Observation of Optical Anisotropy in deep ice at the South Pole

Using the Oriented Dust Logger

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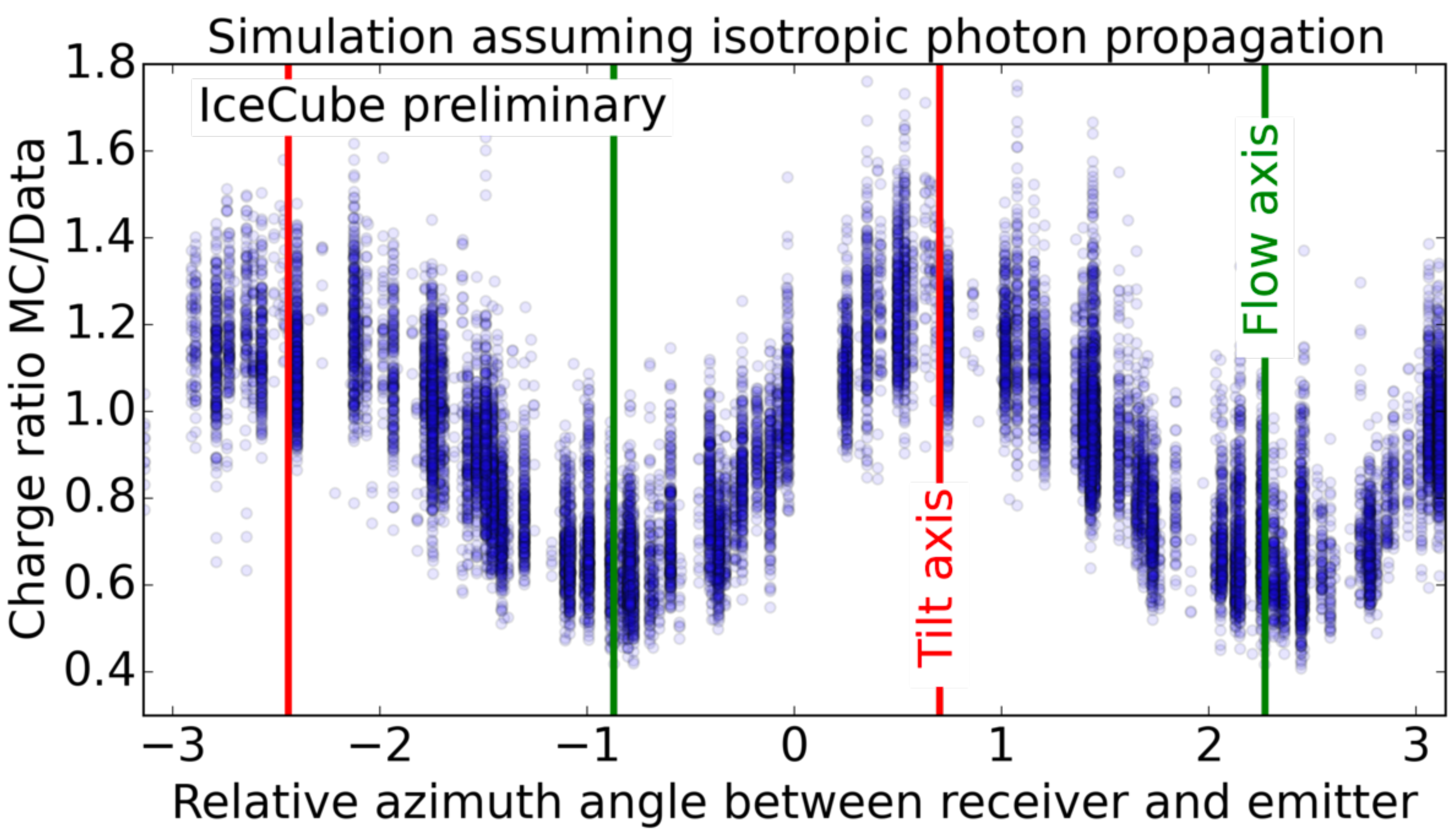
Motivation

Several indications of optical anisotropy at South Pole

[1] Aarsten, et al, JINST (2017)
[2] Chirkin, ICRC 2013
[3] Chirkin, Rongen ICRC 2019

- Light appears to propagate more efficiently along the glacial flow than perpendicular to it
  - Observed with IceCube “flashers” (LEDs) [1,2] and “stopping” (minimum ionising) atmospheric muons
  - Important source of uncertainty for many IceCube analyses
  - Effect appears consistent with light propagation through birefringent ice [3]



