Ultrafast time-of-flight imaging with SPAD and picosecond laser for validation of the stray light rejection in an optical calibration facility

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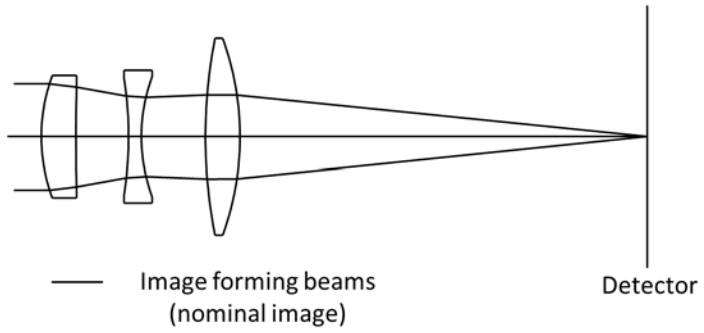
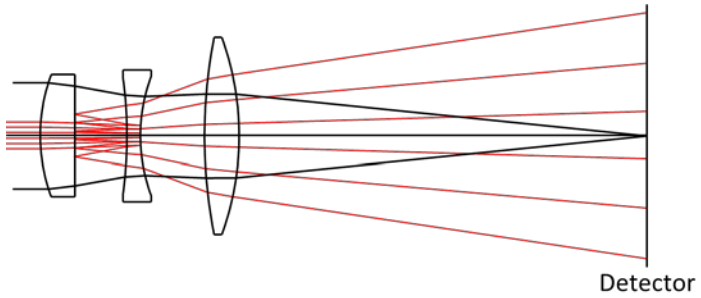
What is stray light ?

- **What is Stray Light (SL) ?**
  - Unwanted/parasitic light reaching the detector of an optical imaging system
  - It comes from the field observed (in-field SL) or out of the field (out-of-field SL)
  - Stray light degrades the images

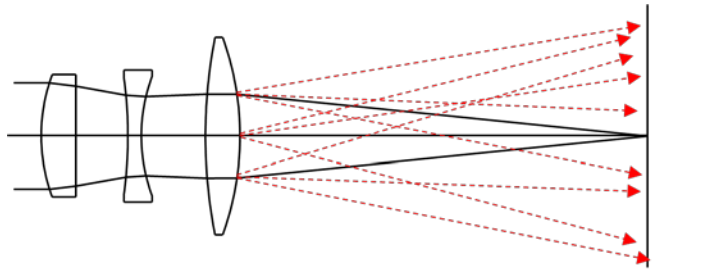
Ideal case



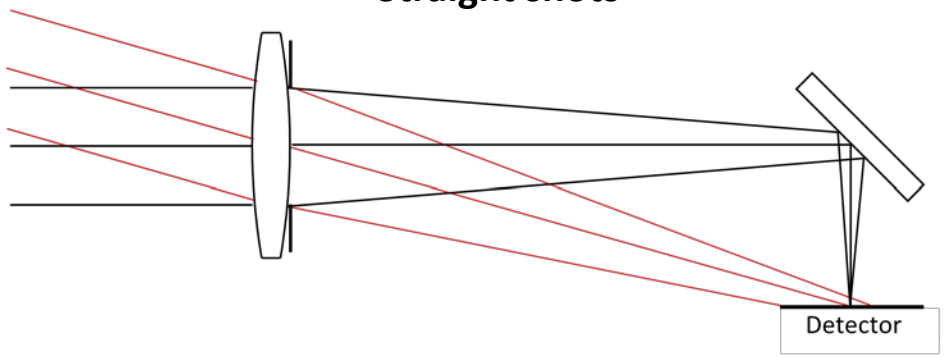
Ghost reflection



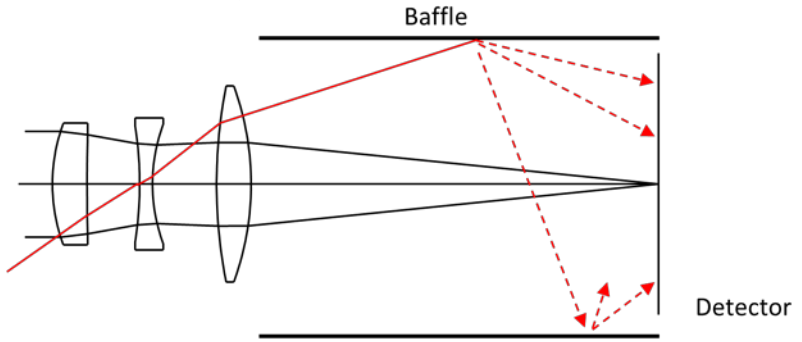
Scattering on optical surfaces



Straight shots



Scattering on mechanical surfaces



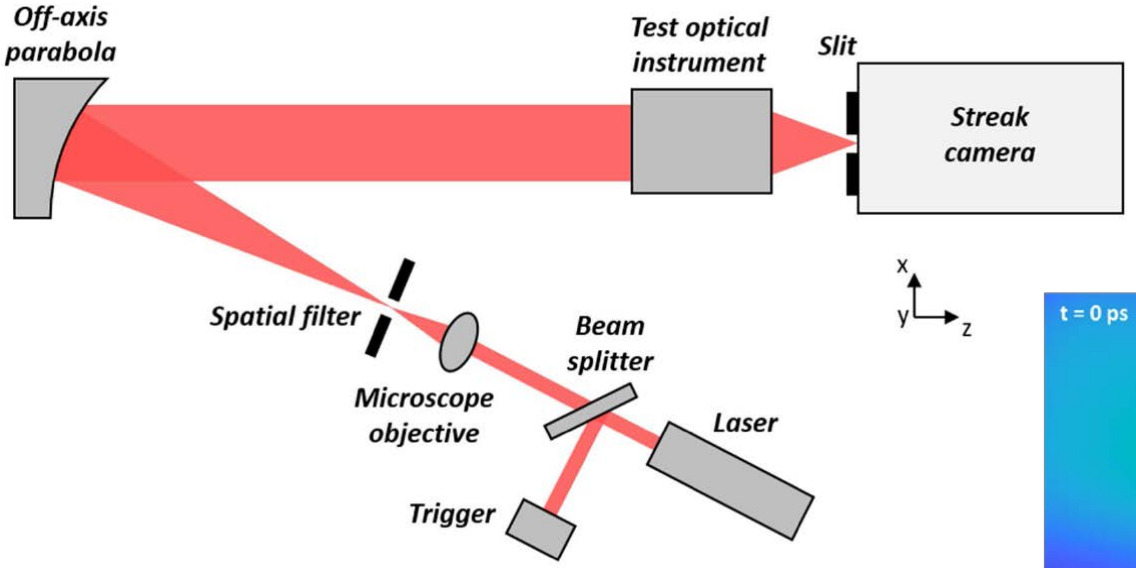
Innovative way to characterize SL

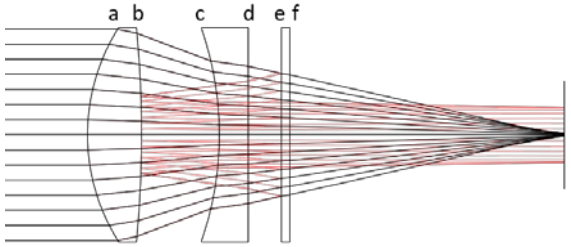
- **Innovative way to characterize SL** *L. Clermont, W. Uhring, M. Georges, Sci. Rep. 11:10081 (2021)*
  - Discrimination of SL components in function of their Optical Path Length (OPL)
  - SL components reach the detector at specific time

