CHARACTERIZATION OF OPTICAL PROPERTIES OF THE SITE OF THE ANTARES NEUTRINO TELESCOPE

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OUTLINE

- THE ANTARES NEUTRINO TELESCOPE
- LIGHT PROPAGATION IN DEEP SEA WATER
- EXPERIMENTAL PROCEDURE: DATA AND MC
- PRELIMINARY RESULTS
- CONCLUSIONS AND PERSPECTIVES

THE ANTARES NEUTRINO TELESCOPE

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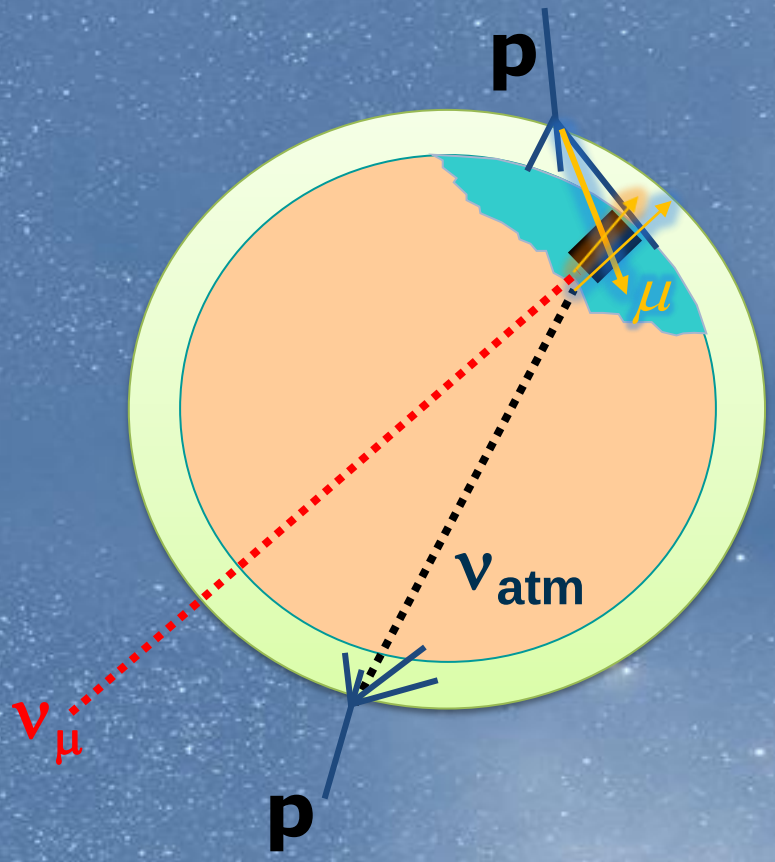
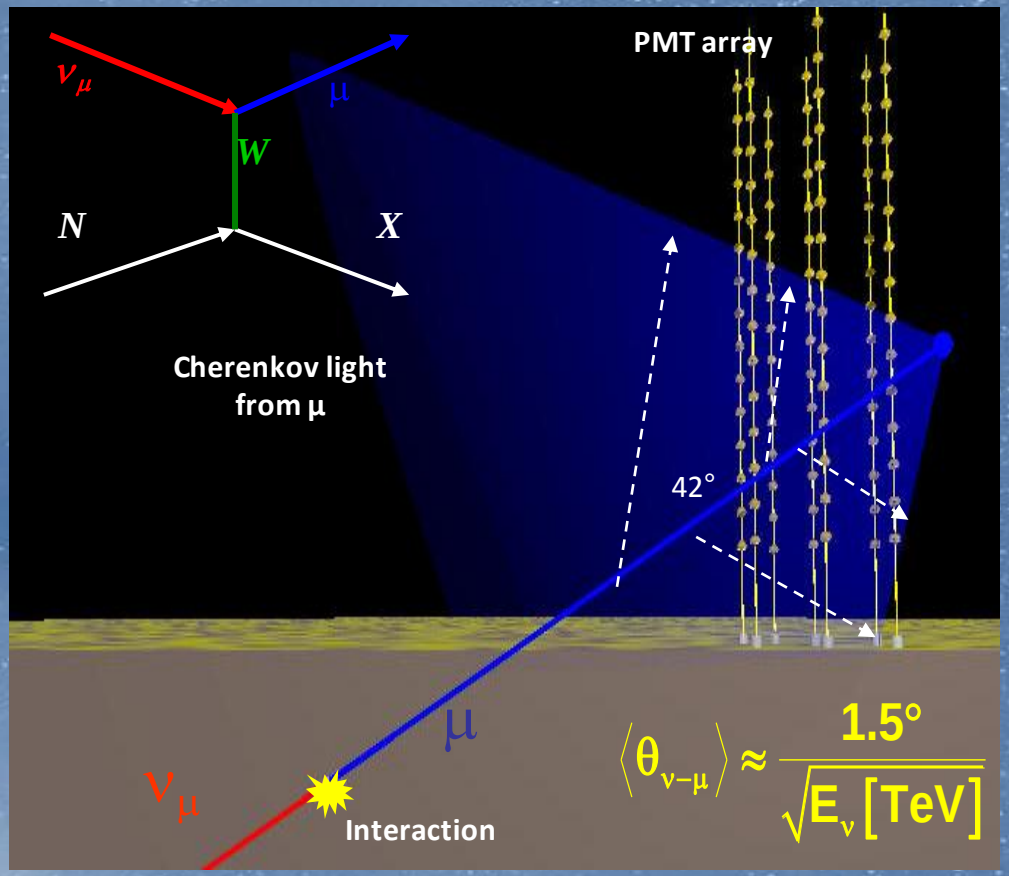




Main detection channel:

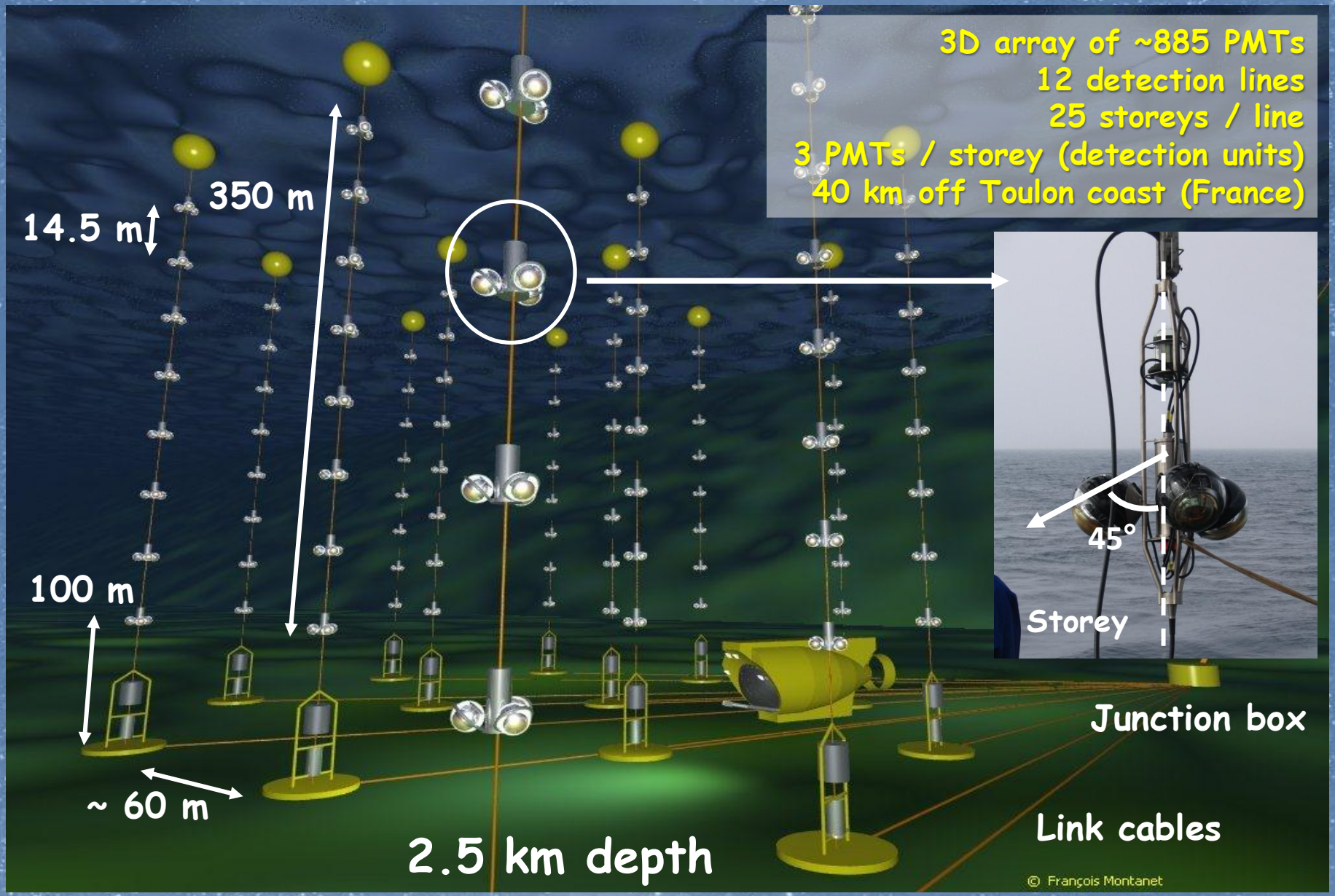
• ν_μ interaction giving an ultra-relativistic μ inducing Cherenkov light in a cone (ν_e and ν_t can also be detected).

Two kinds of background at the ANTARES site:

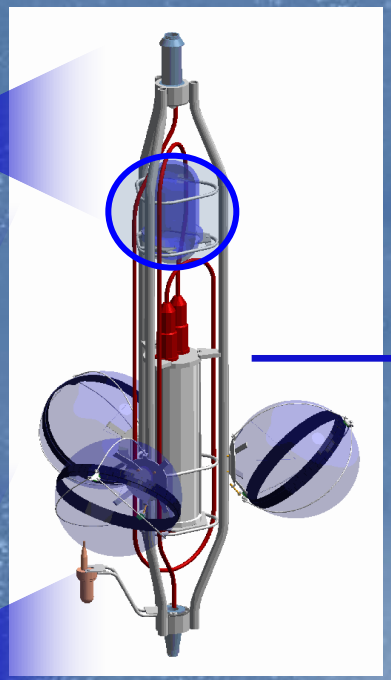
• *Physical Background* : Cosmic Rays interactions (atmospheric μ and ν).

• *Optical Background*: Bioluminescence and ^{40}K decay (sea environment).