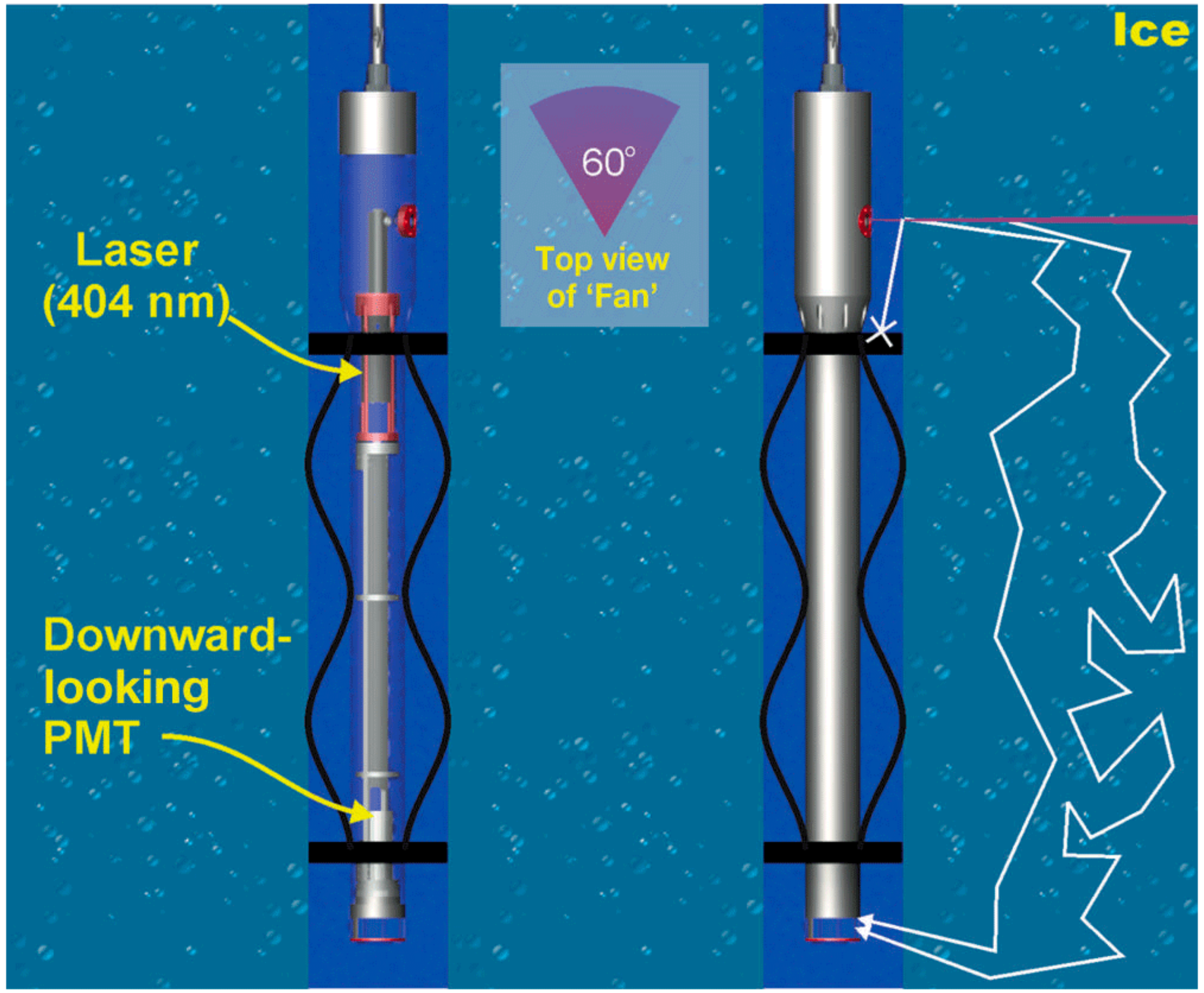
- Want to assess the validity of this model through an independent measurement technique
  - Proper modelling of underlying mechanism should describe all data
  - All IceCube measurements are from **forward-propagation** of light from source to sensor

Experimental setup

The oriented dust logger

More info on dust logger here:
Bramall et al, Geophys Res Lett (2005)

- Dust logger developed to measure glacial ice properties through back-scattered/reflected light
- Light emitted from 404nm laser into ice in fan with 60° opening angle
- Fraction (10^{-10}-10^{-6}) of back-scattered light is detected via 1” PMT on-board
  - Black nylon baffles prevent direct path through the borehole
- Upgraded to include orientation sensor* that uses local magnetic field to deduce absolute pointing with ~3° azimuthal accuracy