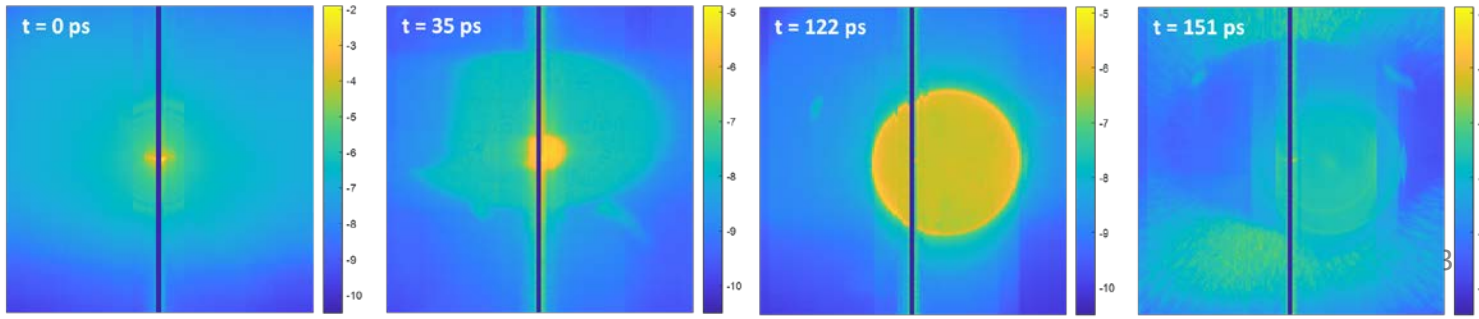
$$dt = N\ [ps] \quad \Leftrightarrow \quad OPL = 0.3N\ [mm]$$

- **Time-of-Flight imaging of SL components of an optical system**
  - Femtosecond laser (Ti:Sapph)
  - Streak camera

$$dt = 2\ ps \quad \Leftrightarrow \quad OPL = 0.6\ mm$$



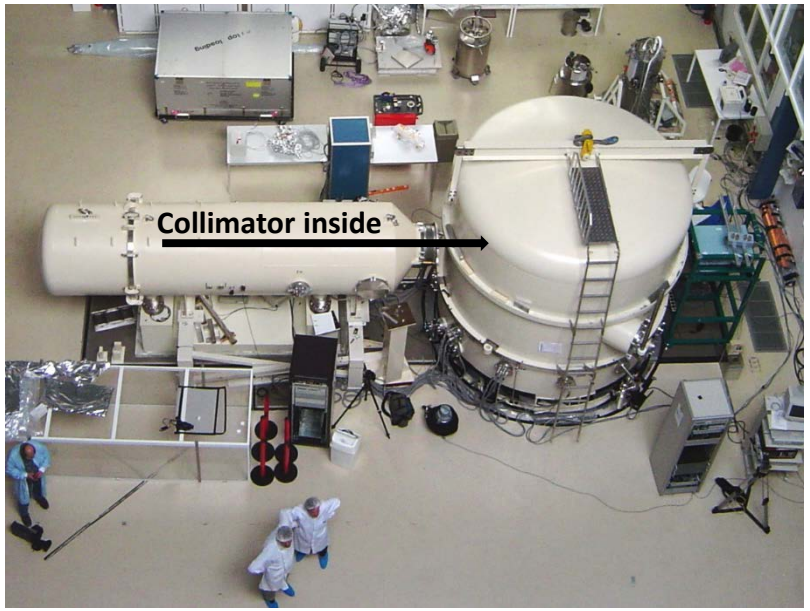


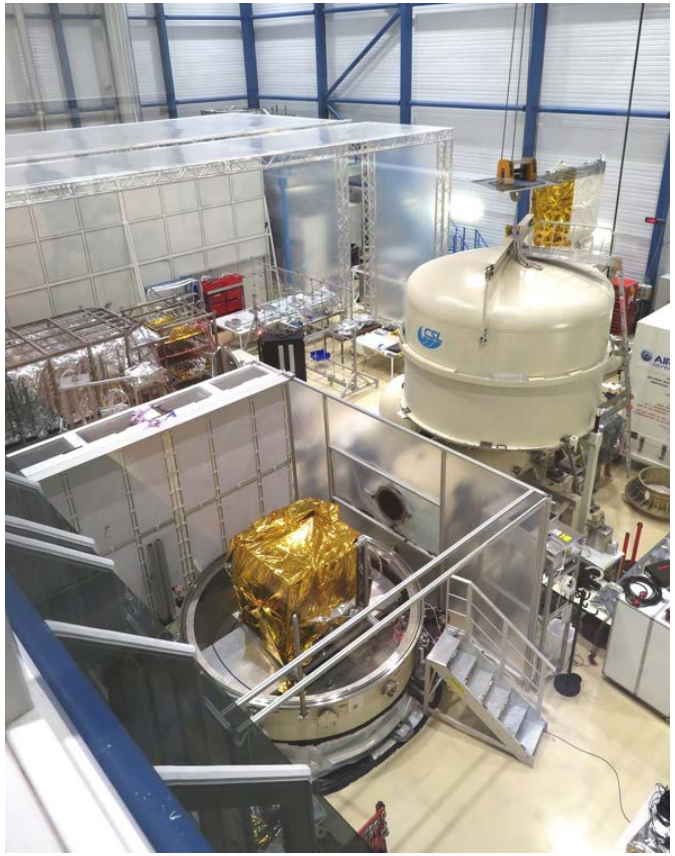


Motivation of this work

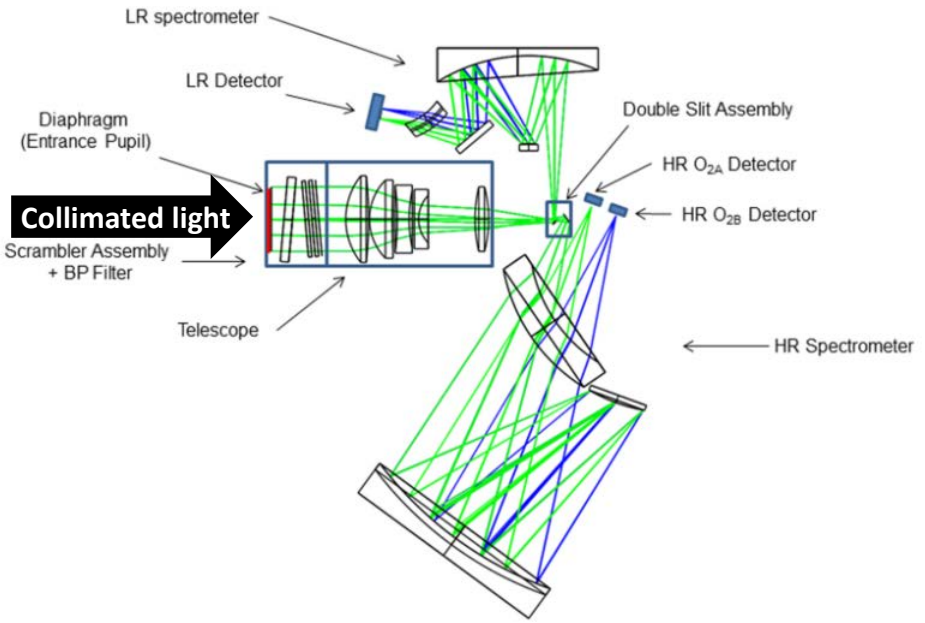
- **Space optical instruments**
  - Earth Observation instruments need to be characterized in term of SL
  - The usual facilities are collimators illuminating the space optical instrument