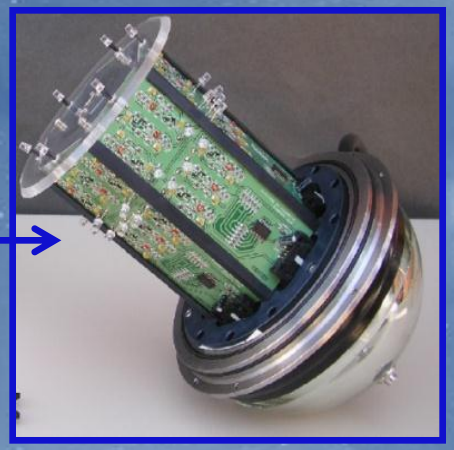
THE ANTARES NEUTRINO TELESCOPE

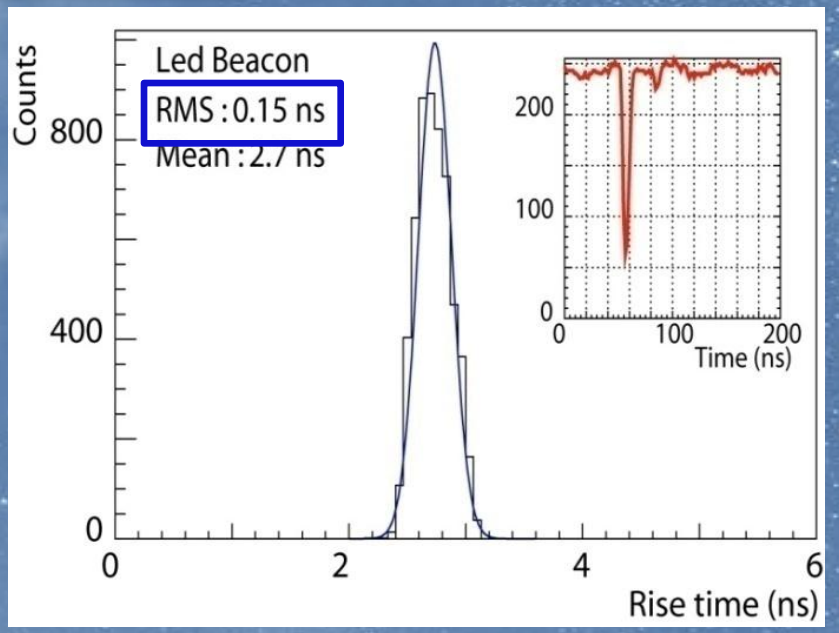


OPTICAL BEACON SYSTEM (OB): LED and LASER fast and controlled sources of pulsed light with a well-known emission time.



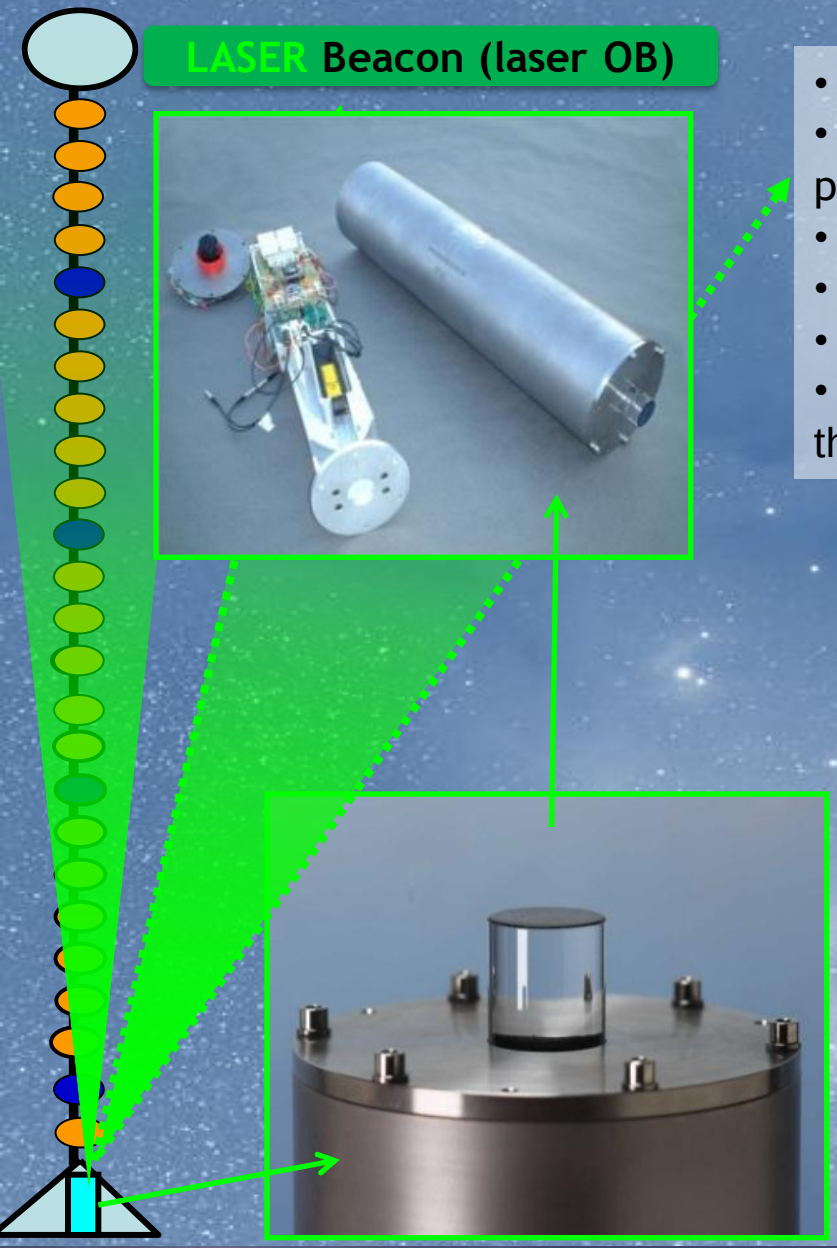
Standard LED Beacon (LOB)



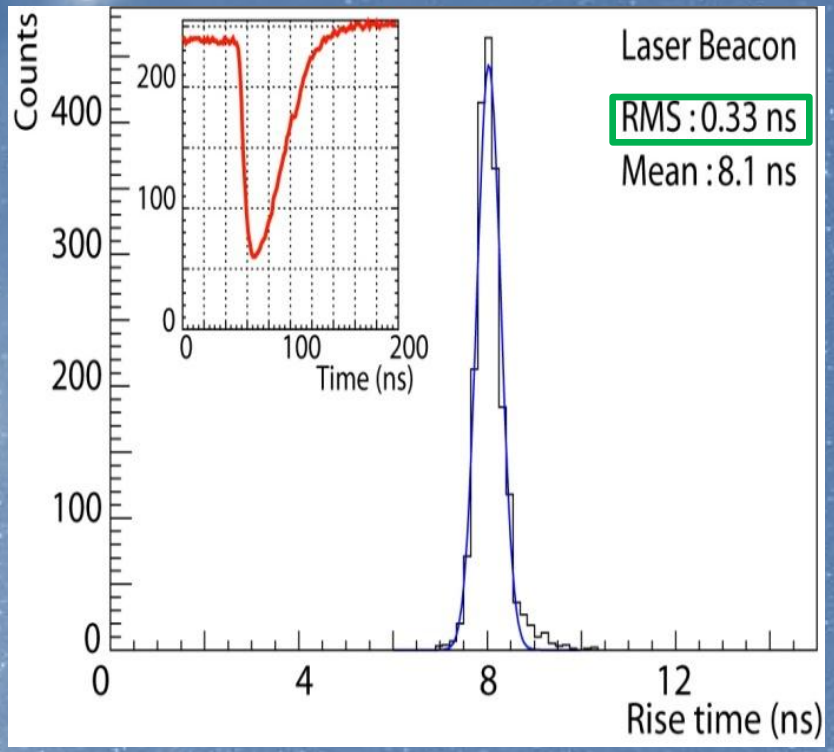


- 4 per line (F2, F9, F15, F21).
- Timing calibration (storeys).
- Optical properties ➔ Multi-Wavelength OB (L6F2); UV OB (L12F2).
- Energy per pulse at peak (DC 24 V) ~ 150 pJ (λ=472 nm).
- Internal PMT Hamamatsu H6780-03 (rise time ~ 0.8 ns) to know the emission time.
- Variable capacitor to synchronize (~200 ps) the emission time of the 36 LEDs.

THE ANTARES NEUTRINO TELESCOPE



- 2 throughout the detector (L7, L8).
- Timing calibration (lines) + positioning + optical properties.
- Crystal rod + diffuser.
- Energy per pulse ~ 1.0 μJ (λ=532 nm).
- Variable light intensity (crystal liquid attenuator system).
- Internal fast photodiode to know the time emission of the light pulse.



LIGHT PROPAGATION IN DEEP SEA WATER

LIGHT PROPAGATION IN DEEP SEA WATER

THE ANTARES WATER MODEL

- Absorption length (λ_{abs}) (disappearance of γ).
- Scattering length (λ_{scat}) (change direction of γ).
- Attenuation/transmission length ($\lambda_{att}/\lambda_{tra}$):

$$\frac{1}{\lambda_{att}} = \frac{1}{\lambda_{abs}} + \frac{1}{\lambda_{scat}}$$

COLIMATED BEAM

$$\frac{1}{\lambda_{att}^{eff}} = \frac{1}{\lambda_{abs}} + \frac{1}{\lambda_{scat}^{eff}}$$

ISOTROPIC SOURCE

$$\lambda_{scat}^{eff} = \frac{\lambda_{scat}}{1 - <\cos\theta>} = \frac{\lambda_{scat}}{1 - (1-\eta) <\cos\theta>_{Mie}}$$

$$<\cos\theta>_{Mie} = 0.924$$

Petzold values for particle scattering

<Cosθ> = Average cosine of the global distribution

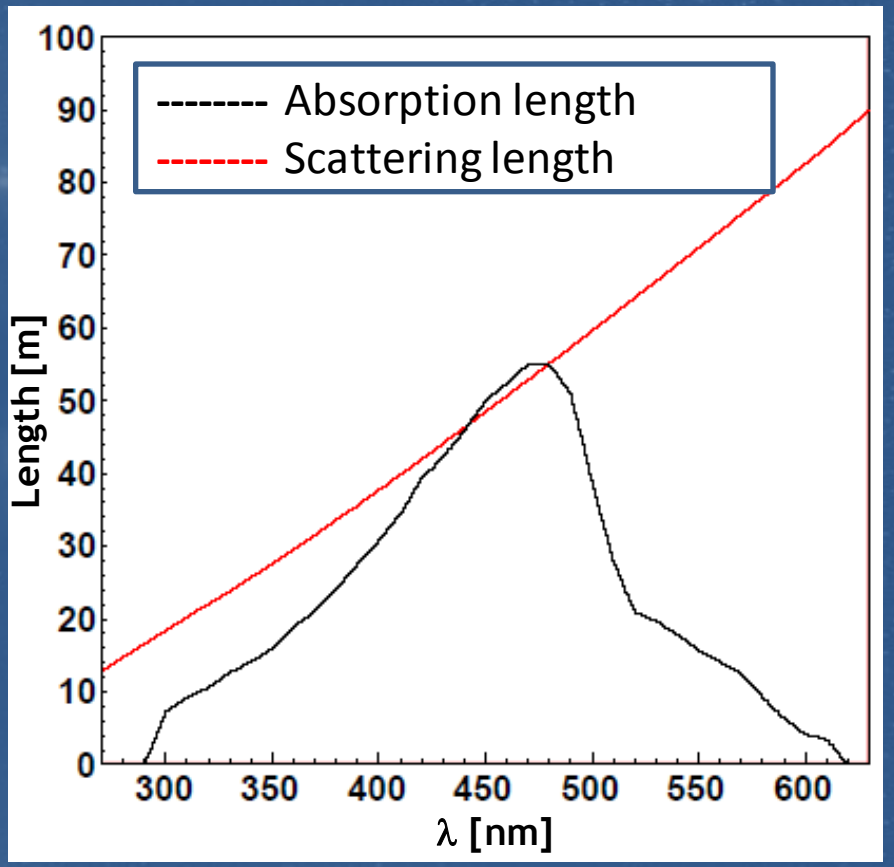
- Scattering phase function (β) (**Morel and Loisel**):

$$\beta^*(\theta) = \eta\beta^*_{Ray}(\theta) + (1-\eta)\beta^*_{Mie}(\theta)$$

Molecular scattering (*Rayleigh*) ➔ Isotropic (<cosθ>=0)

η = contribution of Rayleigh scattering

Particle scattering (*Mie*) ➔ Strong forward peaked (<cosθ>$_{Mie}$=0.924).