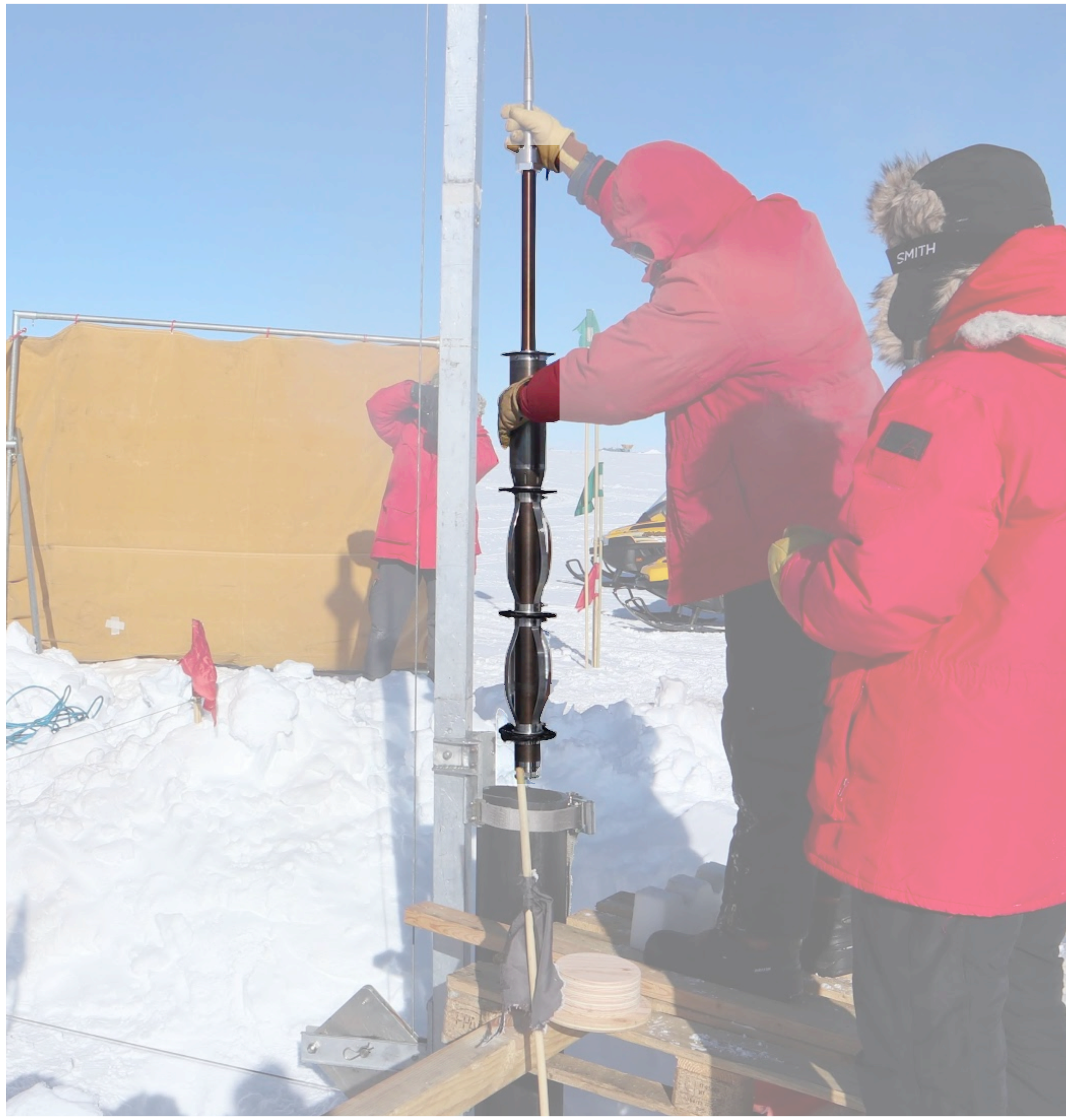
Depth resolution ~few mm

*https://www.appliedphysics.com/_main_site/wp-content/uploads/model-547-micro-orientation-sensor.pdf

The SPICEcore

Open borehole near the South Pole

- Deployed Oriented Dust Logger in the SPICEcore over several seasons (2016/17, 2018/19, 2019/20)
- Used Intermediate Depth Winch from IDP, reaching maximum depth of ~1700m
  - ~350m of overlapping ice layers with IceCube
- Roundtrip deployment (down/up) takes approx. 6 h
- As the logger is deployed into the borehole, it rotates due to residual twist in the cable
- Several deployments are achieved each season over the course of a few weeks



