The Wavelength-shifting Optical Module (WOM)

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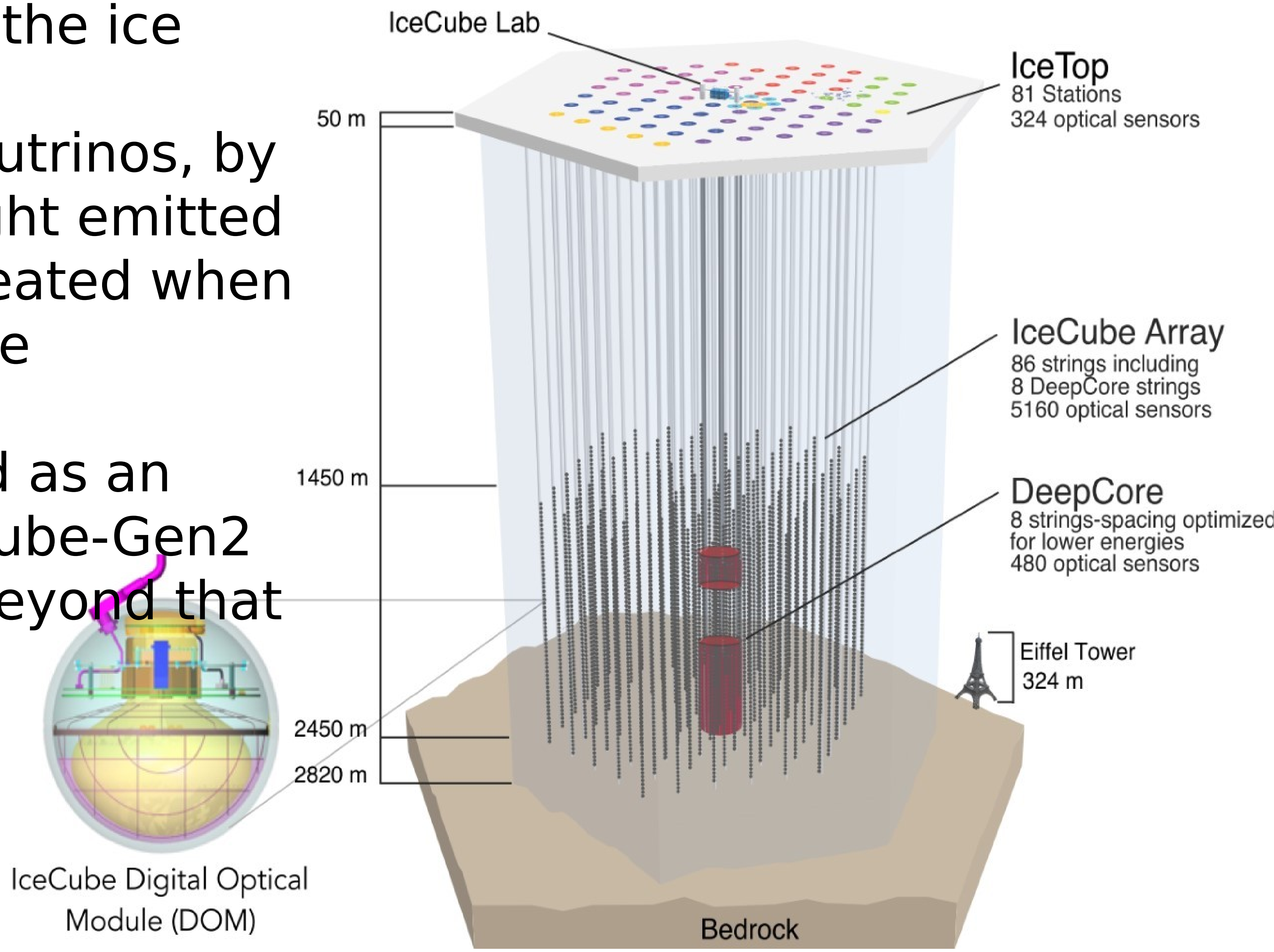
NEPTUNE | Naples | July 19th 2018

Outline

- Original motivation: Next generation of IceCube experiment
- Wavelength-shifting Optical Module concept and status
- Efficency measurements
- Timing measurements

IceCube

- 5160 Digital Optical Modules (DOM)
- 1450 – 2450 m deep in the ice
- Detects high energy neutrinos, by capturing Cherenkov light emitted by charged particles created when by interactions in the ice
- The WOM was proposed as an Optical Module for IceCube-Gen2
  - But has applications beyond that



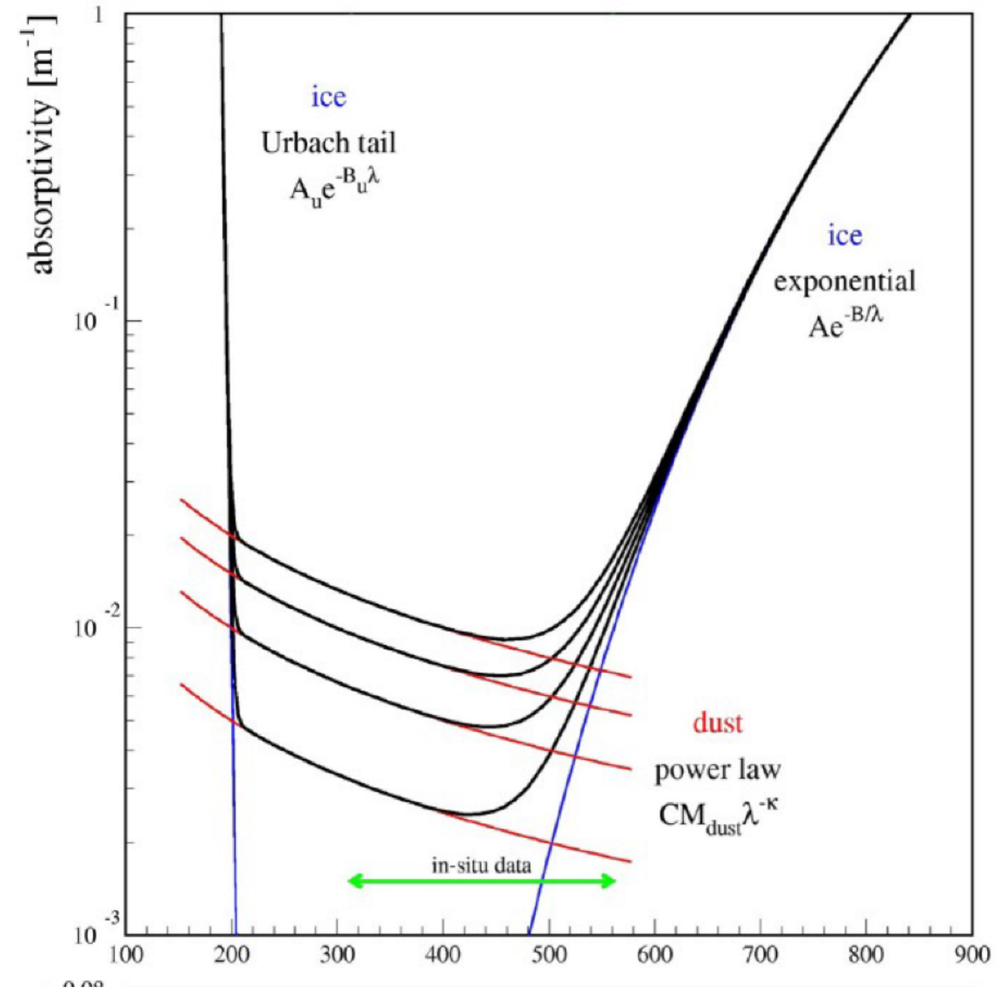
Motivation

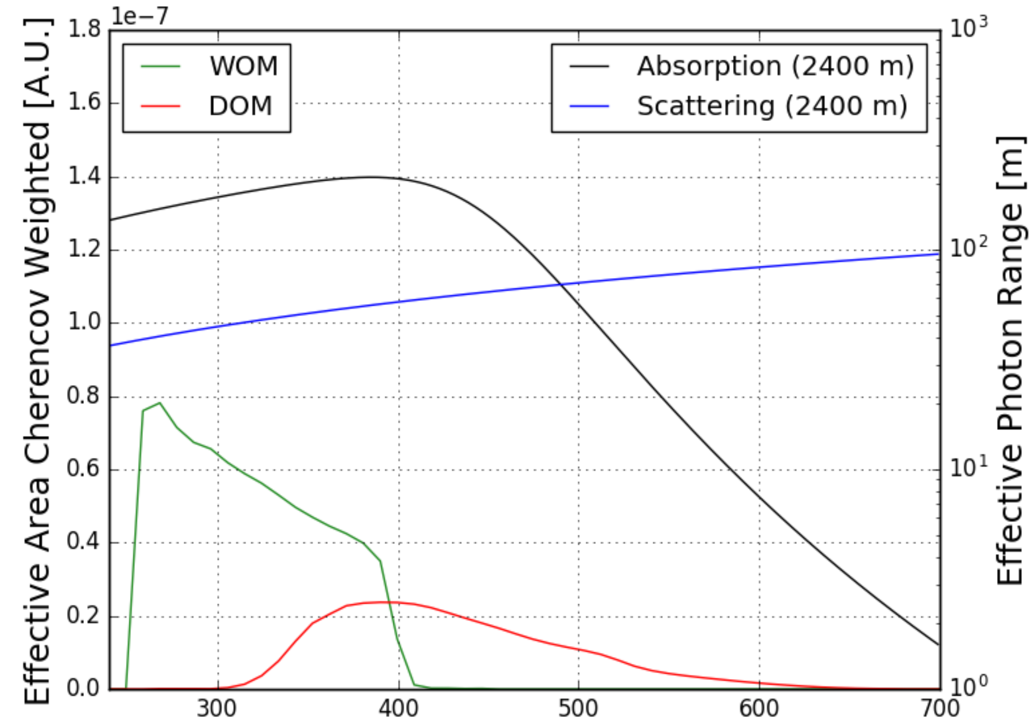
- Cherenkov light peaks in the UV
  - Ice transparent down to ~200 nm
  - PMT / glass-spheres intransparent below 300 nm

- Increase number of detected photons
- → better energy resolution, decreased energy threshold

- Wavelength-shifting photons from UV to visible

- Noise scales with PMT-area
  - Passive light collection area combined with small PMTs allow maximization of effective area while lowering the dark count rate to ~O10 Hz





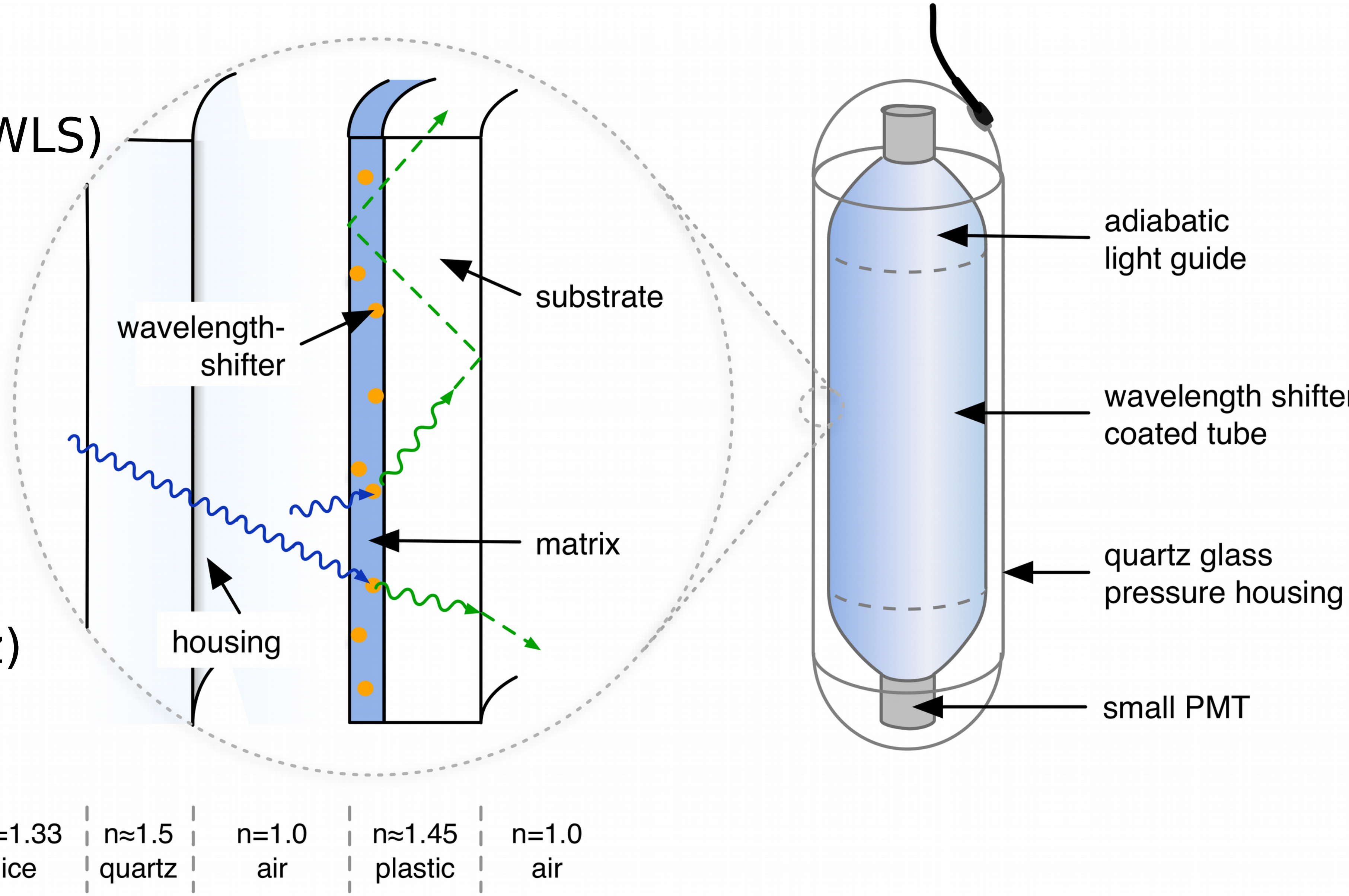
Wavelength-shifting module

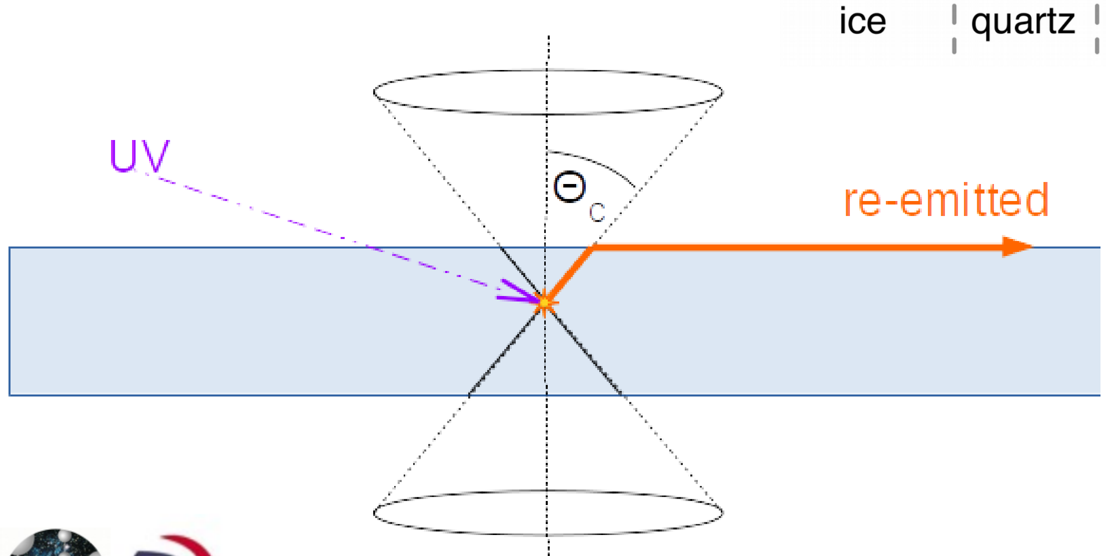
Basic concept

- Wavelength shifters (WLS)
  - ► concentrate light

Features

- large collection area
- better UV sensitivity
- low noise rate (few Hz)
- cost effective

