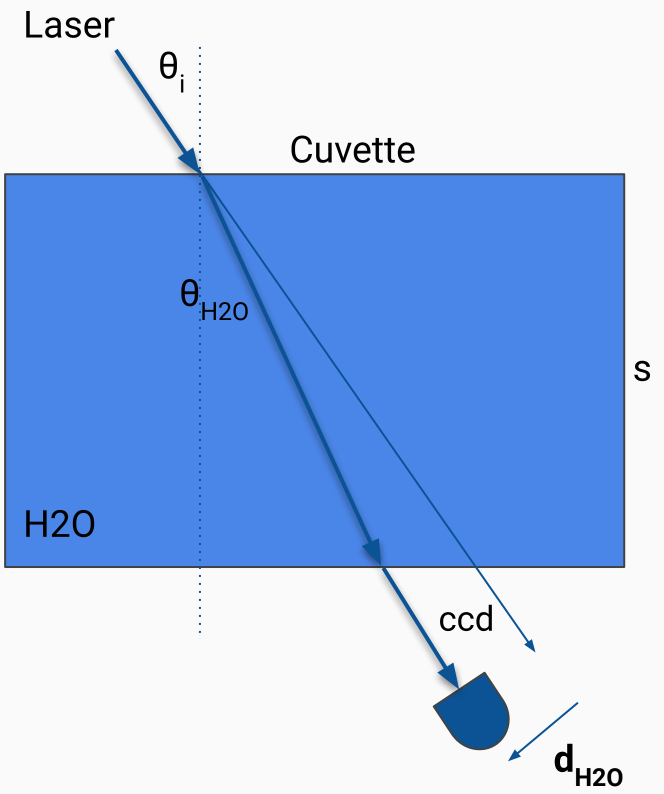
Air

Measure the position of the beam on the ccd

Goal: know well θ_i

Solution: use a material with well known n

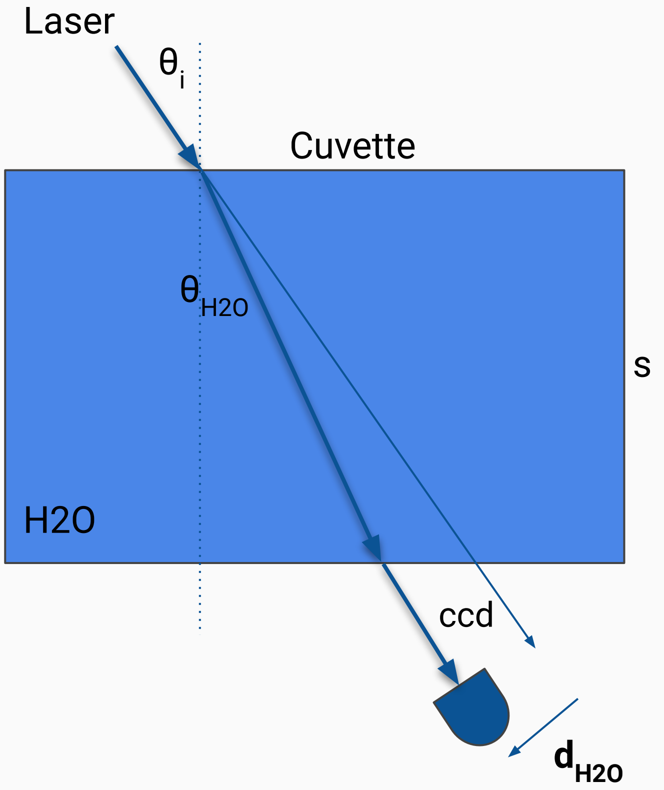
REWIND: Refractive index with refractometer



H_2O - Calibration

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

REWIND: Refractive index with refractometer



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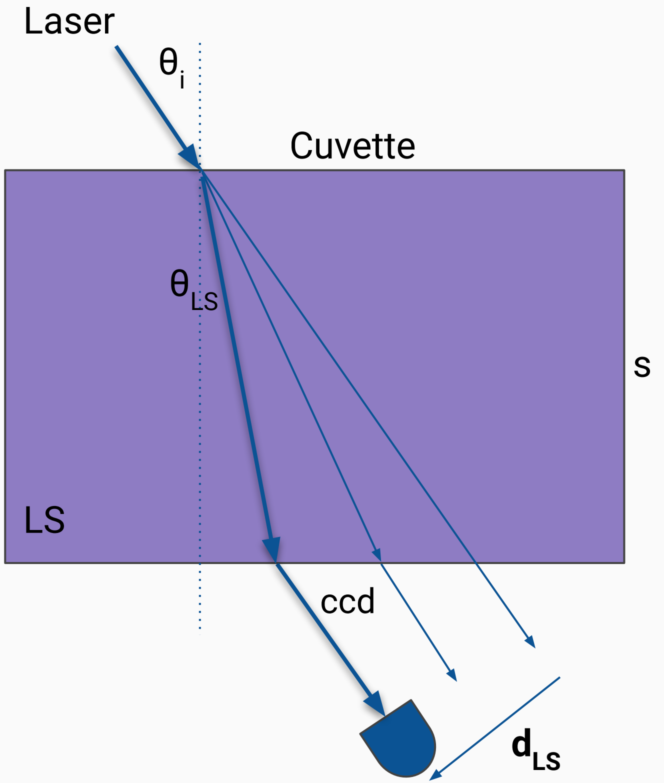
Measure the position of the beam on the ccd ⟶ $\mathbf{d_{H2O}}$

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

Extract value of θ_i with high precision

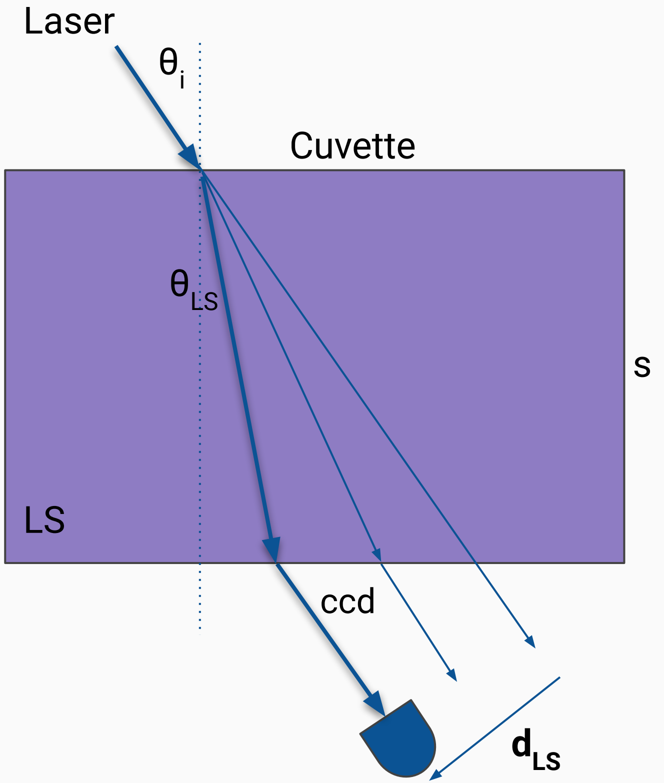
REWIND: Refractive index with refractometer