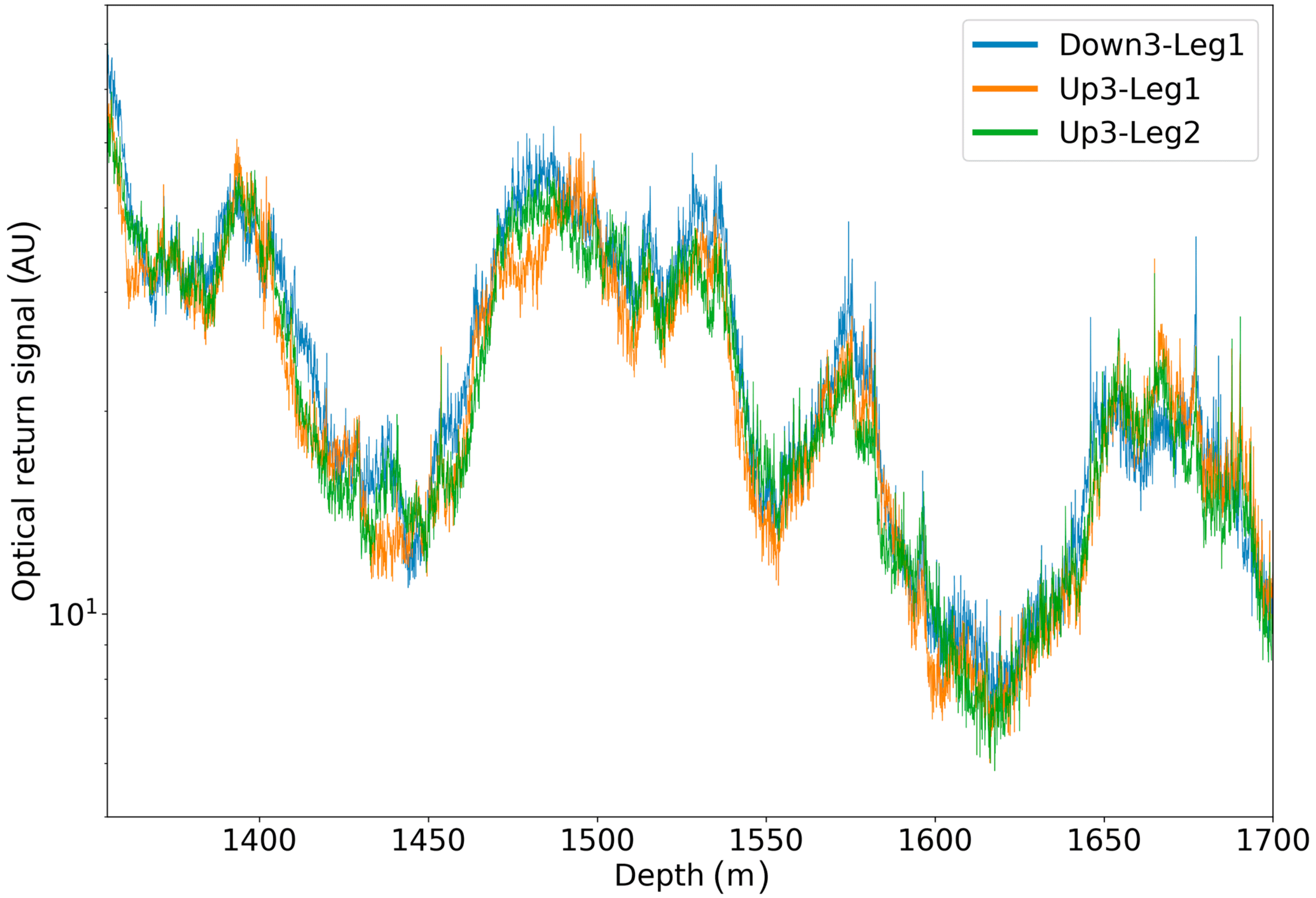
Deployment in 2018/19

Analysis strategy

Method

- For each deployment, we record orientation, depth from winch payout (coarse, refined later), PMT signal captured in 10ms intervals (~every 2.5 mm)
- Same depths are logged several times, but the return signal is not exactly the same
  - Each deployment follows a unique azimuthal rotation, embedding the anisotropy signature
- By taking ratios of data collected at the same depth, but with different logger orientations, we can extract the anisotropy signature
  - Analysis is based on real-data only (no simulation)

Real-time data acquisition/display



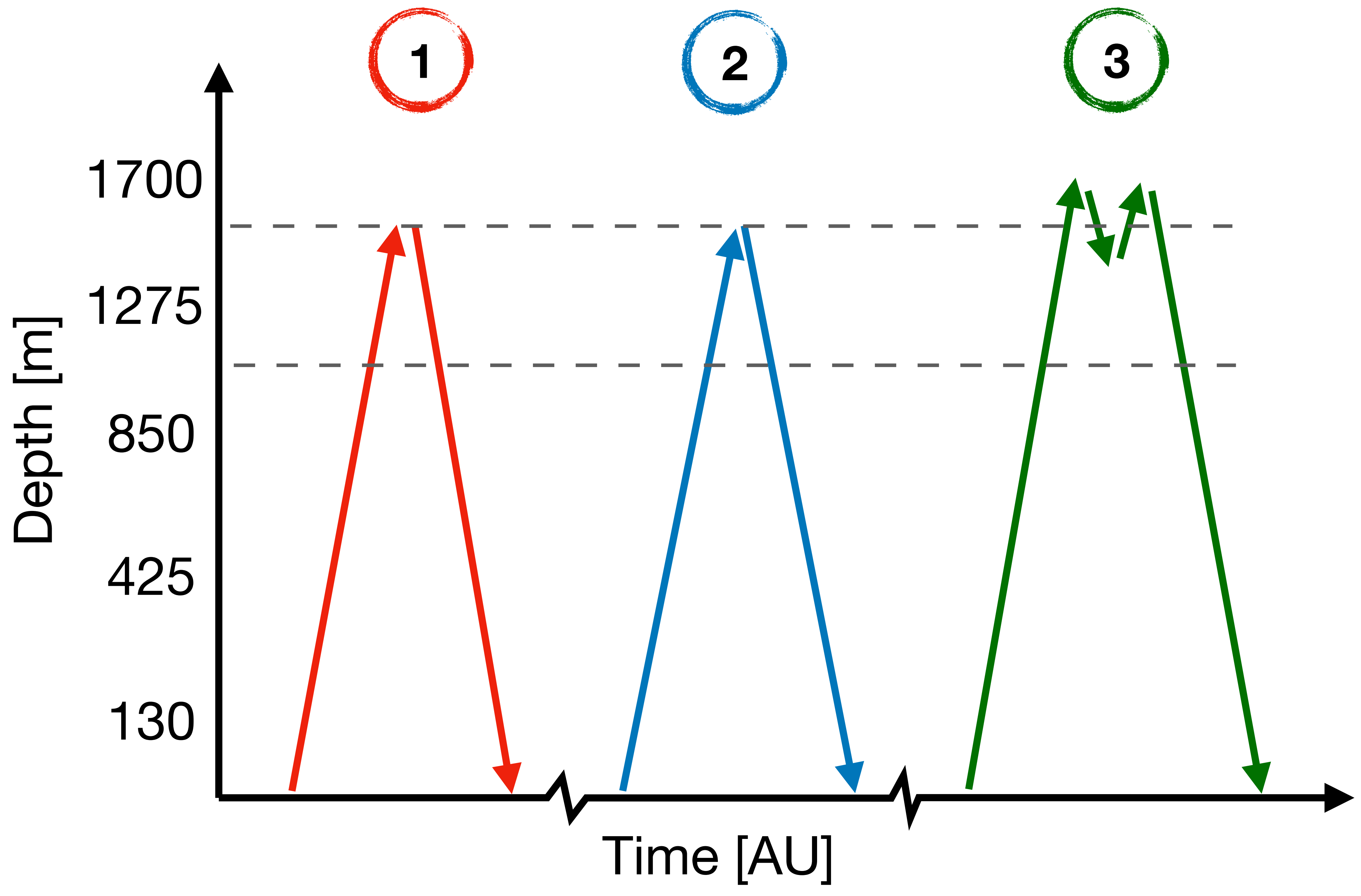
SPICEcore stratigraphy from 3 logs

Analysis strategy
Data processing

- 2 deployments from 2016/17 and 1 from 2018/19
- Cable length extended in 2018/19 to reach ~120m deeper ice
- Light intensity is adjustable in-situ to account for the changing ice properties with depth
  - Not optimised in (1), leading to some saturation
  - Raw return signal is corrected for changes to brightness
- Depth calibration between logs is refined to cm-scale through matching characteristic volcanic features