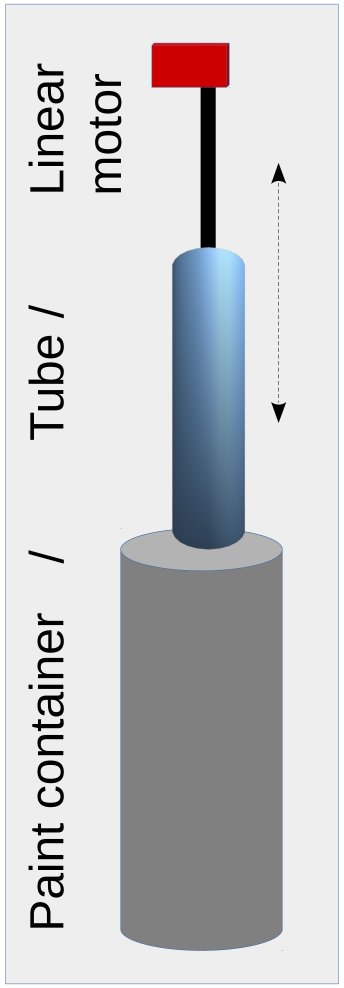




Principle of light-capture by TIR:
~26 % of light lost in loss cone.
→ 74% captured (for n=1,5)

Tube production

Dip-coater

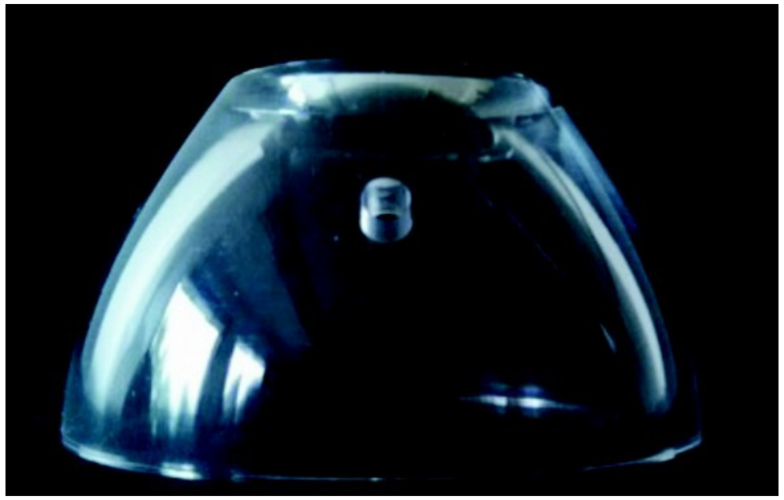


- Dip tube (quartz or PMMA) in WLS solution
- Withdraw with a controlled speed

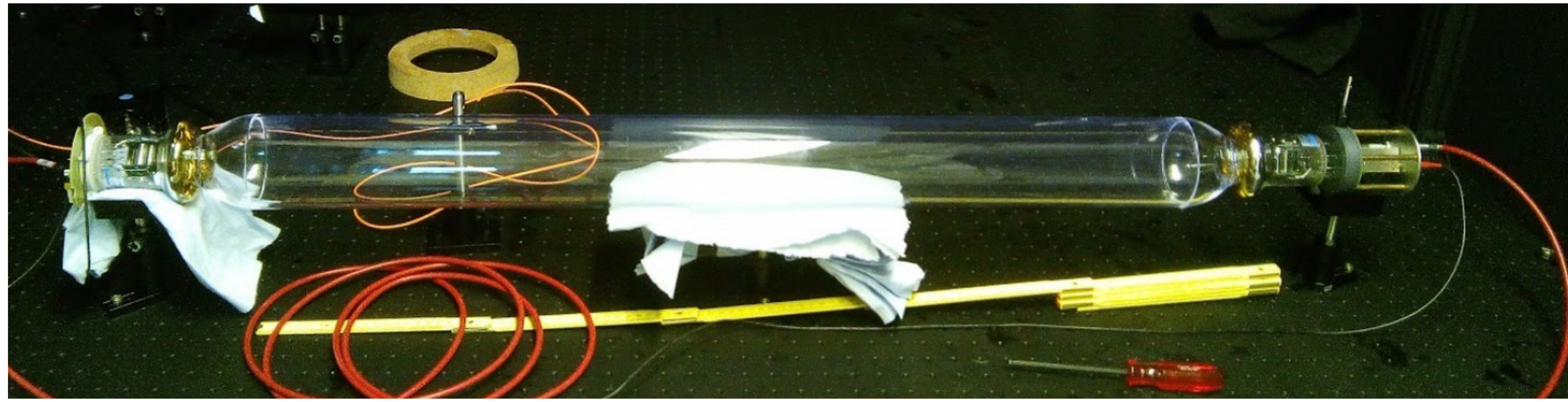
- WLS-solution:
  - Toluene
  - +Paraloid B72 (plastic)
  - +bis-MSB
  - +p-terphenyle

- Tube has to dry for at least a day
- Quartz tubes require surface treatment before coating.
  - Citric acid, acetone, distilled water, isoporpanole
  - Without that treatment, the paint peels off after cold/heat cycling the tube