Kopelevich parameterization

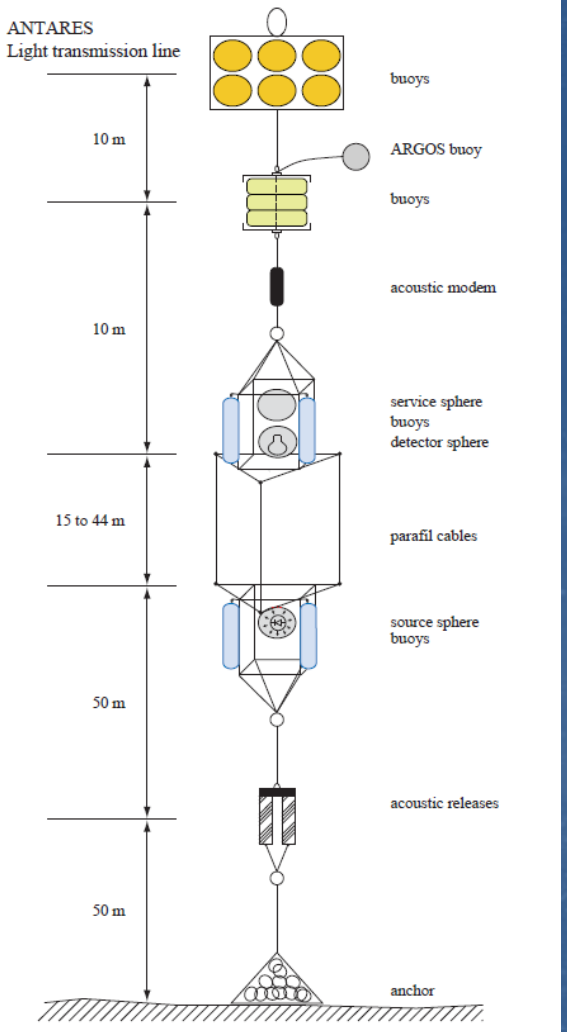
$$\frac{1}{\lambda_{scat}} = 0.0017\left(\frac{550}{\lambda}\right)^{4.3} + 1.34 v_s \left(\frac{550}{\lambda}\right)^{1.7} + 0.312 v_l \left(\frac{550}{\lambda}\right)^{0.3} [m^{-1}]$$

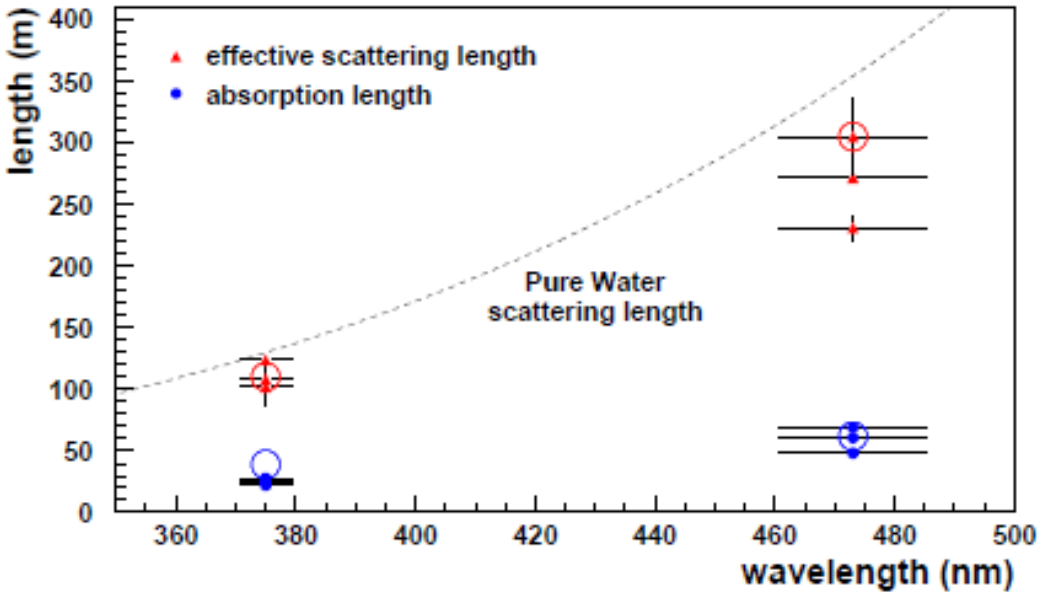
v_s, v_l = scattering centers (SC).

LIGHT PROPAGATION IN DEEP SEA WATER

ANTARES SITE R&D PHASE (TEST 3')

- Several tests with autonomous lines during the R&D phase (1998-2000).





Summary of the results for the blue data (statistical error only)			
Epoch	$\lambda_{att,eff}$	λ_{abs}	$\lambda_{scat,eff}$
July 1998	60.6±0.4	68.6±1.3	265±4
March 1999	51.9±0.7	61.2±0.7	228±11
June 2000	46±1.9	49.3±0.3	301±3

Scattering Centers (SC) = **0.0075 ppm** (*in-situ*) n = 1.345

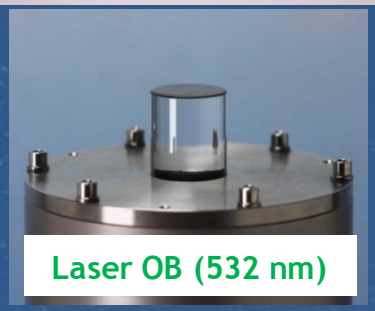
EXPERIMENTAL PROCEDURE: DATA AND MC

EXPERIMENTAL PROCEDURE: DATA AND MC

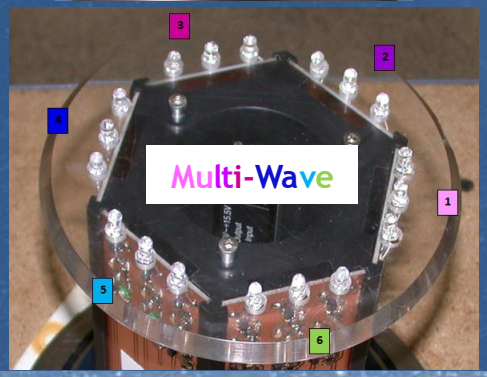
NEW EFFORTS ON WATER PROPERTIES MEASUREMENTS IN ANTARES

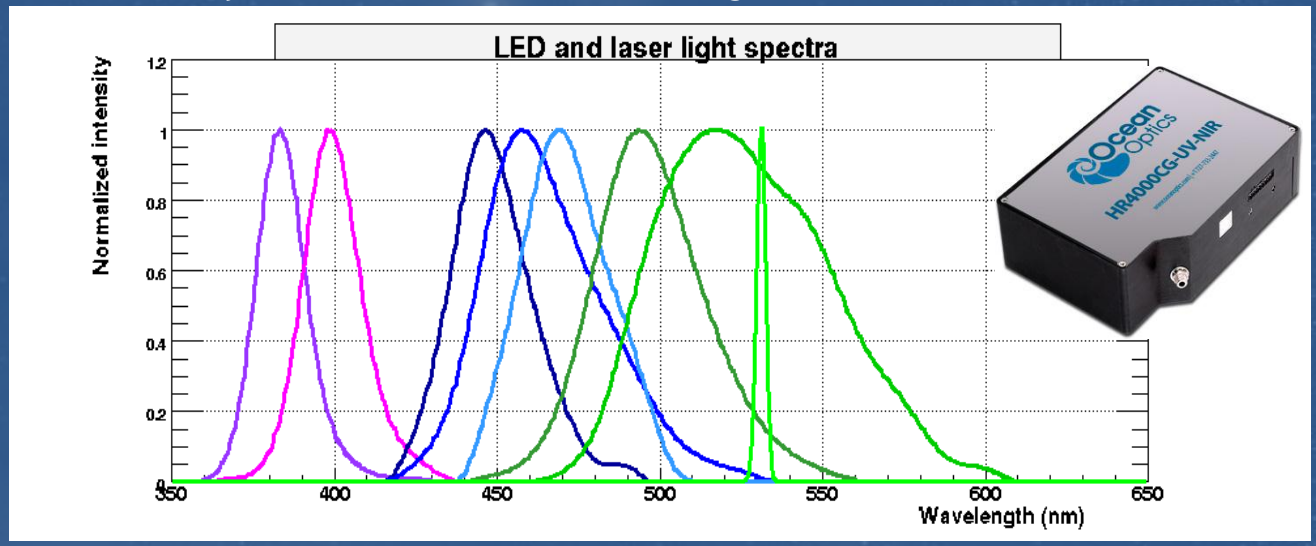
• Almost uniform light sources ($50° < \theta < 120°$) + Adjustable light output: different LED faces at different voltages + Reliable and stable calibration systems; Available sources of light:

Standard LOB (470 nm)



Laser OB (532 nm)





	Provided by the manufacturer		Measured at IFIC	
LED	Mean [nm]	FWHM [nm]	Mean [nm]	RMS [nm]
VAOL-5GUV8T4	385	5	384	9
HUVL400-520B	400	20	400	10
Ultrabright Pink	440	-	447	13
HLMP-CB30-K000	460	35	458	19
HLMP-CB15-RSC00	472	35	469	13
HLMP-CE36-WZ000	505	30	494	18
SLA-580ECT3F	518	35	518	25

EXPERIMENTAL PROCEDURE: DATA AND MC

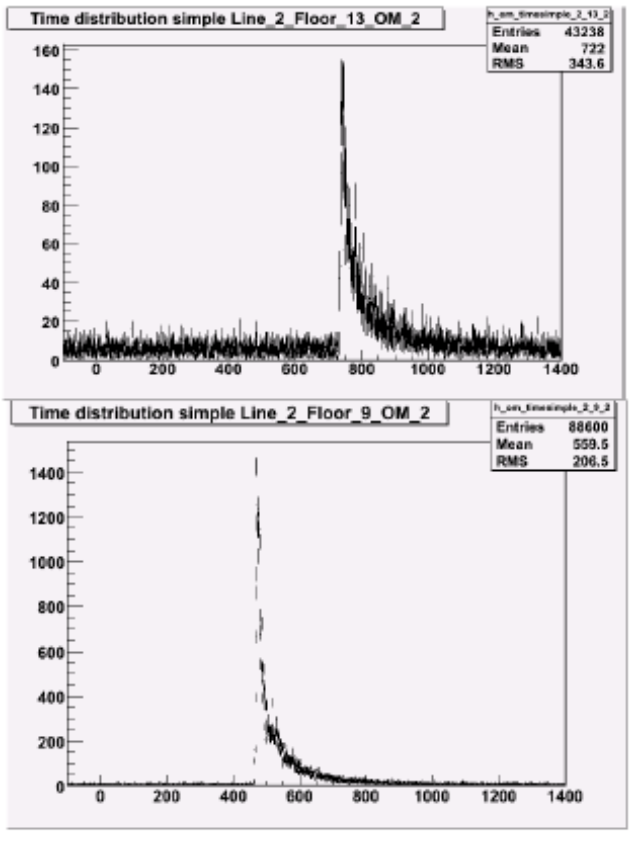
Refractive index measurement (DATA)