LS

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

REWIND: Refractive index with refractometer



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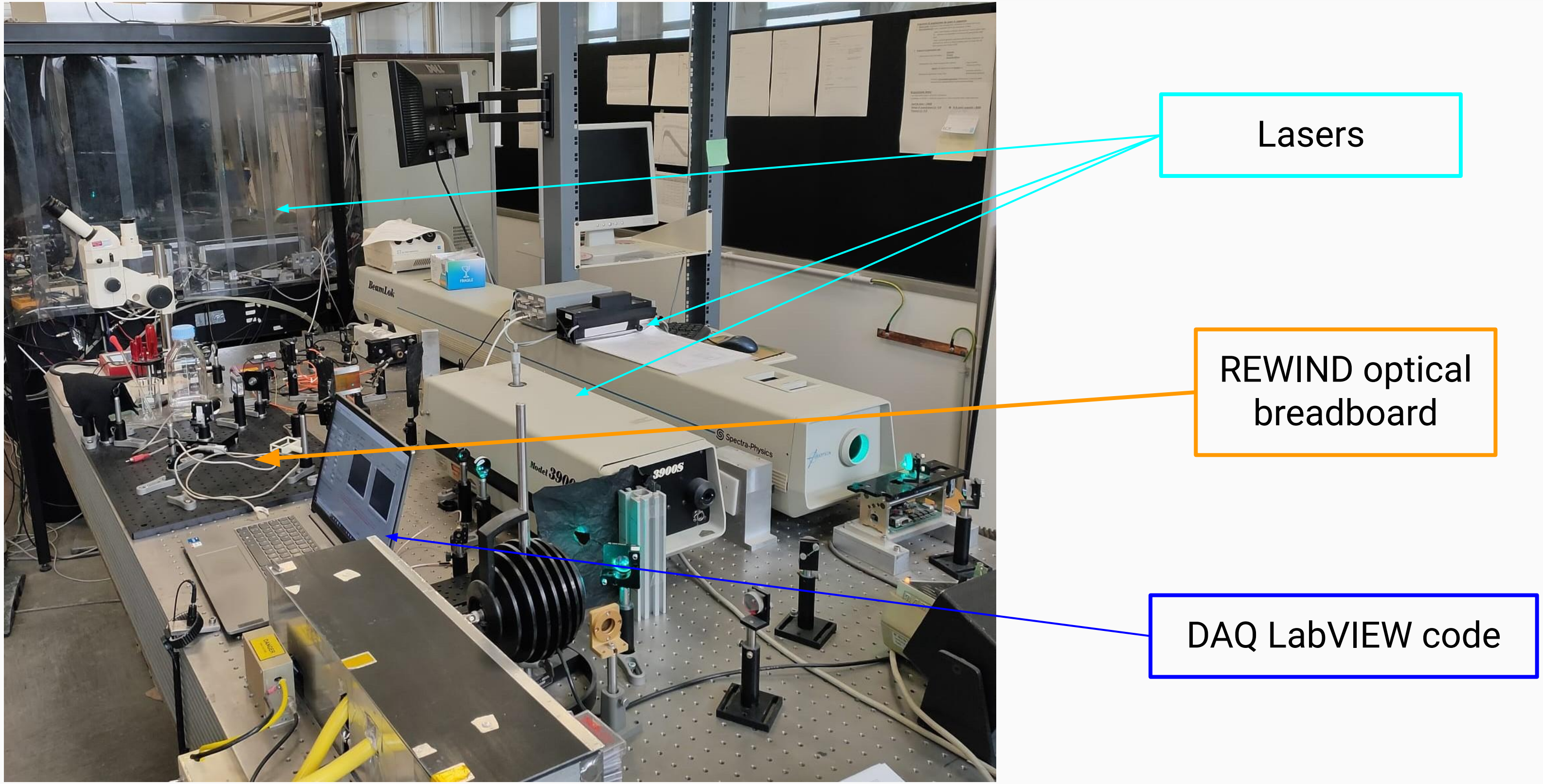
↓

$\mathbf{n_{LS}}$

REWIND: Laboratory



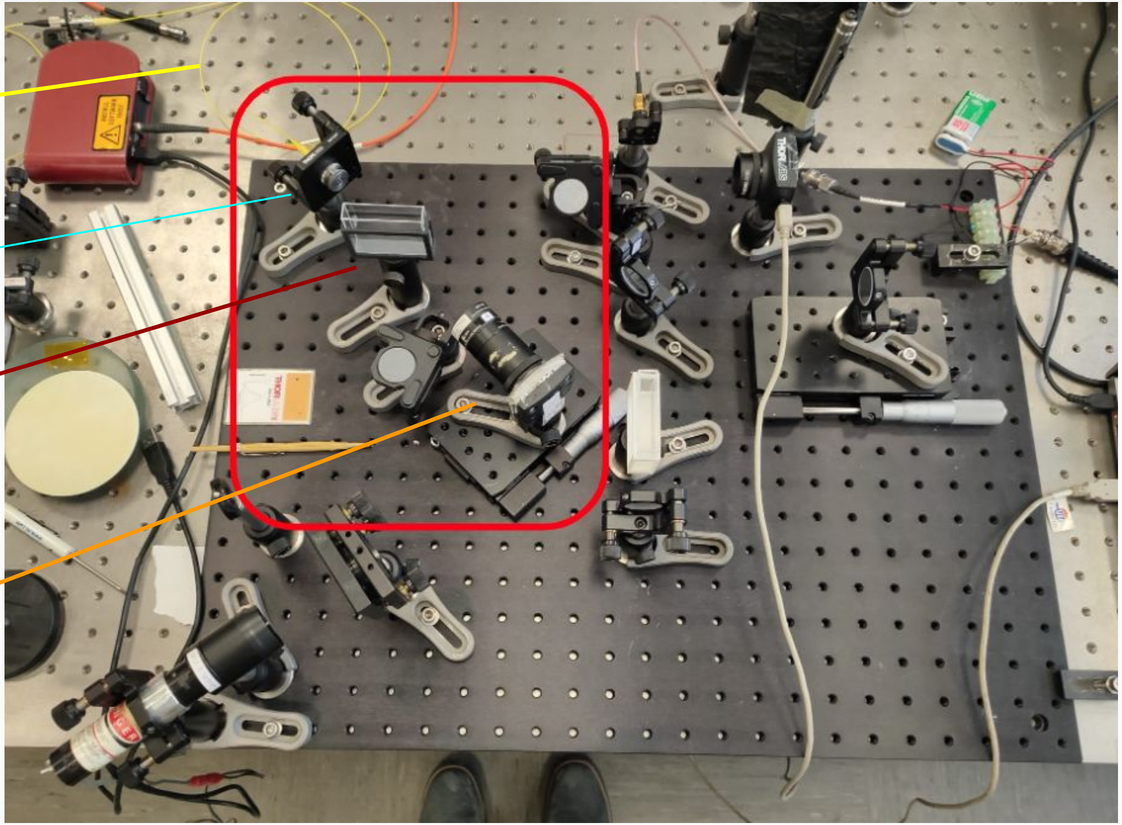
REWIND: Refractometer experimental setup

Optical fiber transporting light

Collimator

Cuvette

CCD (5.2 µm)



REWIND: Refractive index recent results

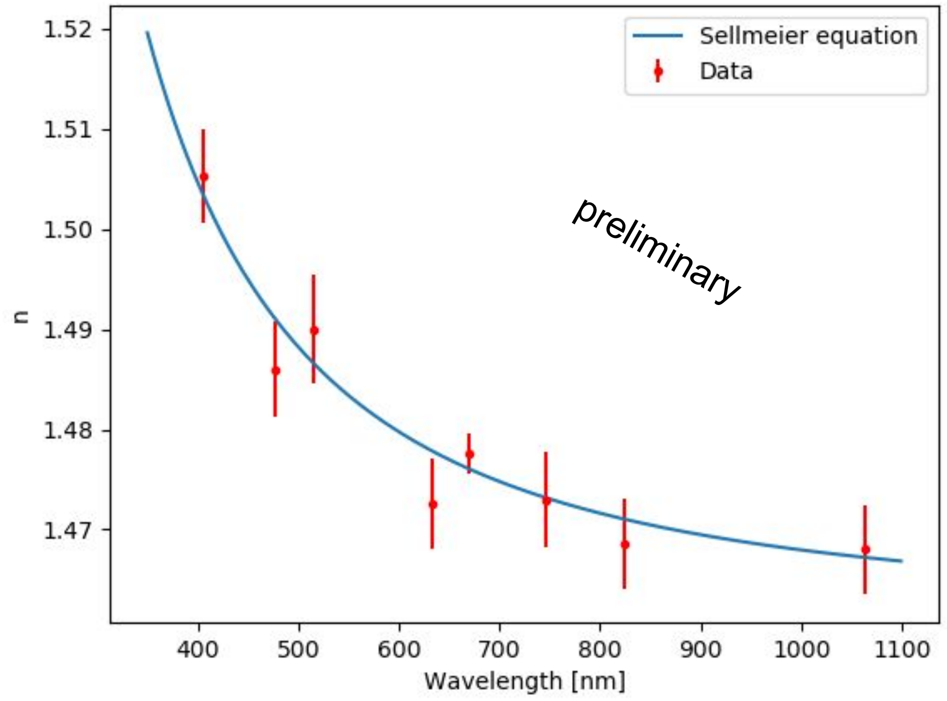
Wavelength (nm)	Refractive index
405.5	1.505 ± 0.007
476.5	1.486 ± 0.007
514.5	1.49 ± 0.008
633	1.473 ± 0.007
670	1.478 ± 0.003
745.7	1.473 ± 0.007
823.5	1.469 ± 0.007
1064	1.468 ± 0.007