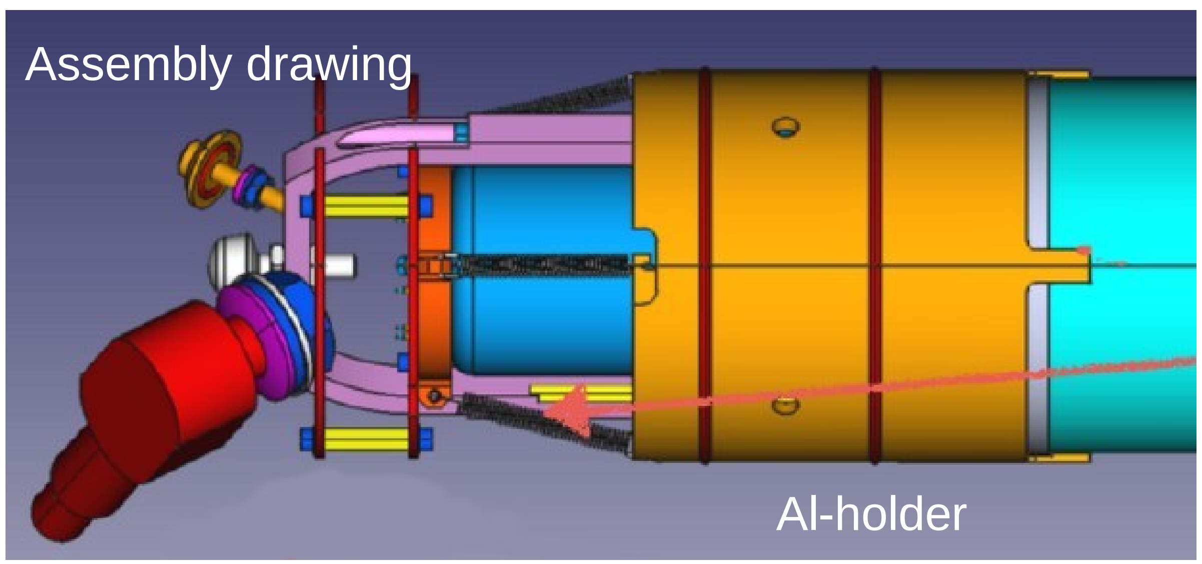
Components and prototype

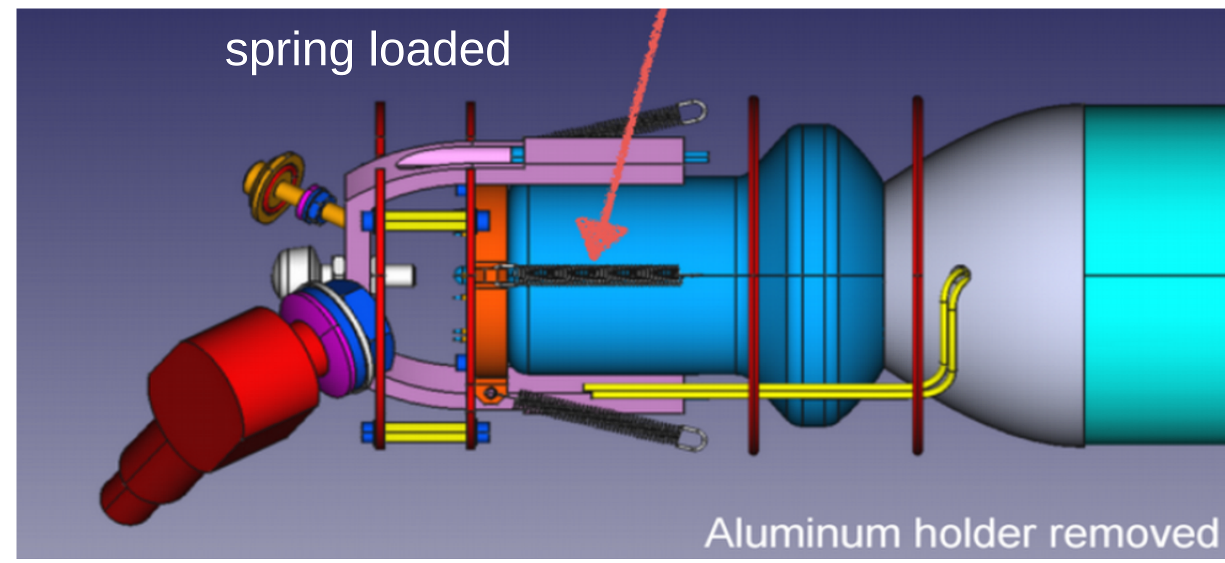


Adiabatic light guide

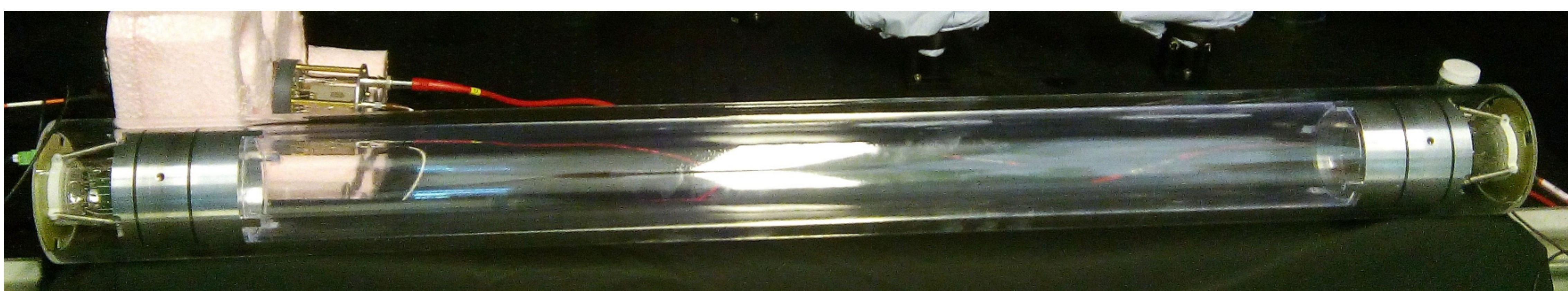


...mounted on tube with UV curing glue

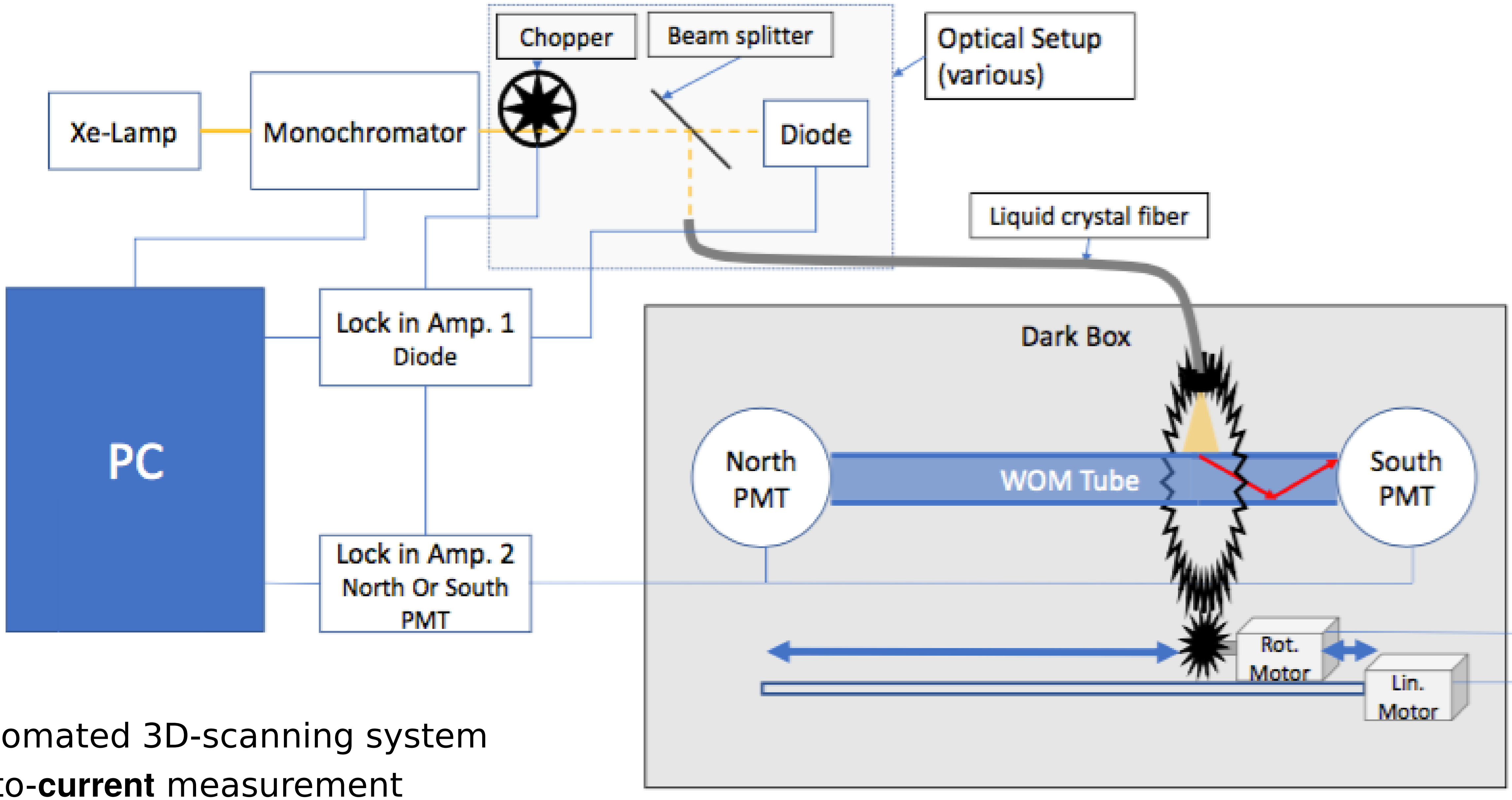




Assembly test



WOM test setup in Mainz

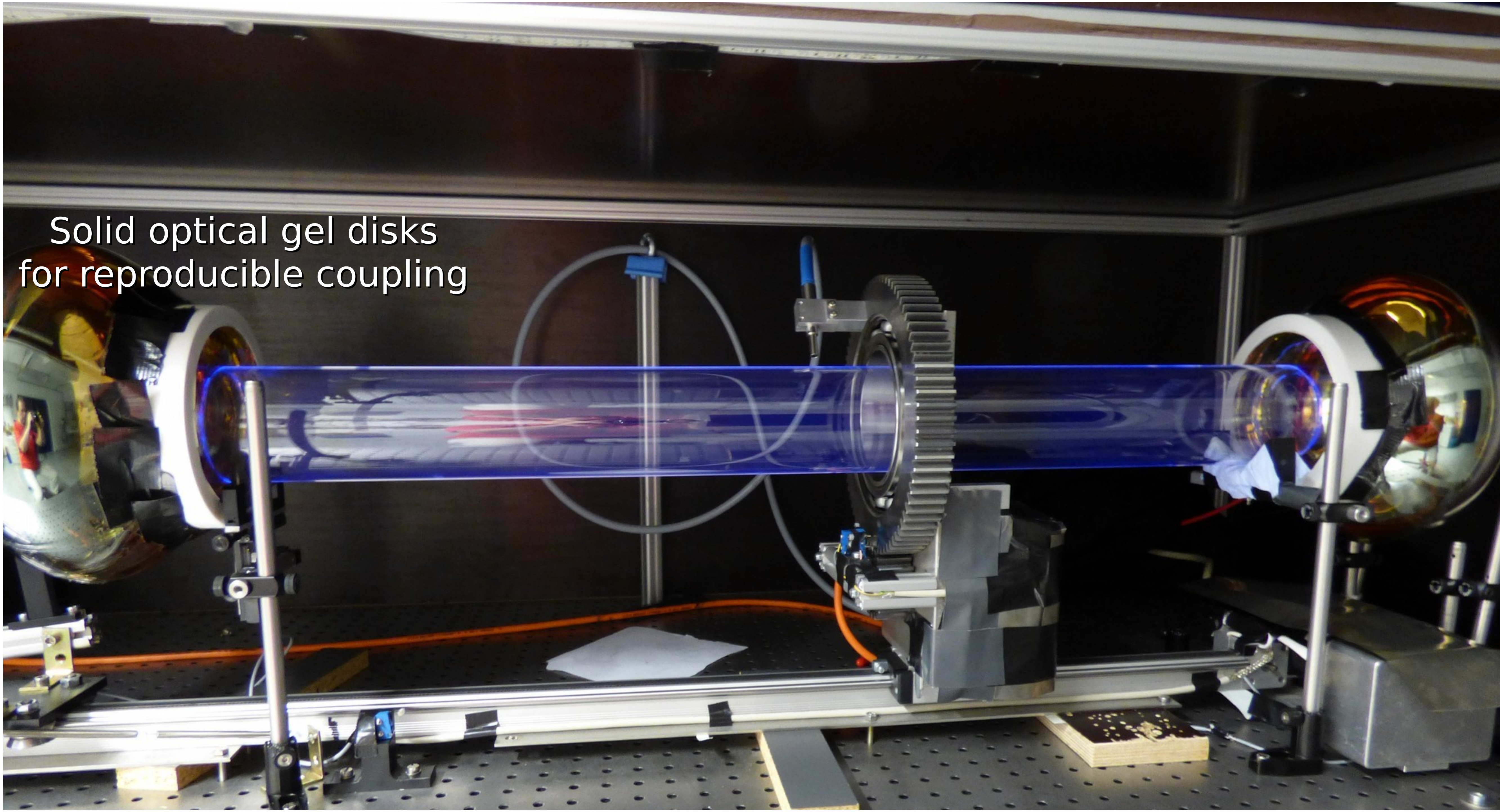


Fully automated 3D-scanning system

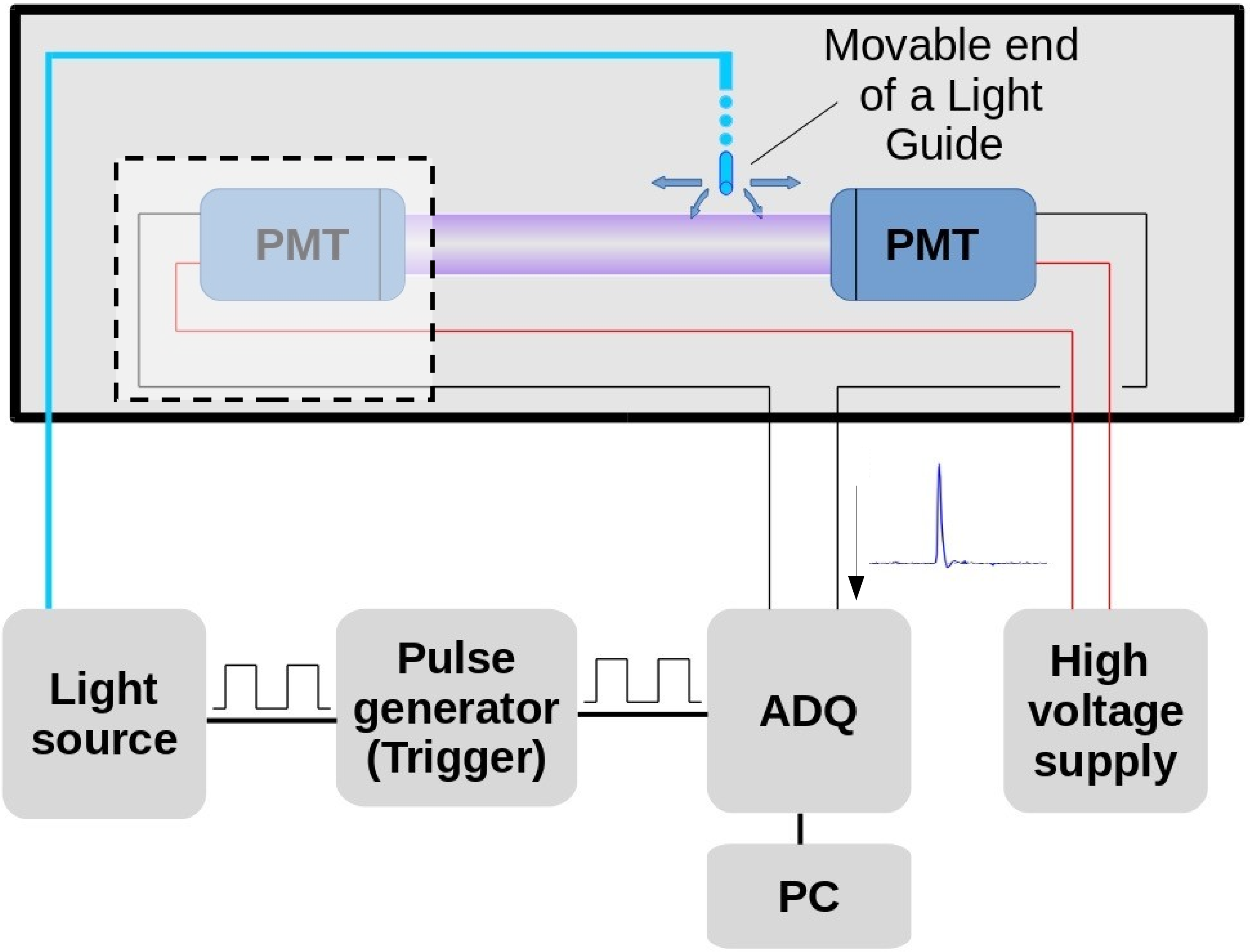
- photo-**current** measurement
- Fast tube evaluation
  - 2 sec per point in λ, x, φ

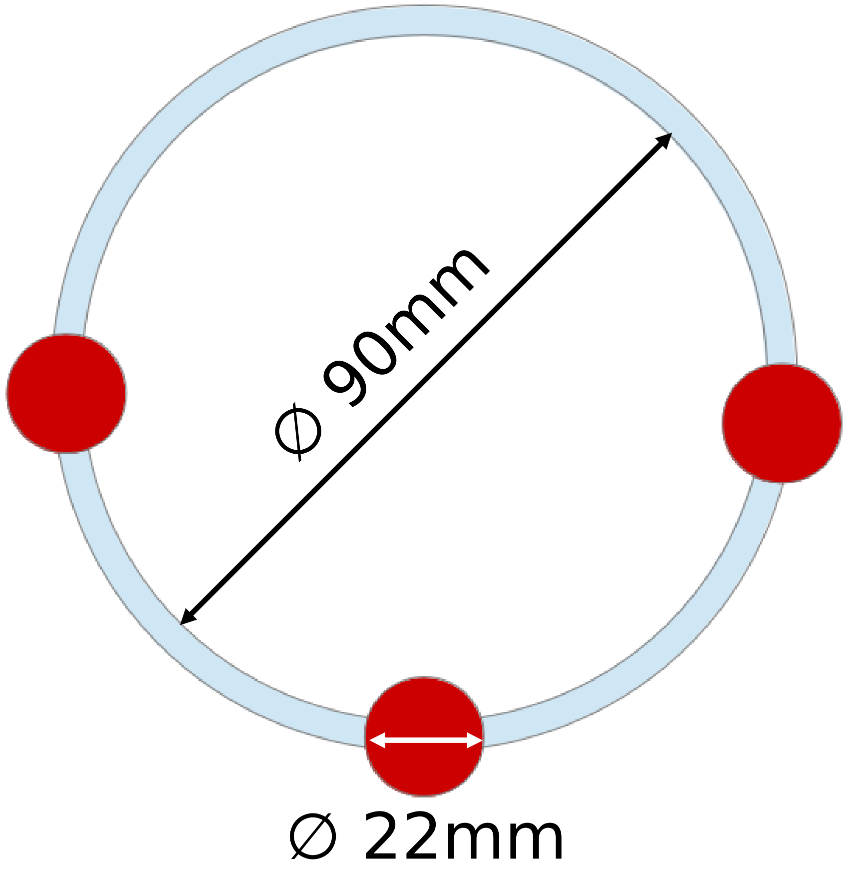
- systematics errors < 10%
  - focus on efficiency measurements

WOM test setup in Mainz



WOM test setup in Berlin

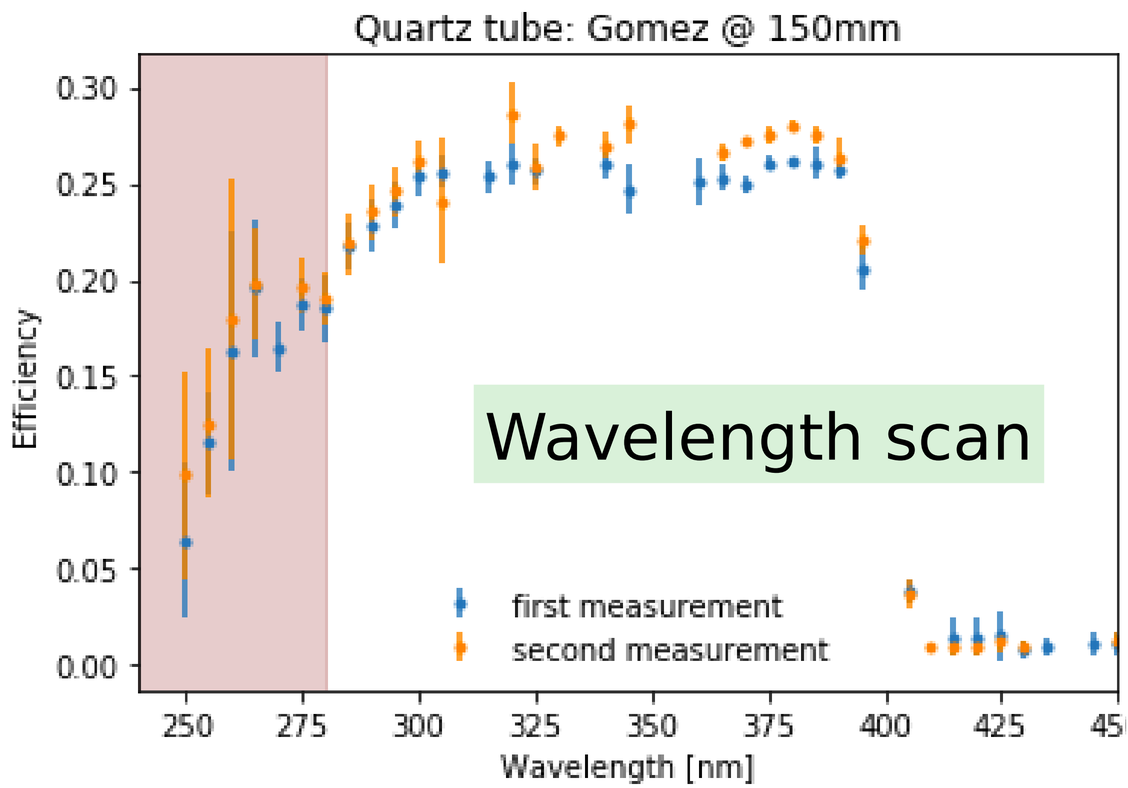


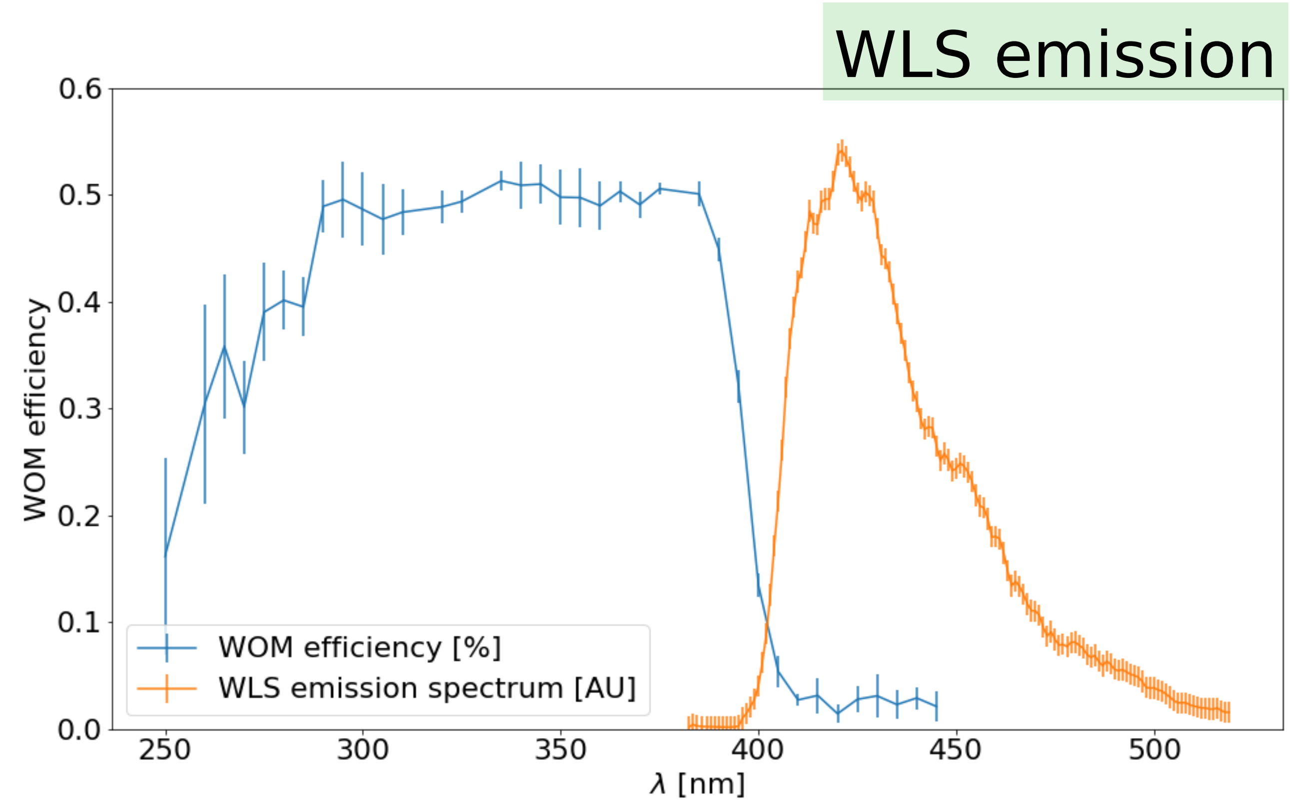


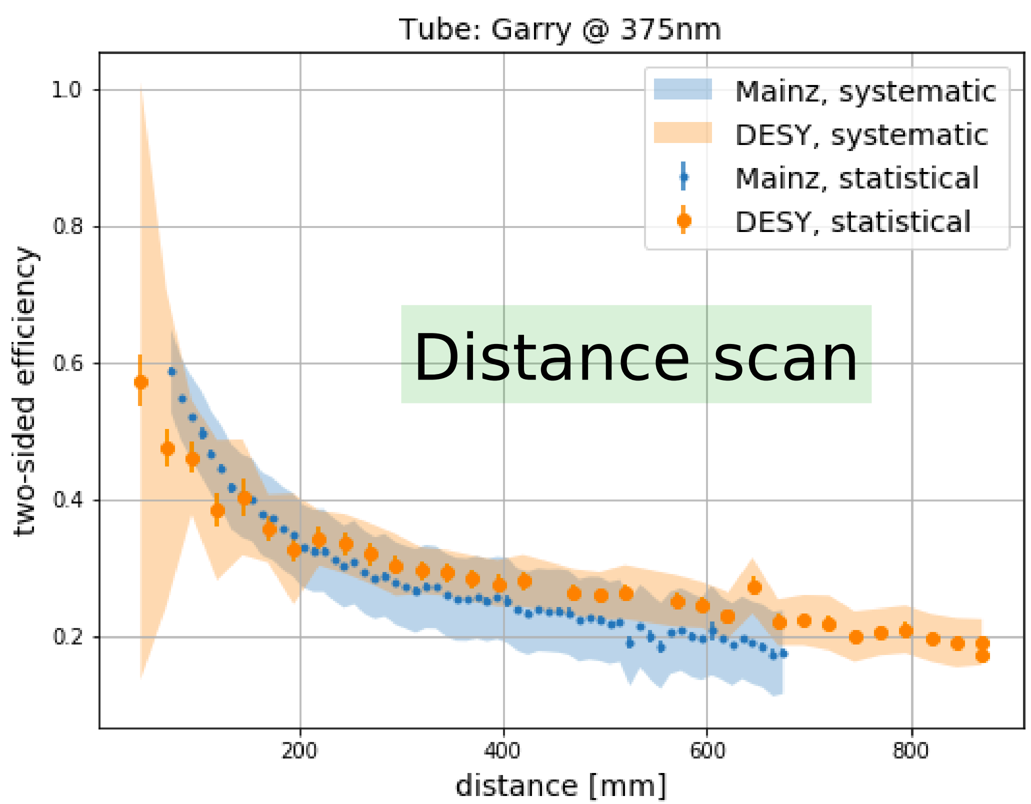
- p.e. **counting** measurement
- small PMTs
  - spot-measurement

