Technische Universität München

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OCEAN NETWORKS CANADA

STRAW – Optical analysis of the Pacific Ocean Neutrino Experiment (P-ONE) site using data from the first pathfinder mooring

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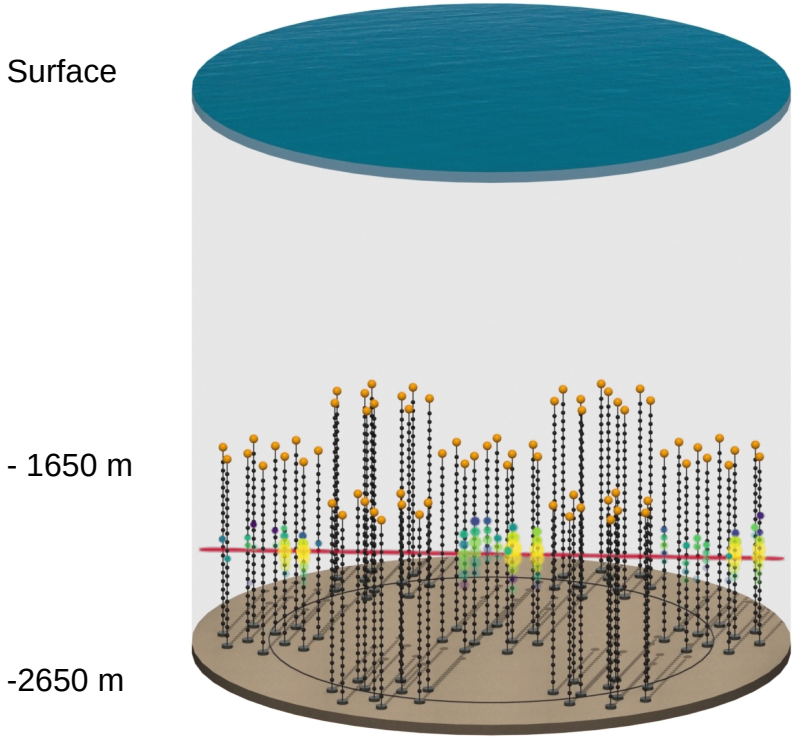
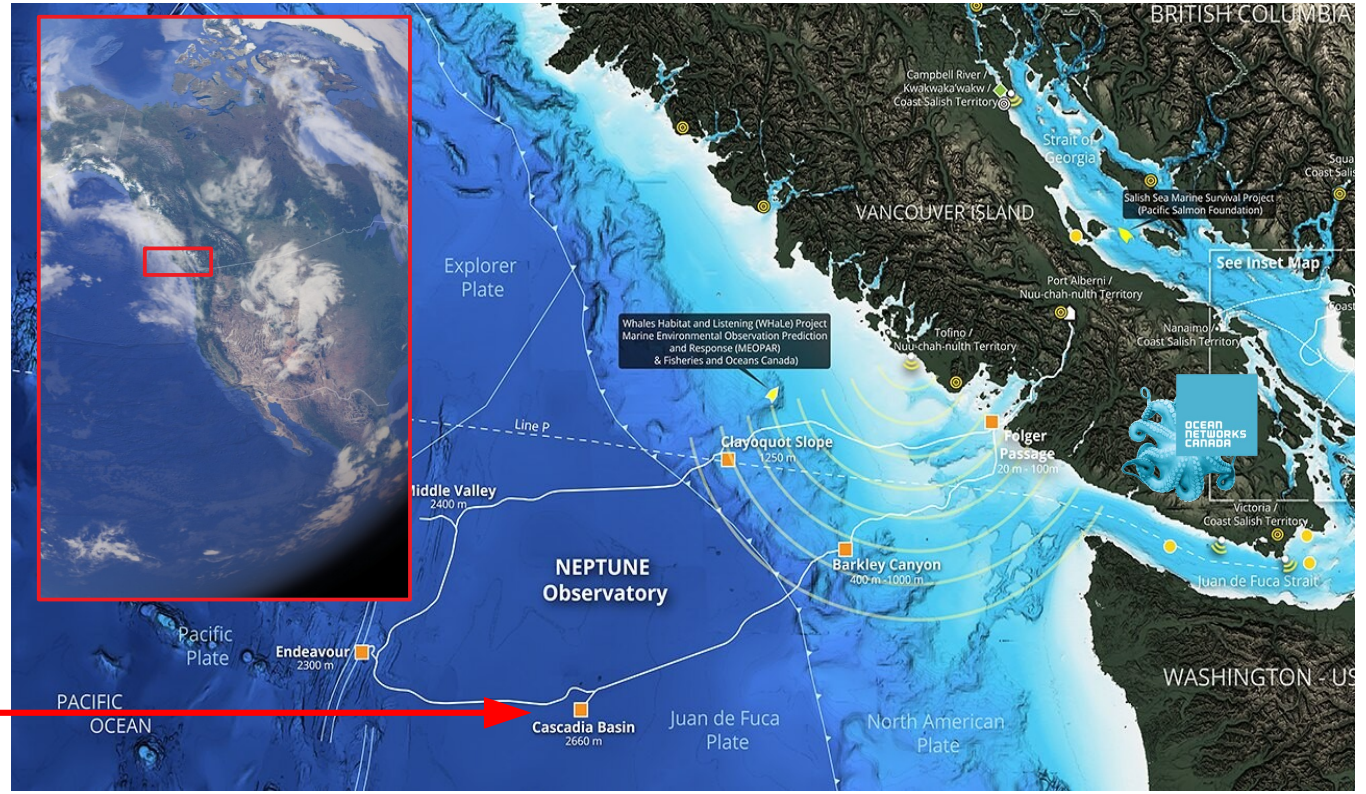
for the P-ONE Collaboration

Cascadia Basin – site for a new large-scale neutrino telescope

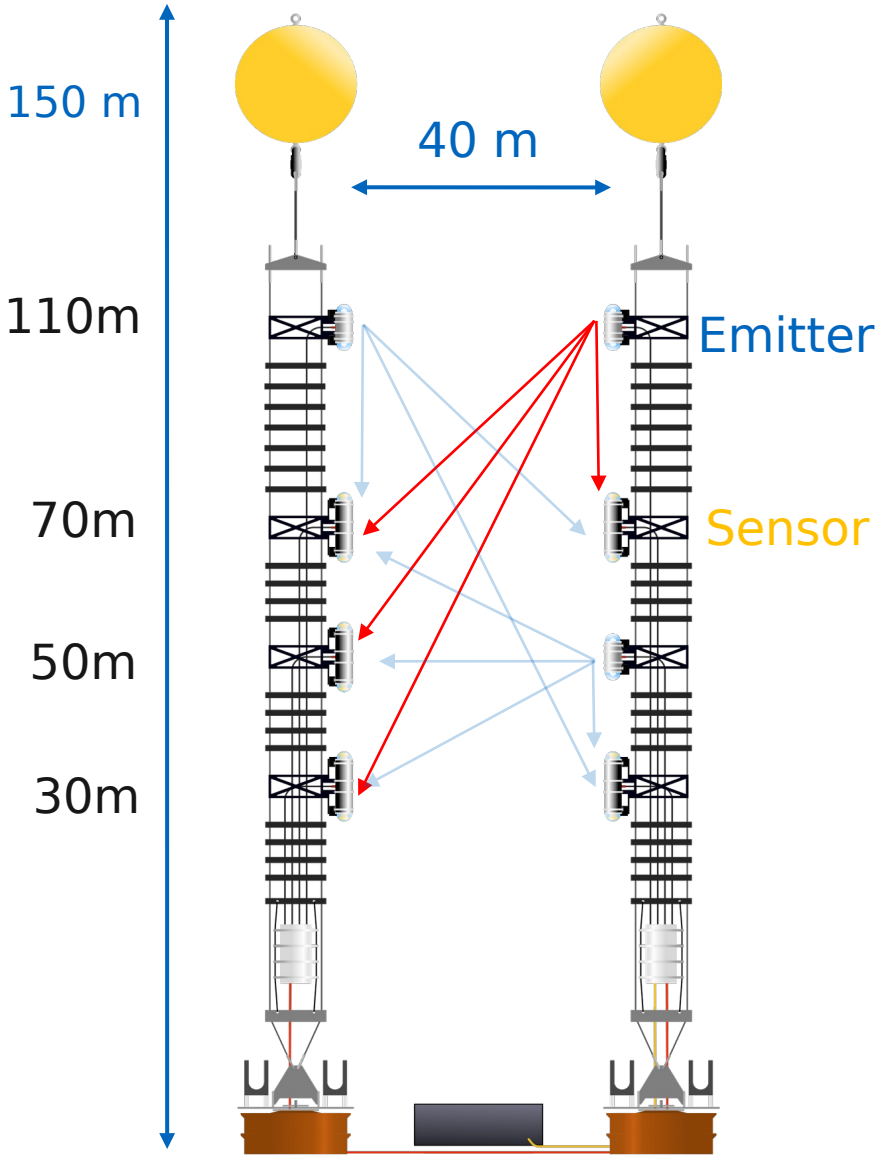
- Growing collaboration between TU-Munich and Canadian/US university groups
- Final goal: Build multi km³ neutrino telescope in the deep ocean
- Strong support from Ocean Networks Canada (ONC) with extensive deep-sea experience
- See also ICRC2021 #1272 and #1270