FOCAL3 facility at CSL

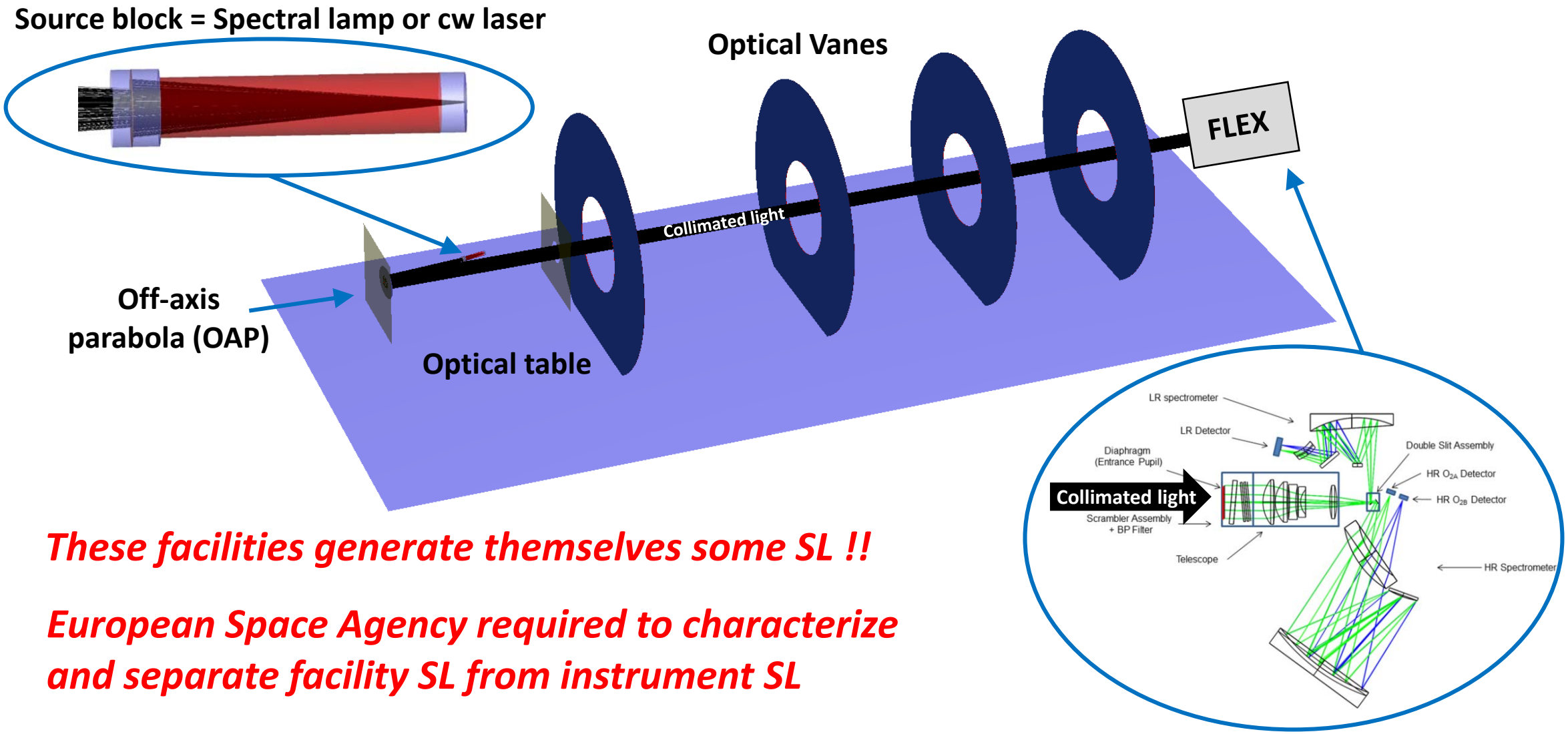




FLEX mission spectro-imager



- **Facilities for SL characterization**

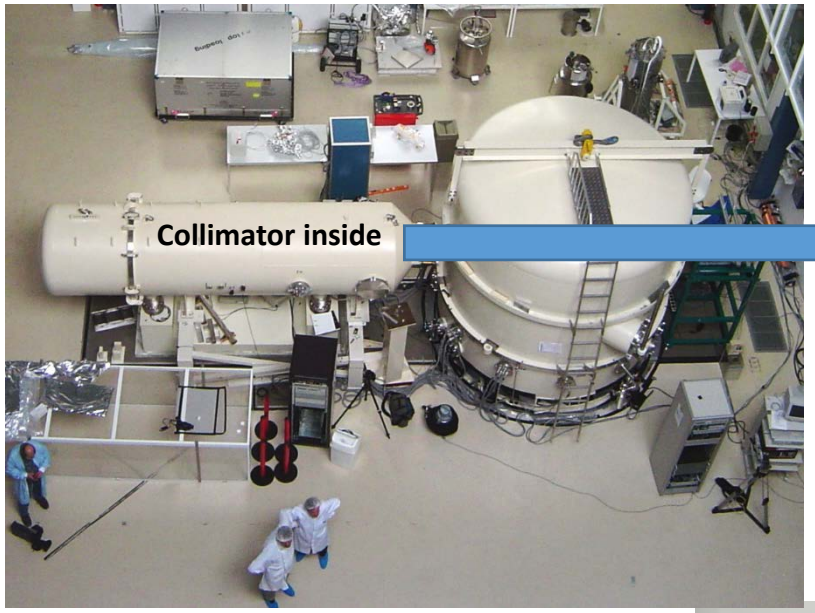


These facilities generate themselves some SL !!

European Space Agency required to characterize and separate facility SL from instrument SL

Characterize SL generated by the facility

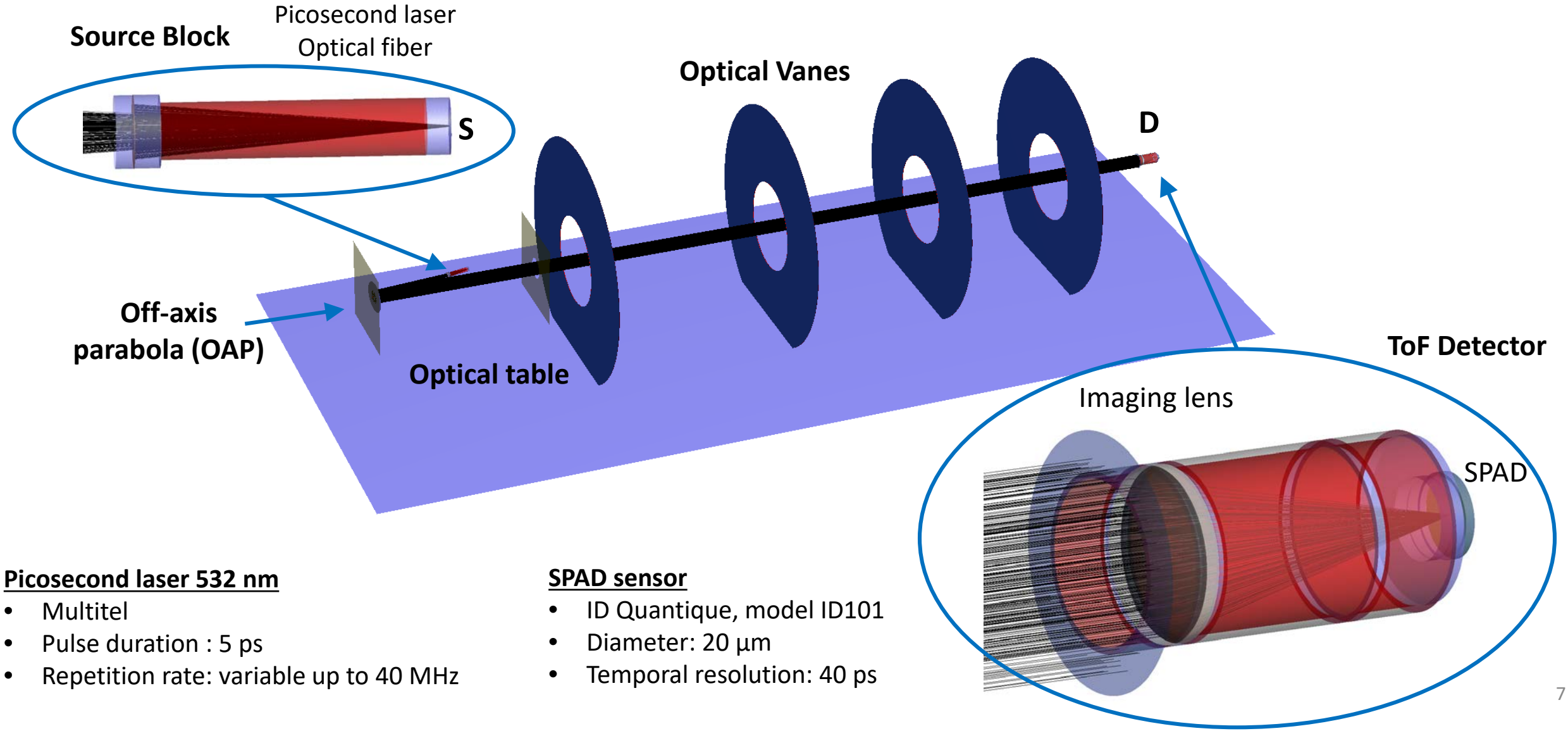
- **Characterization of facility-linked SL by Time-of-Flight method**