$\sigma_n<0.5\%$

Fit with Sellmeier equation

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

REWIND: Refractive index recent results



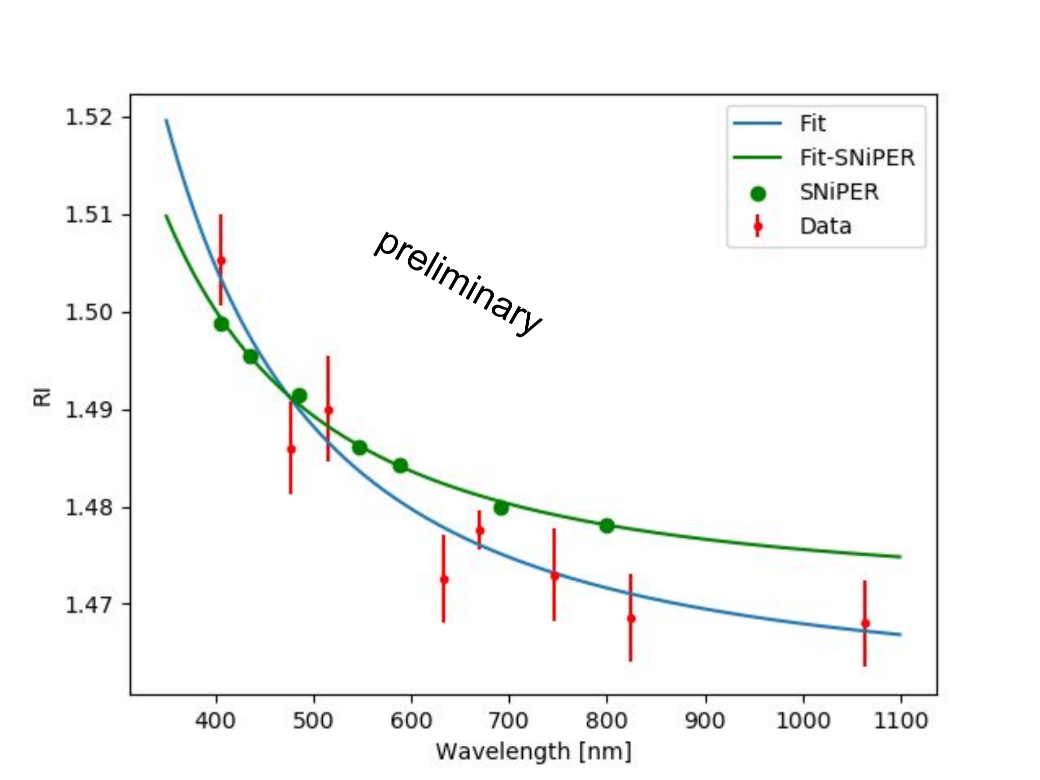
$$n^2(\lambda) = 1 + \frac{B}{1 - C/\lambda^2}$$

B	1.136 ± 0.008
C (nm^2)	(1.618 ± 0.213)x10^4
$corr_{B-C}$	-0.876
χ^2/ndf	0.44

Good agreement with the model

The result is used to predict the group velocity

REWIND: Refractive index recent results



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

B	1.136 ± 0.008
B_SNiPER	1.164
C (nm^2)	$(1.618 \pm 0.213) \times 10^4$
C_SNiPER (nm^2)	1.123×10^4

Relative difference <1% @~800 nm

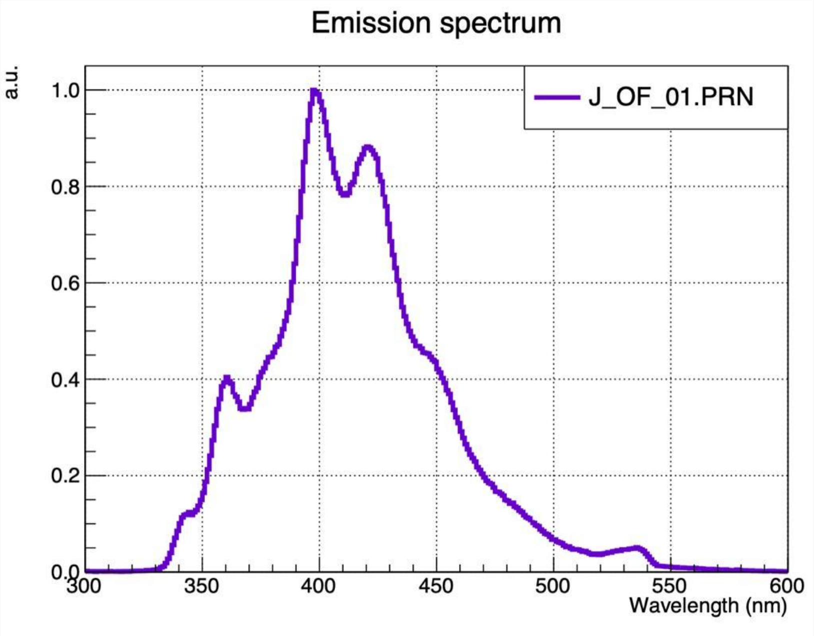
Planning on decreasing wavelength:
~~258~~-350 nm

REWIND: Group velocity

Group velocity

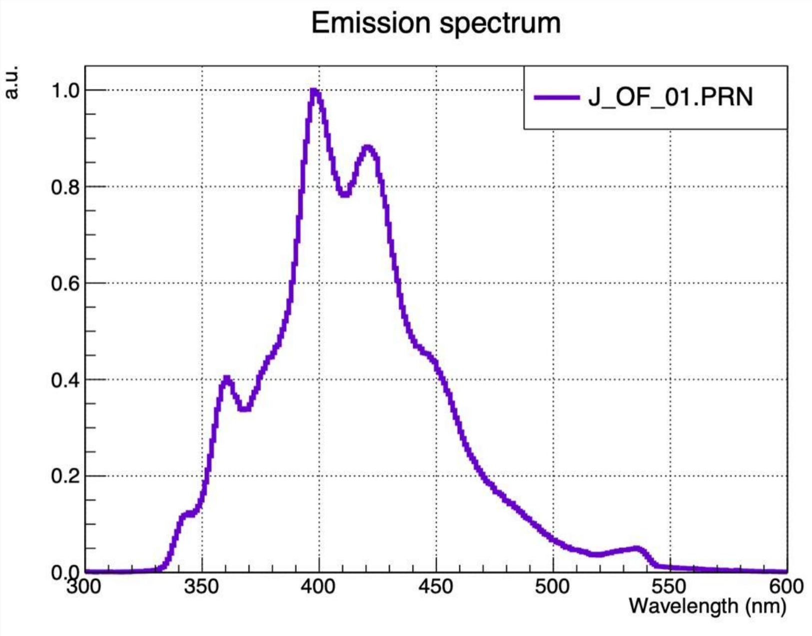
REWIND: Group velocity

LS emits photons with different wavelengths



REWIND: Group velocity

LS emits photons with different wavelengths



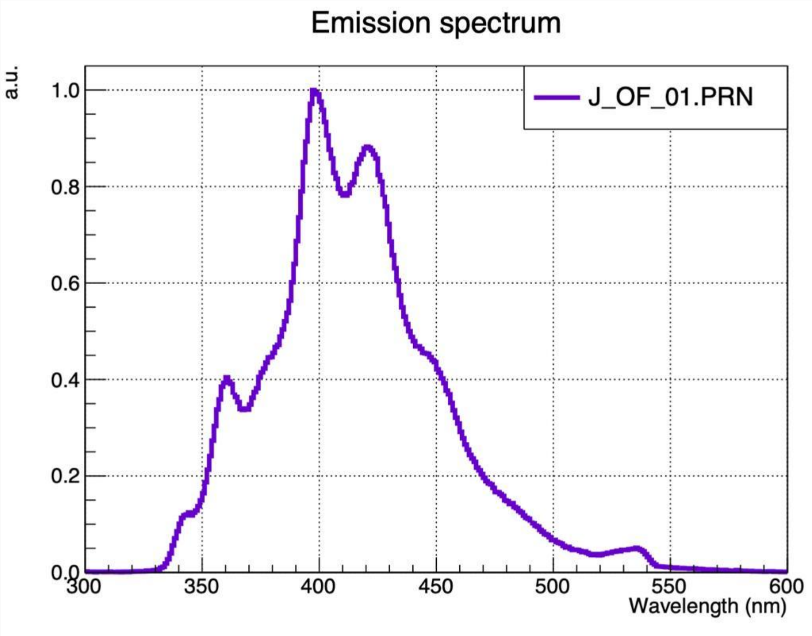
The propagation of light should be predicted by the group velocity v_g