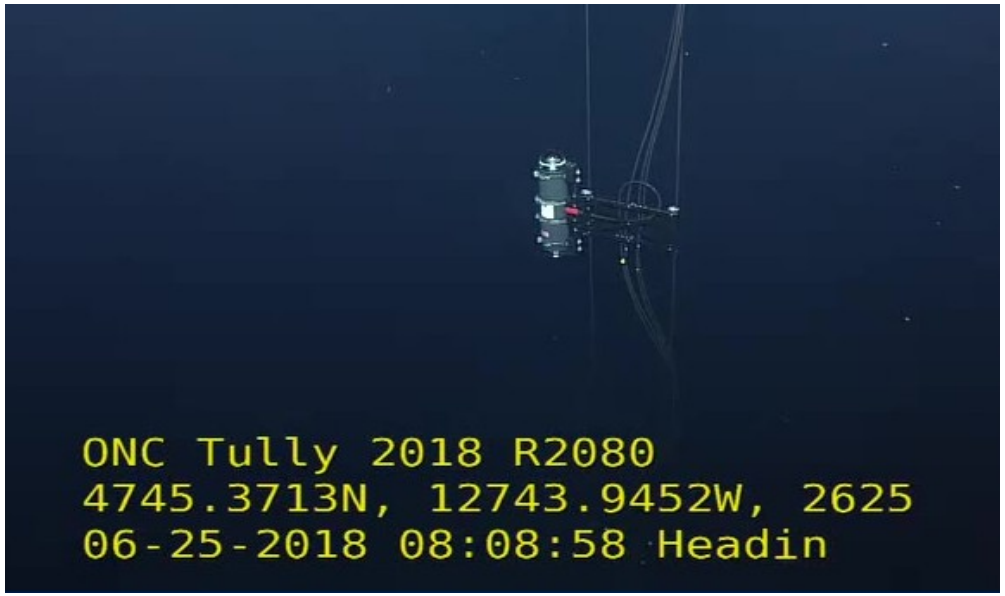


- Pathfinder deployments in 2018 and 2020 – testing technology, characterizing the site
- STRings for Absorption length in Water (STRAW) results will be presented!

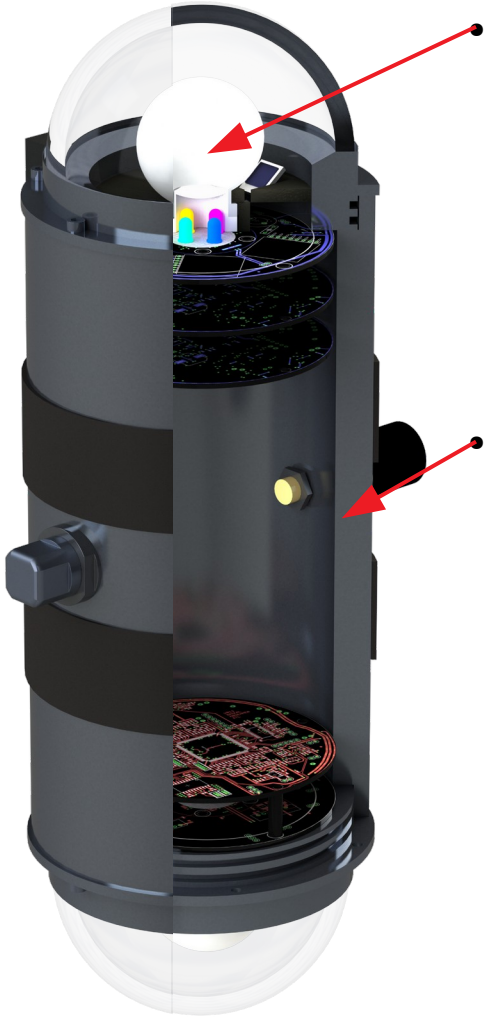
STRAW – STRings for Absorption length in Water



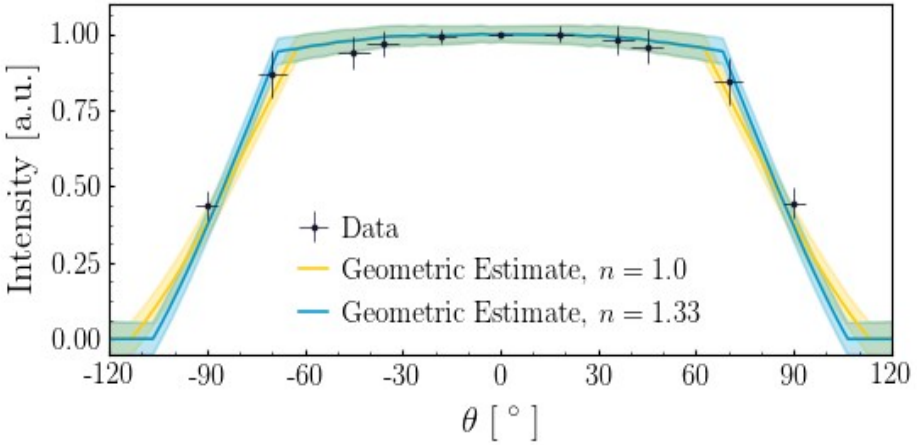
- Two-string detector with eight instruments
  - **Emitter:** Precision Optical Calibration Module (POCAM)
  - **Sensor:** STRAW Digital Optical Module (sDOM)
    → counting single photons
- Design based on expected optical properties (pure seawater)
  Smith, R. C. & Baker, K. S. Appl. Opt. 20, 177–184 (Jan. 1981).
- Technical details published in JINST
  M. Boehmer et al 2019 JINST 14 P02013

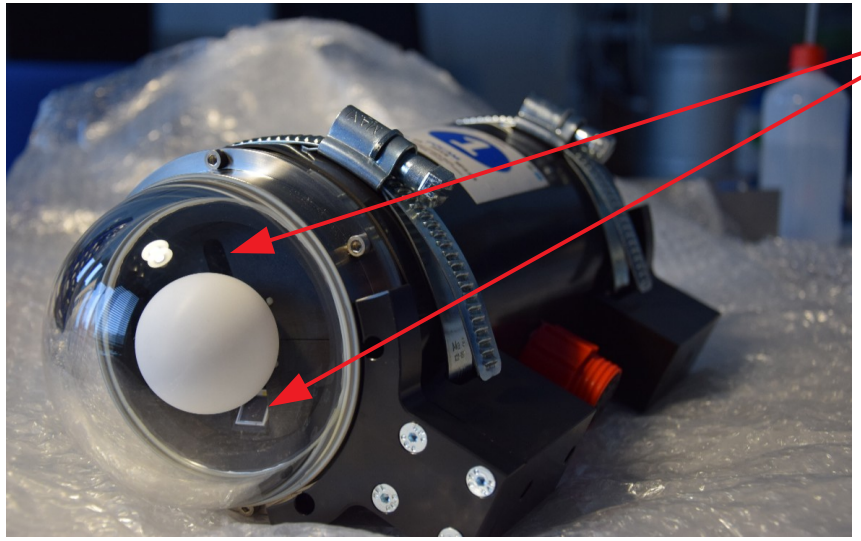


The POCAM flasher – calibration unit for IceCube Gen2



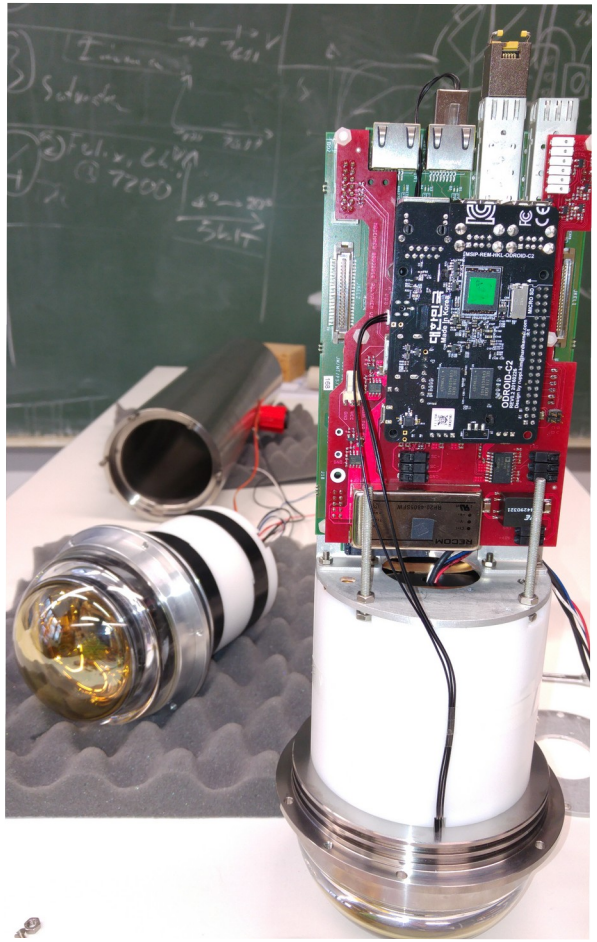
- Precision Optical Calibration Module
- Isotropic ns light flashes
  - Kapustinsky flashers
  - Intensity adjustable
  - LEDs: 365, 400, 450, 585 nm (effective)
  - PTFE diffusing spheres
  - 2 hemispheres adding up to near isotropy
- Titanium housing designed for 1400 bar