Test collimator has been transferred to the lab

Characterize SL generated by the facility

- **Characterization of facility-linked SL by Time-of-Flight method**



Picosecond laser 532 nm

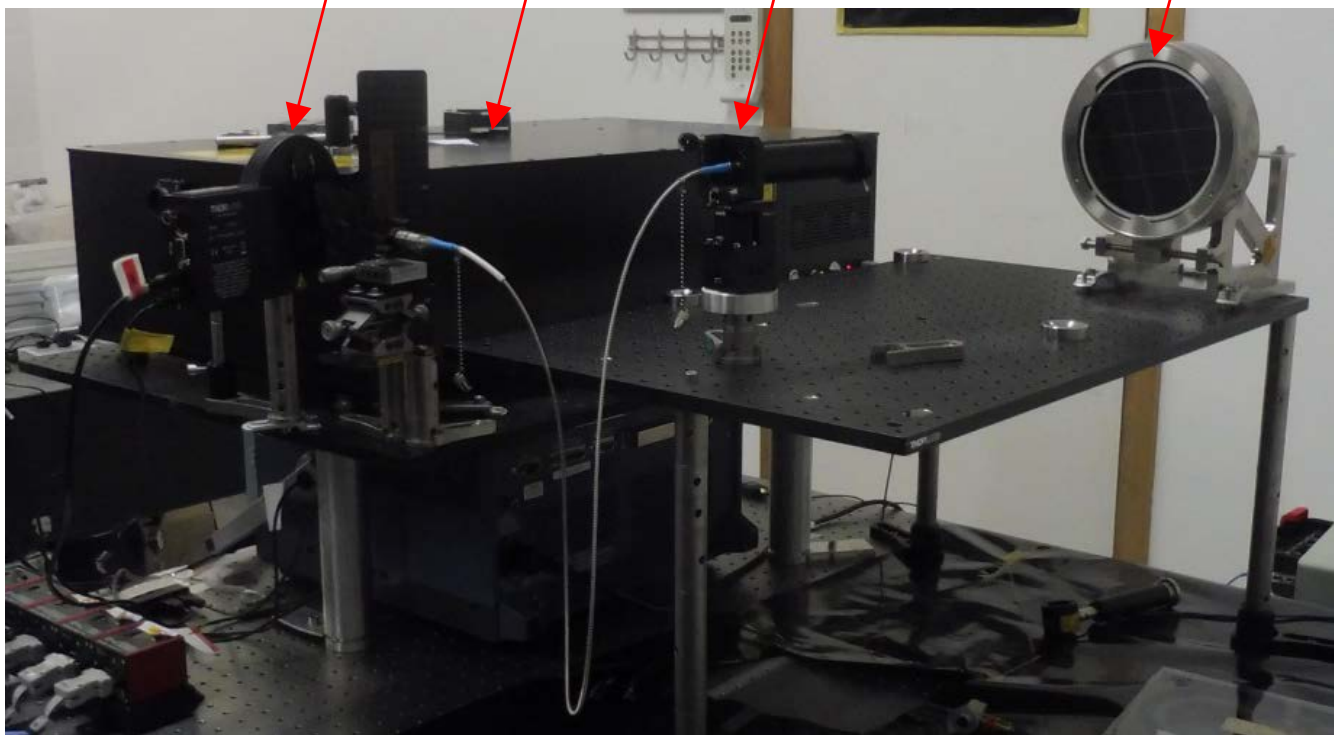
- Multitel
- Pulse duration : 5 ps
- Repetition rate: variable up to 40 MHz

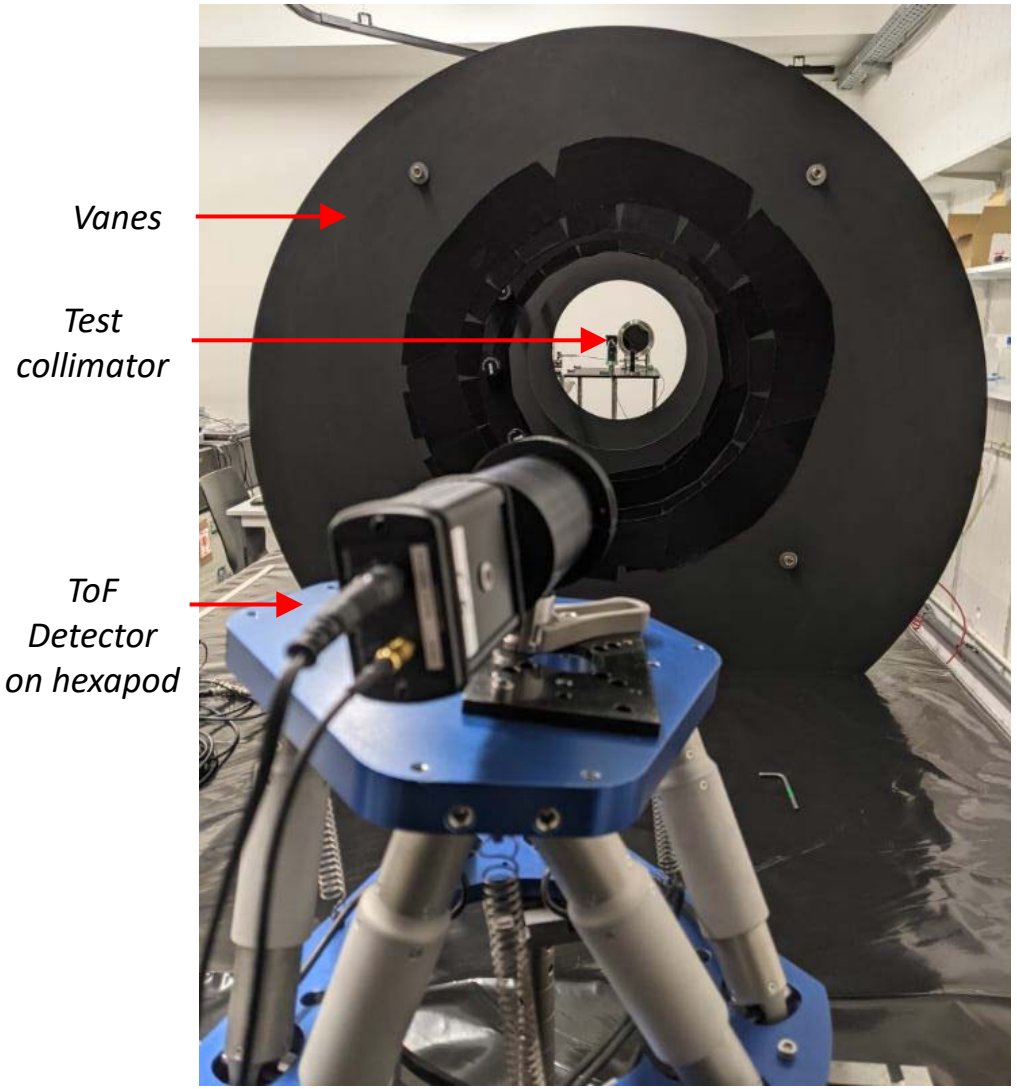
SPAD sensor

- ID Quantique, model ID101
- Diameter: 20 µm
- Temporal resolution: 40 ps

Experimental set-up

Test collimator



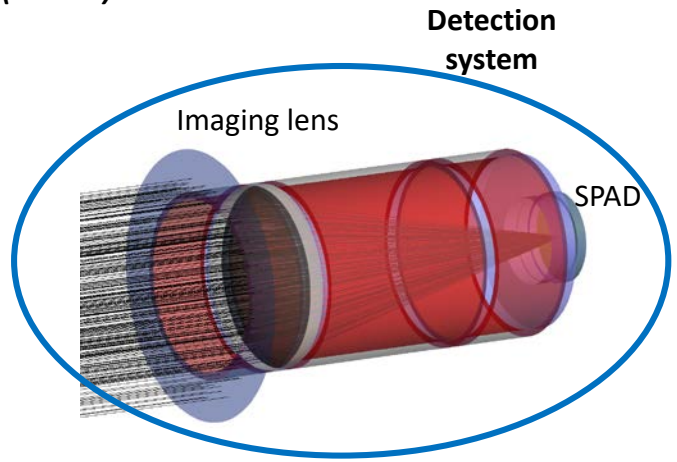


Measurement method

Single ToF acquisition

At the focal plane of the detection system, the SPAD measures a ToF spectrum from light coming within the iFOV (β=±0,0141°) of the imaging lens