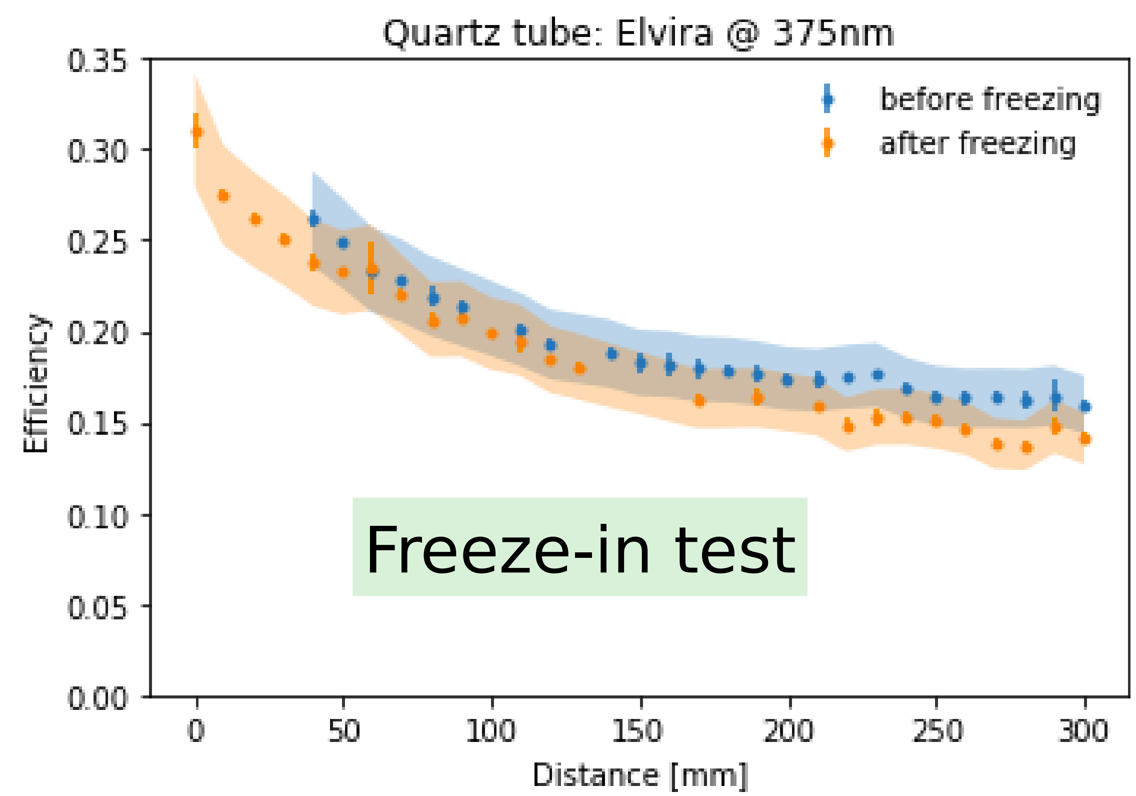
- fast light source & digitizer (ADQ14)
  - simultaneous efficiency & timing measurements

Some test setup results









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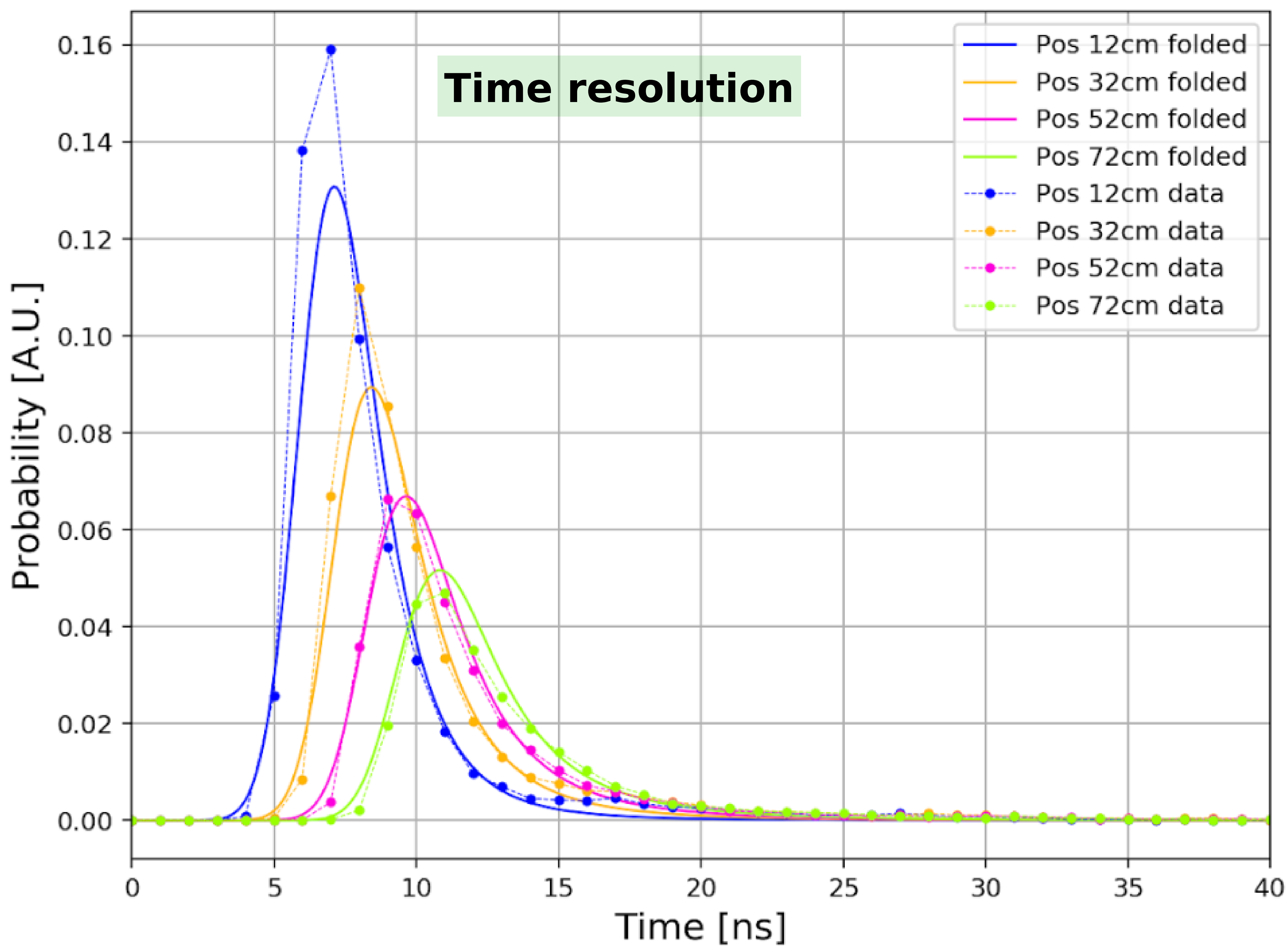


Coating campaign

PMMA tubes

- coated 8 tubes (90cm)
- large coater setup
  - ►limited speed granularity
  - ►large fluctuations

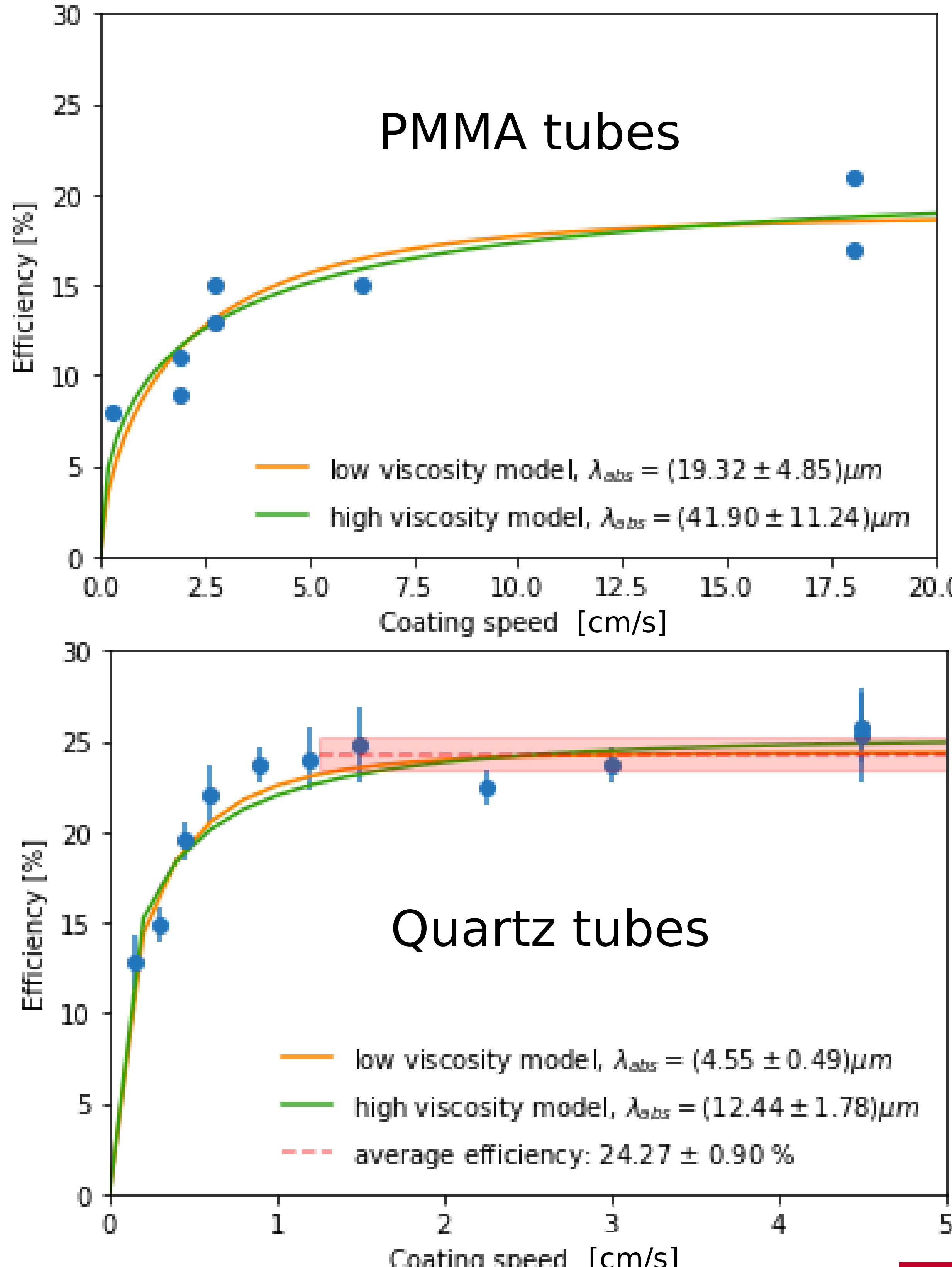
Quartz tubes

- used 4 tubes (50cm)
- small commercial coater
  - repeated coatings
  - ►very well reproducible

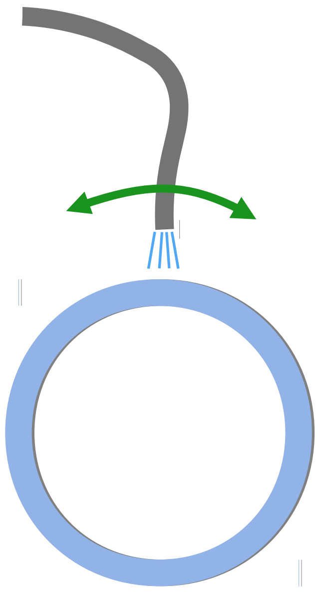
Average efficiency @ 150mm

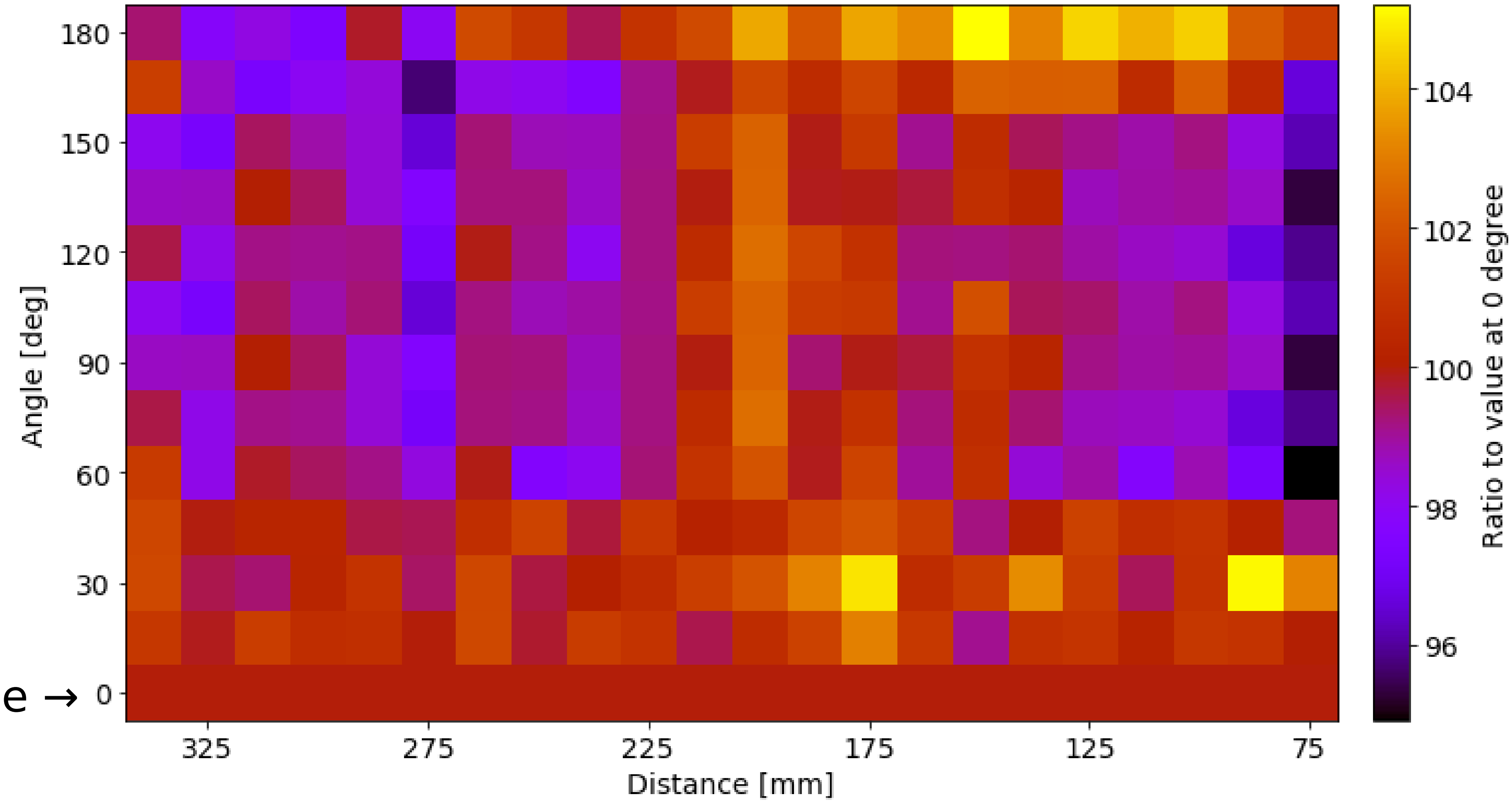
- one-sided: **ε = 24.3 ± 1%**
- WLS fibers: ε = 3.1%

→ New baseline for inner tube!