Usable logs from 2016/17 and 2018/19 seasons

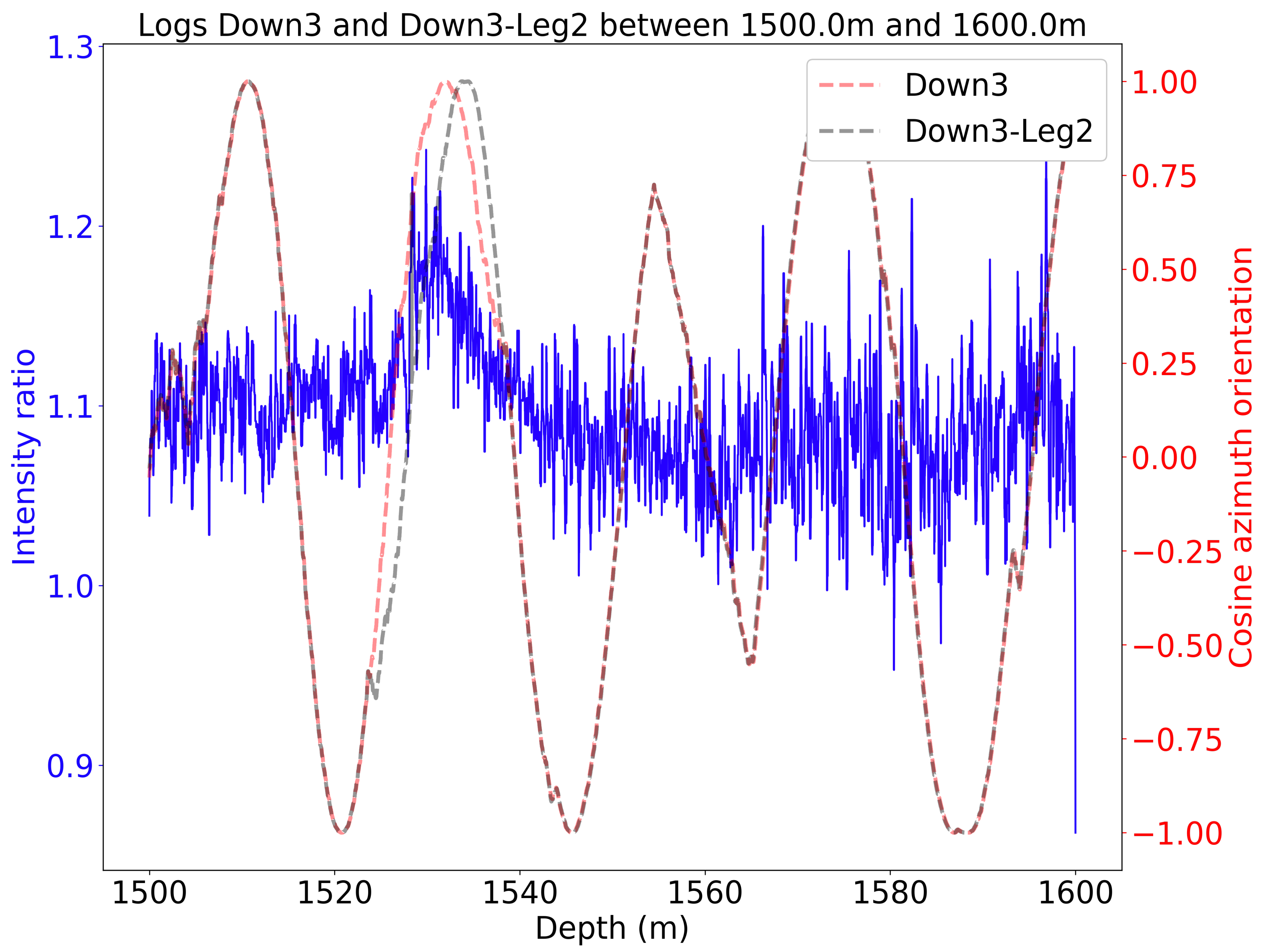
Log	Depth (m)	Note
Down1	130–1577	Saturated above 1000 m
Up1	1577–130	Saturated above 1000 m
Down2	130–1580	–
Up2	1580–130	–
Down3-Leg1	130–1703	–
Up3-Leg1	1703–1354	–
Down3-Leg2	1354–1704	Near identical orientations to Down3-Leg1
Up3-Leg2	1704–130	–



Analysis strategy

Extracting the signal

- Due to relatively slow logger rotation, data ratios are taken over 100m segments
  - Allows for several full logger rotations
- Ratios exhibit slow, continuous variations caused by changing borehole fluid properties and accumulation of grime on Nylon baffles
  - Calibrated out with second degree polynomials
- By chance, two logs have nearly the same logger orientation on descent from 1500-1600m
  - Ratio of 1.0 ± 2% confirms calibration method and sets the scale for typical short-term fluctuations in absence of signal