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

v_g impacts on photons arrival time to PMTs

REWIND: Group velocity

LS emits photons with different wavelengths



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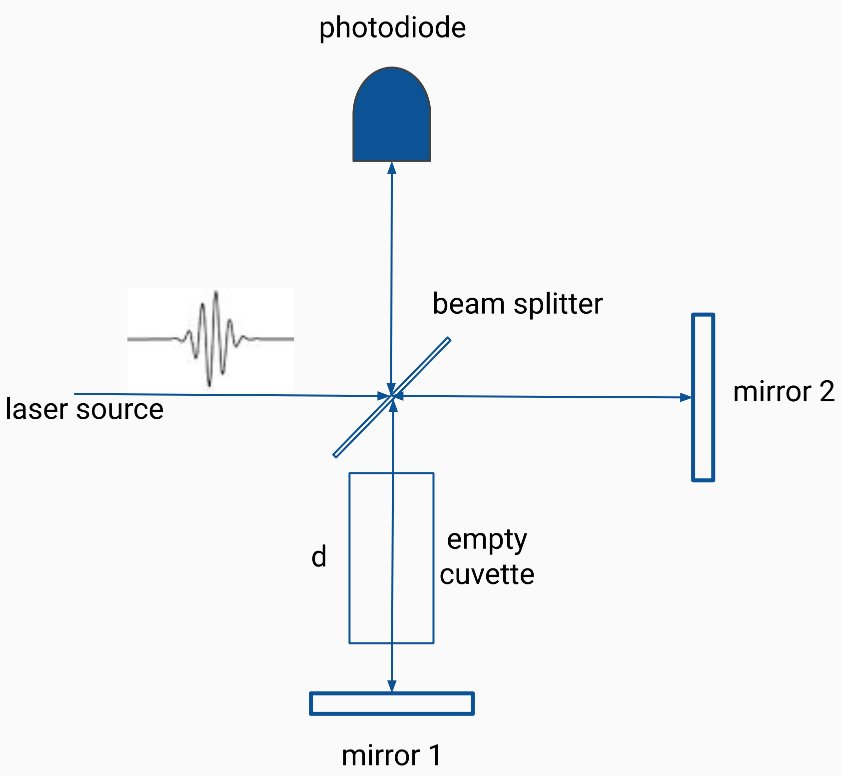
v_g impacts on photons arrival time to PMTs

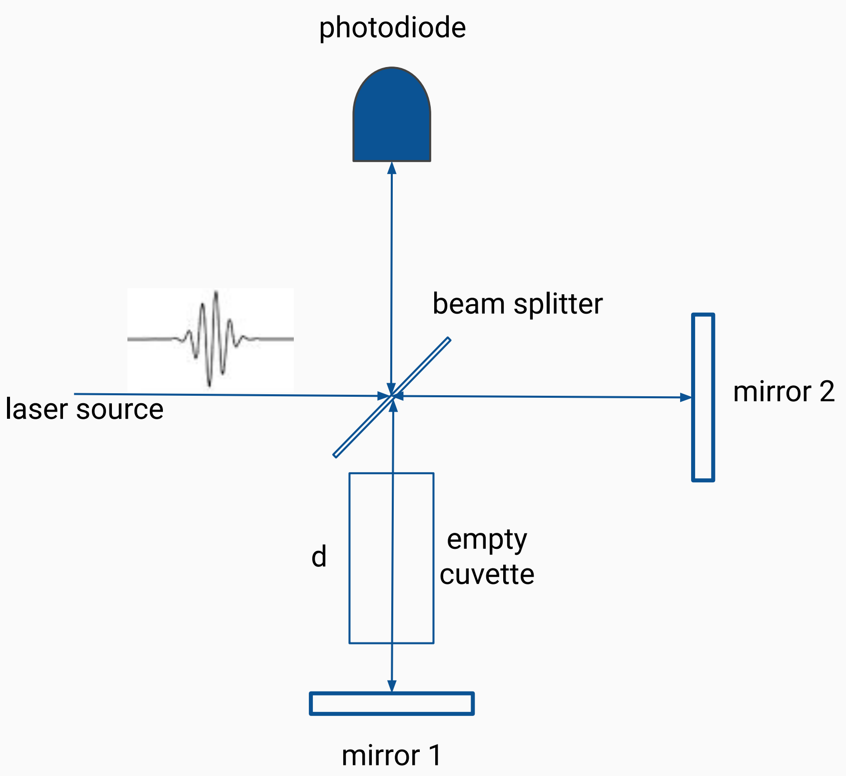
Precise measurement of v_g provides the correct model for light propagation

REWIND: Group velocity with interferometer



v_g: Arrival time measurement

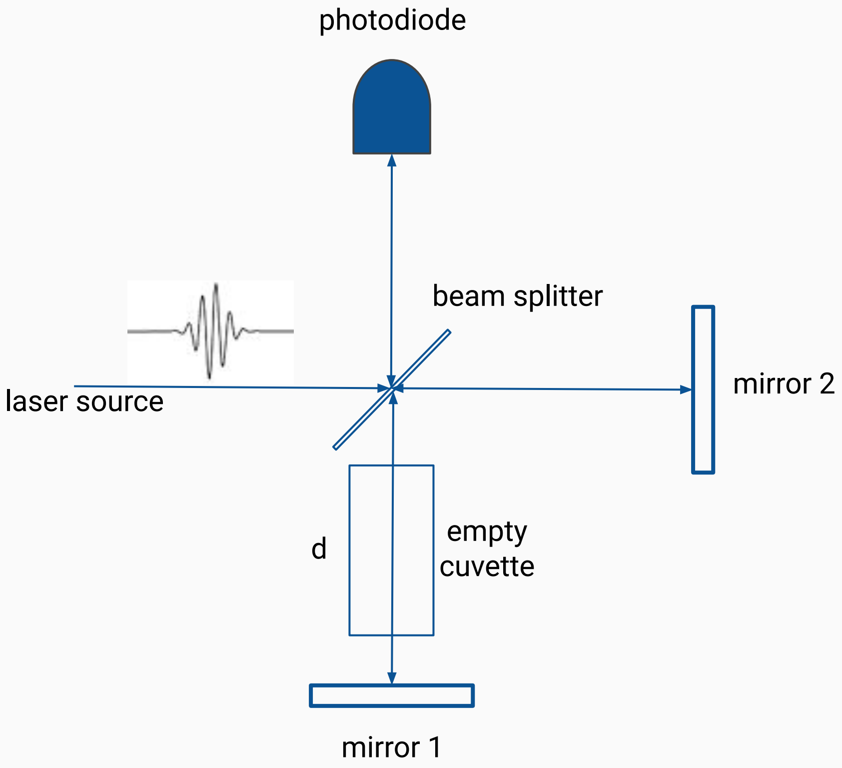
REWIND: Group velocity with interferometer



v_g: Arrival time measurement

For this measure we use an **interferometer**:

REWIND: Group velocity with interferometer

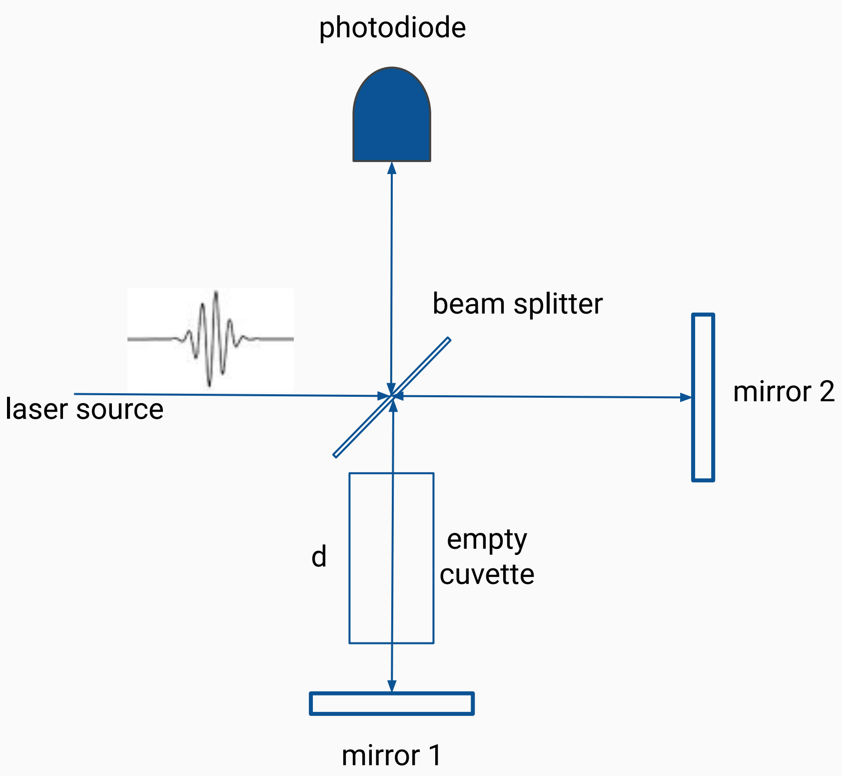


v_g: Arrival time measurement

For this measure we use an **interferometer**:

- Laser emits a wave packet

REWIND: Group velocity with interferometer

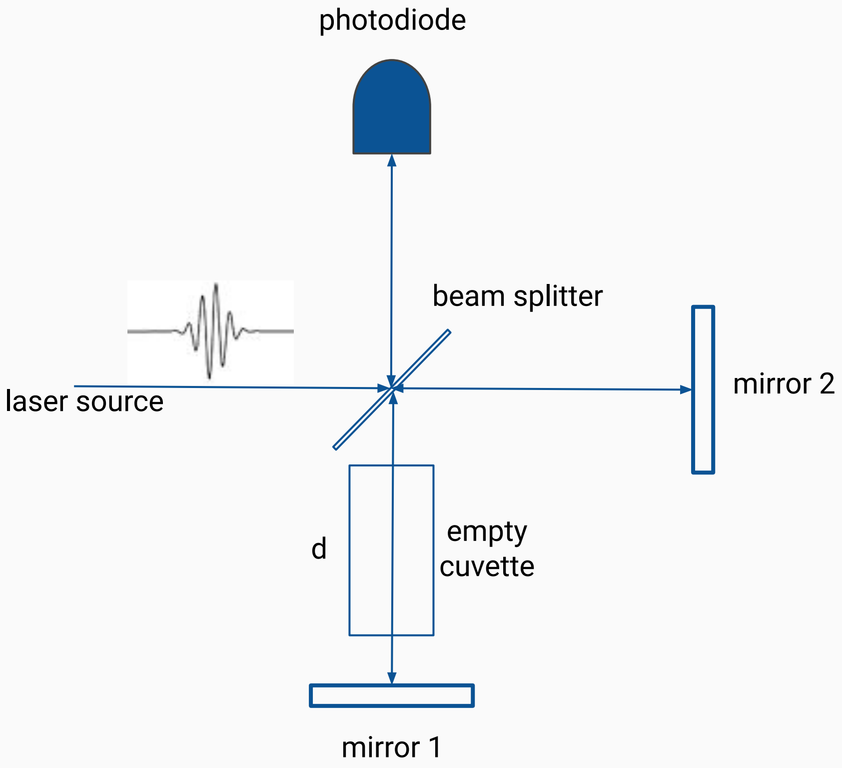


v_g: Arrival time measurement

For this measure we use an **interferometer**:

- Laser emits a wave packet
- Packet splitted

REWIND: Group velocity with interferometer

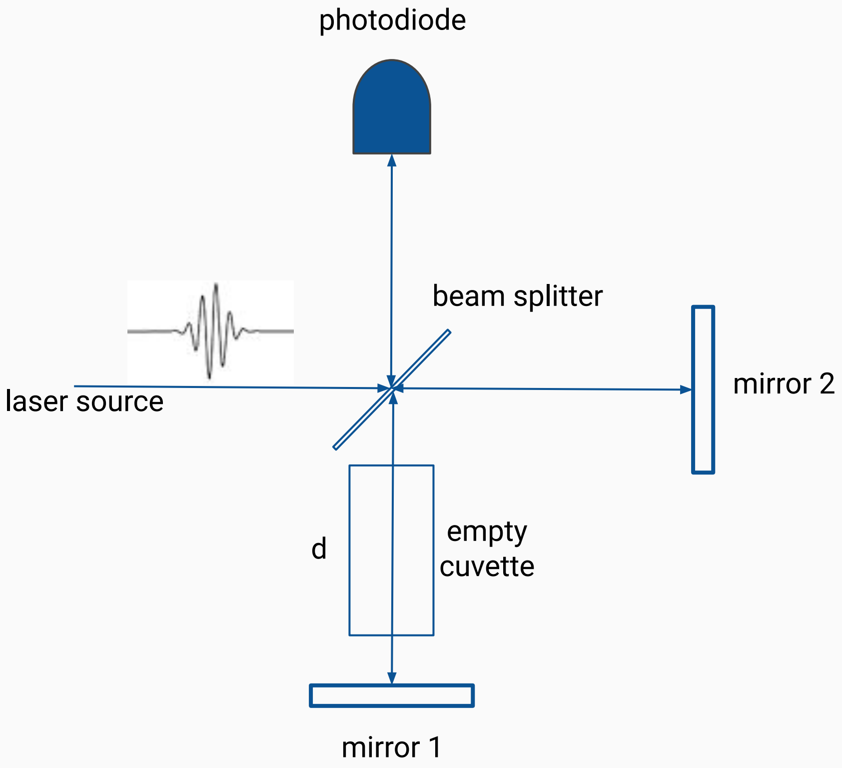


v_g: Arrival time measurement

For this measure we use an **interferometer**:

- Laser emits a wave packet
- Packet splitted
- Two beams are reflected

REWIND: Group velocity with interferometer



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For this measure we use an **interferometer**:

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- Overlapping detected by the photodiode

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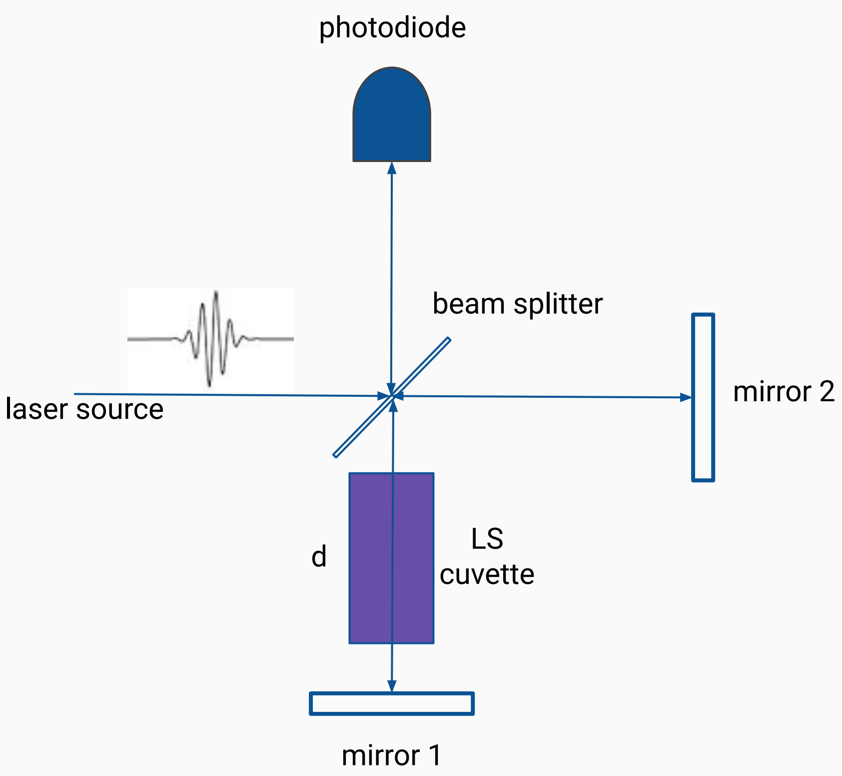

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For this measure we use an **interferometer**:

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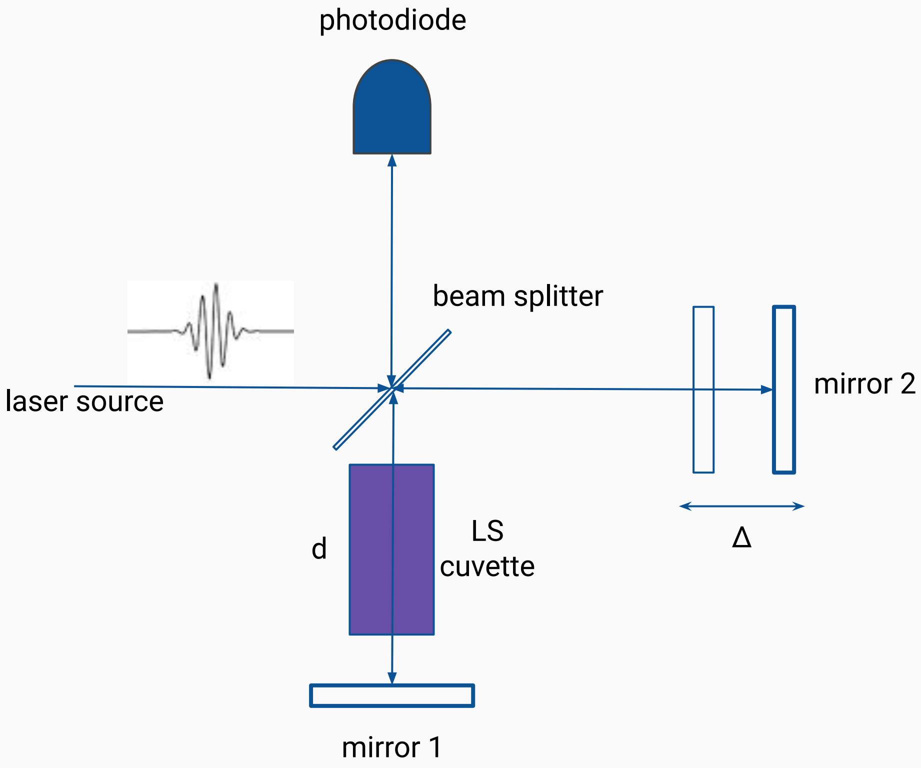
- Inserting the LS in one arm causes delay in time

REWIND: Group velocity with interferometer



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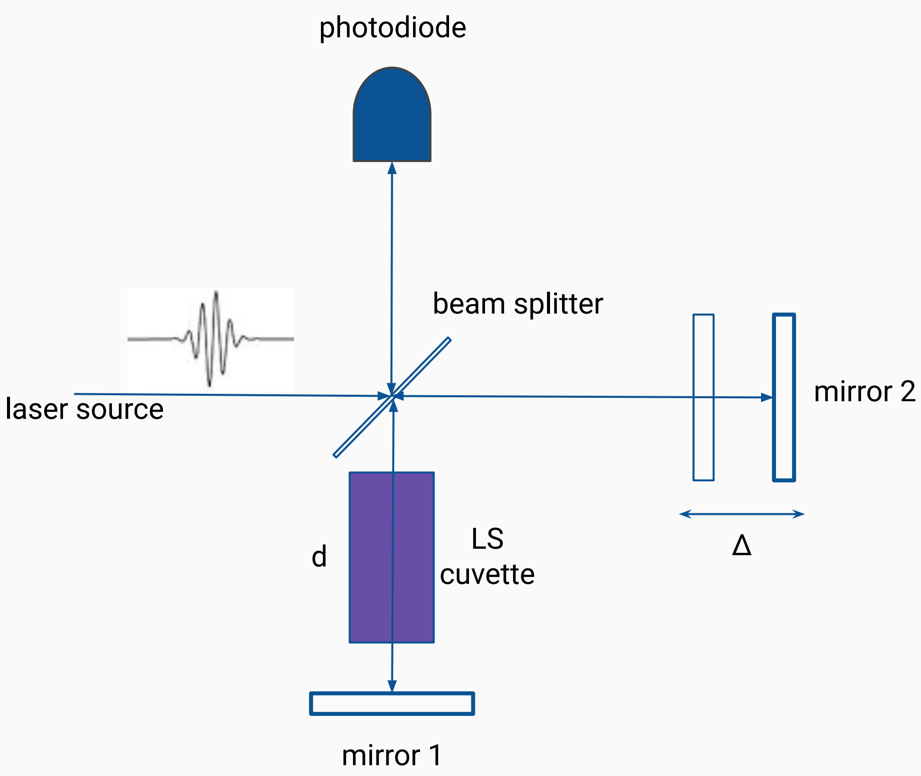
- The delay is recovered by shifting the mirror 2 of **Δ**

REWIND: Group velocity with interferometer



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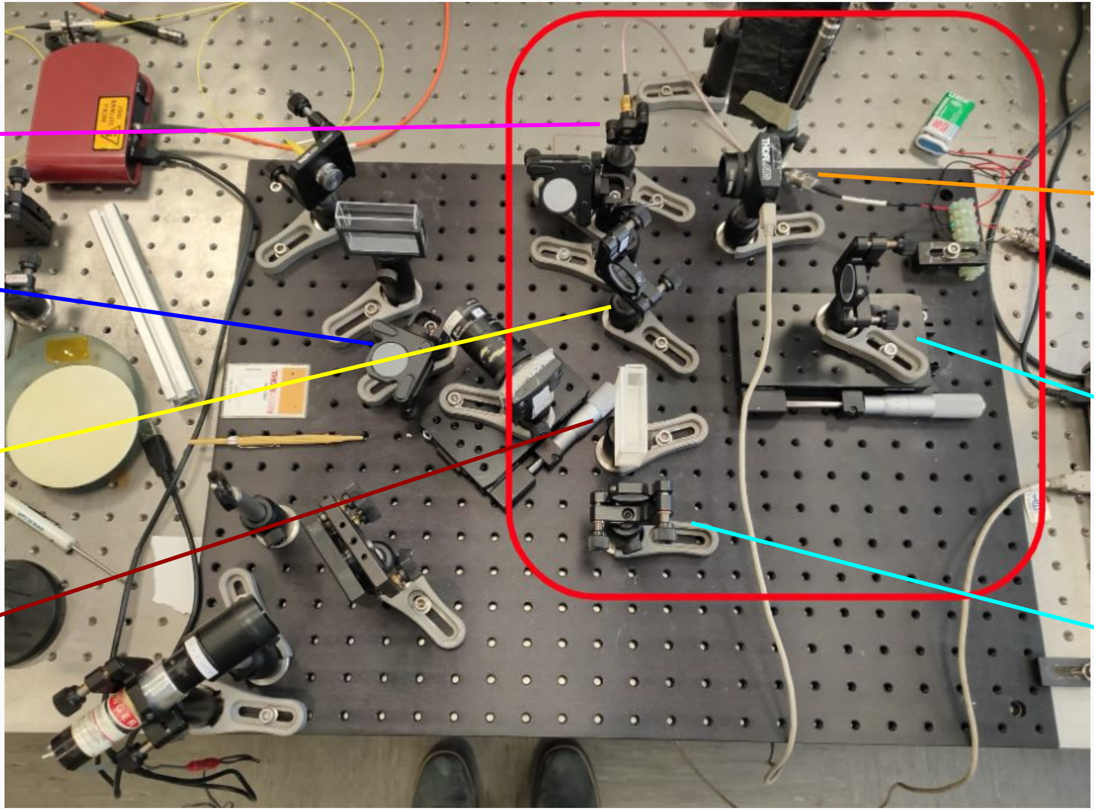
$$n_g = n_{air} + \frac{\Delta}{d} \Rightarrow v_g(\lambda) = \frac{c}{n_g(\lambda)}$$