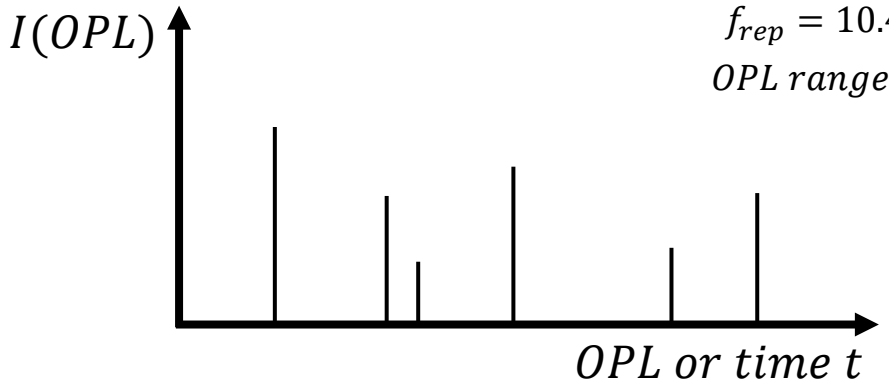
OPL=f(time)



Laser

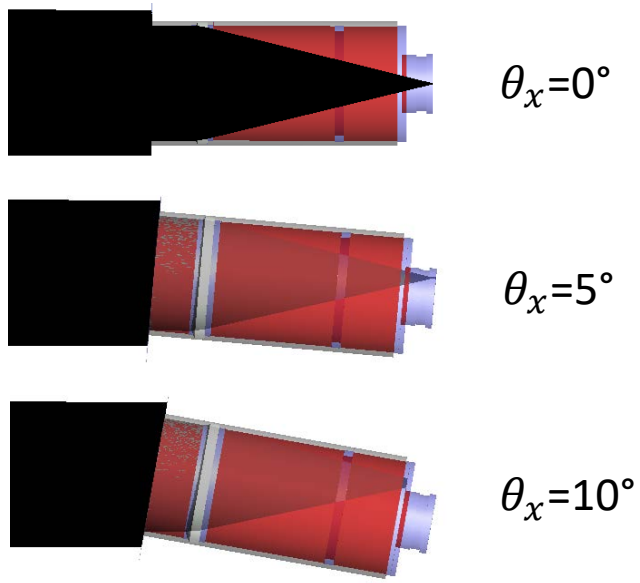
$f_{rep} = 10.4\ MHz$

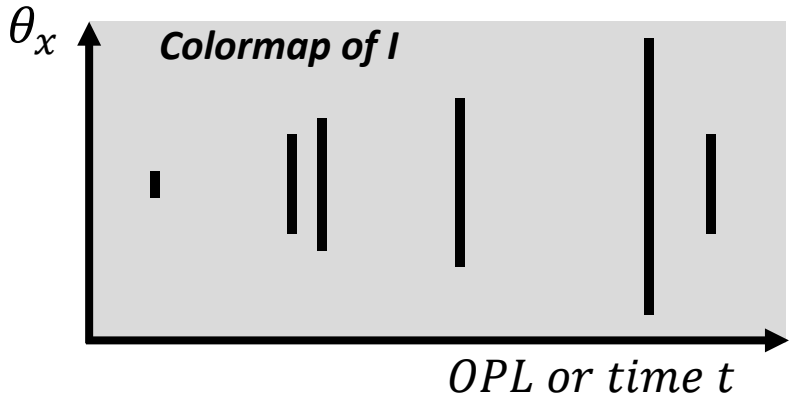
$OPL\ range \sim 29\ m$



Angular scan

We rotate the detection system around its pupil and acquire a ToF spectrum at each angle. We measure the SL in the facility decomposed in the spatio-temporal dimensions

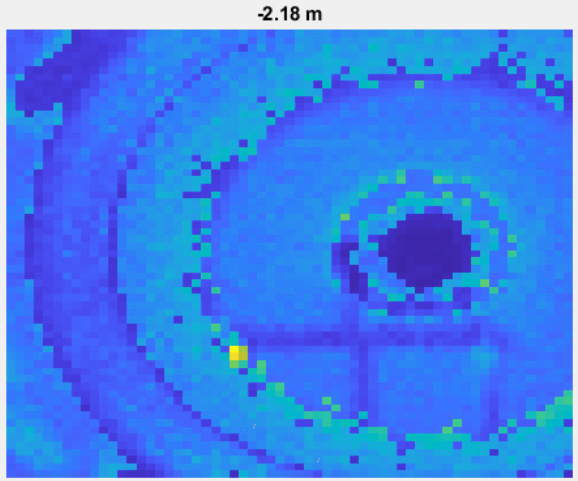




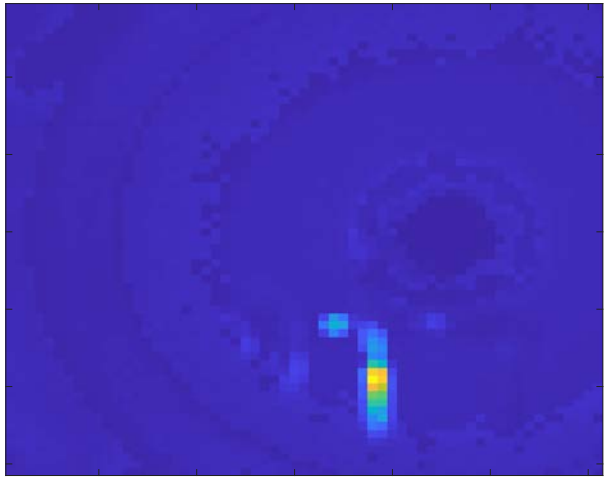
Experimental Results

- **Full 2D reconstruction of SL components**
  - Angular scan along 2 directions θ_x θ_y
  - A movie of $I_{SL}(\theta_x, \theta_y, OPL)$ is obtained

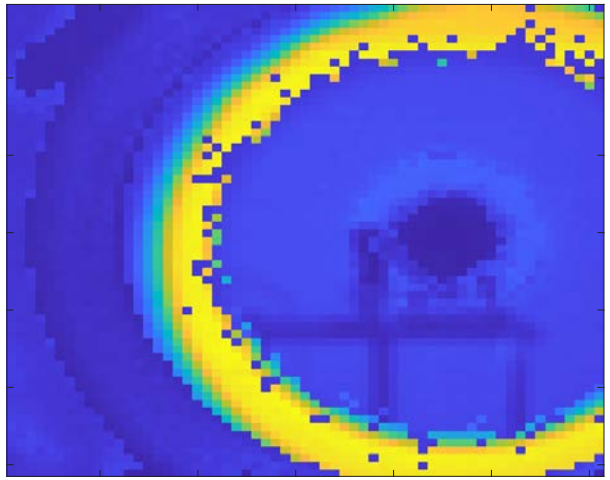
- **Coarse angular scan: large FOV**



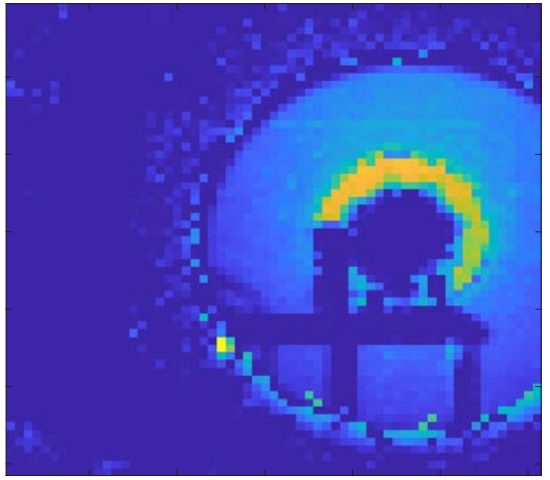
SL from the optical fiber (OPL = -1.1m)