Both the phase and group velocity depend on the wavelength of the photons. This is usually referred to as chromatic dispersion:

$$n_g = \frac{n_p}{1 + \frac{\lambda}{n_p}\frac{dn_p}{d\lambda}},$$

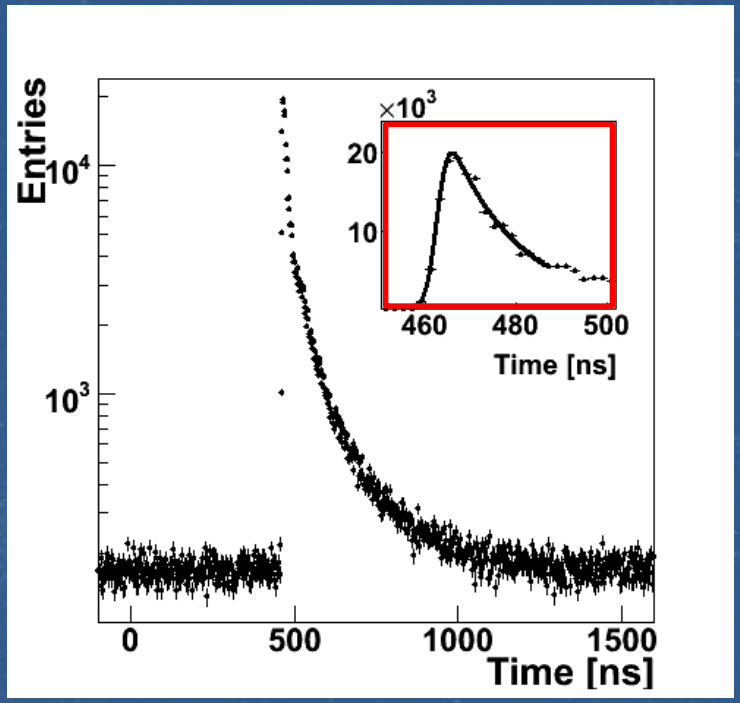
λ = wavelength of light.

n_g = ratio of the speed of light in vacuum and the group velocity of light in water.



EXPERIMENTAL PROCEDURE:

1. Measure the light time delay at different distances from the light source (Optical Beacons) along the same line for different wavelengths.
3. Fit the time distributions to the convolution of Gaussian + exponential.
4. Plot the mean values of the Gaussian distribution per storey as function of the distance to the light source, fit to a linear function and extract its slope which have to be related to the refractive index.

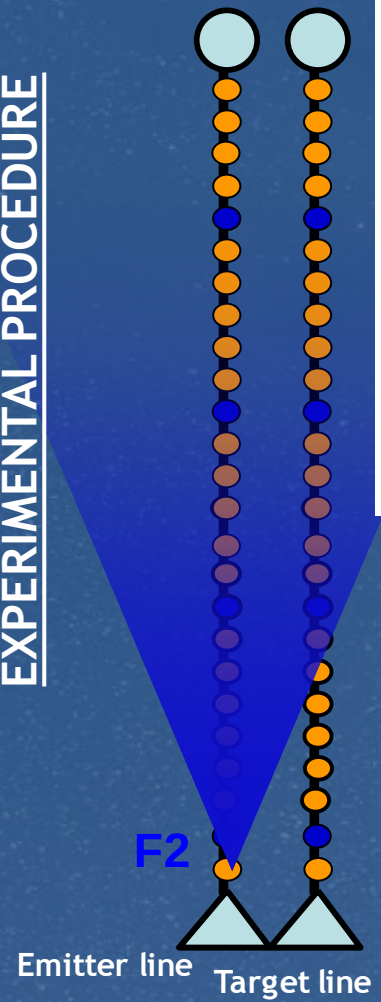


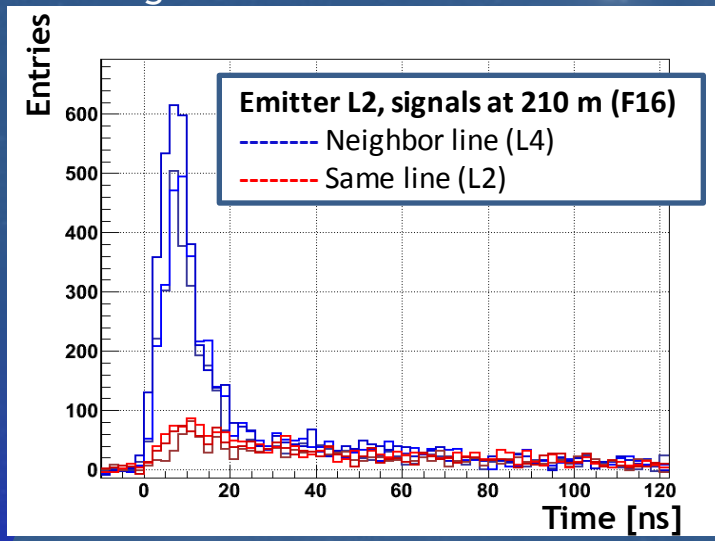
EXPERIMENTAL PROCEDURE: DATA AND MC

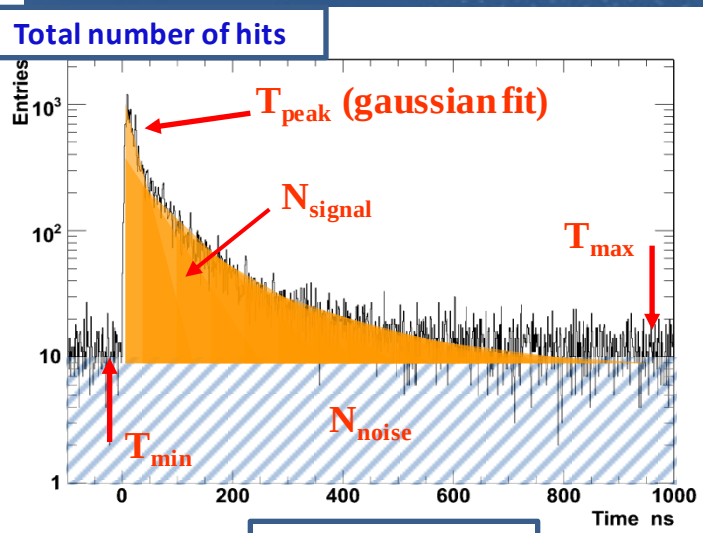
Transmission (attenuation) length measurements (DATA)

1. One single top LED of the lowest OB in the line flashes upwards and the light is collected by a neighboring line ➔ To avoid "shadowing" due to its own mechanical structure ➔ Direct photons.

EXPERIMENTAL PROCEDURE







TOTAL NUMBER OF HITS:

- Hits selection between $[T_{min}, T_{max}]$

$T_{min} = T_{peak} - 3\sigma$.

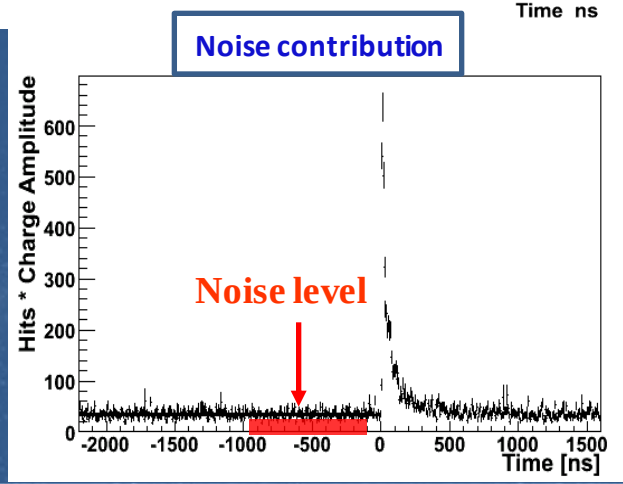
$T_{max} = T_{peak} + 1000$ ns.

- Calculate their overall hits N_{tot}.

NOISE CONTRIBUTION:

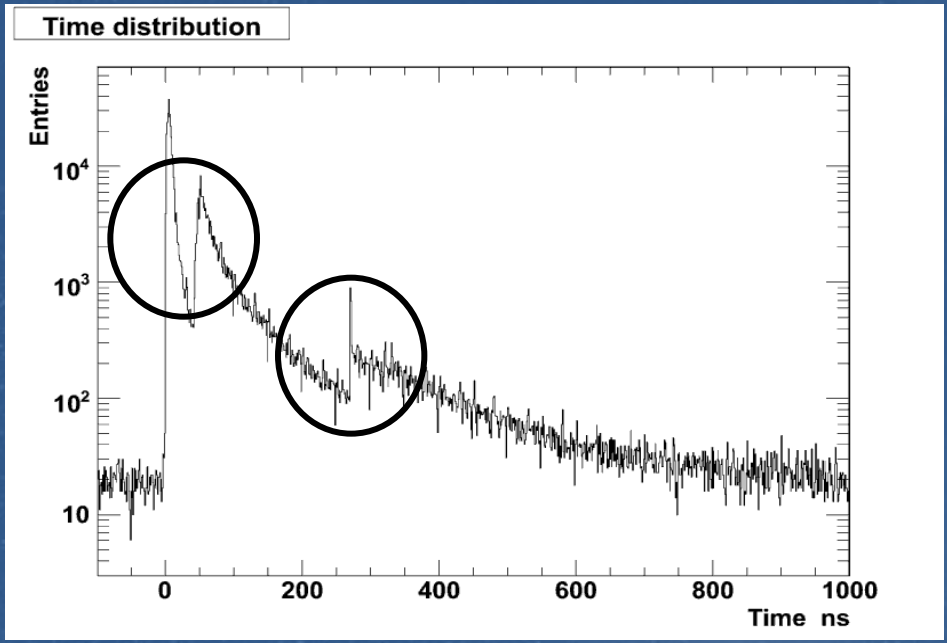
- Fit a constant between [-50, -1000] ns ➔ "Background level" (B) ➔ $N_{noise} = B(T_{min} - T_{max})$.

SIGNAL: $N_{signal} = N_{tot} - N_{noise}$



EXPERIMENTAL PROCEDURE: DATA AND MC

2. Signal hits are plotted and fitted (between R_{min}, R_{max}) by means of an exponential function:
- To avoid the electronics dead time (related to R_{min}): region where the probability to get more than one photoelectron is negligible (i.e < 1 %) ➔ 2 front-end cards in token ring mode per PMT.
- To avoid noise fluctuations at large distances (related to R_{max}): region where the signal will be greater than the noise.