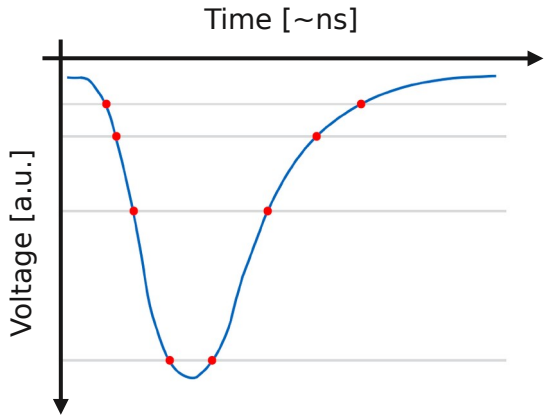


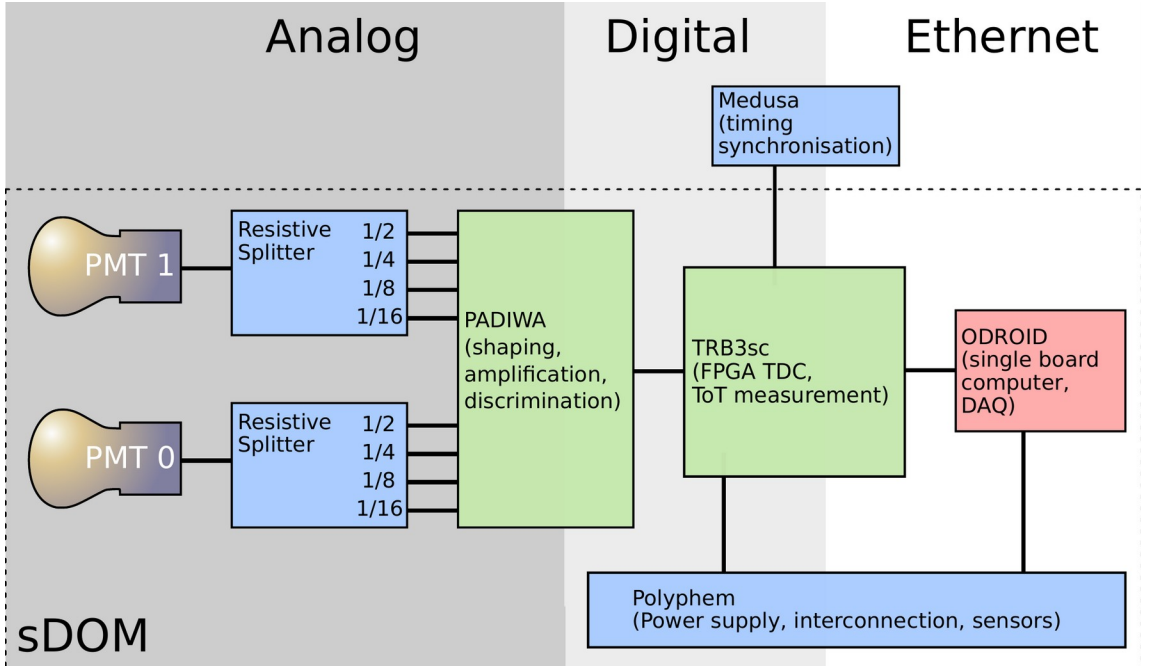
- Use internal photosensors for self-calibration
  - SiPM and Photodiode for dynamic range
  - See also ICRC2021 #578

sDOM – the STRAW digital optical module



- Design based on POCAM
- Two 3“ PMTs (Hamamatsu R12199)
- Readout with TRB3 and PaDiWa (TDC designed by GSI) http://trb.gsi.de/
- 4 channels per PMT



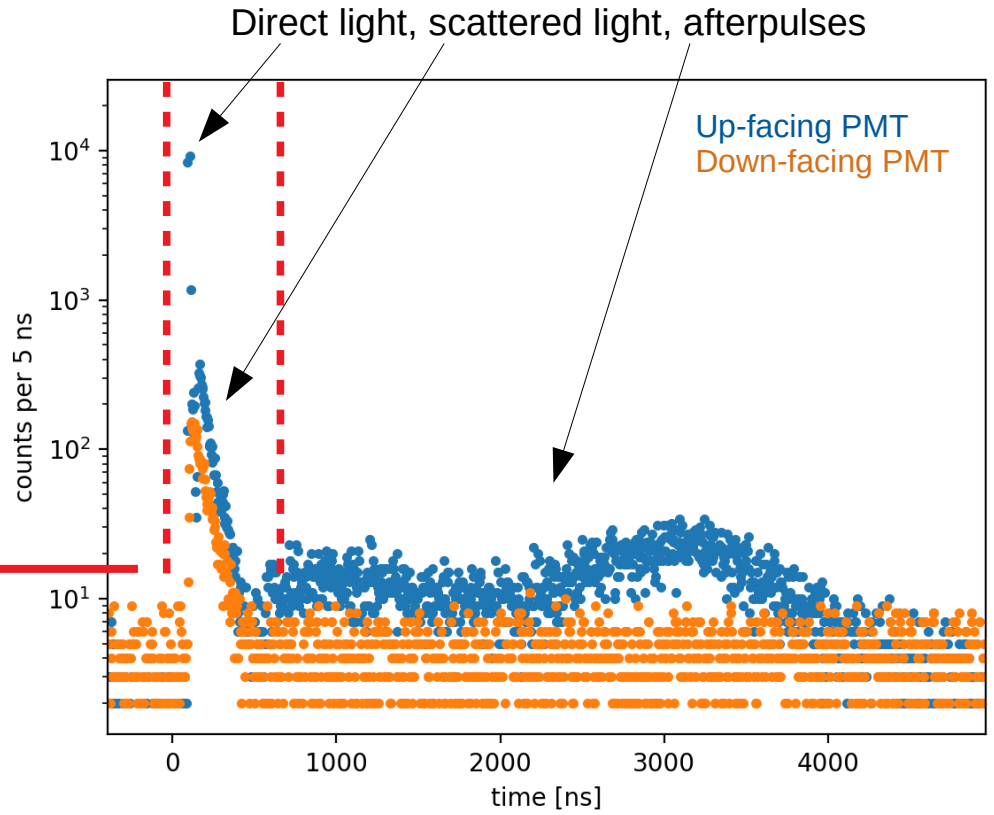


Two modes for data taking:

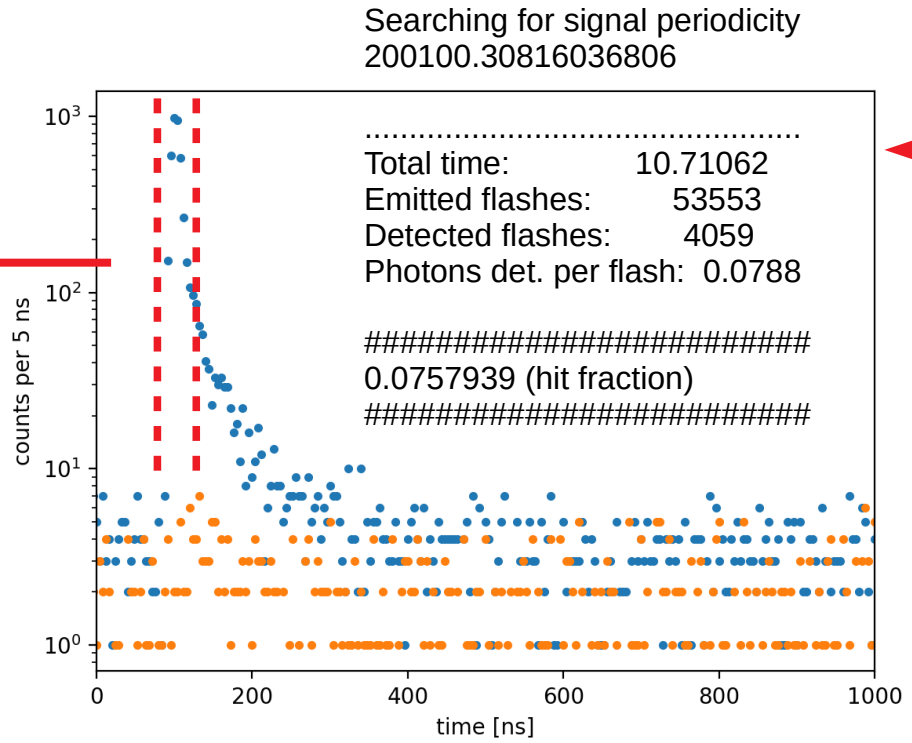
- Fast ToT readout, absolute timestamp for each channel → attenuation length
- Counting threshold crossings (photons) → measuring background rates

POCAM flashes and absorption measurement

- POCAM flashing at 2.5 kHz
- Intensity adjusted to <1 ph.e. on average at sDOM
- Phase-folded histogram of sDOM timestamps
- Extracting un-absorbed/-scattered photons from 30ns window
- Calculating ‘hit fraction’



“hit fraction”



Modeling the STRAW Detector

Average number of arriving photons at sDOM:

$$\overline{N_{\mathrm{ph}}} = P \cdot S \cdot N_0(U) \cdot \frac{R^2 \pi}{4\pi d^2} \cdot e^{-\frac{d}{\overline{\lambda}}} \cdot \epsilon \cdot Q \cdot \Pi(\theta) \cdot \Sigma(\theta)$$

Indiv. POCAM ‘efficiency’ corr.

Indiv. sDOM ‘efficiency’ corr.

Number of emitted ph.

PMT quantum efficiency at LED wavelength

Trigger threshold eff.

Attenuation length

sDOM emission profile

Angular response of sDOM:

$$\Sigma(\theta) = \left| \cos\left(\frac{\theta}{2}\right)^{\gamma} \right|$$

Emission profile of POCAM:

$$\Pi(\theta) = 0.75 + 0.25 \cdot |\cos(\theta)^{\frac{2}{3}}|)$$

hit fraction:

$$h = 1 - P_{\overline{N_{\mathrm{ph}}}}(0) = e^{-\overline{N_{\mathrm{ph}}}}$$

Likelihood:

$$\log(\mathfrak{L}) = \sum_{i=1}^{N} -\frac{(h_i - h_{i,\mathrm{model}})^2}{\Delta h_i^2}$$

Modeling the STRAW Detector

Model has the following parameters:

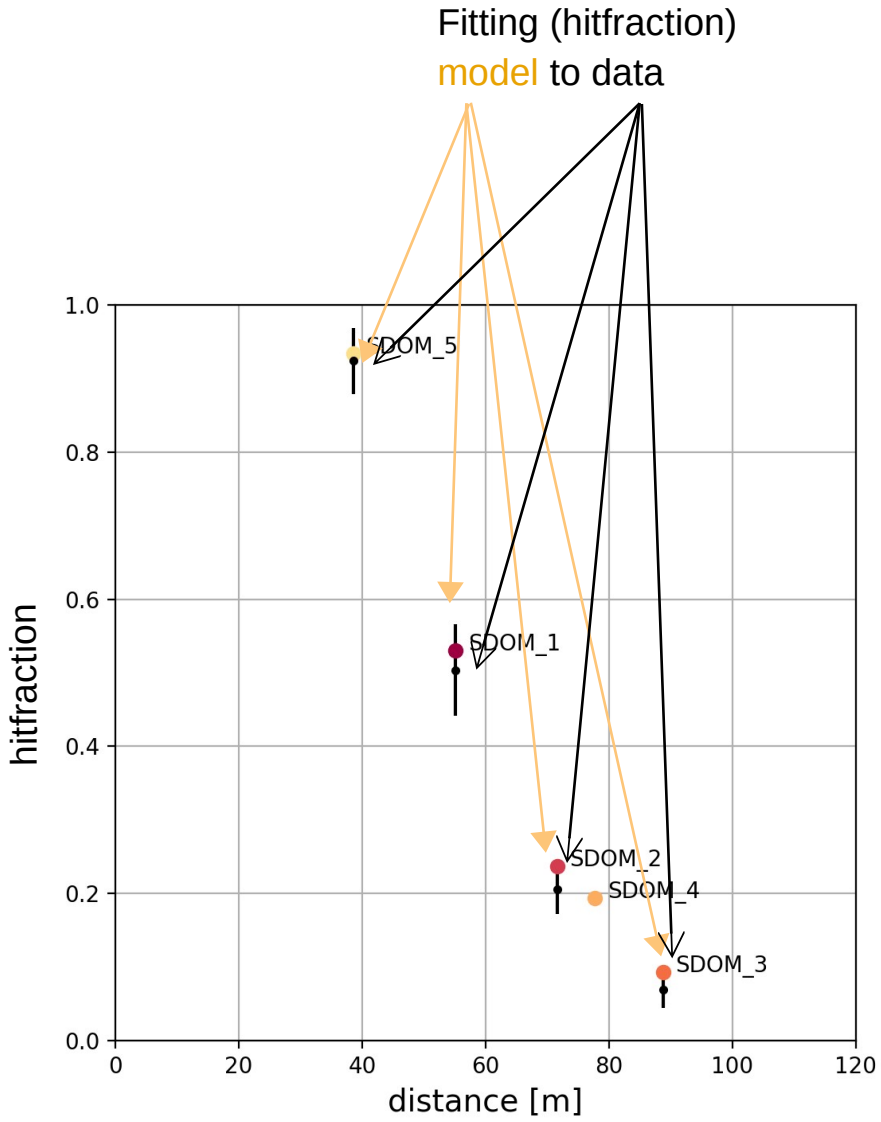
POCAM:
→ Cal. corr. 1x per POCAM/LED (+/- 10%)

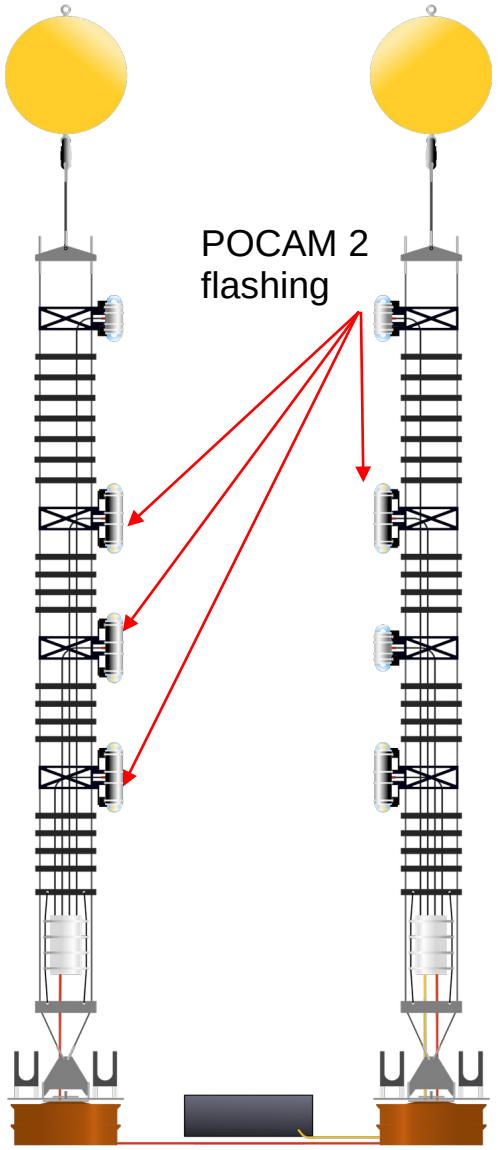
sDOM:
→ Cal. corr. 1x per sDOM (+/- 25%)
→ QE (+/- 10%, relative)
→ Trigger efficiency (75% +/- 25%)
→ Angular acceptance corr. (+/- 0.2)

STRAW:
→ **attenuation length**
→ y offset (+- 1 m)