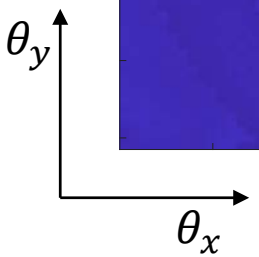


SL from the first vane (OPL = 3.5m)



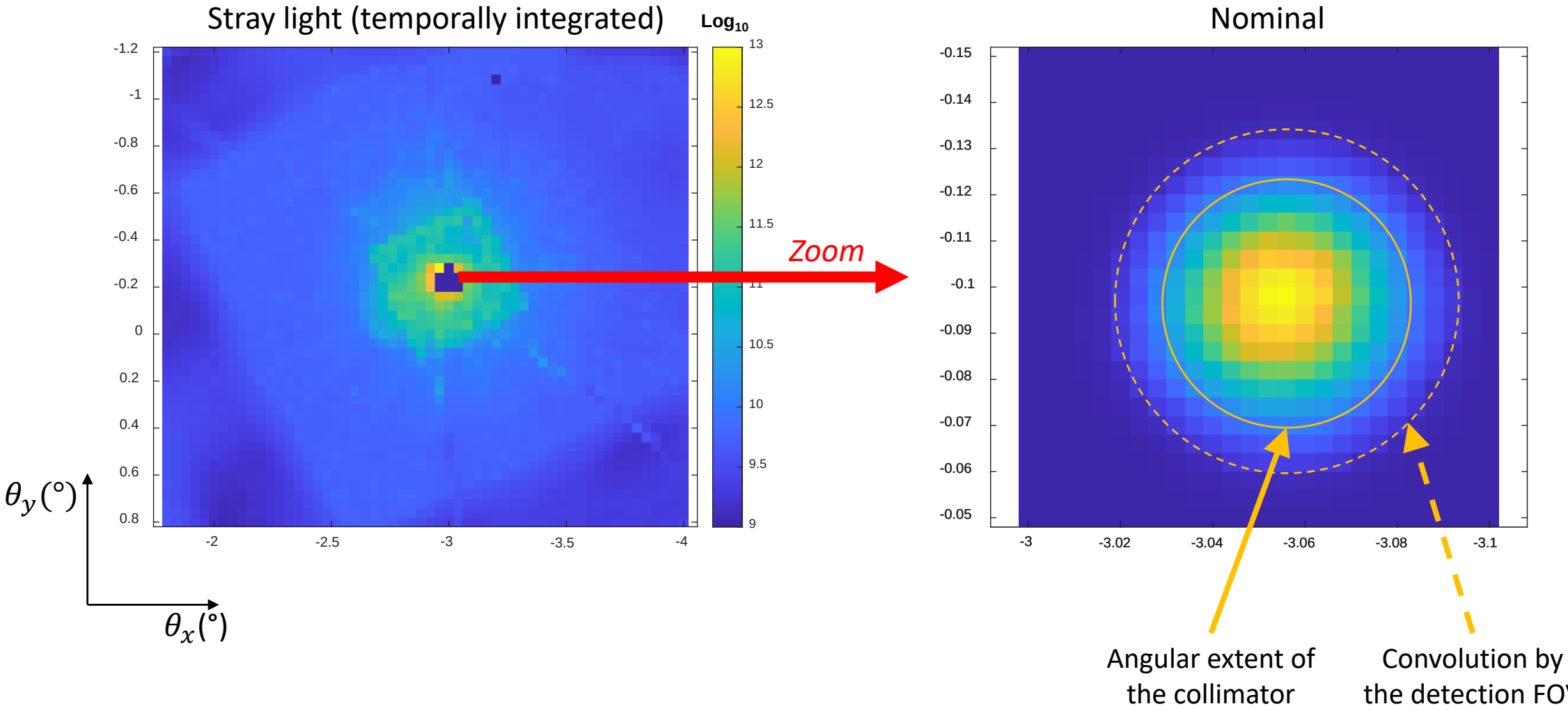
SL around the collimator and on the back wall (OPL = 4.33 m)





Experimental Results

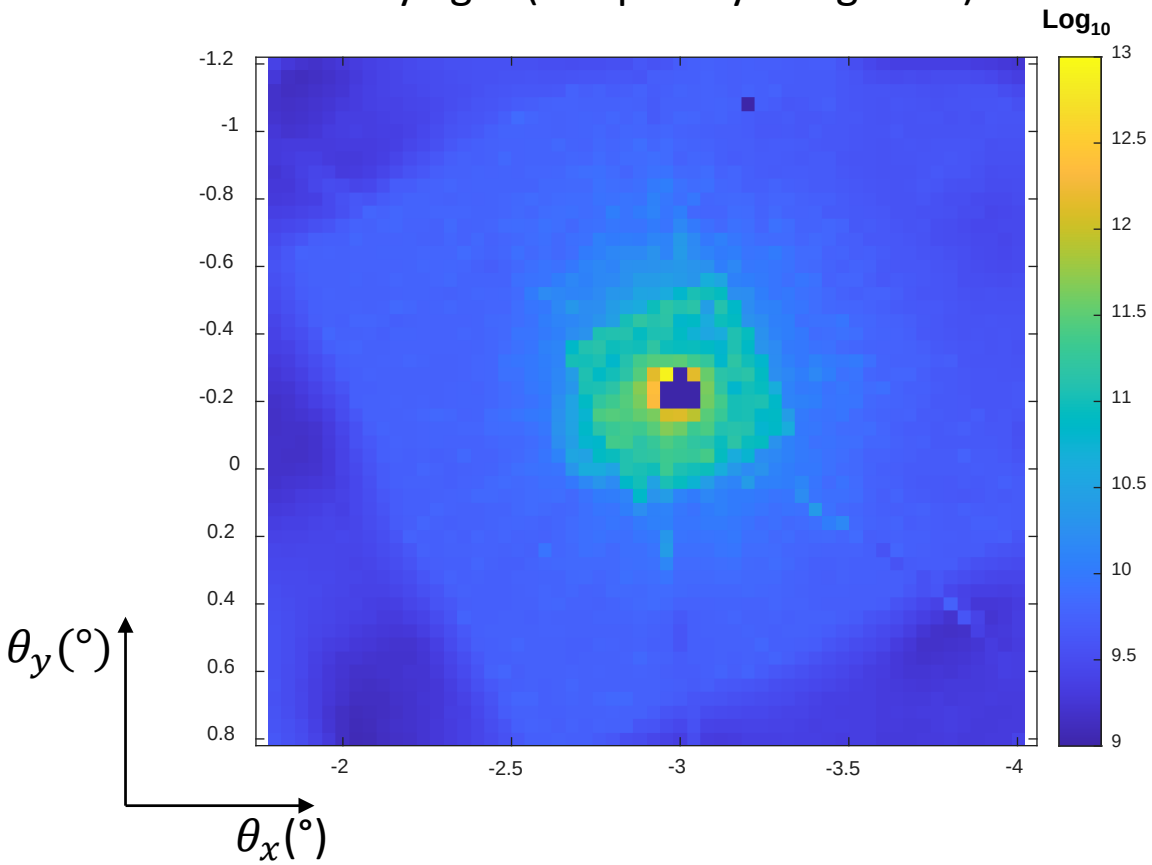
- **Refined angular scan (small FOV –field near the nominal peak)**