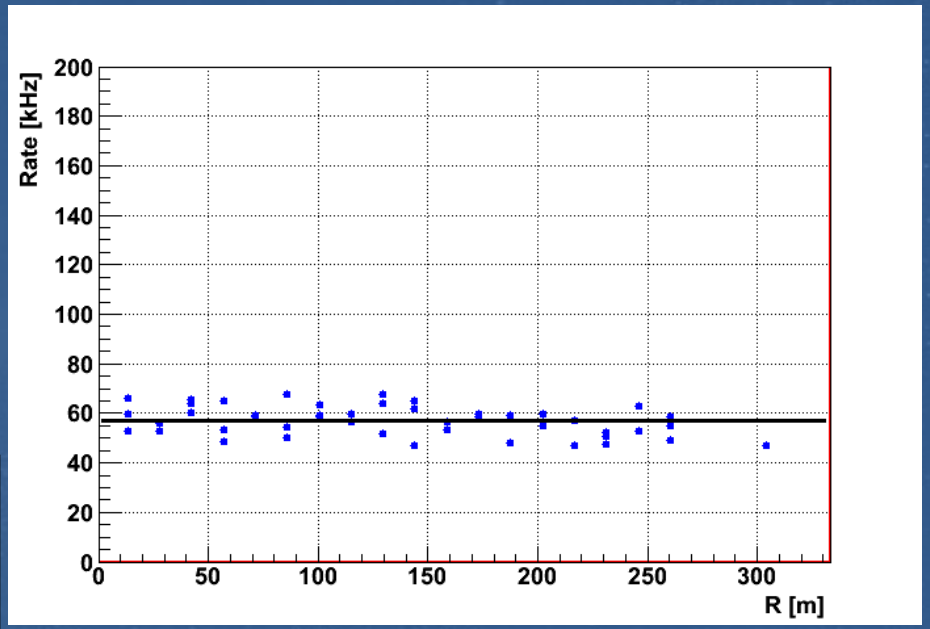
$$\mu = \frac{N_{hits}}{N_{flashes}}$$

$$P(N_{hits} > 1) < 1\%$$

$$\mu < 0.1$$

3. Low efficiency PMTs cleaning.

4. Low background rates along the line: BKG < 100 kHz:



EXPERIMENTAL PROCEDURE: DATA AND MC

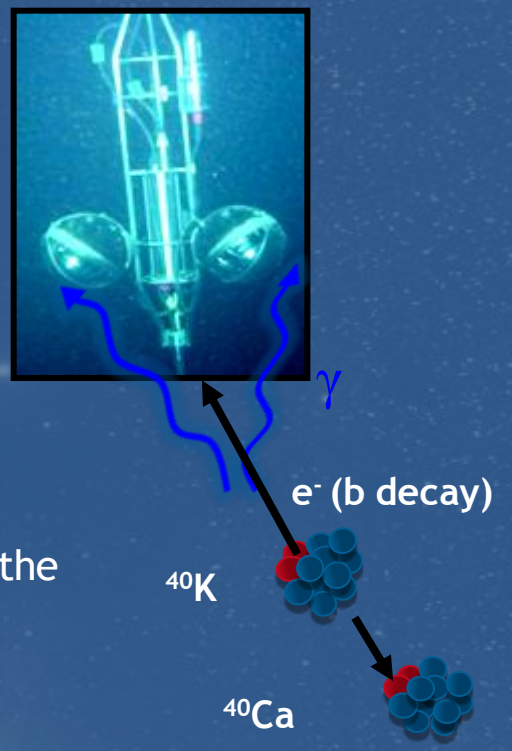
5. PMT efficiencies are computed from ^{40}K coincidences analysis:

• The relative sensitivities of the three PMTs in a triplet S_i can be computed by solving the system of 3 equations:

$$R_{ij} = R_0 * S_i * S_j \qquad \text{where } i, j = 1, 2, 3$$

R_0 is the nominal ^{40}K coincidence rate (R_0=16 Hz, for a 0.3 pe ARS threshold).

• Using these formulas is possible to produce PMT sensitivity tables.



6. Treatment of data by means of "Student's t": Usual treatment for the estimation of the mean and standard deviation of a gaussian distribution when none of the two parameters are known:

• Three intensity measurements per storey (3 PMTs).

• Assume these measurements are independent and gaussian distributed.

• One signal intensity per storey as the average of the 3 PMTs.

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad s^2 = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2$$

$$t = \frac{\bar{x}}{s} \qquad \sigma = t\frac{s}{\sqrt{n}}$$

EXPERIMENTAL PROCEDURE: DATA AND MC

Simulation: Muon and Neutrino tracks

Detection medium description

↓

Hit probability for a given PMT

↓

Physics events reading and PMT hits production based on event geometry and hit probability tables ➔ Detector events: signal hits (μ, not hadronic showers), physical BKG

↓

SIMULATIONS OF ATMOSPHERIC ν INTERACTIONS
Tracking of particles from the hadronic showers (also μ)

↓

TRANSLATION OF INFO ASCII FILES INTO ROOT FORMAT

↓

Electronics smearing effects and optical BKG

↓

Reconstruction of track direction and information arrangement

Simulation: Optical Beacon light

WHAT ARE WE MEASURING? ➔ $N_{pe} \propto \frac{N_0^{pe}}{R^2} e^{-\frac{R}{L}}$

↓

L ➔ Convolution of optical properties. MC Tools to clarify what parameter is.

↓

MC TOOLS SIMULATION

CALIBOB Monte Carlo:

Special simulation code for timing calibration with Optical Beacons based on muons tracks simulation code.

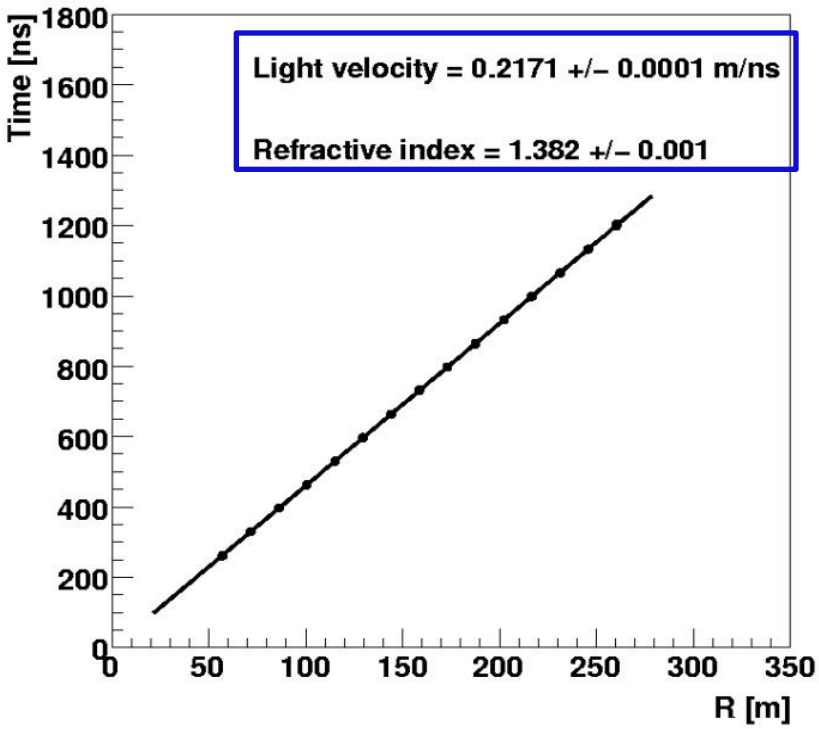
Main features:

- Width of the light pulse.
- Absorption+ Scattering in water simulated.
- PMT response simulated (parameterization for 10" Hamamatsu PMTs).
- Gain fluctuations simulated.
- TTS of PMTs simulated.
- X-talk and walk effect corrections.

PRELIMINARY RESULTS

PRELIMINARY RESULTS

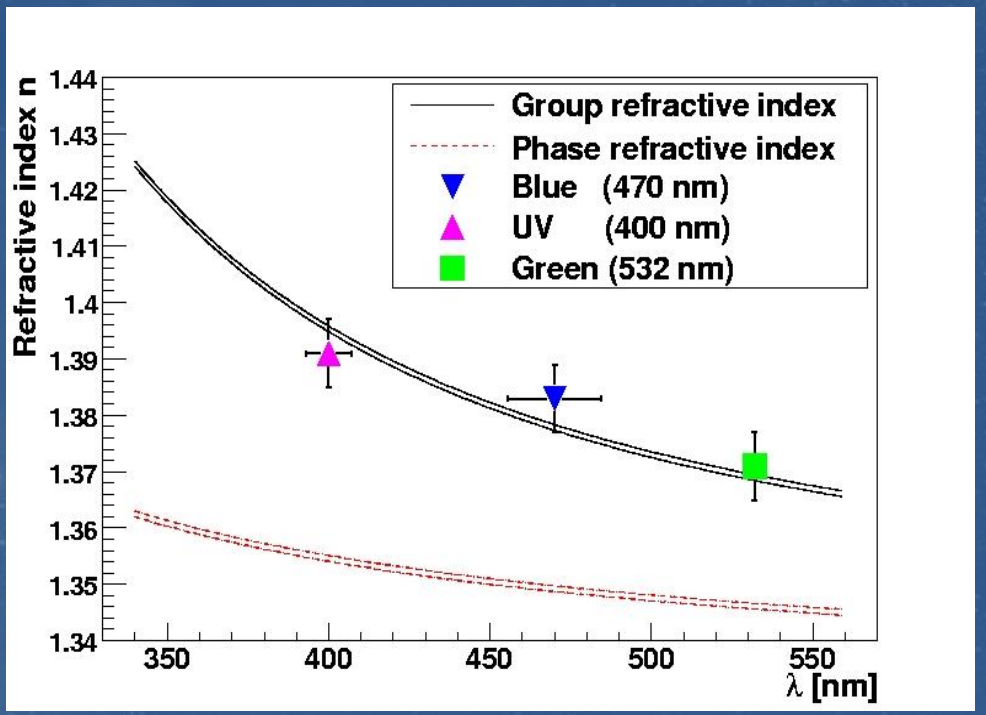
Refractive index measurement (DATA)



n = n(T, S, P)

T = Temperature.
S = Salinity.
P = Pressure.

$$n_p(\lambda, p) = 1.32292 + (1.32394 - 1.32292) \times \frac{p - 200}{240 - 200} + \\ + \frac{16.2561}{\lambda} - \frac{4382}{\lambda^2} + \frac{1.1455 \times 10^6}{\lambda^3},$$



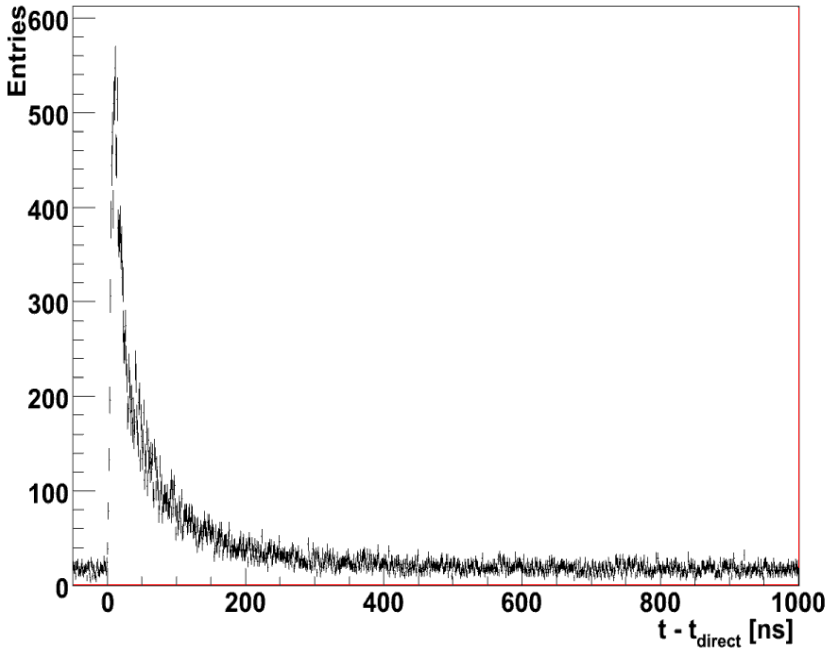
Parameterization of by Quan and Fry (data Austin and Halikas).
T = 13.2 °C, S=3.844%