Efficiency homogeneity

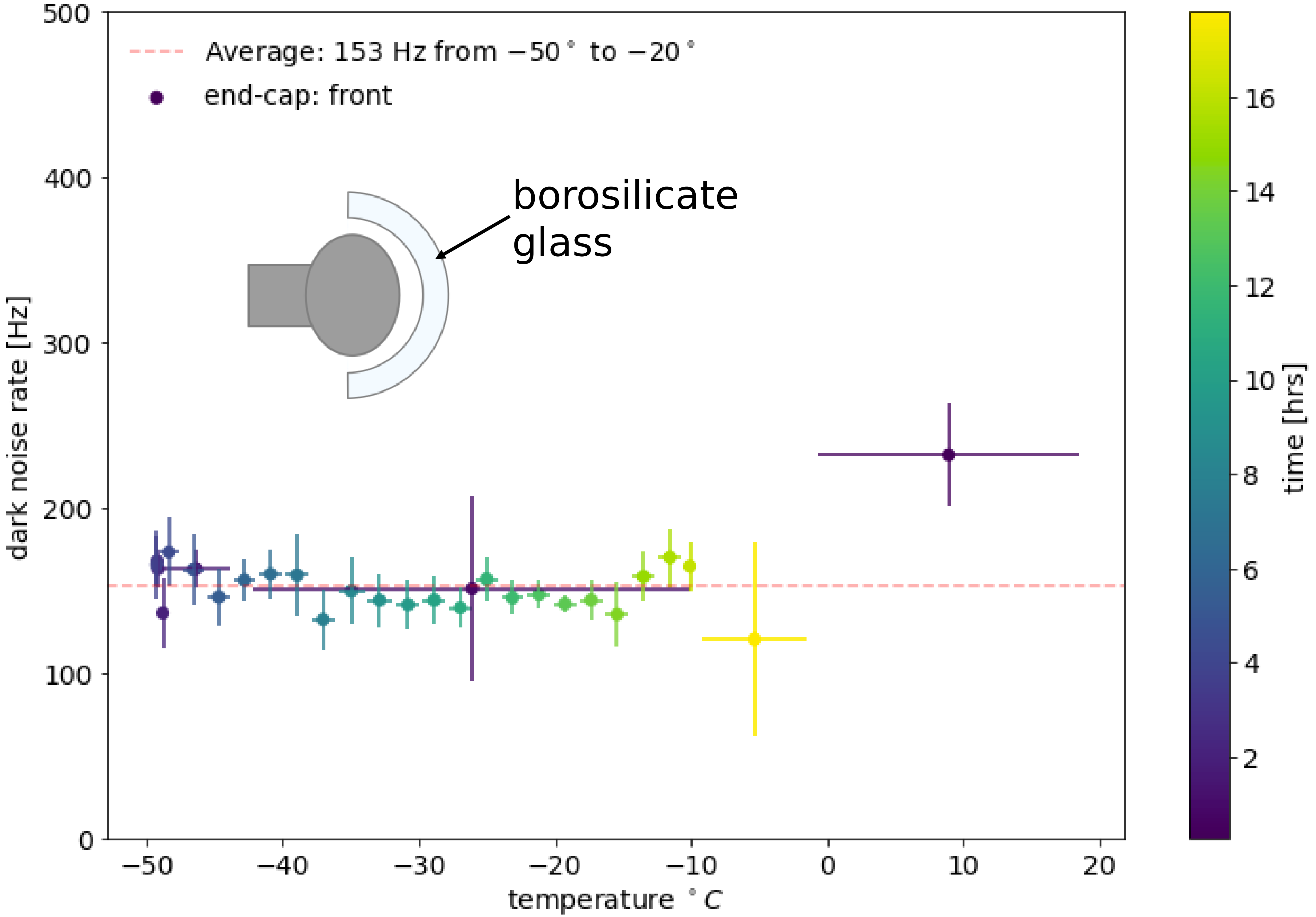




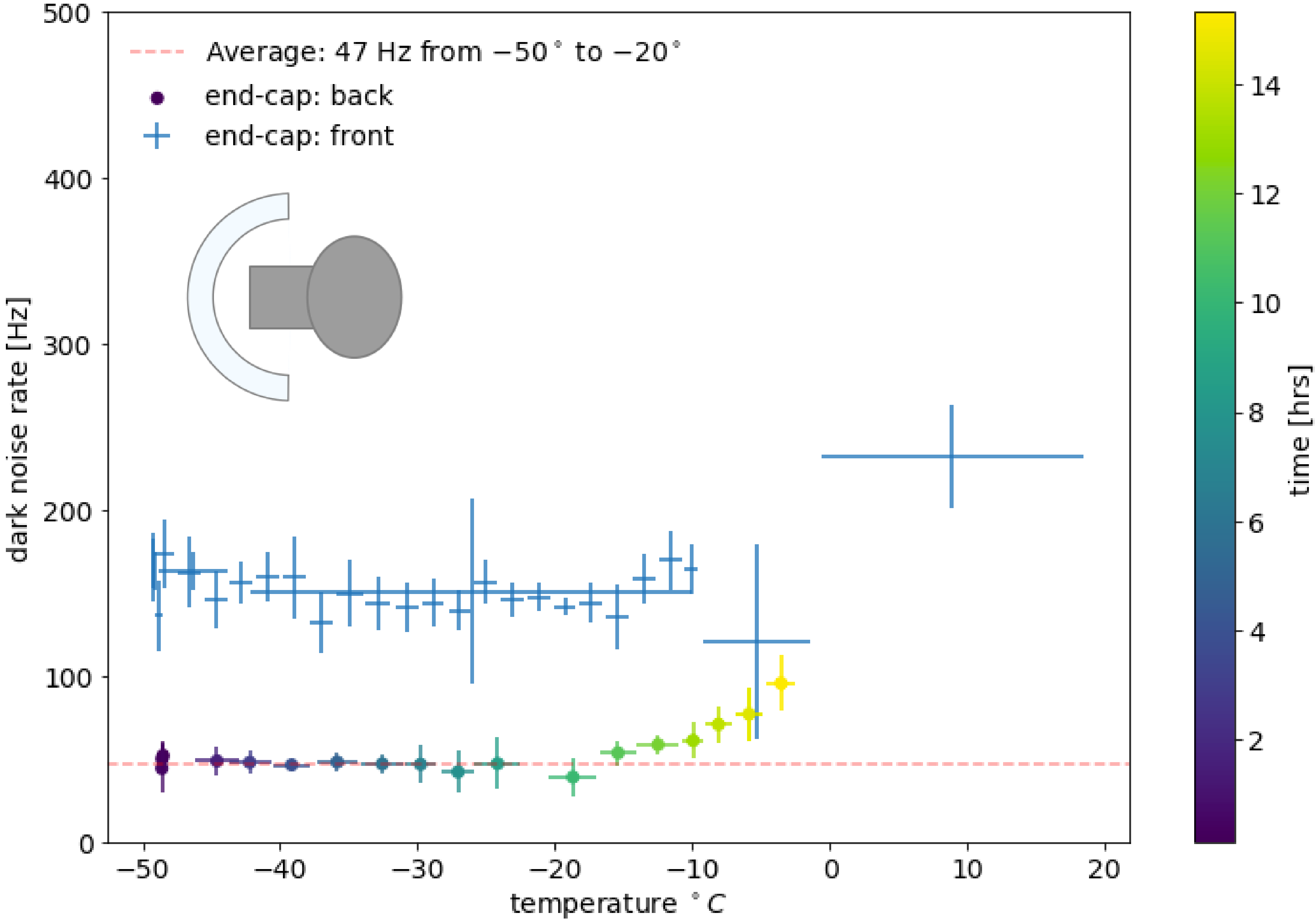
Homogeneity

- efficiency is homogeneous to **±5%** over full length of tube
  - ►investigating several other coating procedures (roll-/spray-coating,...)

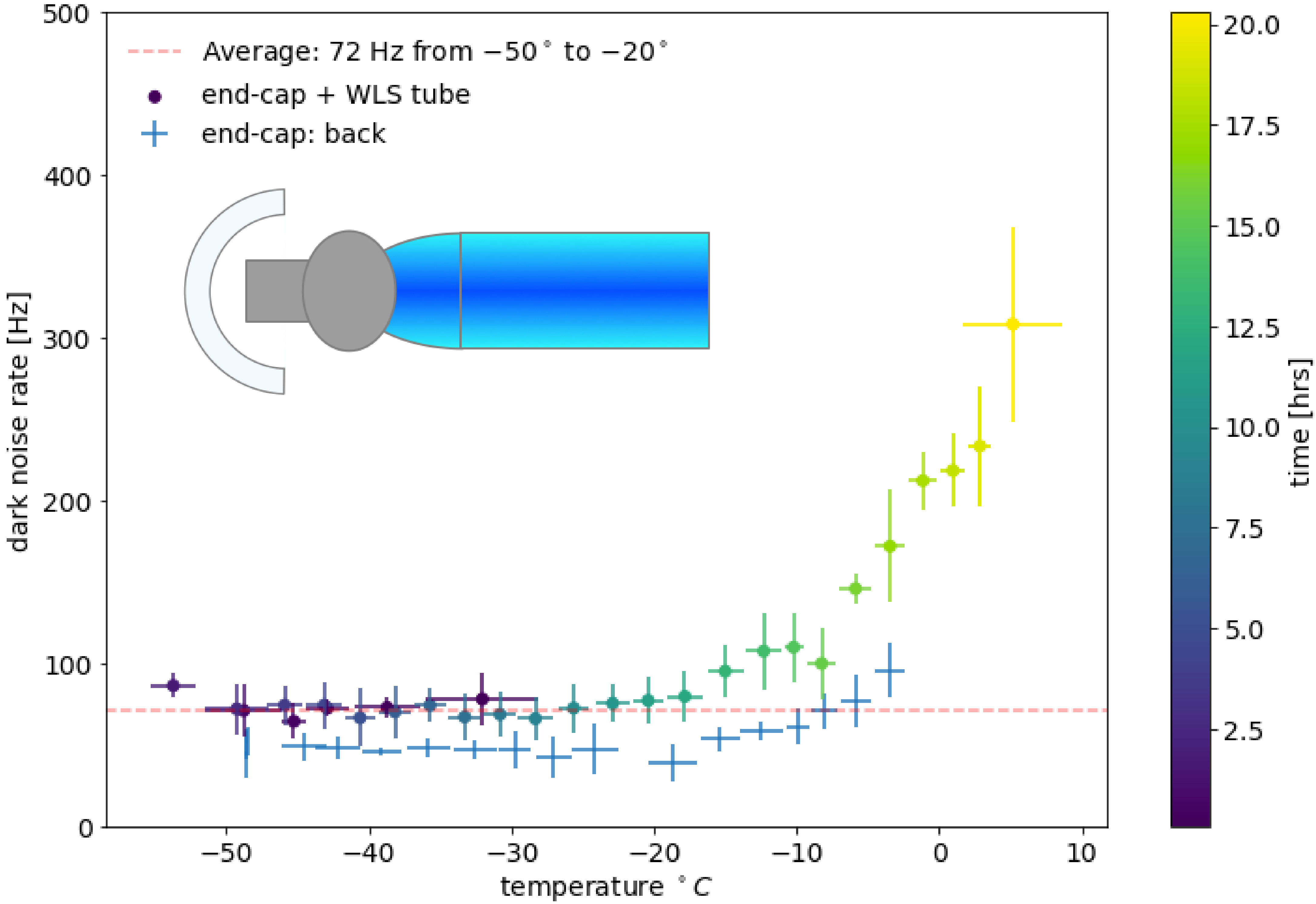
Noise measurements



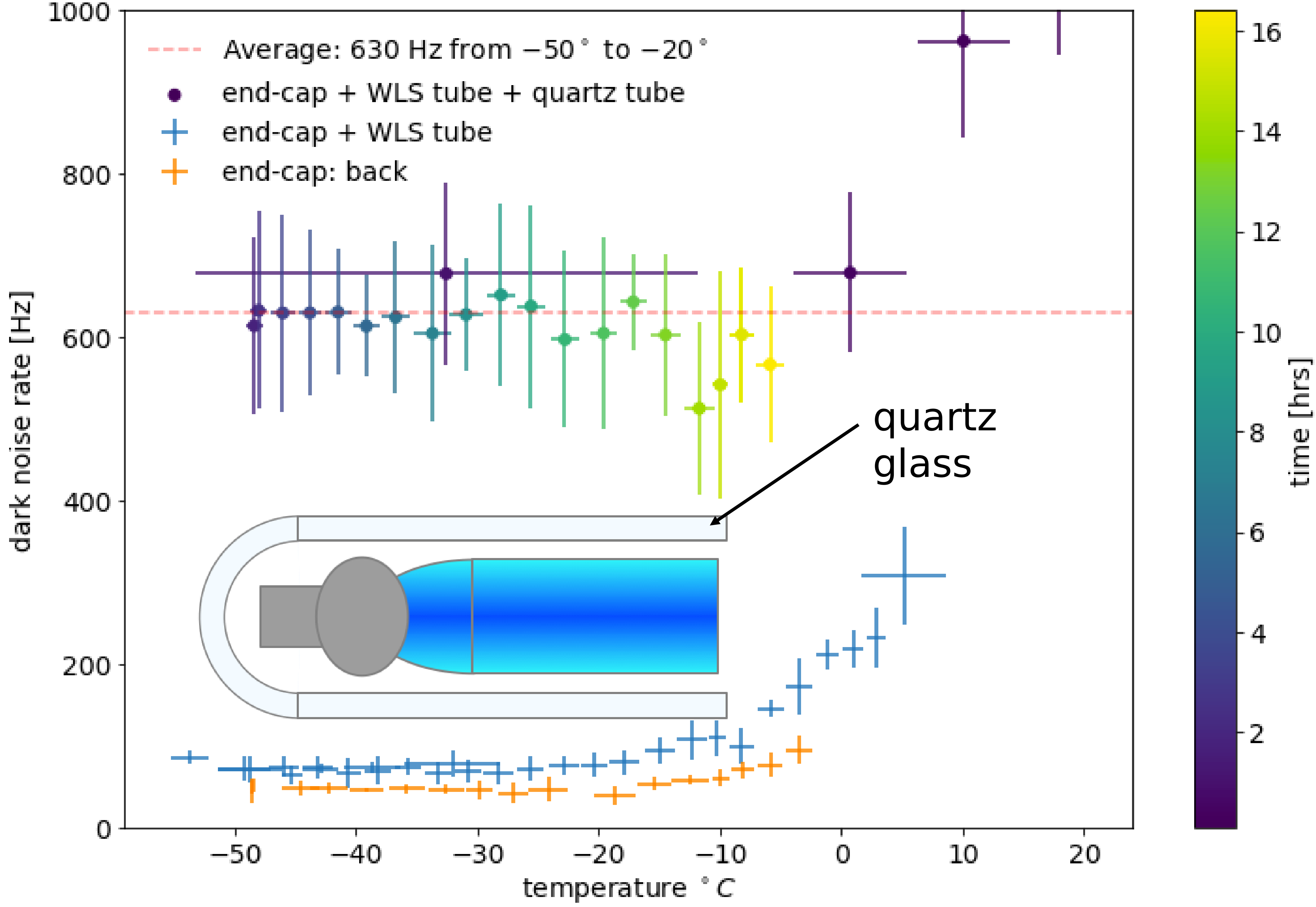
Noise measurements



Noise measurements



Noise measurements



Quartz pressure housings

Nautilus
MARINE SERVICE GmbH

Measurements

- Long-duration gamma spectroscopy (4 samples)
- Neutron-activation analysis (1 sample)
  - ~150 Bq/g ^{238}U in Quartz tubes from Nautilus!

Alternatives

- Heraeus quartz
  - typical < 10 Hz/tube
- SUP310
  - flame fused
  - down to < 200nm
- HSQ/HLQ
  - electrically fused
  - down to ~250nm

Heraeus

mBq/kg	226-Ra	228-Th	228-Ra	40-K	Price /tube [€]
HSQ 300	480±30	< 86	< 90	< 200	< 1400
SUP 310	< 29	< 46	< 43	< 100	< 6500
RQ200	350±120	< 270	< 370	< 1920	?
RQ500	520± 80	< 360	< 340	< 1150	?