REWIND: Interferometer experimental setup



Photodiode

Flipping mirrors

Beam splitter

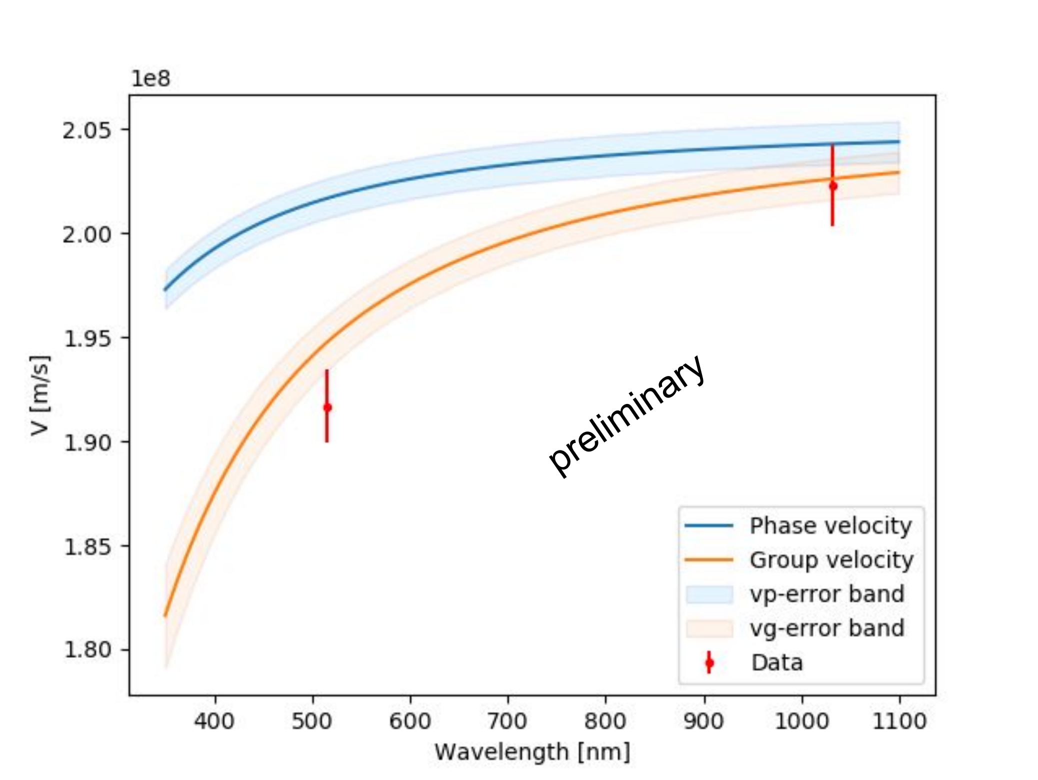
Cuvette

CCD (5.2 μm)

Mirror 2
+
Sliding plate

Mirror 1

REWIND: Group velocity recent 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

Planning on decreasing wavelength and fill the gap between 500 nm and 1000 nm

CONCLUSIONS

REFRACTIVE INDEX

- The experimental setup is installed (✓)
- We performed measurements of **n** between 405-1064 nm (✓)
- Planning on measure **n** with lower wavelengths **(in progress)**

GROUP VELOCITY

- The experimental setup is installed (✓)
- We performed two measurements of v_g at 516 and 1032 nm (✓)
- Planning on measure v_g with other sources **(in progress)**

Thank you for your attention

BACKUP SLIDES

JUNO liquid scintillator (LS) - light emission

Recipe: LAB (solvent) + 2.5 g/l PPO (scintillator material) + 3 mg/l bis-MSB (wavelength shifter)

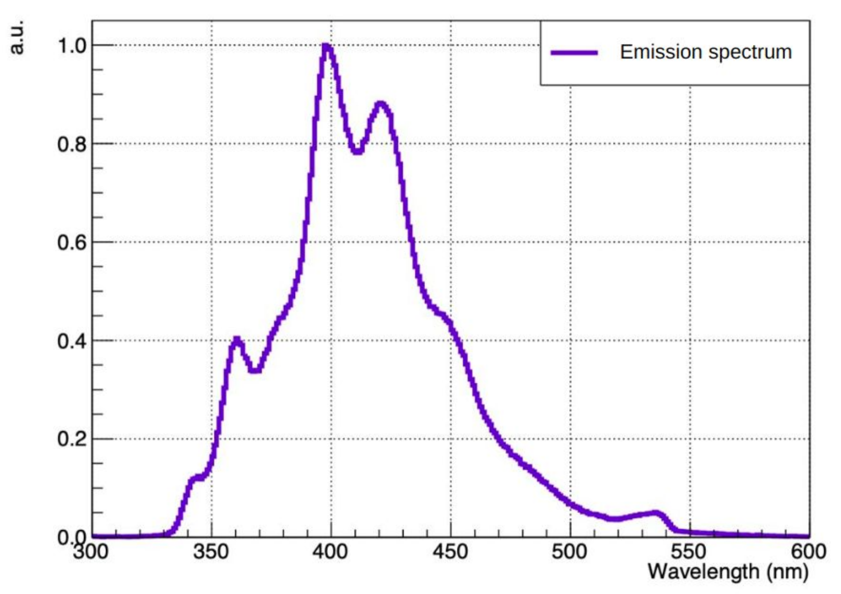
Charged particle passes through the LS

Scintillation/Fluorescence
- transition from excited to ground state
- Light-yield: 10^4 ph/MeV
- isotropic
- **τ**: few ns to few μs