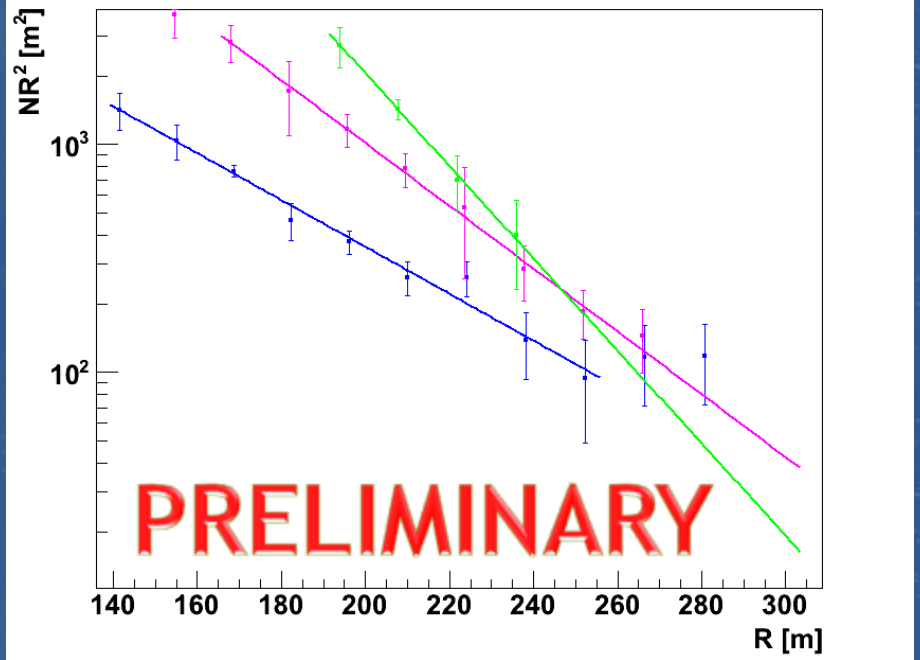
REFRACTIVE INDEX AT 470 nm:

- Slope = $1/v_m$
- $n = c/v_m$
- $c = 3X10^8$ m/s

PRELIMINARY RESULTS

Exponential fit to the collected number of hits (DATA)





Two pieces of information:

- Dependence of N_{hits} on distance.
- Delay in hit arrival times.

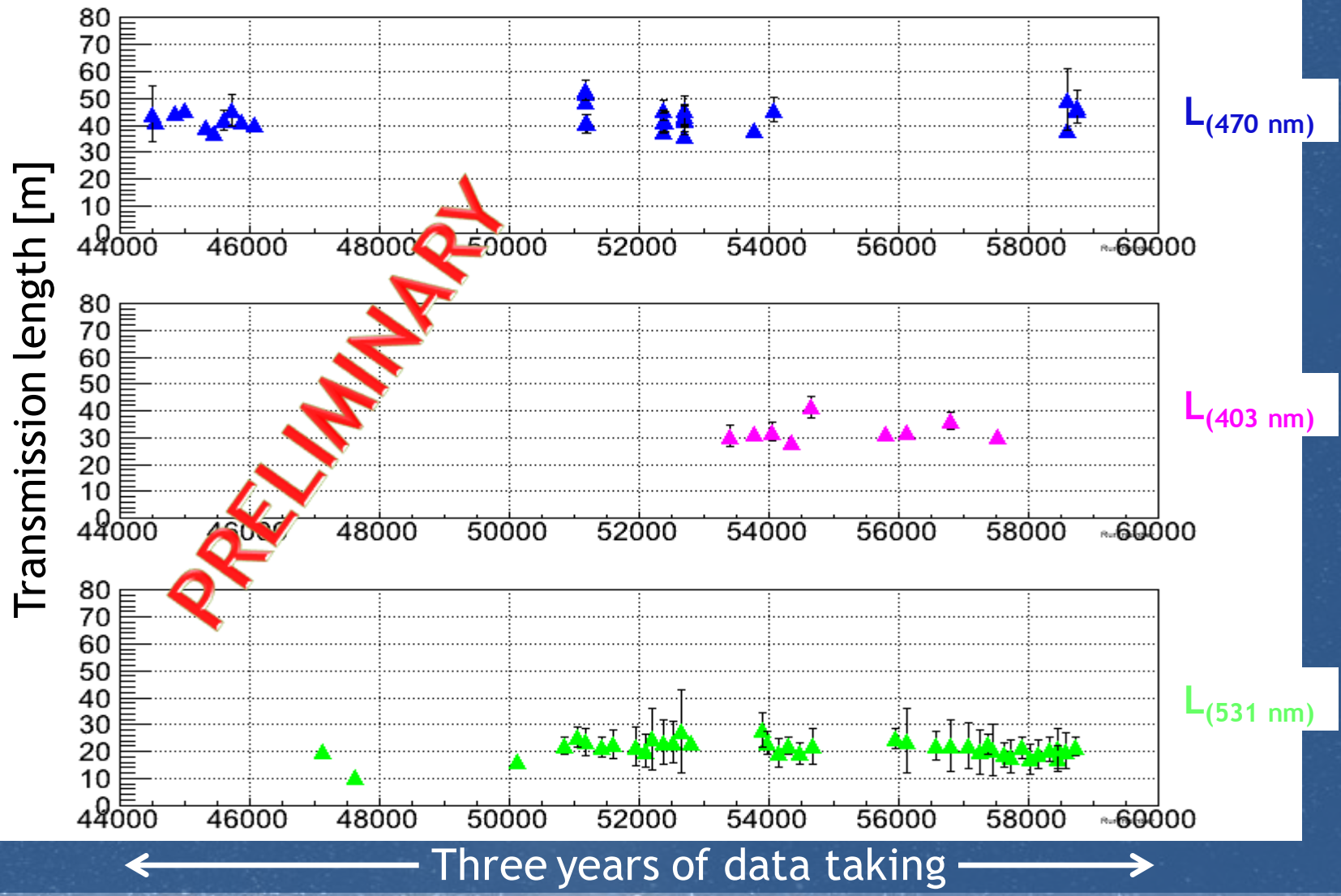
$$N_{signal}^{hits} R^2 \propto N_0^{hits} e^{-\frac{R}{L}}$$

$L_{(403\ nm)} = 31.5 \pm 2.7$
$L_{(470\ nm)} = 42.3 \pm 3.6$
$L_{(531\ nm)} = 21.4 \pm 4.2$

Wavelengths at 387, 449, 462, 494, 518 nm to be analyzed ➔ impact of the width of the source on the measurements.

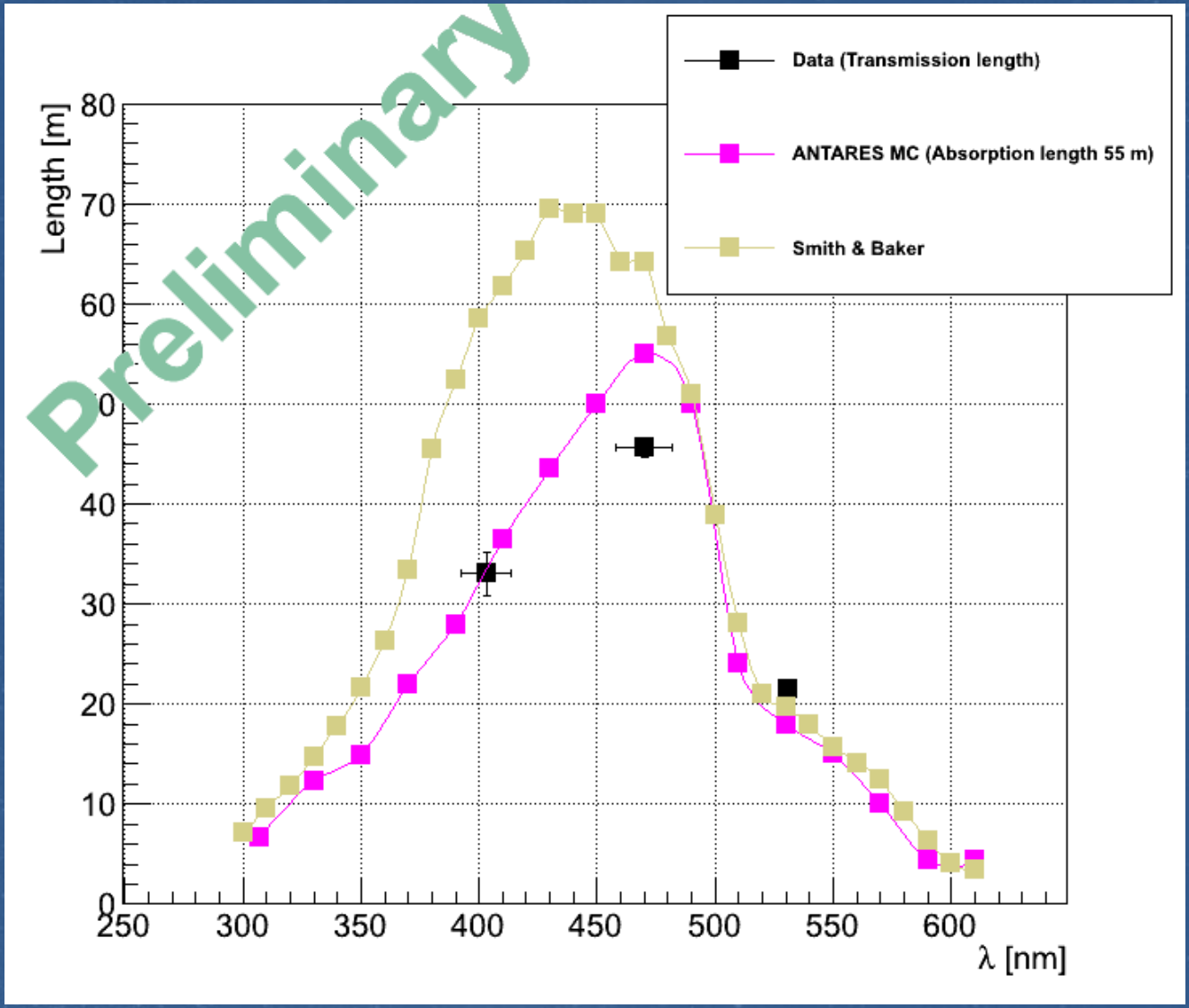
PRELIMINARY RESULTS

Transmission length stability in time (DATA)



PRELIMINARY RESULTS

Transmission length spectrum



PRELIMINARY RESULTS

Monte Carlo simulation for Optical Beacons: time distributions

What do we compare?

DATA:

- 28 runs blue, high intensity (selection based on large statistics, etc.)
- Mean value of the 3 PMTs in the storey.
- Distributions normalized to the peak of the first floor.
- A shift of about (~2 ns) has to be applied.
- Correction by PMTs orientation to be applied, neither late pulses.