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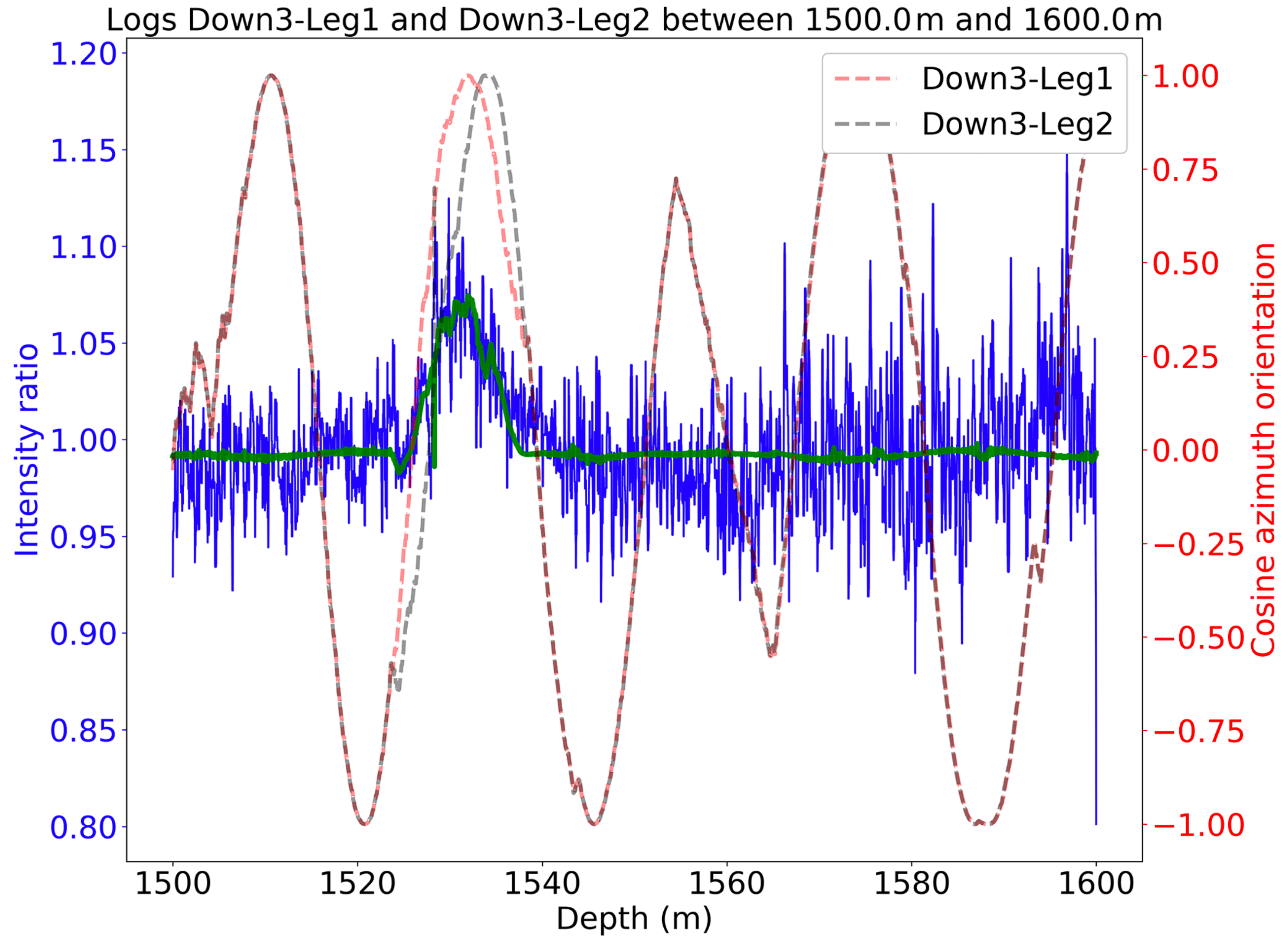