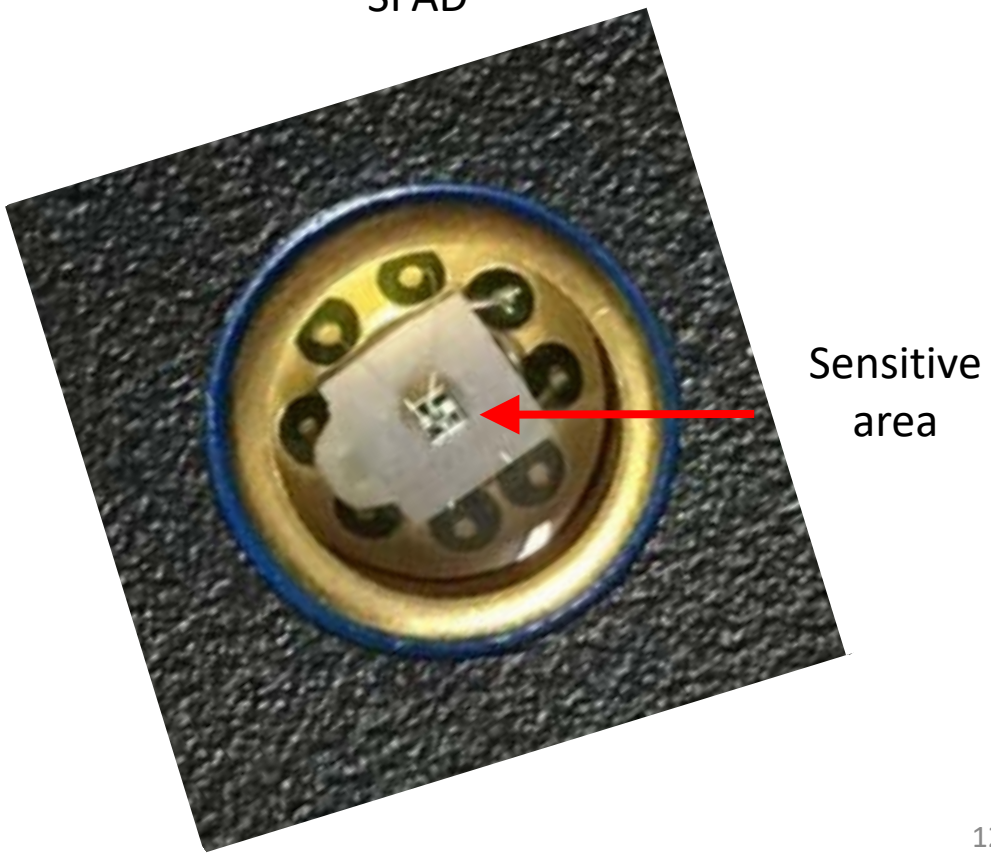
- **Measurement at small angles (near-field)**

We observe that the SPAD “sees itself” ! As the detection system is scanned angularly, light illuminates the surrounding of the SPAD and create a ghost
➔ A diaphragm will be used to hide the surrounding of the SPAD

Stray light (temporally integrated)



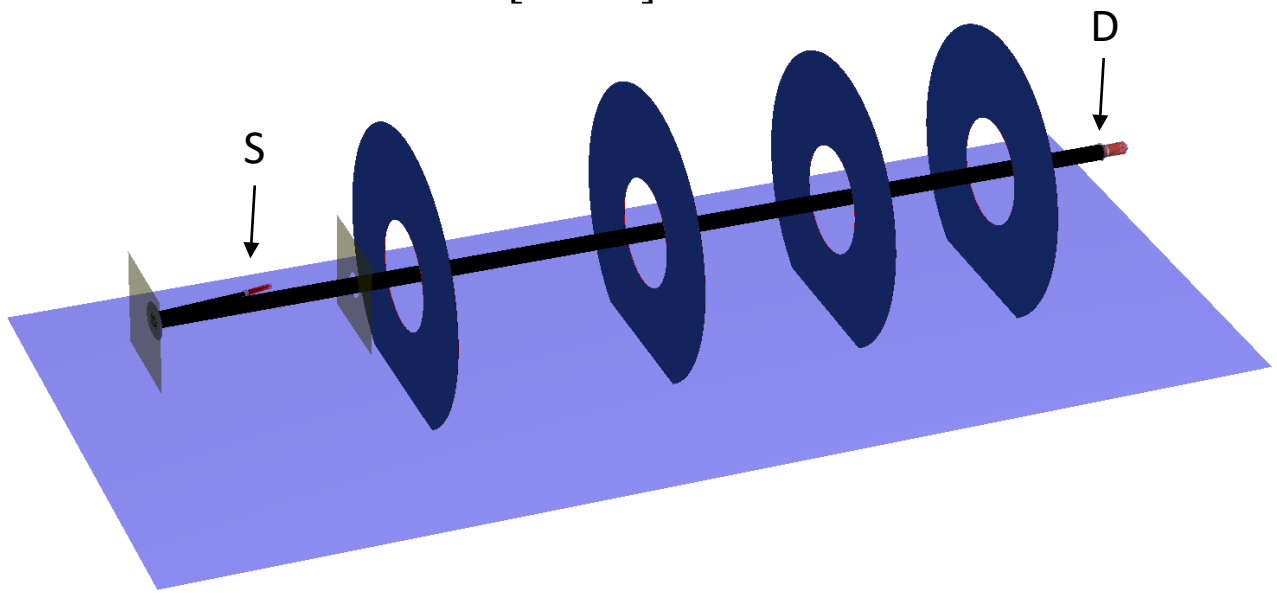
SPAD

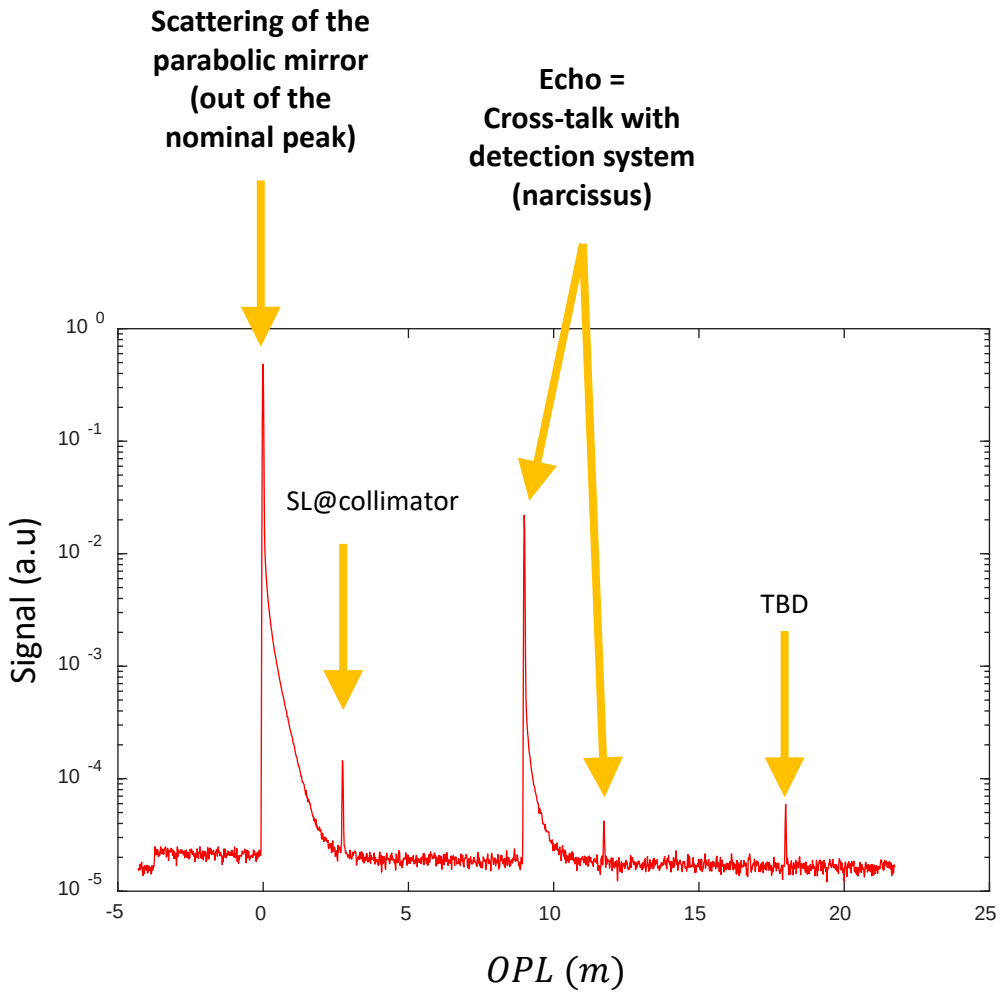


- **Measurement at small angles (near-field)**

A measurement at a single angle in the near field allows to decompose the different contributors:

$$distance\ [S-D] \sim 4.5\ m$$

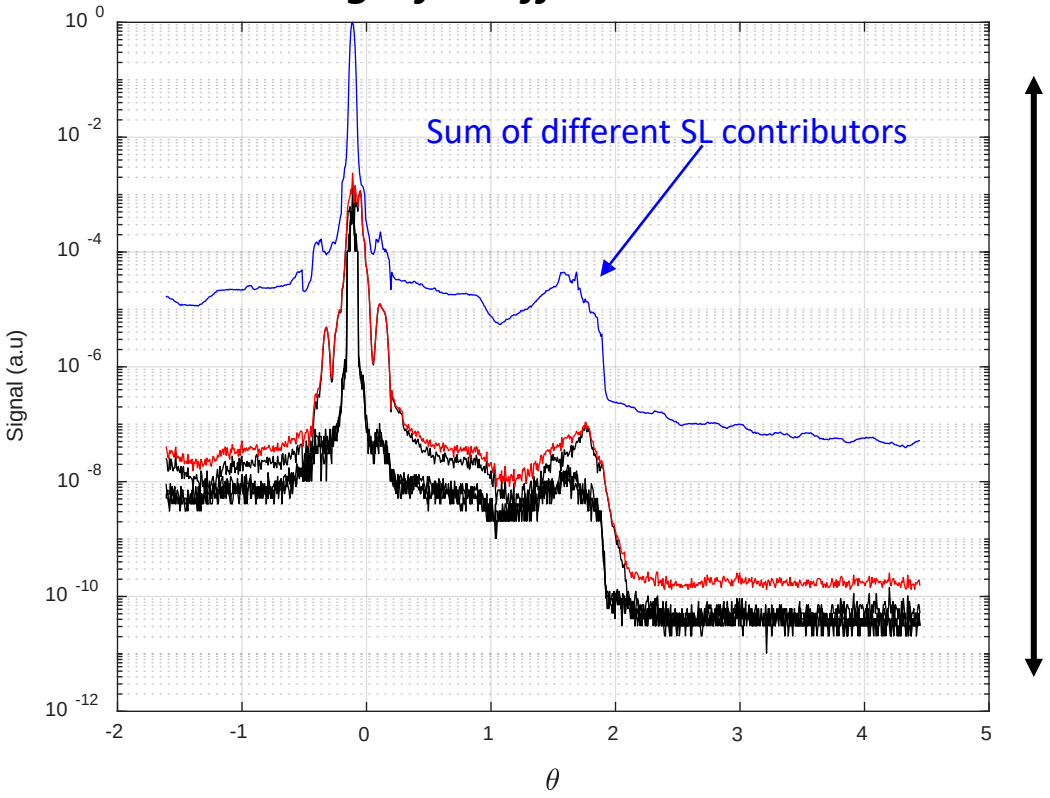




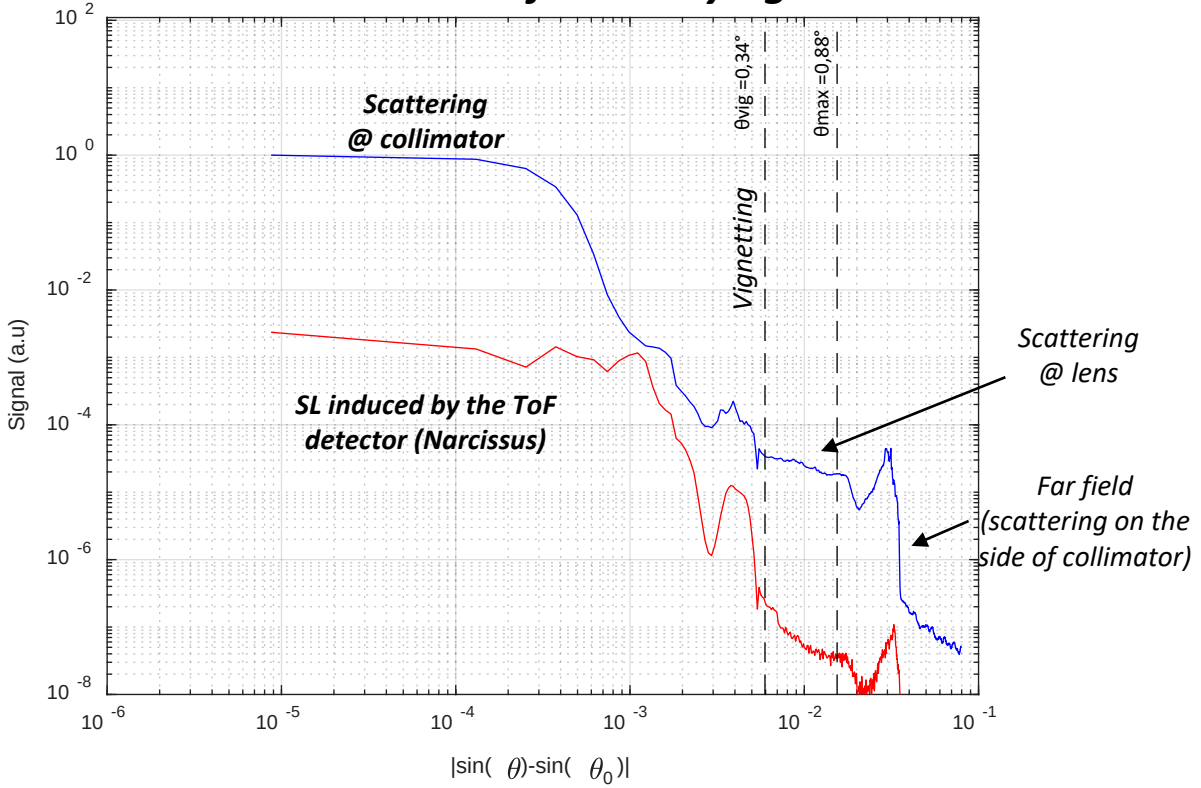
Experimental Results

- **Measurement at small angles (near-field)**

SL vs angle for different contributors



BSDF & near-field stray light



Already in our preliminary measurements, **we have achieved a dynamic range of 10^{-11}**

We characterize the facility signature by acquiring ToF spectra in the near-field. We isolate:

- SL contribution from the facility alone (time t_0)
- SL induced by the ToF detector assembly

Conclusion - Perspectives

- **Straylight can be characterized by ToF imaging**
  - Every straylight contribution is characterized by its OPL
  - ToF imaging allows separating them in time
  - Picosecond resolution were obtained in the past based on
    - Femtosecond laser
    - Streak camera
  - Application : SL in optical instruments (ghosts, scattering,...)
- **In this study**
  - Lower temporal resolution is shown based on
    - SPAD detector with 40 ps resolution
    - Picosecond laser 40 MHz repetition rate
  - Longer OPL
    - Measurement range : a few meters
    - Resolution : centimeters
  - Application :
    - European Space Agency requests now a verification of usual SL calibration facilities (not ToF based)
    - ToF based method is recommended (one day mandatory ?)
    - Low resolution presented here is the key
    - SL inherent to facility could be separated to the one of the instrument