CALIBOB MC:

- 25 combinations for each absorption length:

λ_{abs} = 50, 55, 60, 65, 70 m

η = 0, 0.05, 0.1, 0.30, 0.35

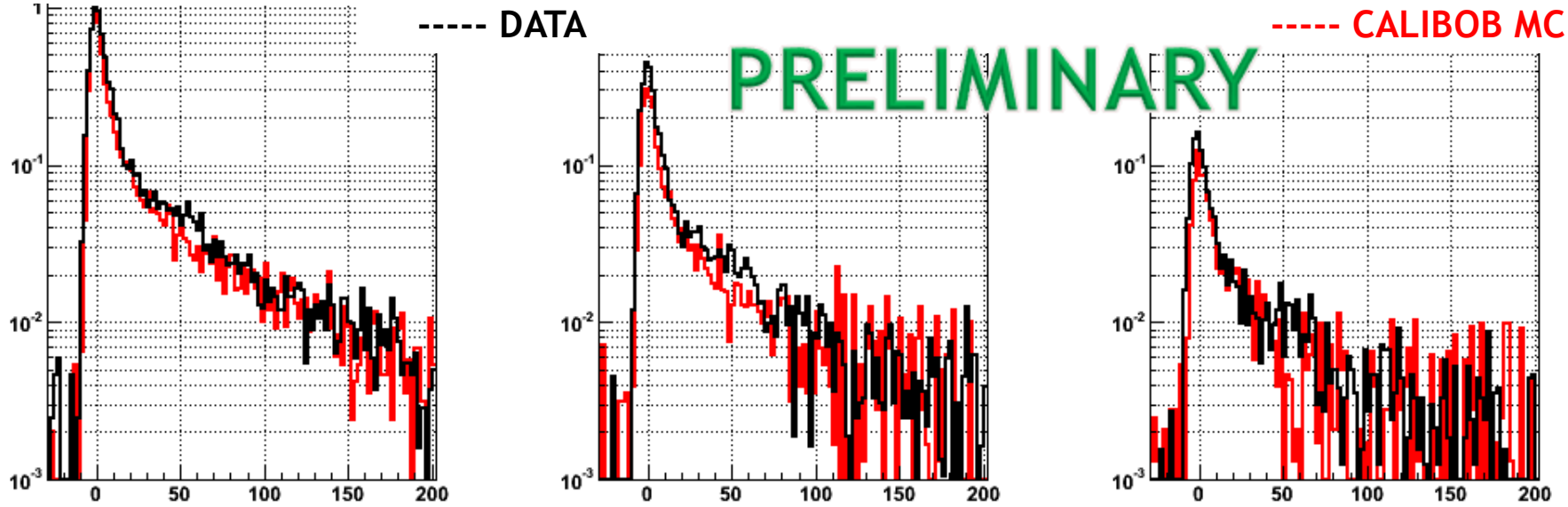
λ_{scat} = 20, 30, 70, 80

A PARTICULAR EXAMPLE ➔ λ_{abs} = 50 m, λ_{scat} = 60 m; η = 0.25 (storeys: 14, 16, 18)

----- DATA

----- CALIBOB MC

PRELIMINARY



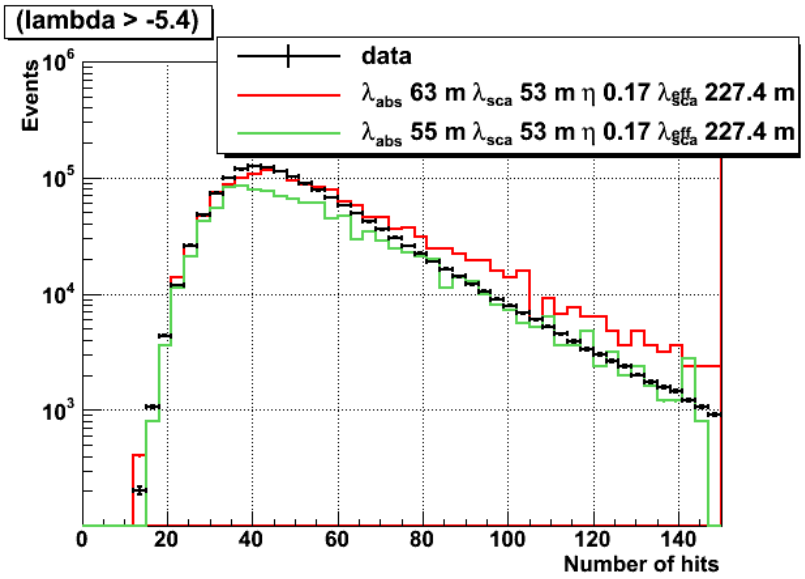
PRELIMINARY RESULTS

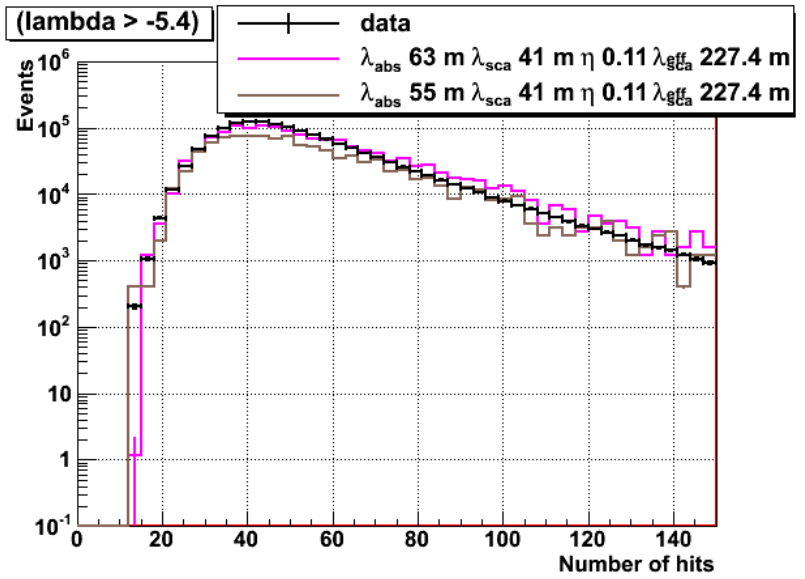
Monte Carlo simulation for muons / neutrinos tracks: testing water optical properties

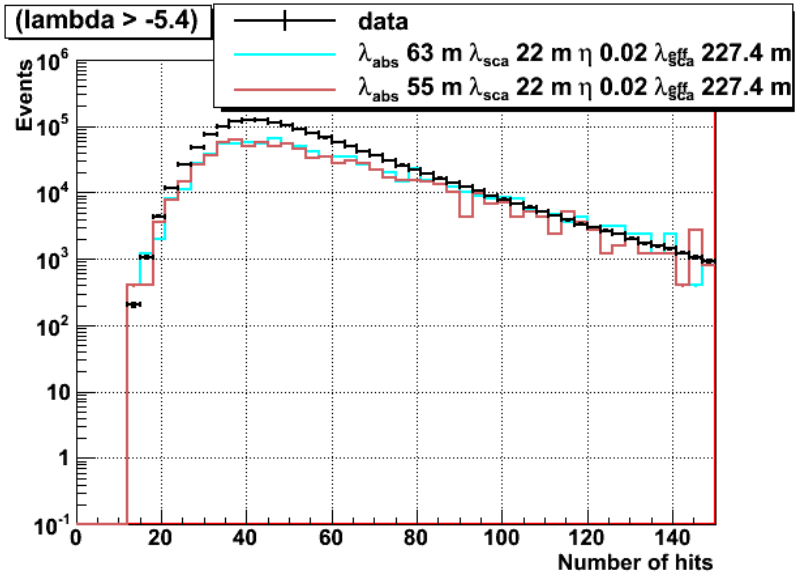
- **AIM** ➔ muon and neutrino-antineutrino production for different water models (absorption and scattering lengths), based on CALIBOB MC results.
- Comparison with real data to:
  - Study the influence of water models in track reconstruction.
  - Extract the parameter ranges best fitting the DATA.
  - Use inputs from previous analysis.
- First tentative:
  - Ten different water models for muons and neutrinos-antineutrinos production.

λ_{abs} [m]	V_s, V_l (scattering centers)	λ_{scat} at 470 nm [m]	η
55	0.0075	53	0.17
55	0.01	41	0.17
55	0.02	22	0.17
55	0.01	41	0.11
55	0.02	22	0.02
63	0.0075	53	0.17
63	0.01	41	0.17
63	0.02	22	0.17
63	0.01	41	0.11
63	0.02	22	0.02

PRELIMINARY RESULTS





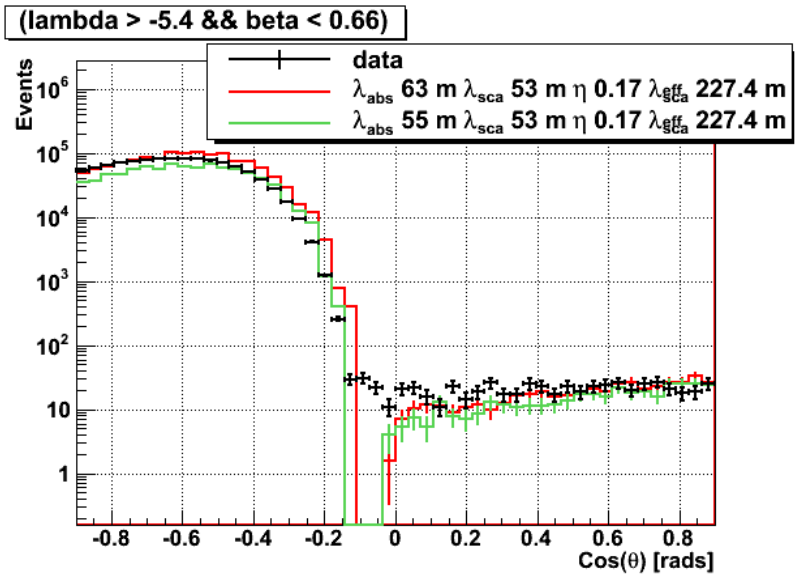


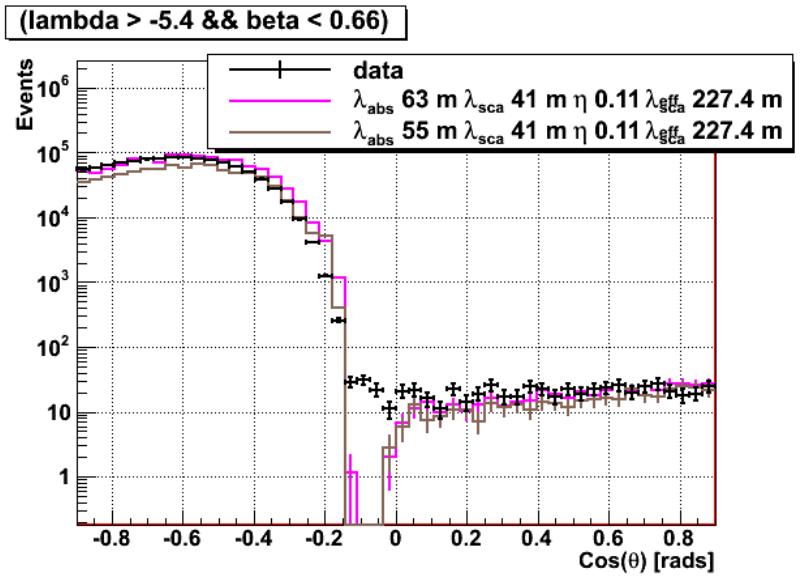
INFLUENCE OF THE NUMBER OF HITS USED IN RECONSTRUCTED TRACKS:

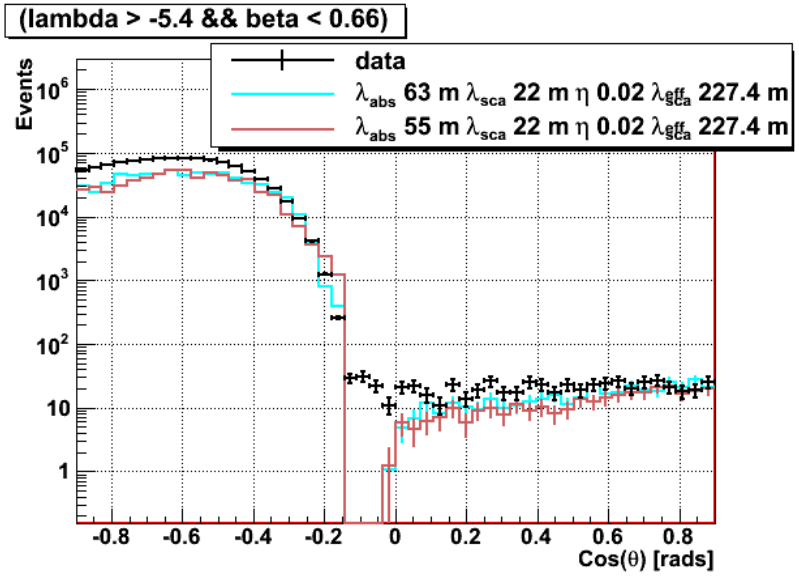
1. Higher λ_{abs} fits better to peak, a reduced λ_{abs} fits better to the tail.
2. Extreme scattering models (λ_{sca}=22 m) show the worst agreement to data and can be discarded.