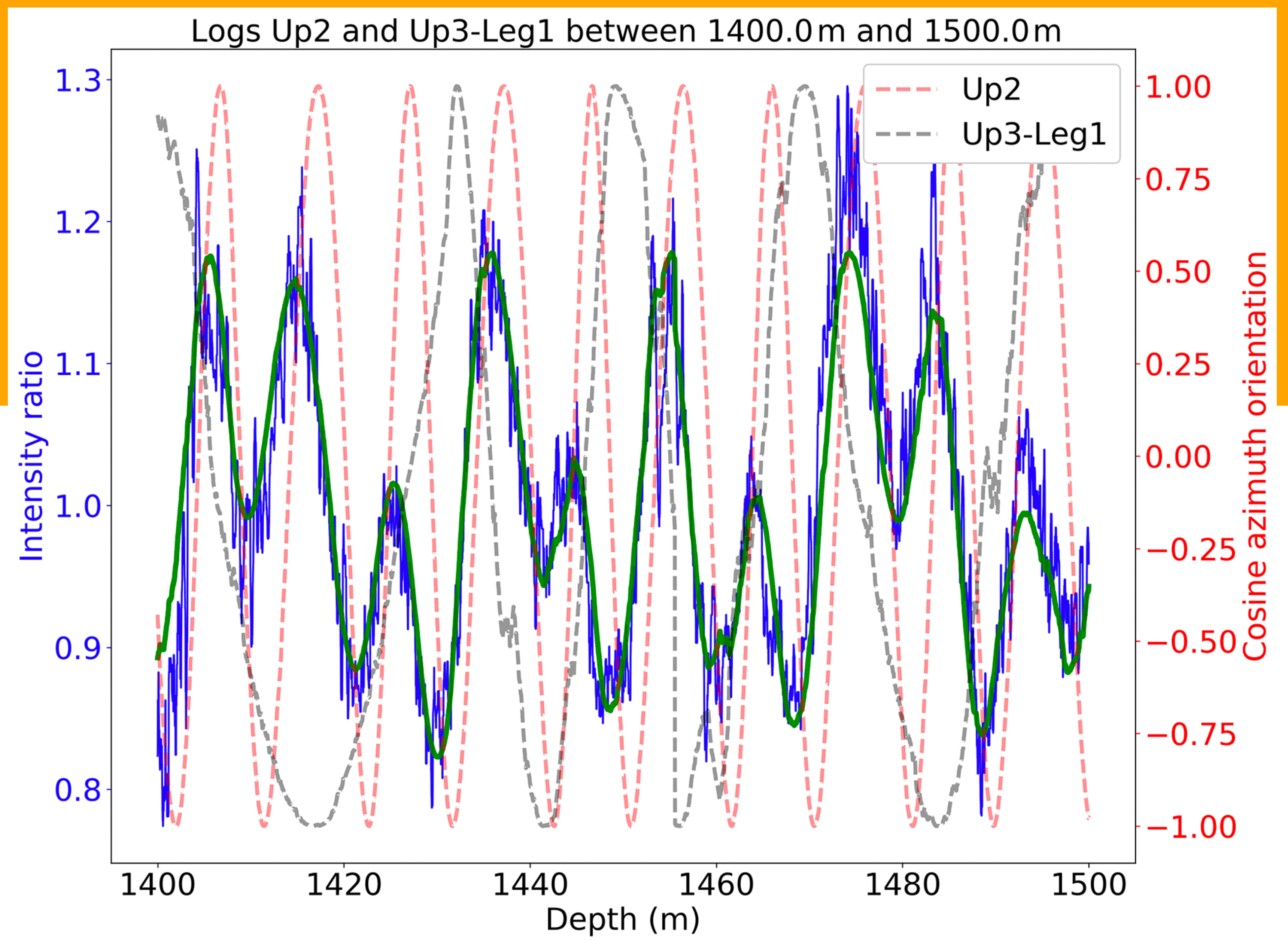
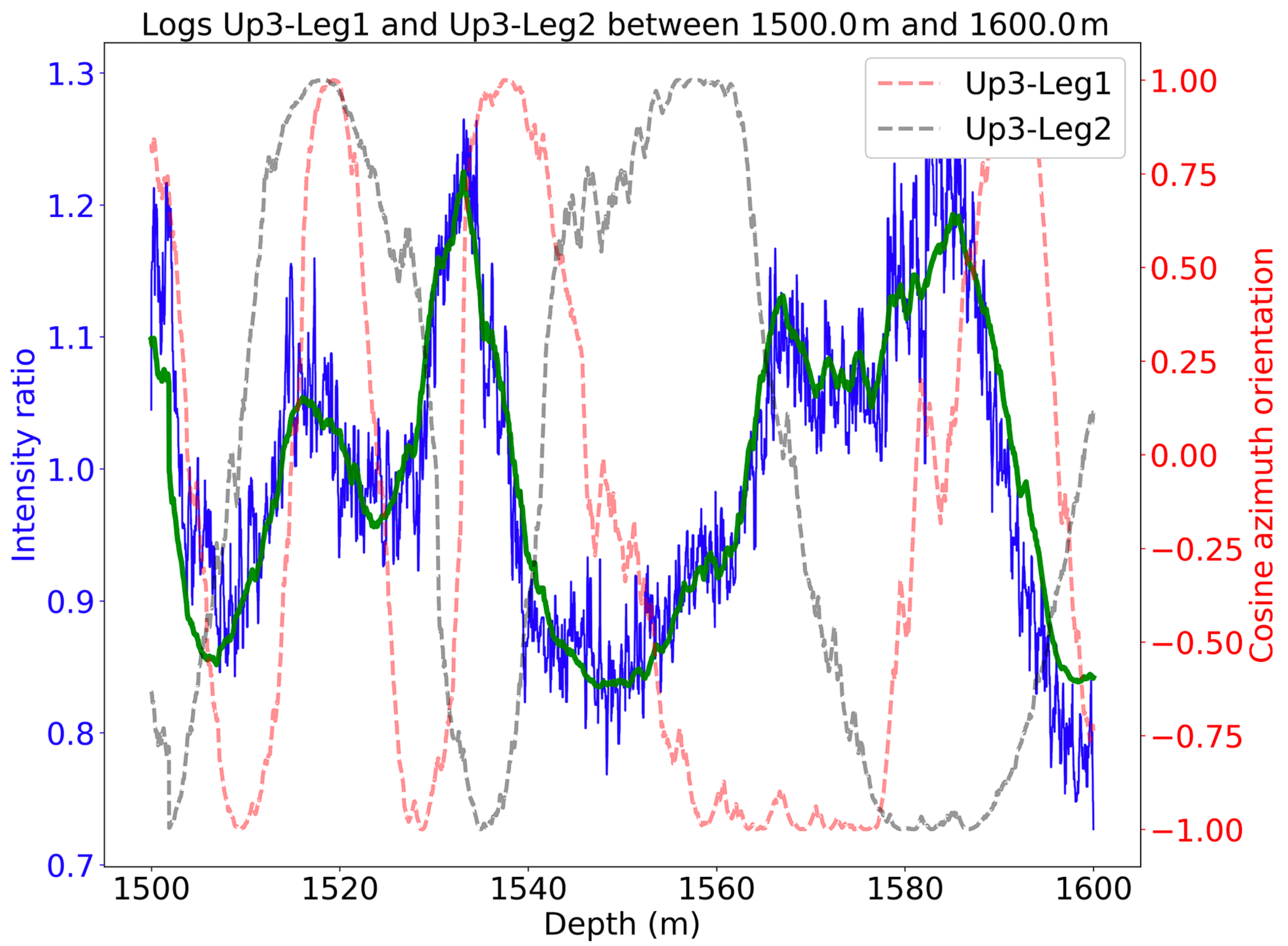