Fit 365 nm, 400 nm, 450 nm and 585 nm simultaneously

→ **MCMC sampling using emcee**
http://dfm.io/emcee/current/





Preliminary attenuation length results from all data

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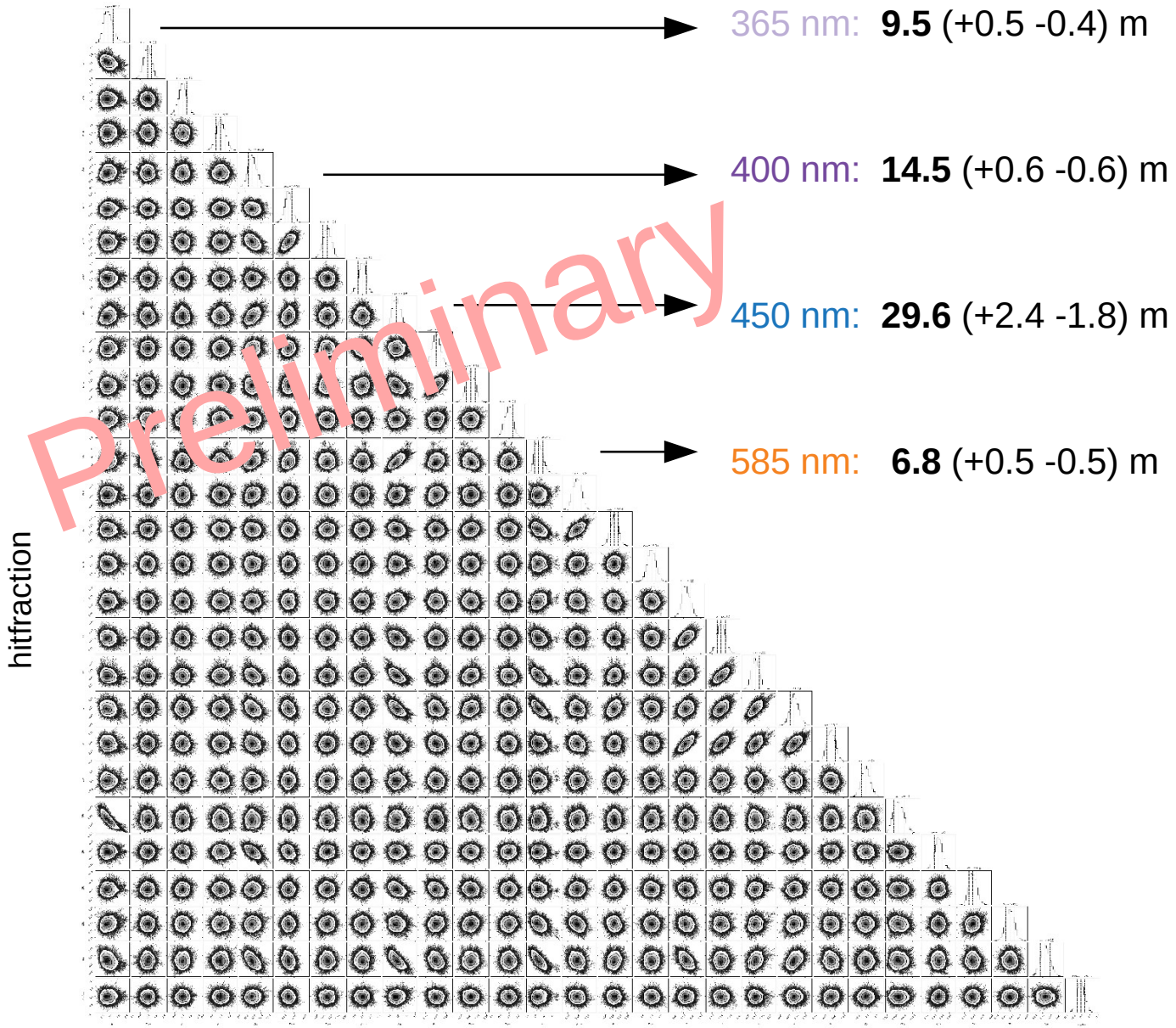

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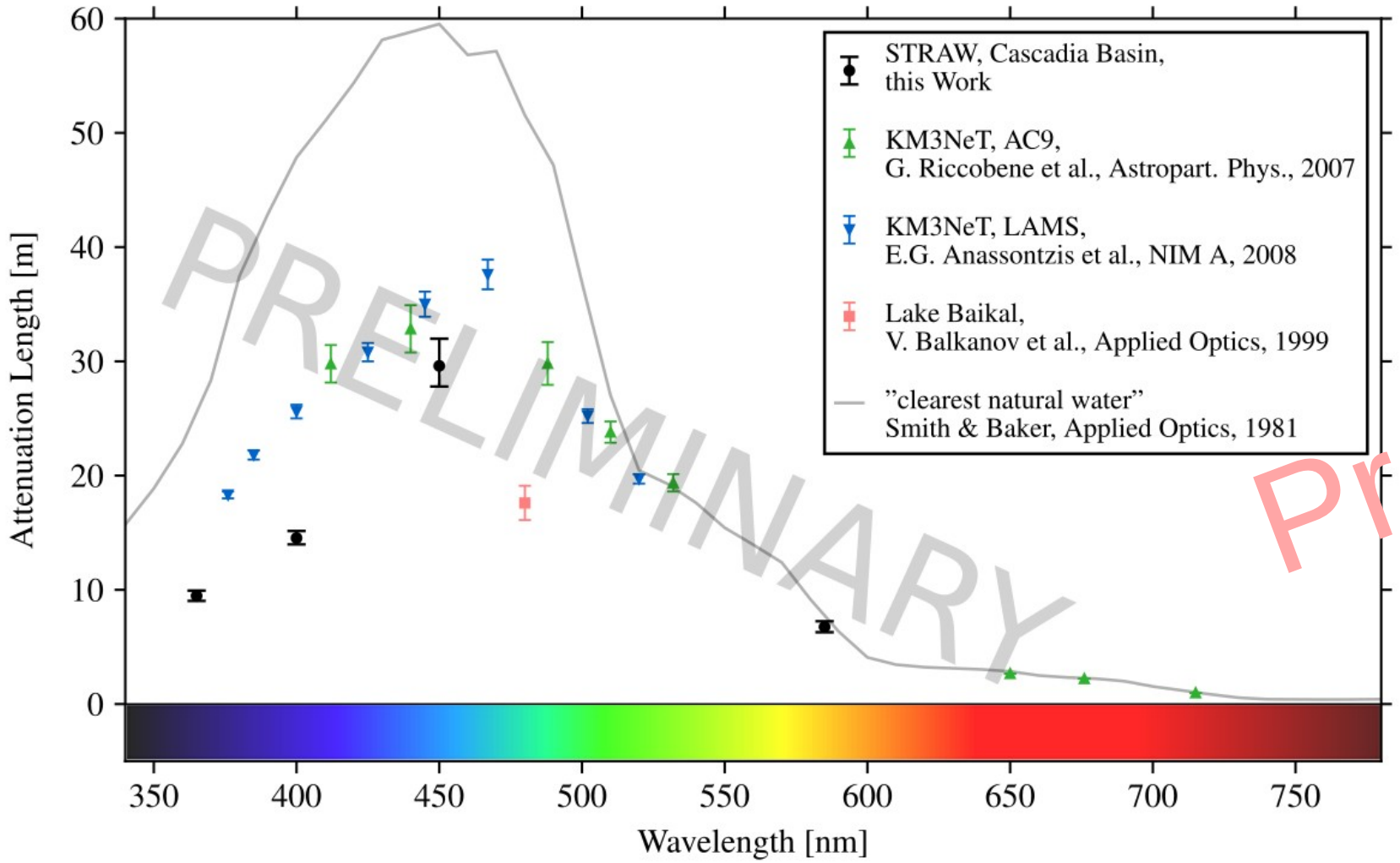