Compatible with Heraeus data

Understanding light propagation

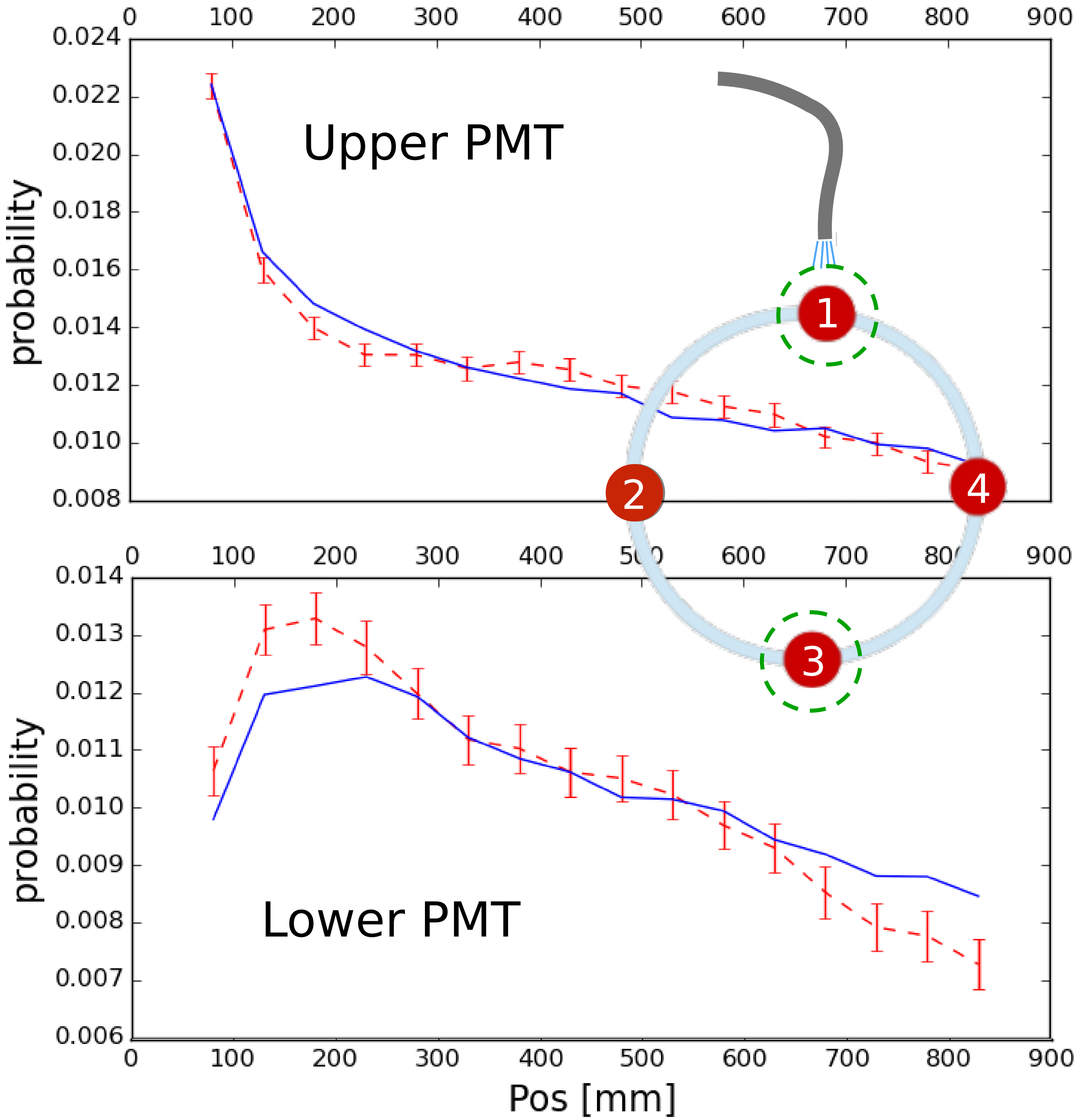
Simplified 2D-model

- neglect curvature of tube
  - ►flatten out

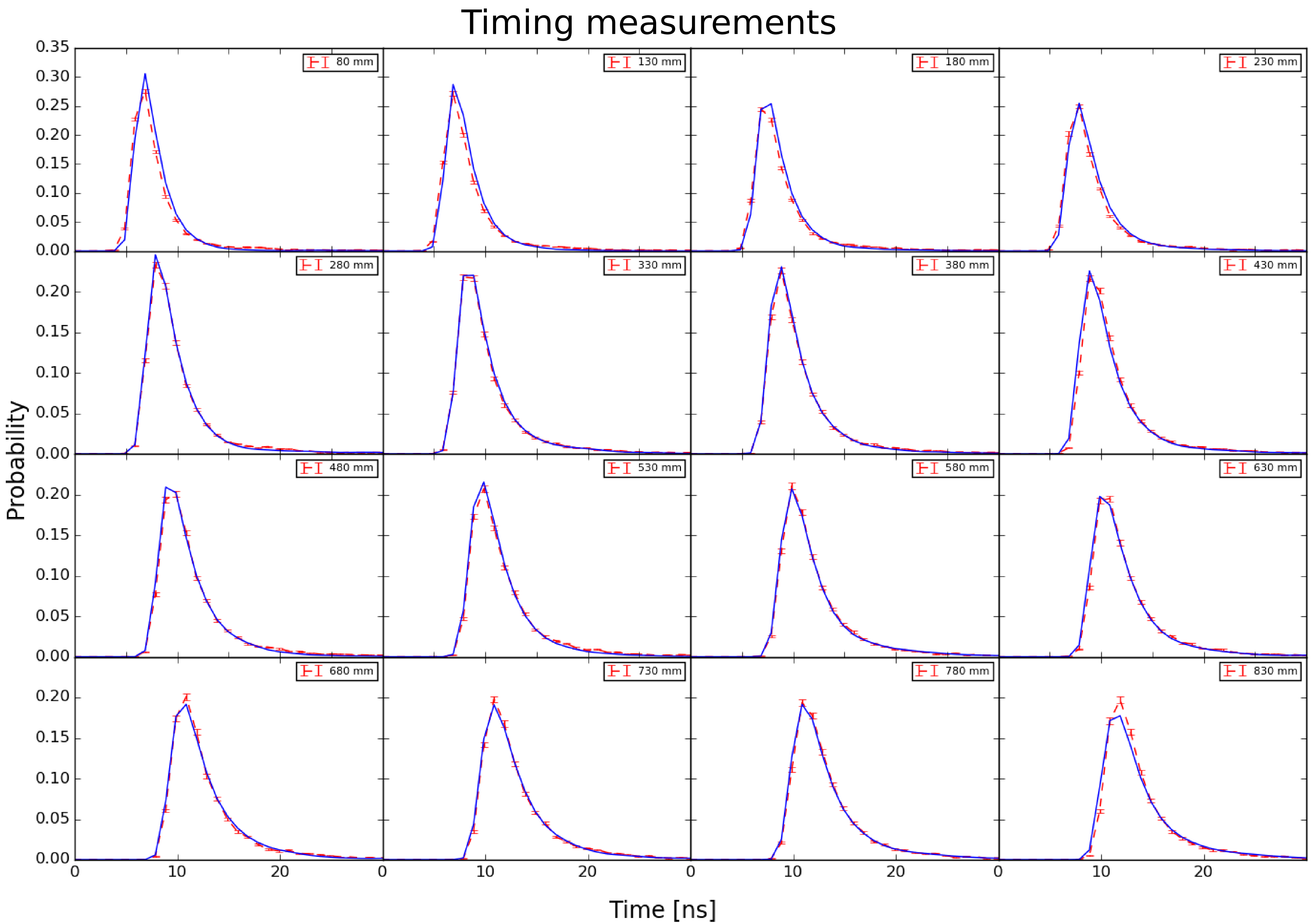
Model parameters

- WOM
  - ►attenuation length λ_{eff} (includes $\lambda_{abs} \cdot \lambda_{scat}$)
  - ►WLS decay time
  - ►averaged efficiency
- PMT
  - ►overall time resolution
  - ►rel. time offsets

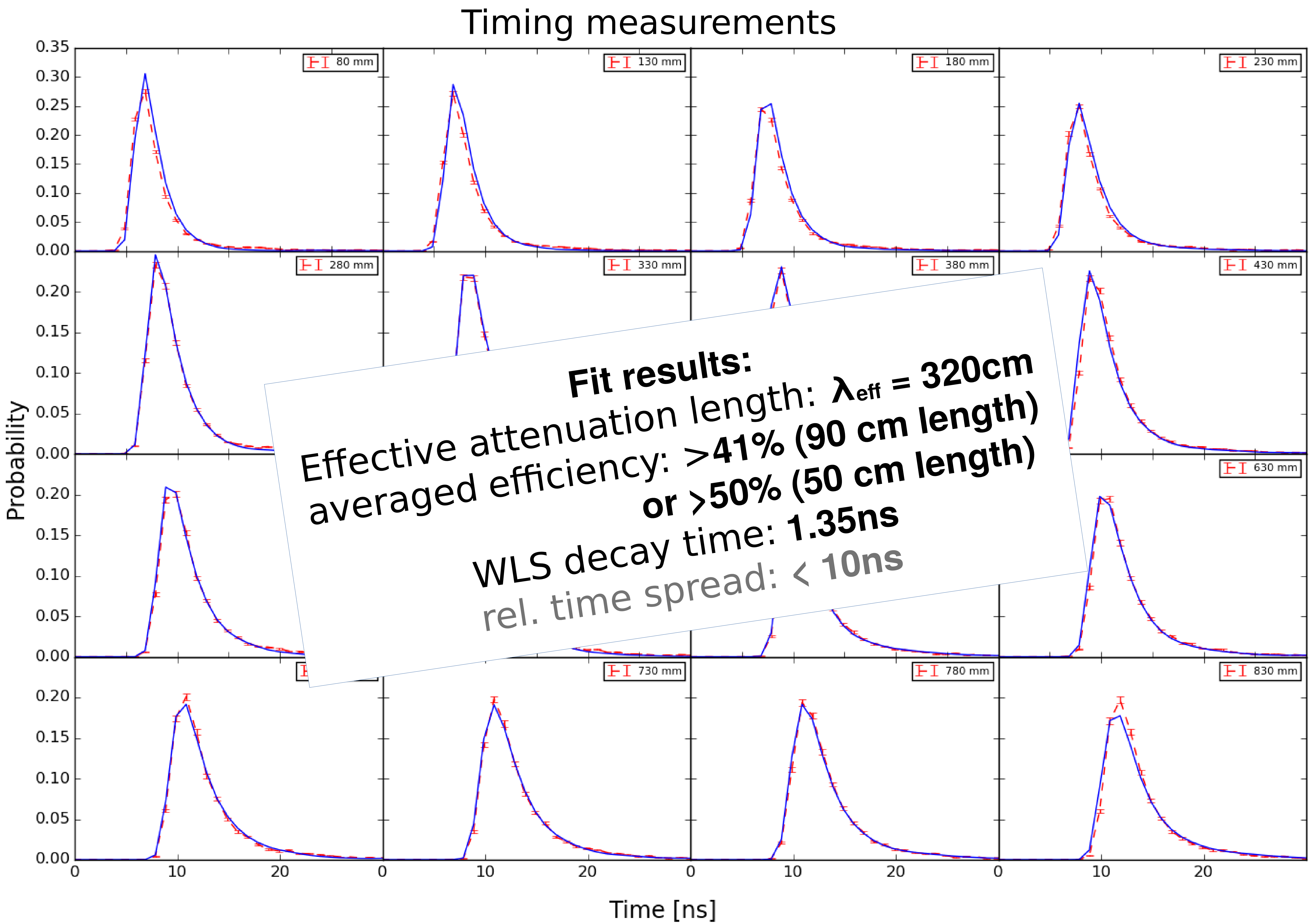
→ good fit to the data



Understanding light propagation



Understanding light propagation



Fit results:

Effective attenuation length: **λ_{eff} = 320cm**

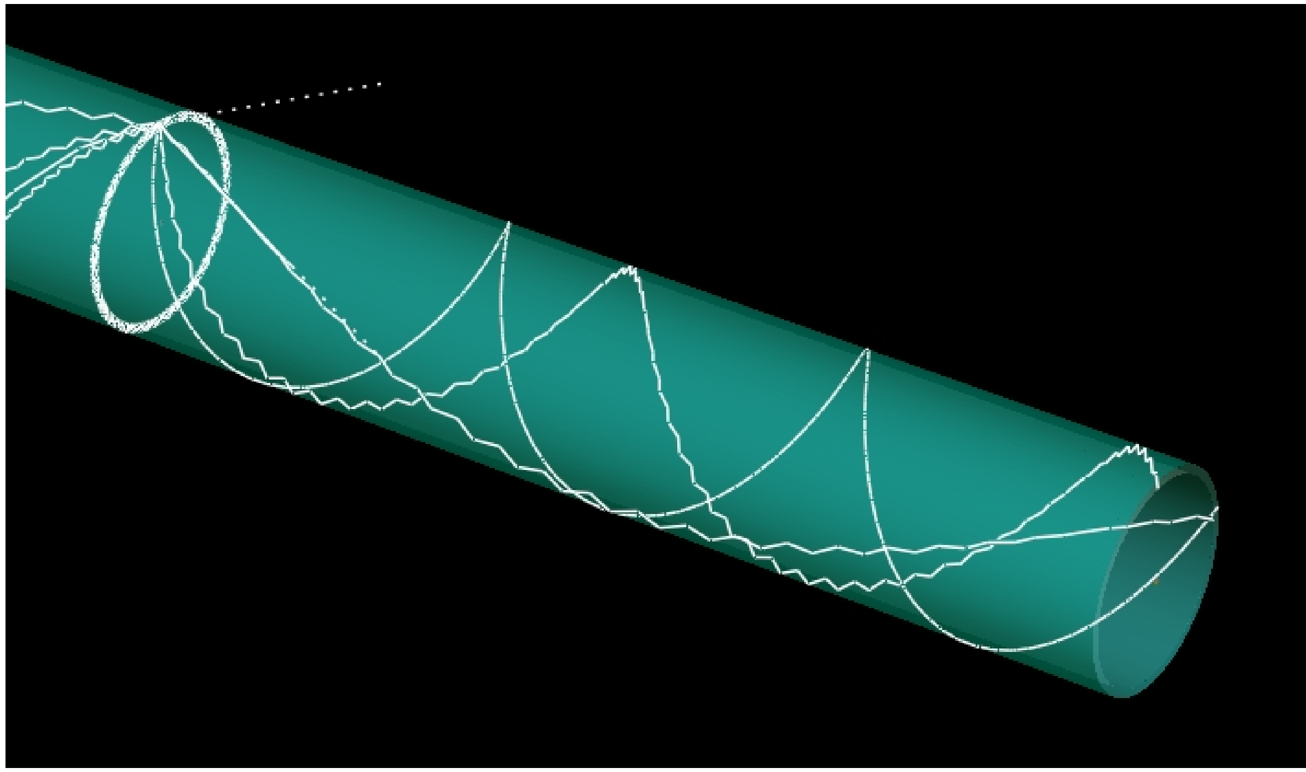
averaged efficiency: **>41% (90 cm length)**

or >50% (50 cm length)

WLS decay time: **1.35ns**

rel. time spread: **< 10ns**

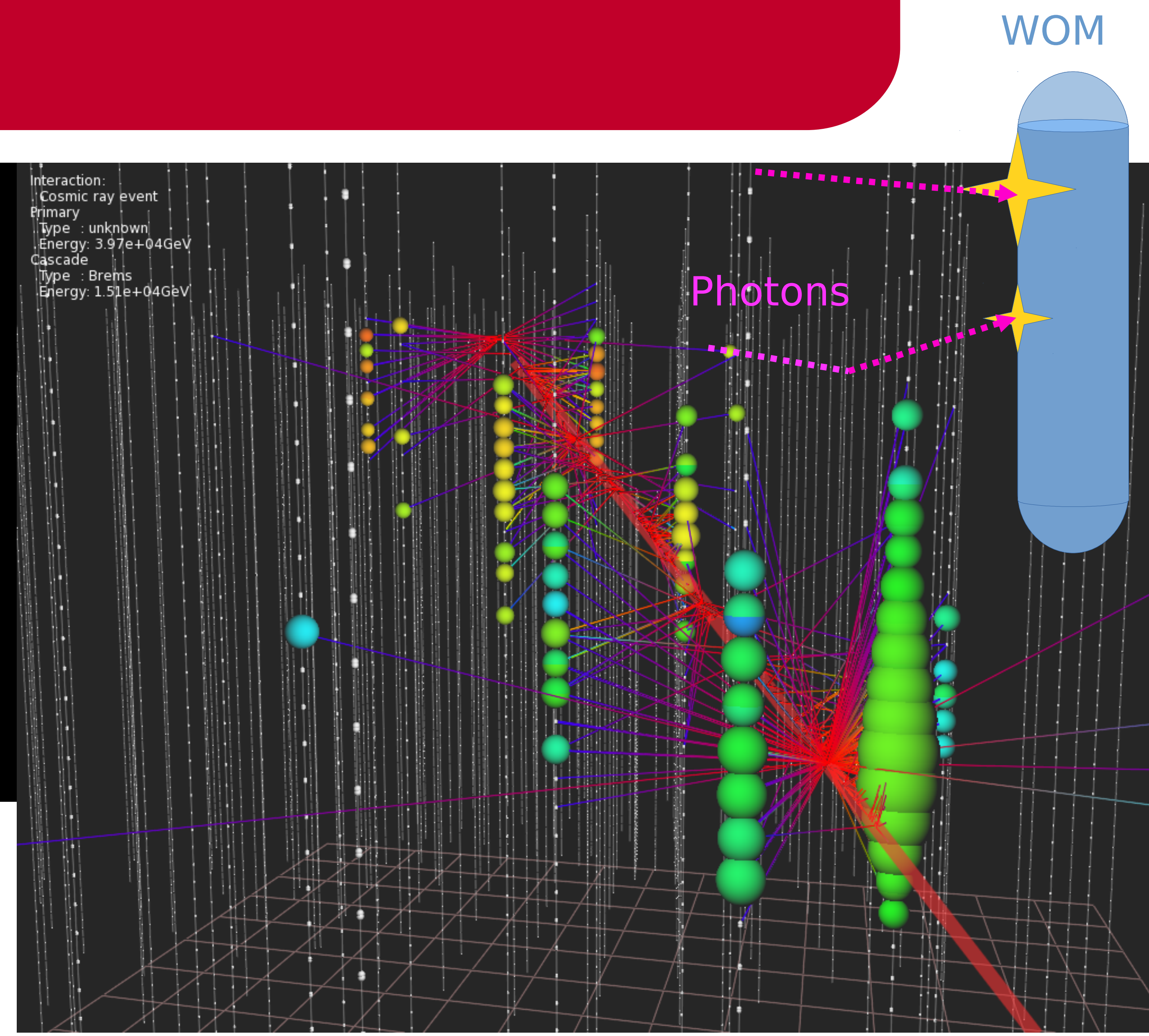
Simulations



Raytracing (FRED):
Different photon paths inside the WOM
Goal: scaleable WOM model and better understanding of loss-mechanisms.