Cherenkov
- β=v/c > 1/n
- ~1% of scintillation
- directional
- instantaneous

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

Emission of light



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)*

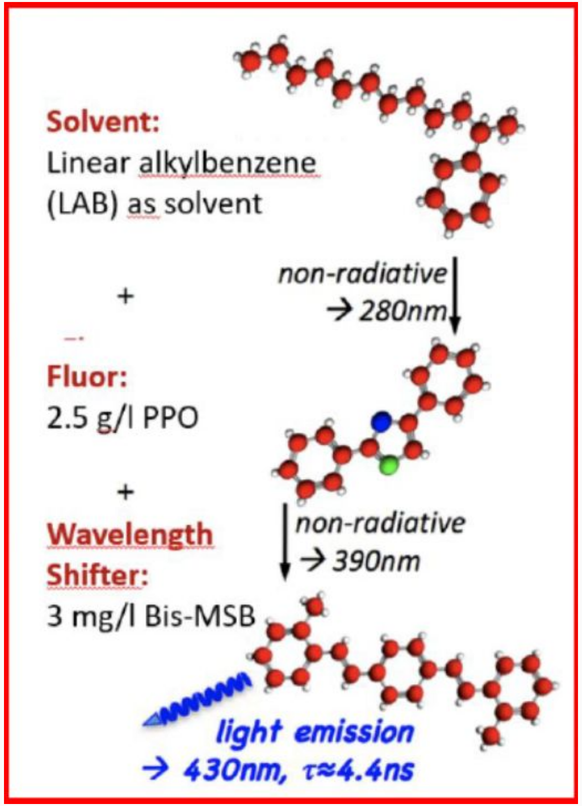
Neutrinos

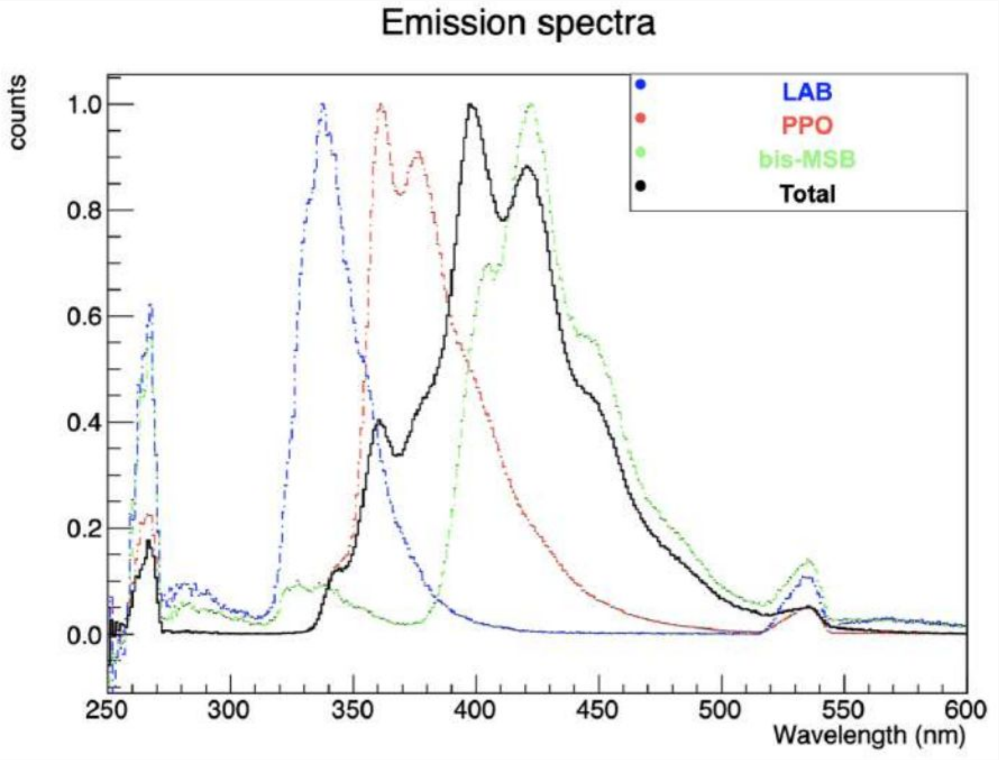
Elastic Scattering

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

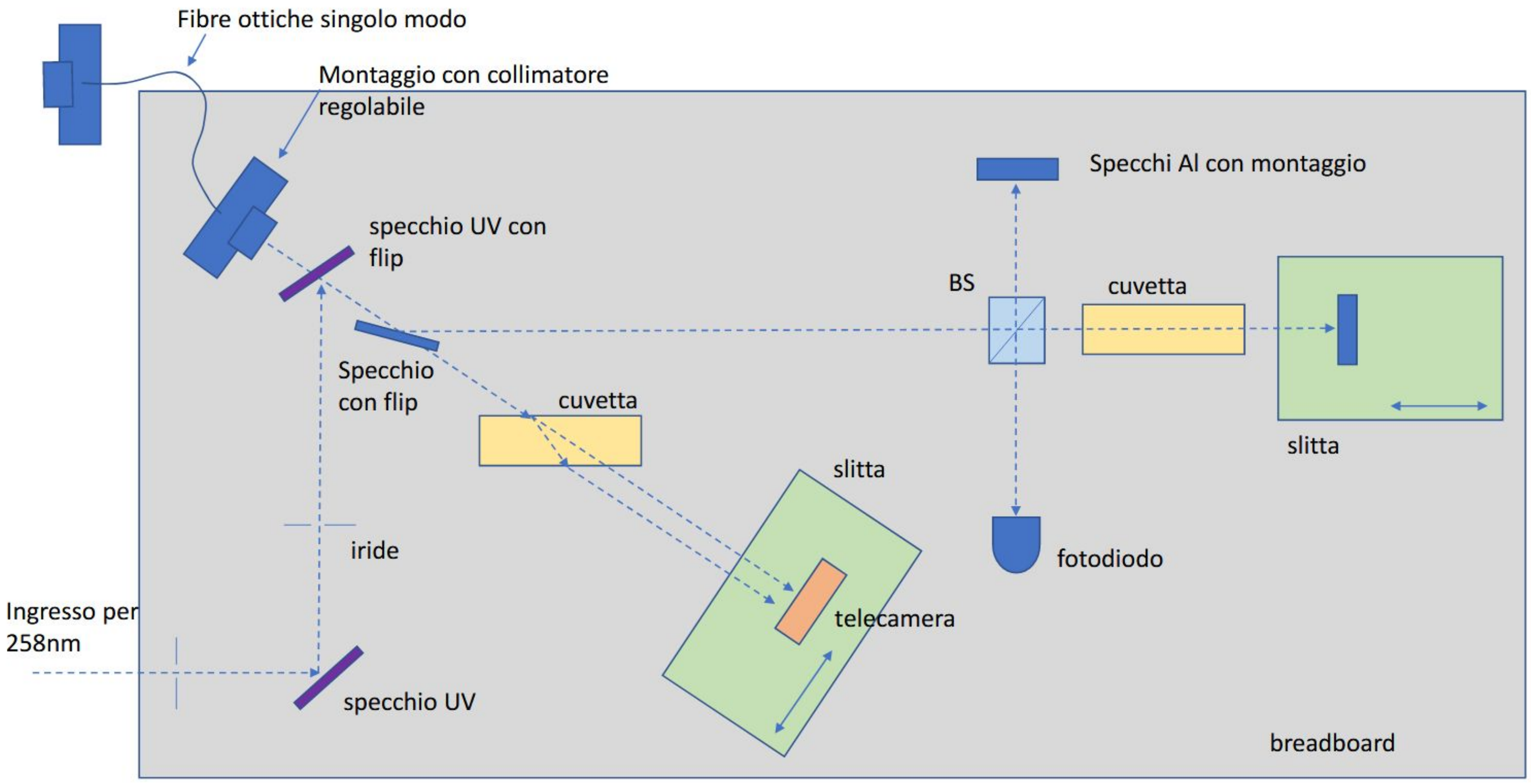
Detection of light by PMTs

LS-Emission spectra





SHELDON - REWIND



Rindex Info

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

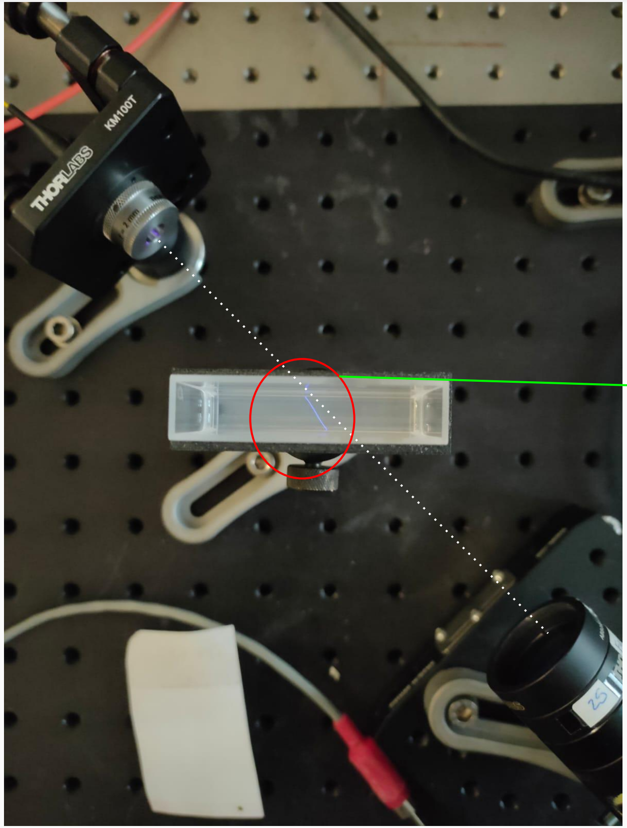
refractiveindex.info

Refractive index with refractometer - laser

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

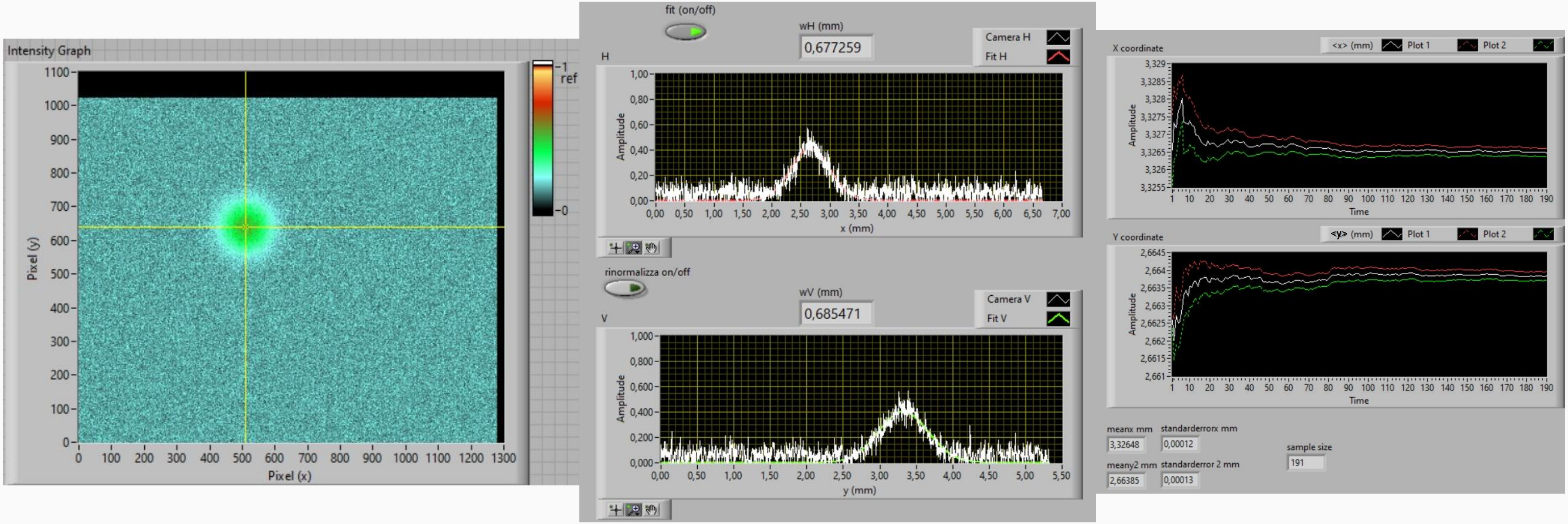
Refractive index with refractometer: real case



Effect of refraction with 405 nm

Absorption and re-emission by LS

Refractometer-LabView



Comparison our data-SNiPER-rae