365 nm: **9.5** (+0.5 -0.4) m

400 nm: **14.5** (+0.6 -0.6) m

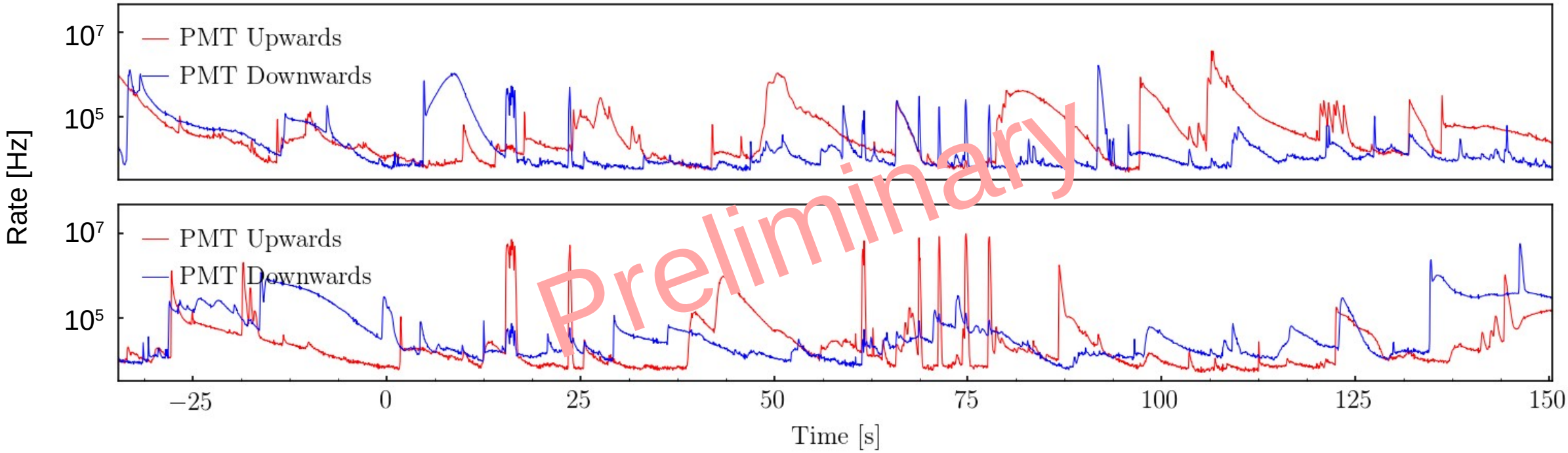
450 nm: **29.6** (+2.4 -1.8) m

585 nm: **6.8** (+0.5 -0.5) m

Preliminary

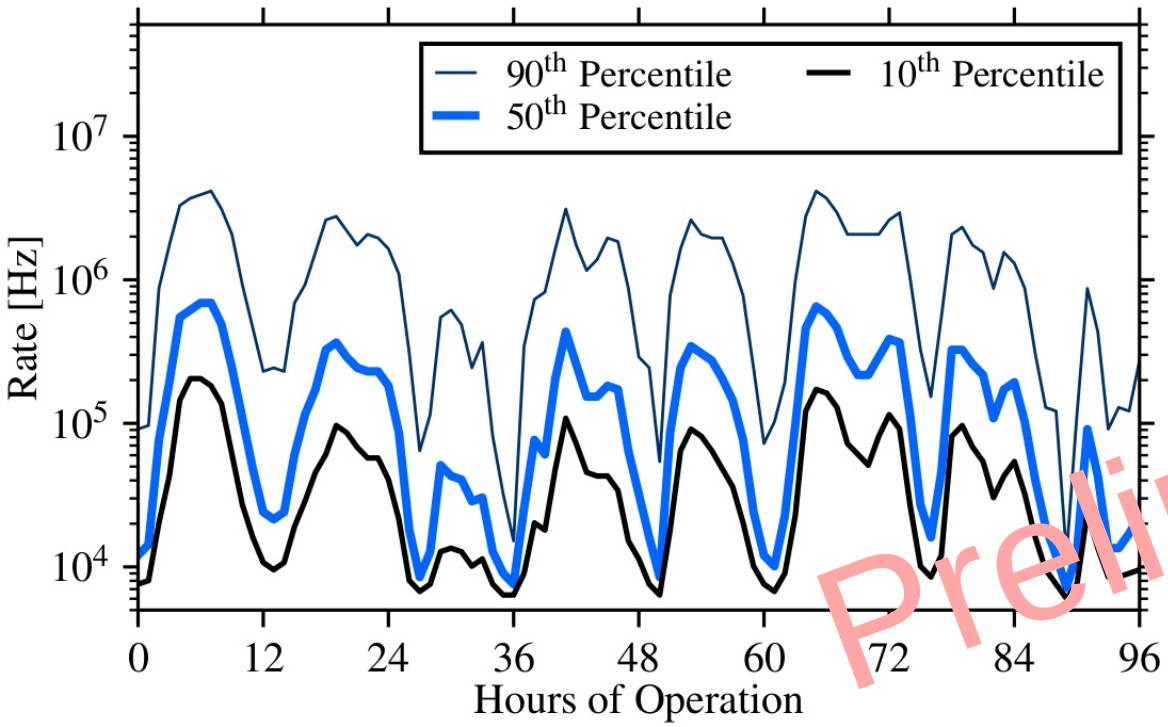
Background measurements

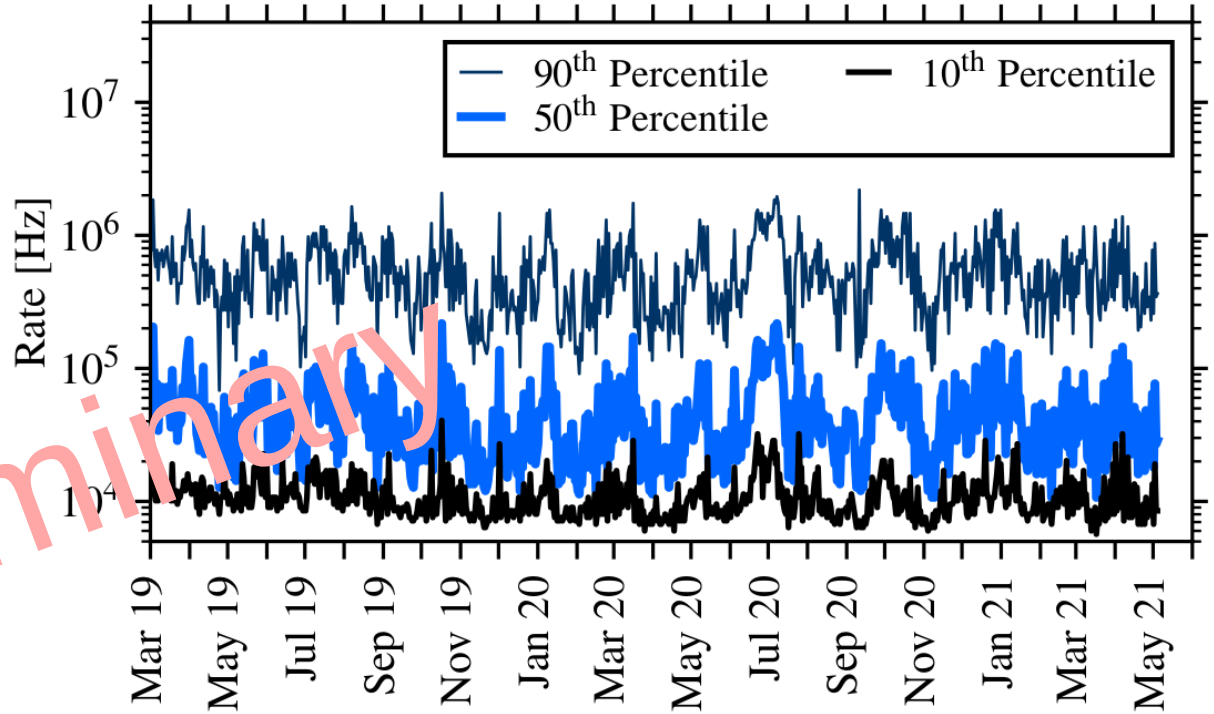
- Counters are read out 30 times per second
- Baseline around ~10 kHz and spikes up to ~10 MHz
- Fast changes, simultaneous spikes lasting ~1 s, seen in several sDOMs
- Probable causes: ^{40}K decay (baseline), bioluminescence (spikes)



Measurement of the background rates over 2+ years

- Rates have been recorded with a live-time fraction of over 98%
- Strong evidence for short-term modulation matching a 12 h cycle (tides?)
- No hint for modulation/trend over long term (within 2 years of operation)