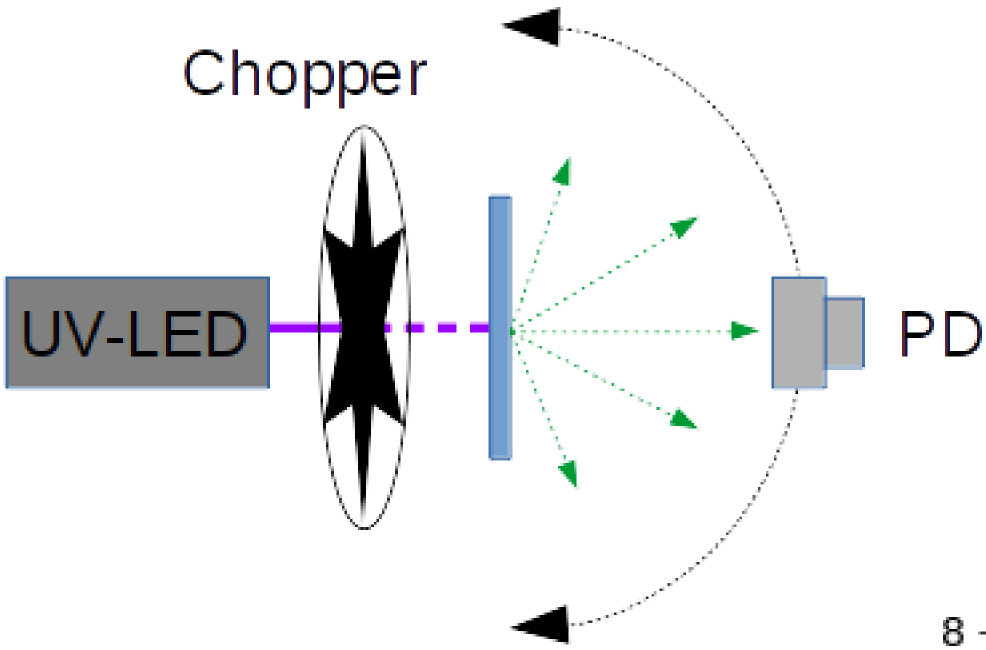
Caveat: processing speed

GPU-based dedicated fast simulation code will be developed in co-operation with the informatics department Mainz



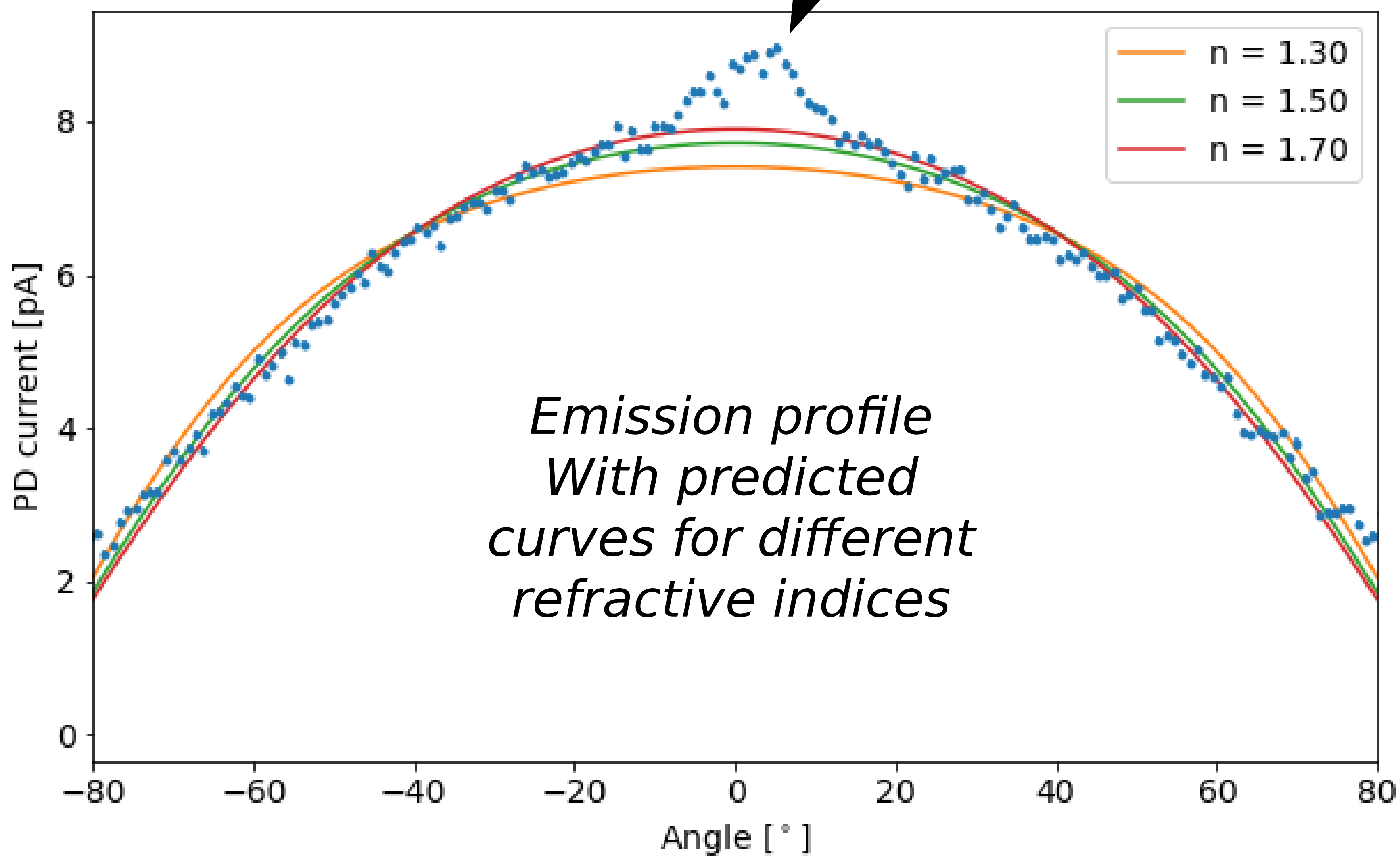
Example of IceCube simulation framework with the WOM added as module.

Angular emission profile

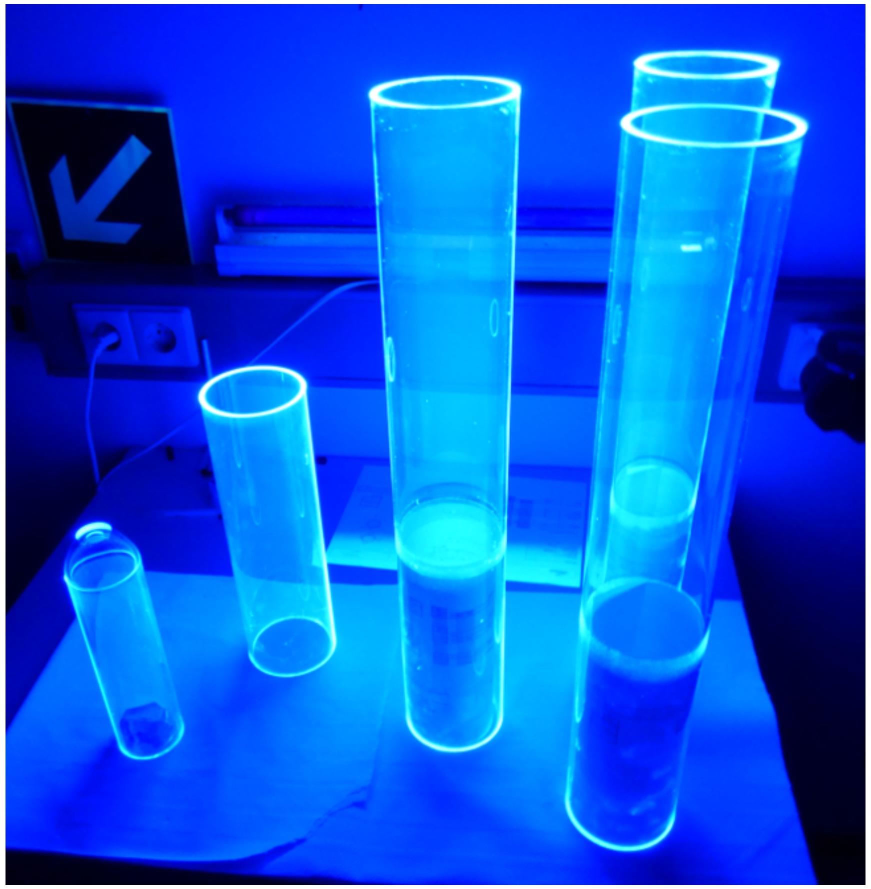


- Photodiode on motorized circular stage.
- Coating on PD-side.
- Measurements with different filters.
- 100% absorption
- Lock-in amplifier read-out

Not yet understood. WLS-shifted, but in forward direction of the incident light



Beyond IceCube



Smaller offspring for SHiP (Search for Hidden Particles) for the muon veto.

With ‚adiabatic' light-guide

In general:

Can extend the effective area of PMTs by a factor of ~16 (more with good ALG) without increasing the noise.

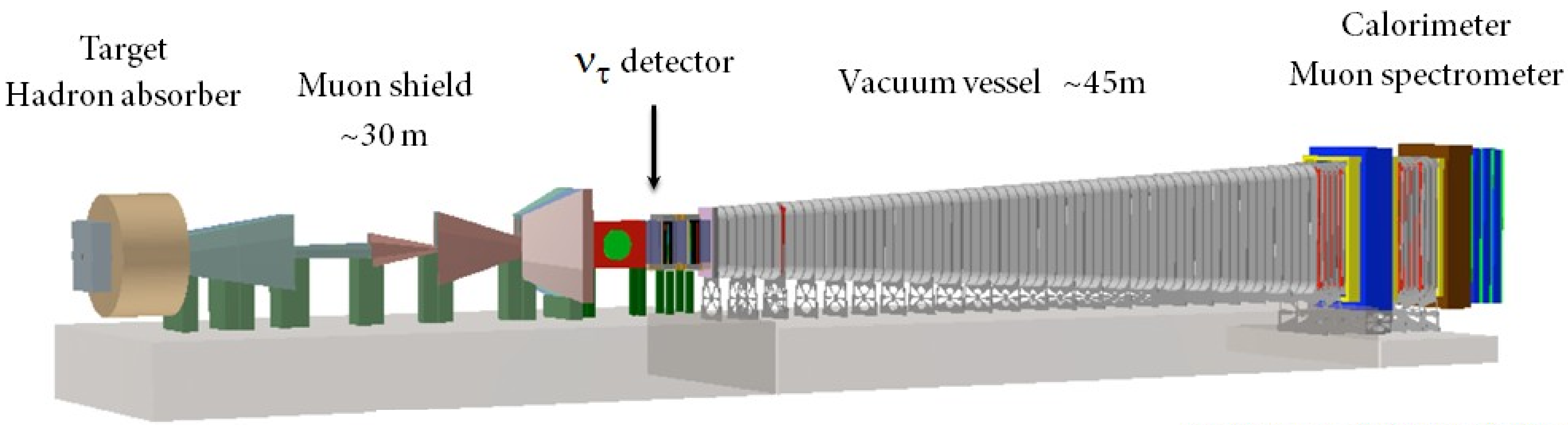
Trade-off: time-resolution (FWHM ~5ns for 0.9m tube)

Might be interesting for Hyper-Kamiokande (e.g. one string in the center)

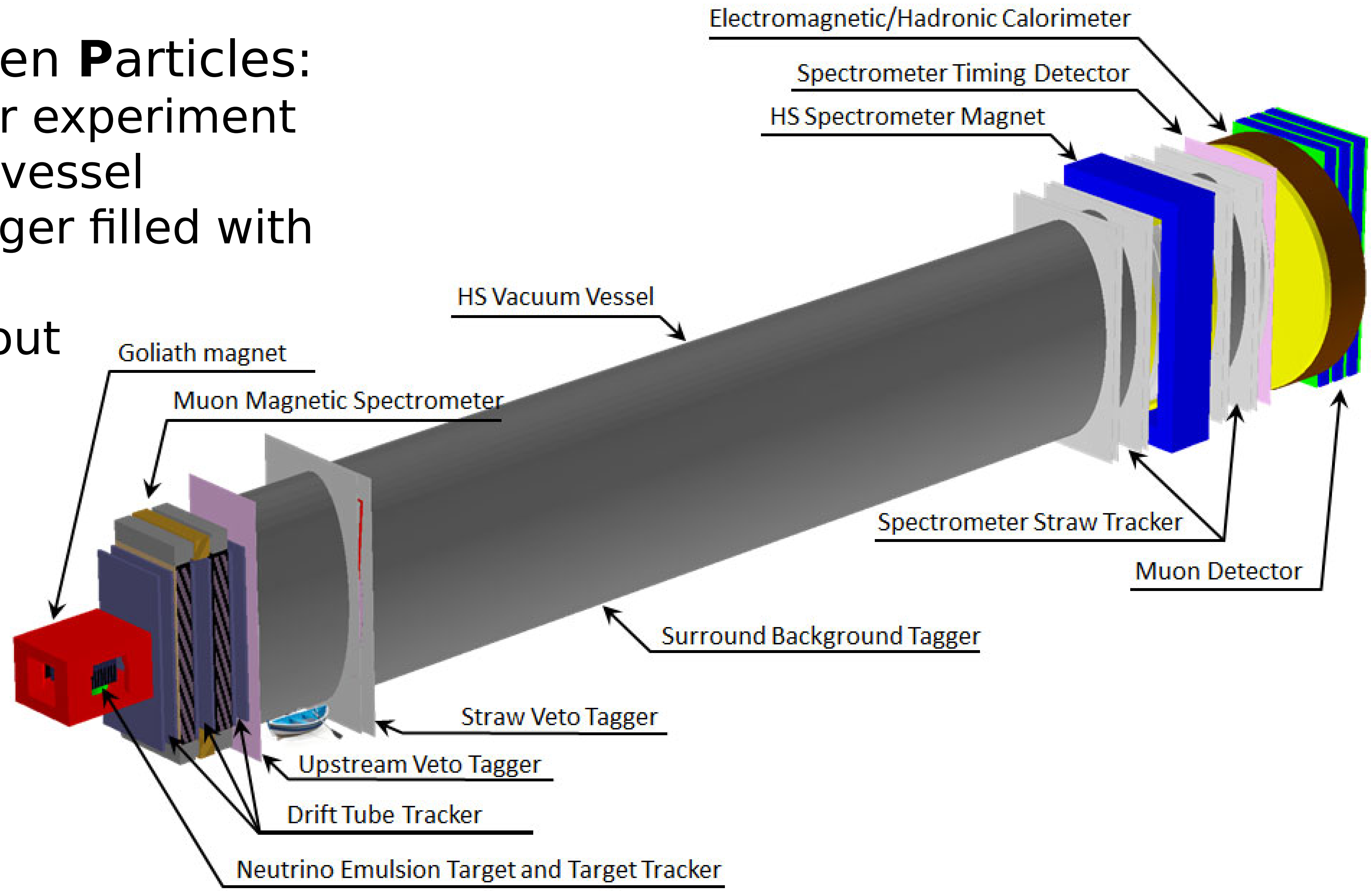
Or for a dedicated, maritime SN-Neutrino detector

And all other UV-detecting experiments that need low noise.