PRELIMINARY

PRELIMINARY RESULTS







INFLUENCE ON THE ZENITH ANGLE DISTRIBUTIONS:

1. An λ_{abs} effect is expected for tracks just close to the horizon.
2. A mass MC production is so relevant in order to support the current analysis ➔ Ongoing.

PRELIMINARY

CONCLUSIONS AND PERSPECTIVES

1. Valuable information on water optical properties can be obtained with the Optical Beacon Calibration system of ANTARES:

- Number of hits versus distance ➔ Transmission length.
- Arrival time distribution ➔ Absorption and effective scattering lengths.

2. The analysis is very sensitive to systematic effects. The Optical Beacon system was optimized for time calibration and not for optical properties measurements.

3. A detailed Monte Carlo program, CALIBOB, is being developed to compare arrival time distributions with real data and to determine the range of the optical parameters.

4. Some preliminary results allow discarding water models with low scattering lengths (λ_{scat} < 40 m at 470 nm).

5. Some systematic effects still to be taken into account (late pulses, OM orientation) to improve the water model selection. More refined analysis is ongoing.

6. Selected water models will be tested and validated with the ANTARES track reconstruction chain.

7. Refractive indexes measured at the ANTARES site are in agreement to the results of Quan & Fry parameterization theory ➔ A paper is ready to be published.

OPTICAL PROPERTIES MEASUREMENTS: OCEAN AND PURE WATER

- *Raymond C. Smith and Karen S. Baker; Optical properties of the clearest natural waters; Applied optics, Vol. 20, Nº2, 15 January 1981.*
- *Robin M. Pope and Edward S. Fry; Absorption spectrum (380-700 nm) of pure water; II Integrating cavity measurements; Applied optics, Vol. 36, Nº33, 20 November 1997:*

SMITH AND BAKER MODEL: 200-800 nm

- Apparent Optical Properties (AOP) description for deep ocean waters (*in-situ*):

$$E(\lambda, z) = E(\lambda, 0^-)\exp[-k(\lambda)z]$$

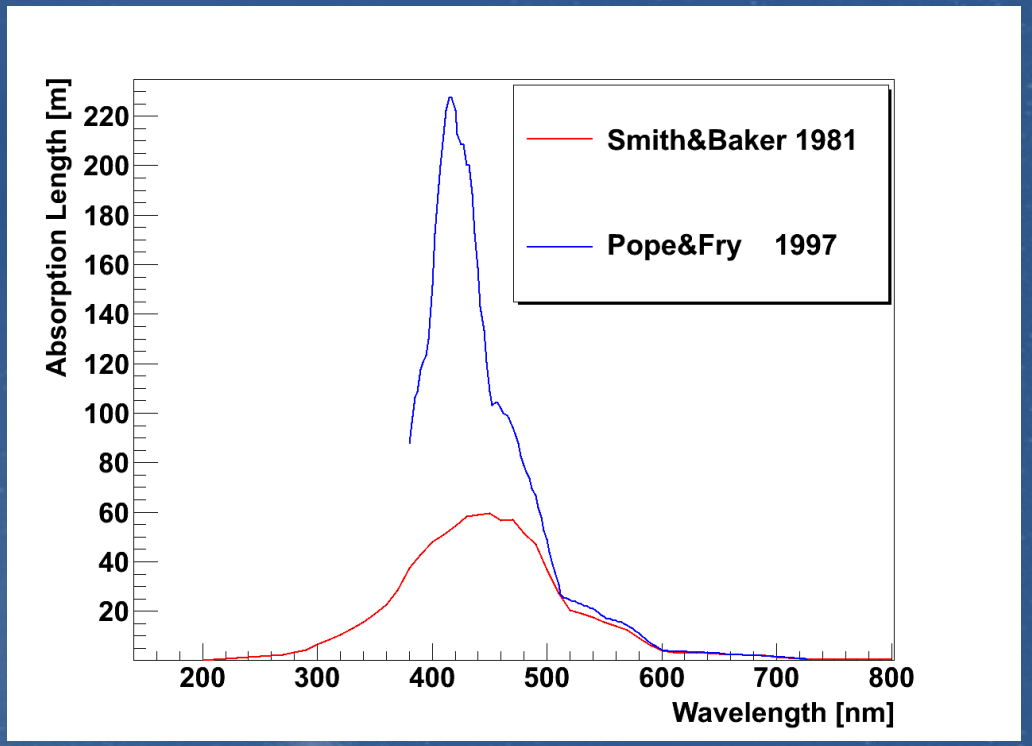
$E(\lambda, z)$=spectral irradiance at z depth.
$E(\lambda, 0^-)$=irradiance beneath the surface.
$K(\lambda)$=ocean optical property (i.e λ_{tra}).

- Low scattering centers (SC) (↓ppm).

POPE AND FRY MODEL: 380-700 nm

- Absolute calibration of the devices.
- Pure water absorption measurements (approaches to ocean waters): non *in-situ*

$$\alpha = \frac{C_1(\lambda)}{4V}[S - C_0'(\lambda)] \equiv C_1'(\lambda)[S - C_0'(\lambda)]$$



α = Absorption coefficient of the sample.
V = Sample volume.
S = Signal.
$C_1'(\lambda)$, $C_0'(\lambda)$= Calibration constants to determine.

STUDENT'S t DISTRIBUTION:

•Each storey provides 3 intensity measurements (3 OMs).

• Assume these measurements are independent and gaussian distributed (check this hypothesis later with results).

• Assign one signal intensity per storey computed as the average of the 3 OMs

– OM signal extraction as before: subtract background, correct by efficiency, discard bad OMs

• Compute error by means of Student's *t* (this is the usual treatment for the estimation of the mean and standard deviation of a gaussian distribution when none of the two parameters are known):

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$$

$$s^2 = \frac{1}{n-1}\sum_{i=1}^{n} (x_i - \bar{x})^2$$

• Then the variable:

$$t = \frac{\bar{x}}{s}$$

follows Student's *t* distribution:

$$f(t) = \frac{\Gamma((\nu+1)/2)}{\sqrt{\nu\pi}\cdot\Gamma(\nu/2)}(1+t^2/\nu)^{-(\nu+1)/2}$$

with ν = n–1 degrees of freedom

• Therefore the error is taken to be: $\sigma = t \cdot s/\sqrt{n}$

• In order to have 68.27% errors, the one-side tail of the cumulative Student function must be 84.13% and thus t = 1.32 (for n=3) or t = 1.83 (for n=2).

• If only one OM in the storey do not use that storey in the fit.

CROSS-TALK EFFECT:

Phenomenon by which a signal transmitted on one circuit or channel of a transmission system creates an undesired effect in another circuit or channel. Crosstalk is usually caused by undesired capacitive, inductive, or conductive coupling from one circuit, part of a circuit, or channel, to another.

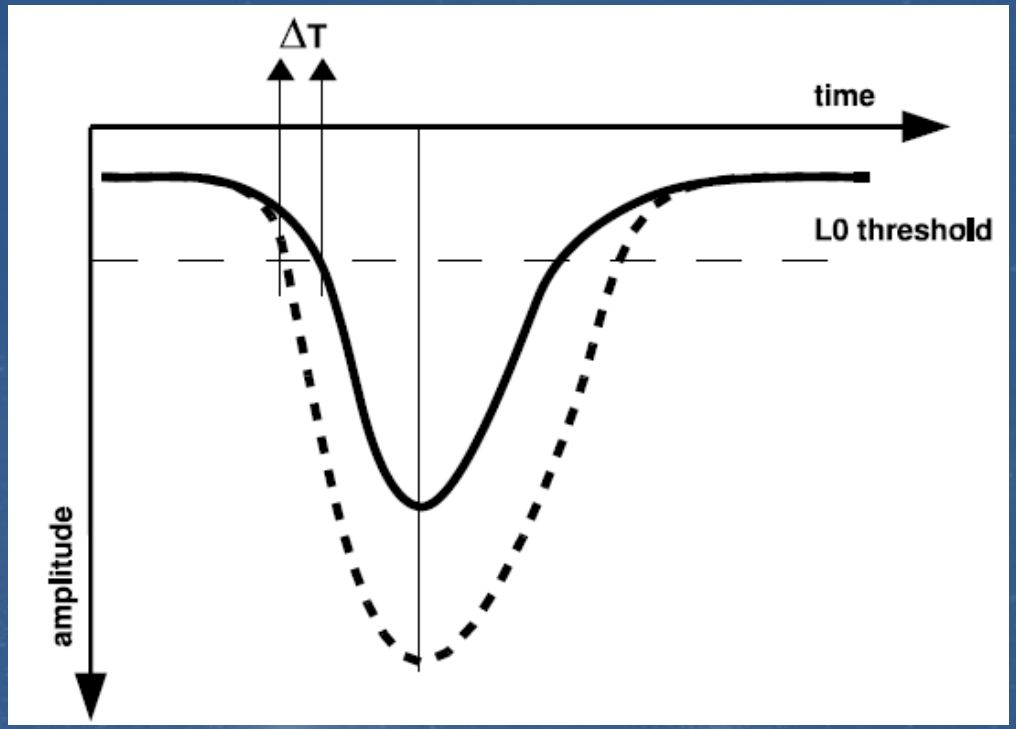
The source of this effect is related to the ARS analog pipeline memory where the digitized charge and time of the signal are stored close-by. Extracted from this storage, the charge of the processed signal shows a small correlation with the digitized time.

This influence is not reciprocal, it only affects the charge of the signal and not the time, so an easy correction of the AVC is possible once the effect is measured and parameterized in the dark-setups. This linear effect, measured during the calibration of the lines as well as during the data-taking in the sea, is described with one single parameter called XT range. The correction equation used to transform from AVC values to corrected AVC values is:

$$AVC_{corr} = AVC - XT_range \frac{TVC - \frac{TVC_{max}+TVC_{min}}{2}}{TVC_{max} - TVC_{min}}$$

WALK EFFECT:

This effect is caused by the variation in the amplitude of pulses recorded in the PMTs. Two coincident signals (same time at their maximum amplitude) cross the L0 threshold at different times depending on their amplitudes.



This effect translates into a correlation between the charge of the signal and the arrival time in the PMT and it induces a delay in the arrival time of photons as a function of the charge.