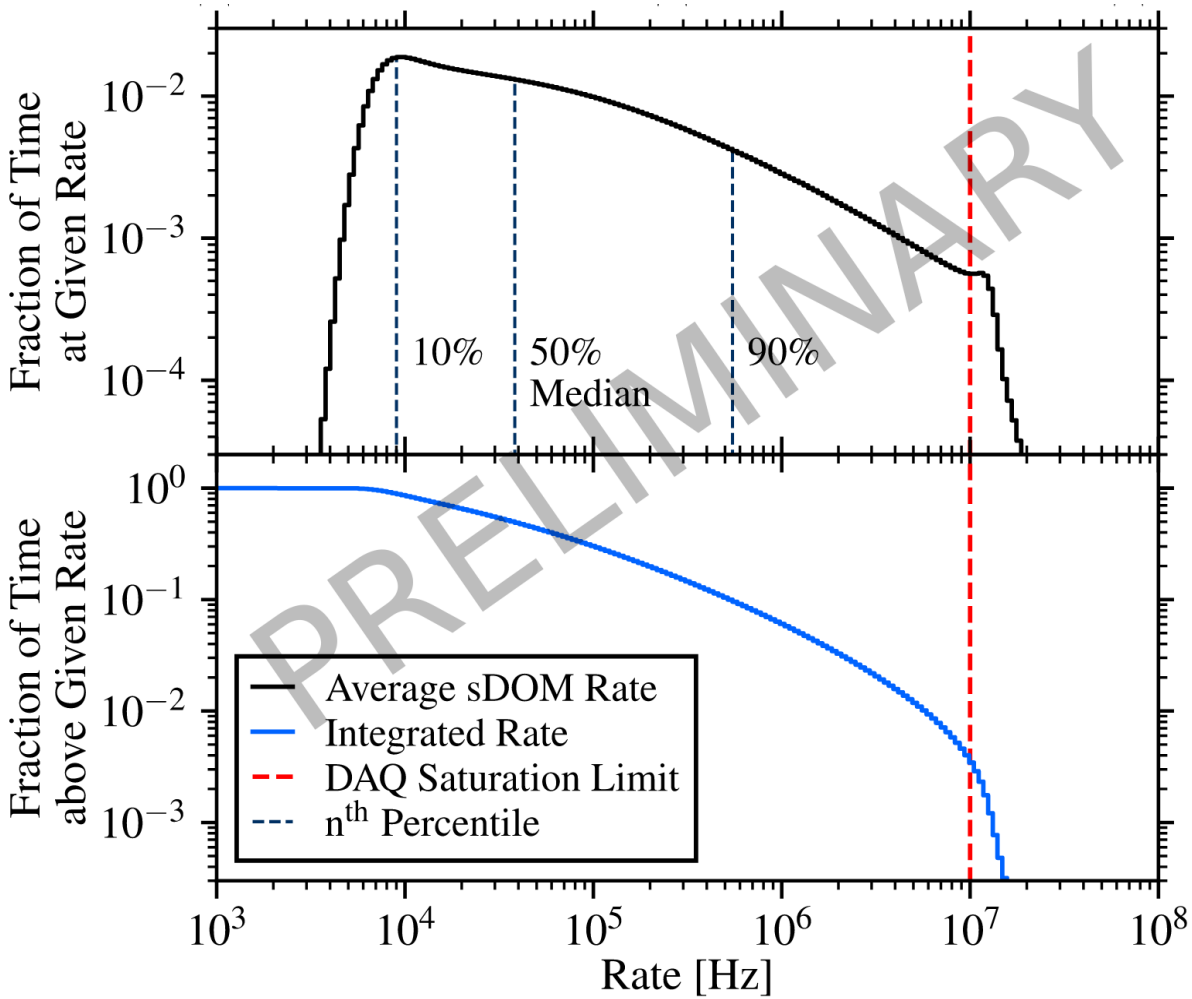




Statistical evaluation of the background rates

- Baseline around 10 kHz found in all sDOMs
  → probably from radioactive decay
- Median rates around 40 kHz
- Rates below 1 MHz about 95% of time
- DAQ saturation around 10 MHz
  → only occurring ~0.5% of time

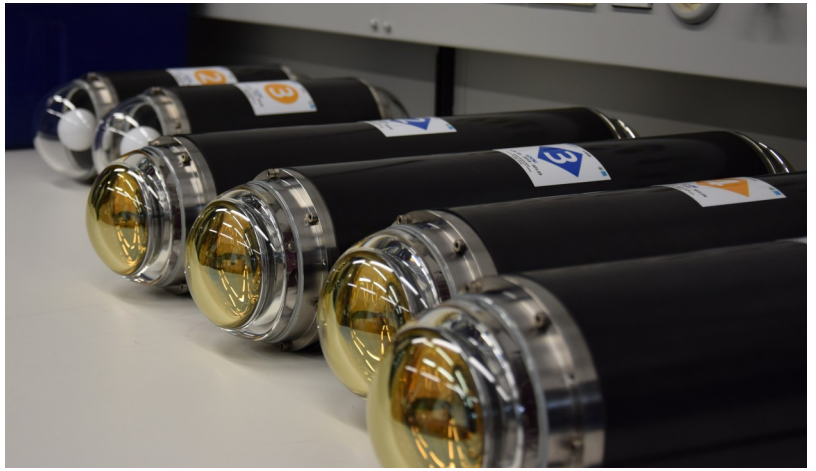
- No hurdle for multi-PMT sensor module with multiplicity trigger

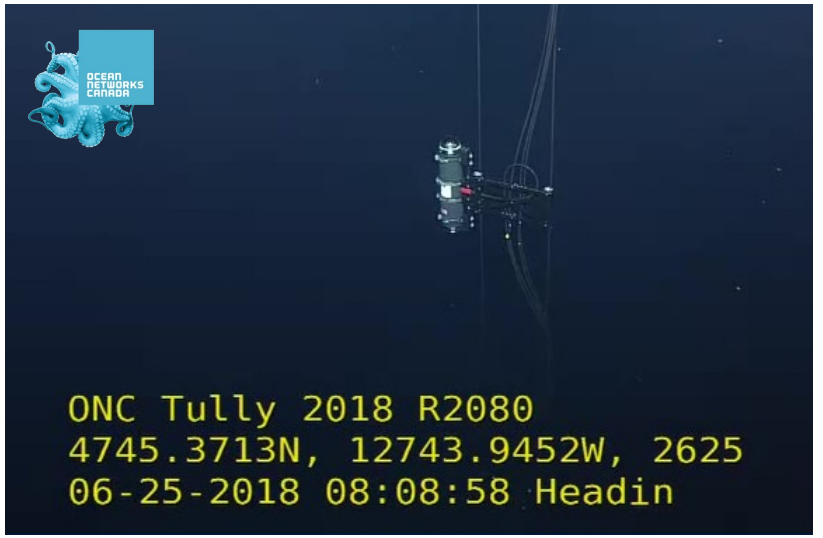


Conclusions and outlook

- Successfully operated first pathfinder mission (STRAW) for future large-scale neutrino telescope (P-ONE) for 2+ years with > 98% live-time fraction
- Measured attenuation lengths at 365 nm, 400 nm, 450 nm and 585 nm with light sources and sensors over multiple baselines (40 – 90 m) in a joint likelihood fit
- Maximum attenuation length of $29.6\ ^{+2.4}_{-1.8}$ m measured at 450 nm (Preliminary !)
- Background rates monitored over the entire time of operation with baseline ~10 kHz and < 1 MHz 95% of the time
- STRAW is still operating nominally
  → more studies (bioluminescence) to follow!
- Plans for P-ONE taking shape!

Thank you for the attention!





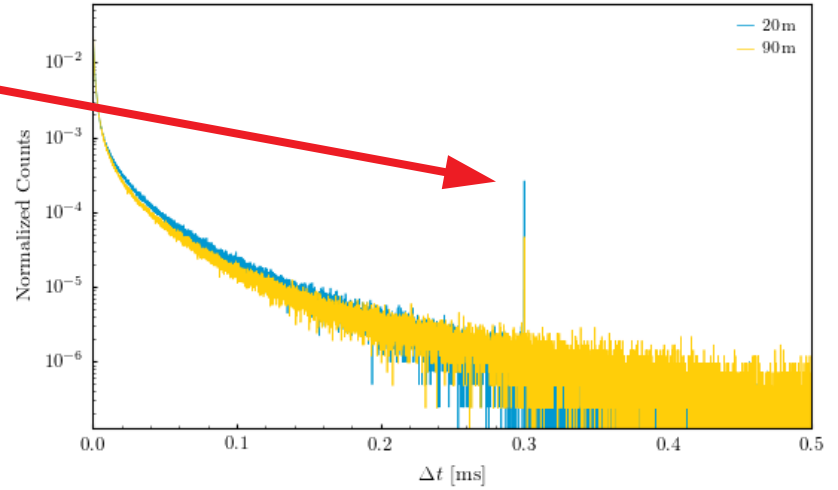
Other contributions to this ICRC:

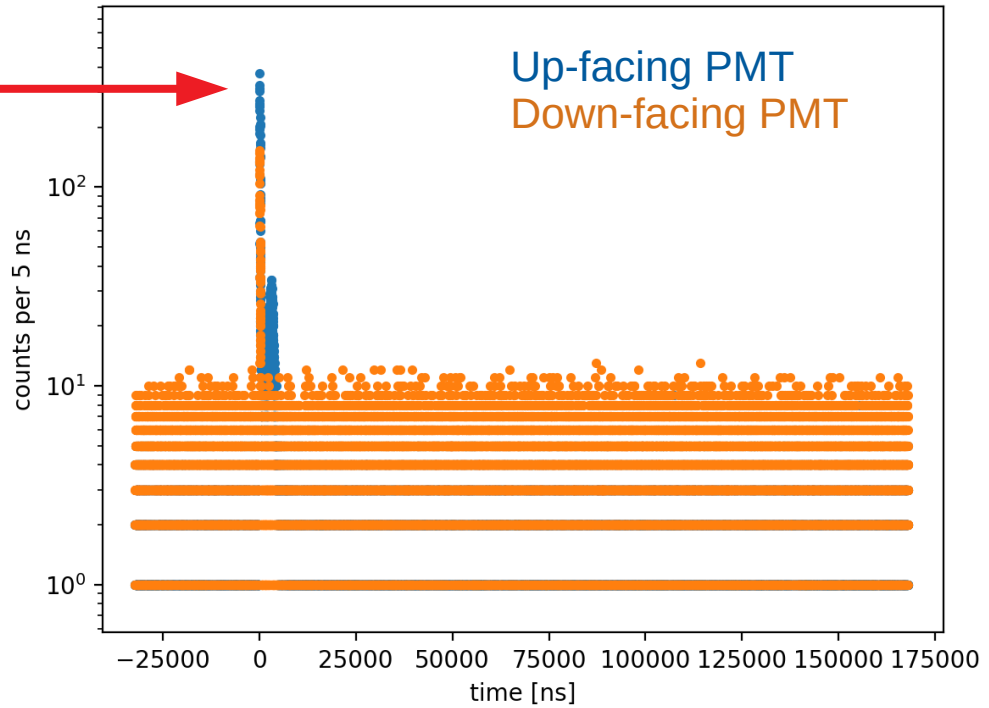
STRAW-b	#1183
POCAM	#578
P-ONE highlight	**#1272**
P-ONE prototype line	#1270
PLEnuM	#594

Backup

POCAM flashes and absorption measurement

- Δt histogram immediately reveals POCAM pulses at expected frequency
- High dark rate causes large fraction of shorter Δt values
- sDOMs are synchronized, but POCAMs are not integrated
- Reconstruction of collected PMT charge from ToT data is challanging
- → Using simple/reliable approach for the analysis:
  - Detected intensity of light only via 'hit fraction' (fraction of detected flashes)
  - POCAM flashes identified via periodicity search (frequency fit)
  - After background subtraction → number of detected flashes
  - POCAM needs to be adjusted to suitable intensity where on average only a fraction of the flashes lead to a detected photon
  - Model instrument and measurement process
  - Fit to data
  - → **Attenuation length!**





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sDOM:
→ QE/PDE error per 1x per sDOM (+/- 25%)
→ QE error (~ +/- 10%, relative)
→ Threshold/light yield
global efficiency (~75% +/- 25%)
→ Angular acceptance correction
(+/- 0.2, in terms of cosine power)

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Fit 365 nm, 400 nm, 450 nm and 585 nm simultaneously

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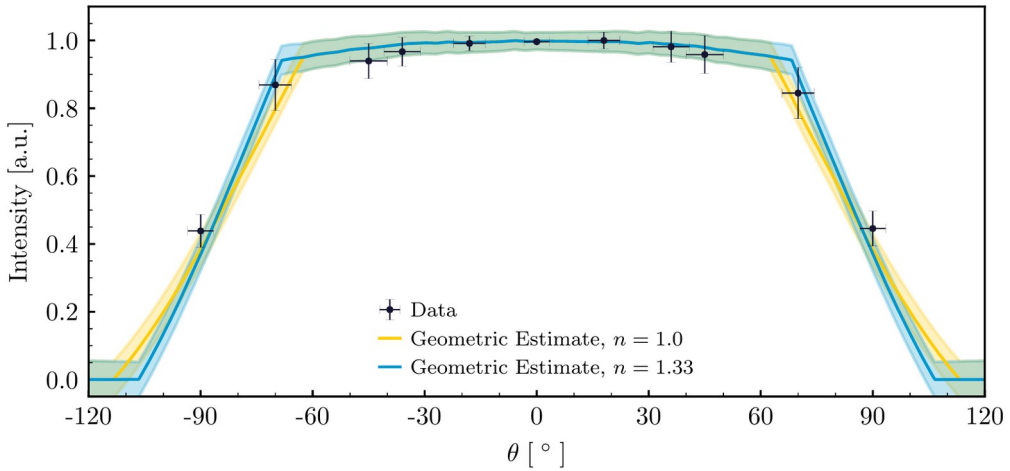
Likelihood:

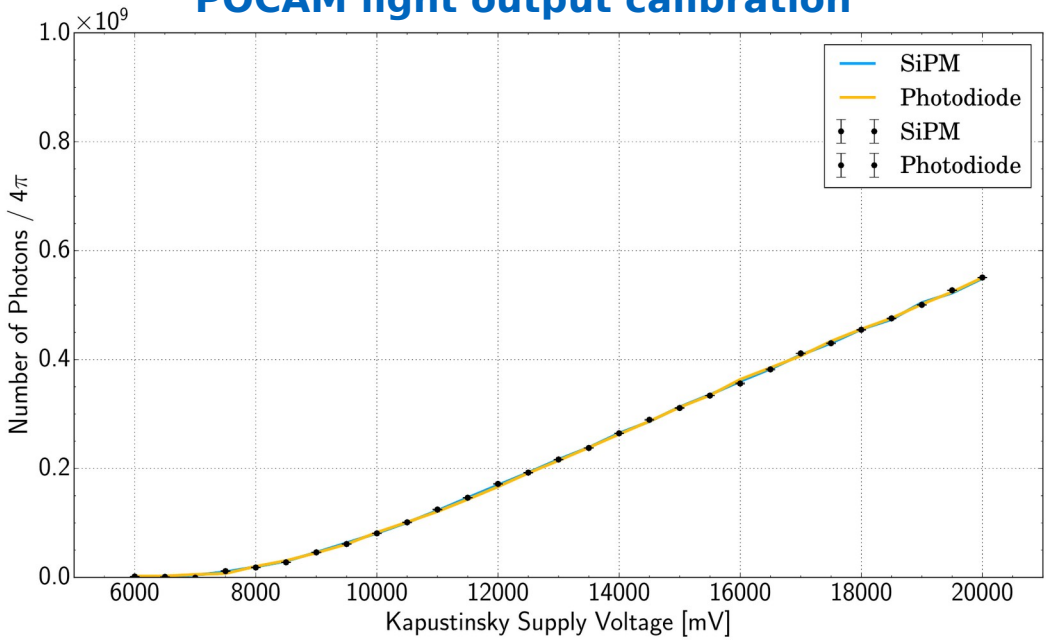
$$\log(\mathfrak{L}) = \sum_{i=1}^{N} -\frac{(h_i - h_{i,\mathrm{model}})^2}{\Delta h_i^2}$$

Modeling and fitting to STRAW data

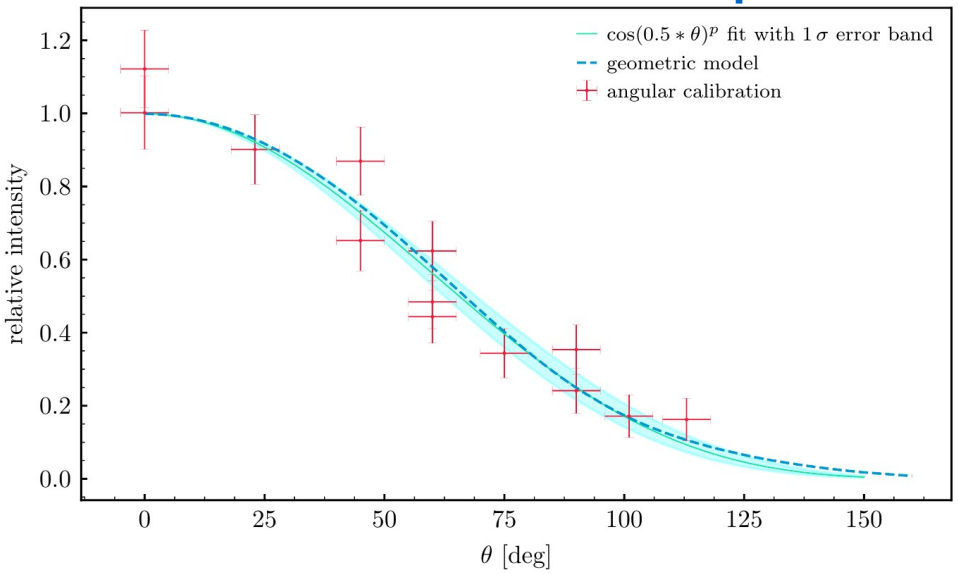
POCAM angular calibration



POCAM light output calibration



Measurement of sDOM acceptance



POCAM/sDOM angular calibration (analytic approx.)