SHiP: WOM in liquid scintillator



Search for **Hi**dden **P**articles:
- Intensity frontier experiment
- Shielded decay vessel
- Background tagger filled with liquid scintillator
  - May be read out with WOMs



Summary

Improved coating procedure

- inner tube from quartz glass
  - **averaged two-sided collection efficiency** over 90-cm tube is **41 ± 1.7%** (reproducible!)
  - 50-cm quartz tube efficiency **>50 %**

Noise rate is 75Hz/PMT

- **150 Hz** per module
  - at about same A_{eff} as mDOM

Simple 3''PMT + 7cm∅ tube setup

- improvement in **SNR > 10** w.r.t to PMT alone

$$SNR_{rel} = SNR_{PMT} * \frac{A_{tube}}{A_{PMT}} * \epsilon_{tube} = SNR_{PMT} * \frac{2l}{r} * \epsilon(l)_{tube} \approx 16$$ with $\varepsilon_{tube} = 0.4$ (without ALG)

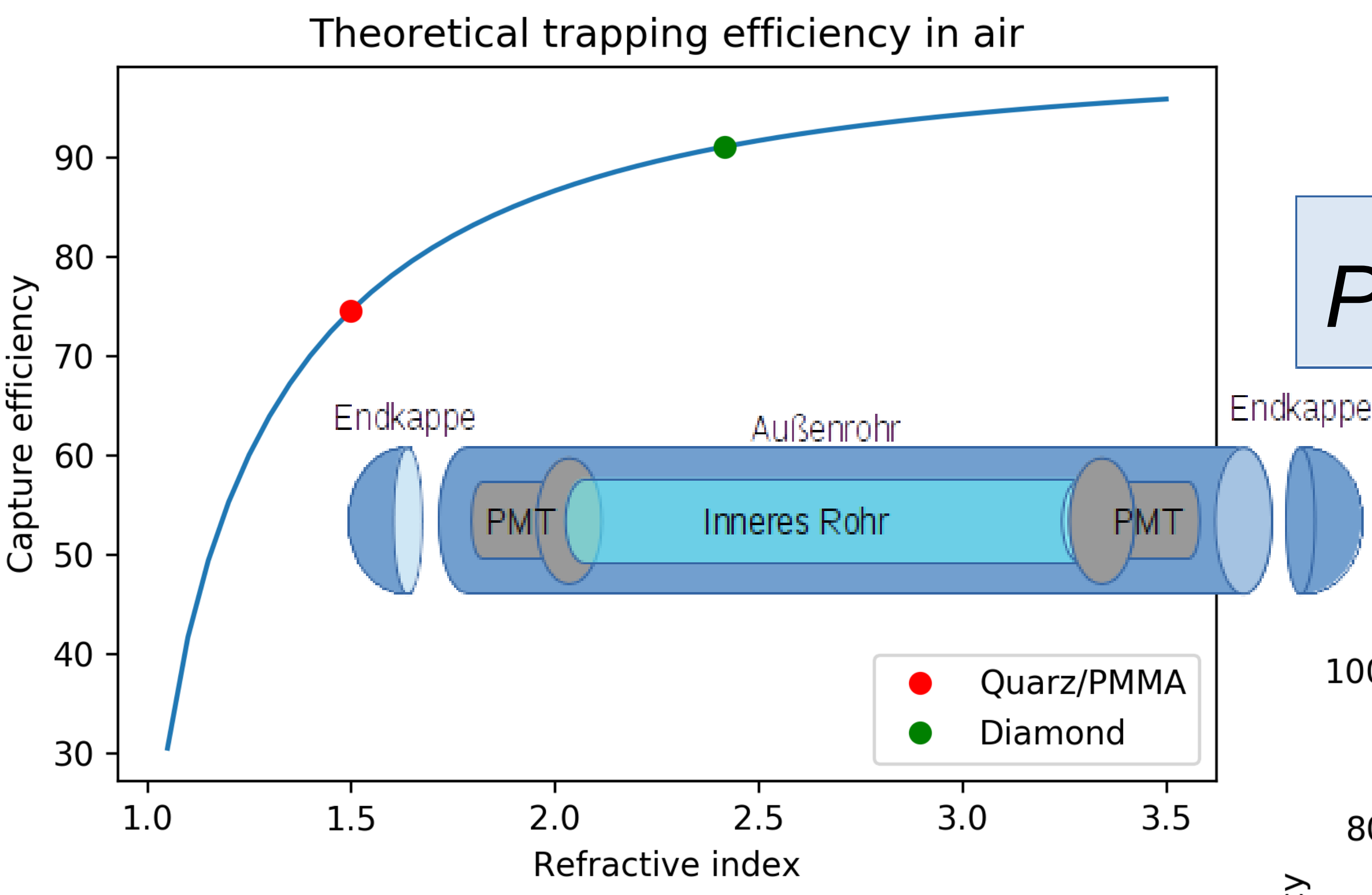
  - can be improved using adiabatic light guide

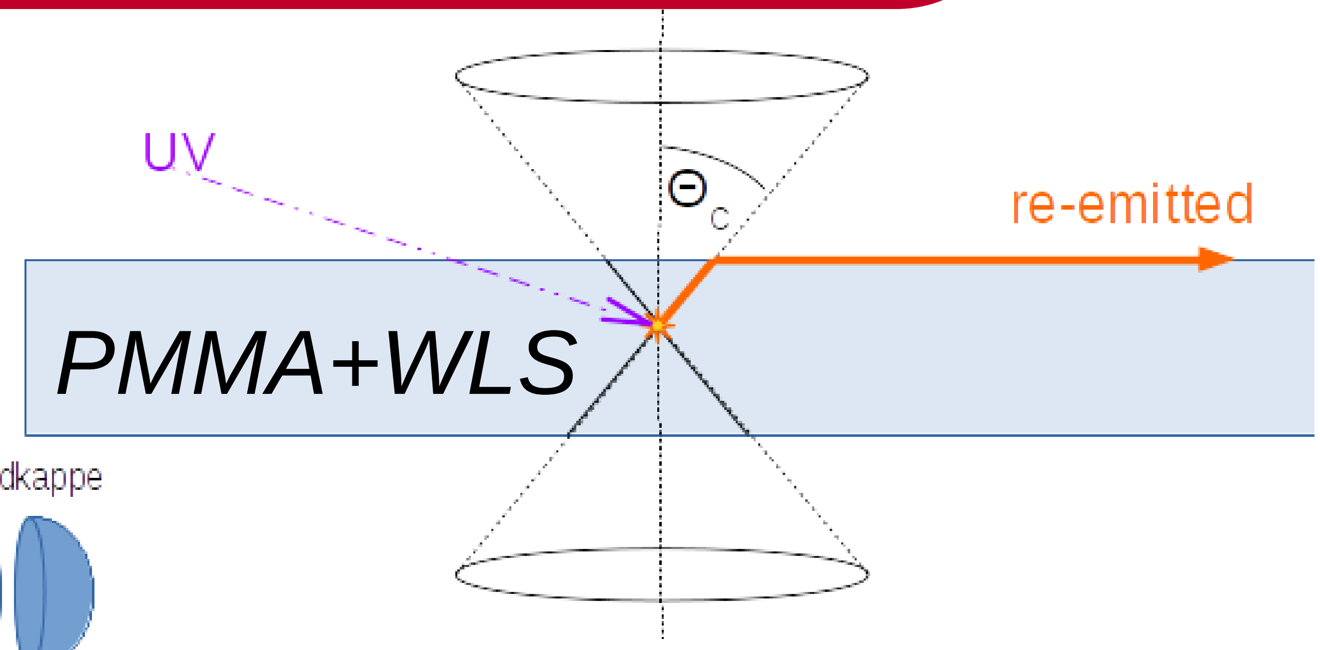
The end (of this talk)

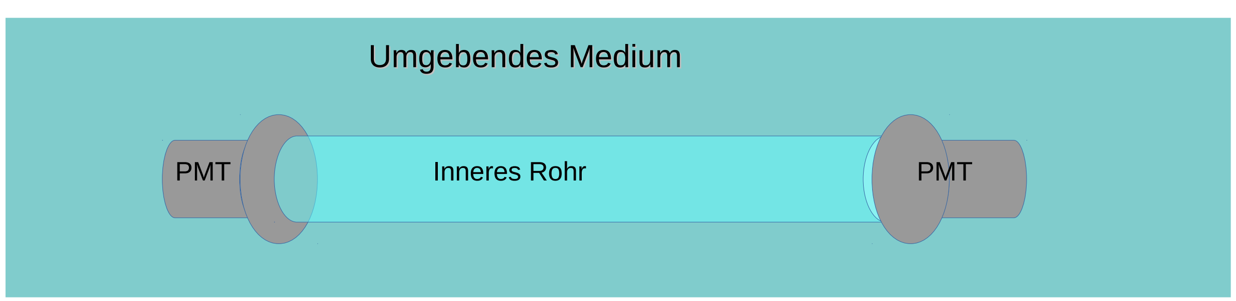
- *Thank you for your attention!*
- *Time for questions :-)*

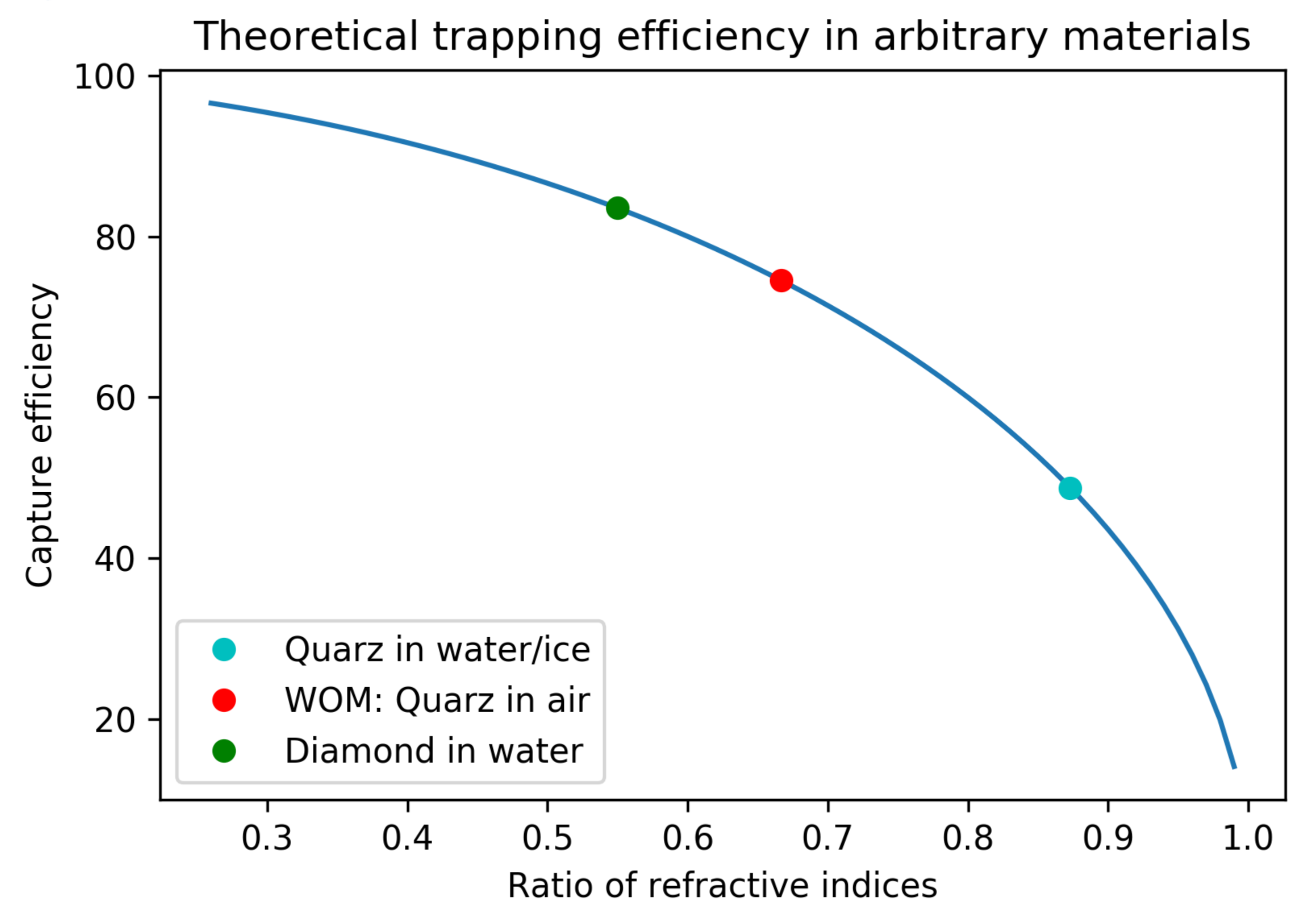
Contact: peter.peiffer@uni-mainz.de

Theoretical maximum efficiency depending on material

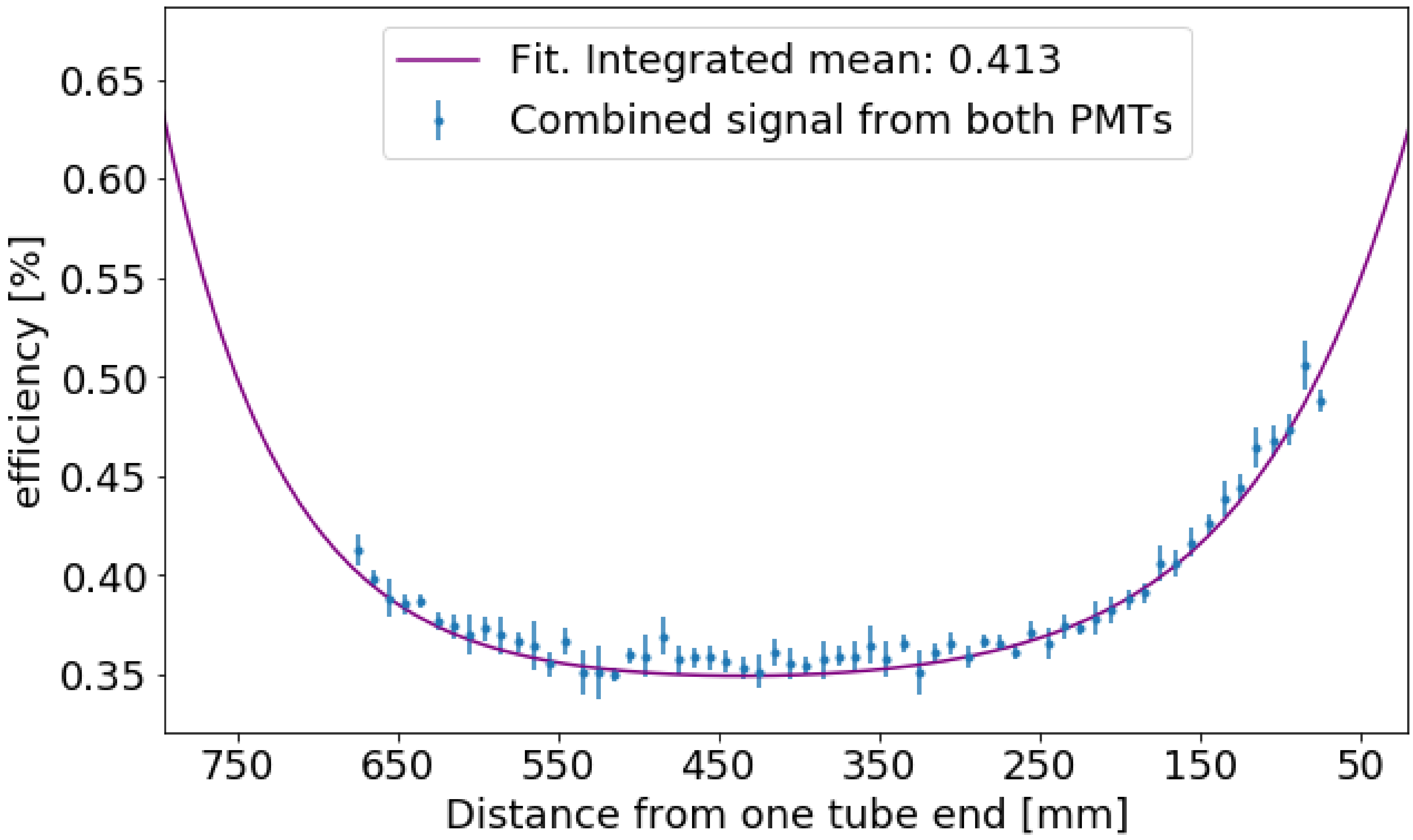








Averaged total efficiency



Absorption spectra for thinner coatings