Example ratios

Anisotropic return signal is evident





- When rotation is different between logs, significantly larger fluctuations in intensity are observed
- In the absence of detector simulation and first principle modelling of the expected effect, we we an empirical model to fit the data ratios

$$\text{Intensity ratio} = \frac{1 + a \cdot \cos(2 \cdot (\alpha_1 - \varphi))}{1 + a \cdot \cos(2 \cdot (\alpha_2 - \varphi))}$$

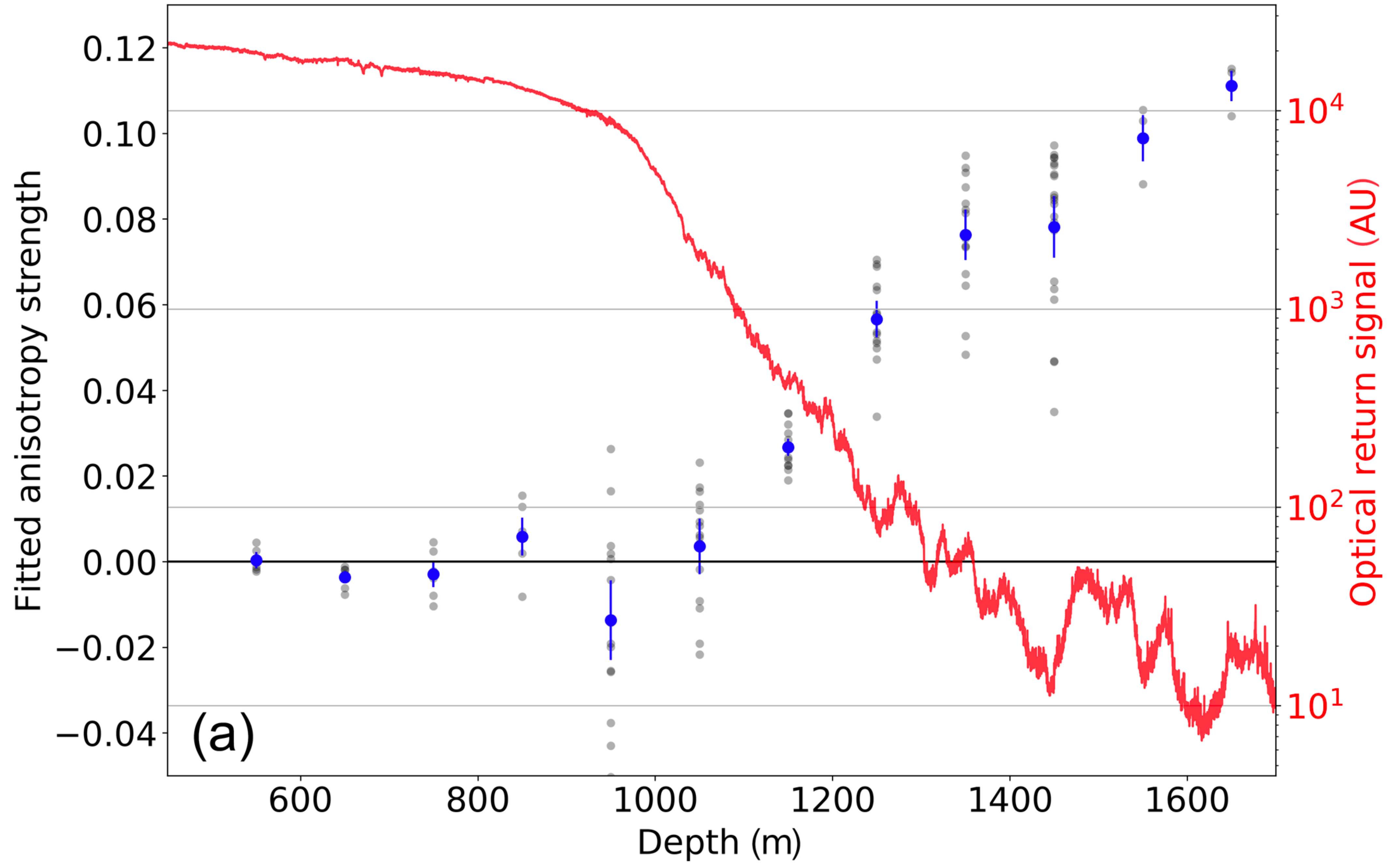
- a reflects the strength of the observed effect, φ is the phase angle of the effect, and $\alpha_{1,2}$ are the log rotations
- This model implicitly assumes that a is a relative modulation to the overall signal

Results

Anisotropy strength

- No anisotropy is observed down to 1100 m
- Below 1100m, strength of effect increases with depth until bottom of borehole is reached
- Error on the mean anisotropy strength at each depth is given as $\sigma_{mean} = \sigma / \mathrm{sqrt}(N - 1)$
  - Scatter of individual ratio results are significantly larger than statistical error of each ratio

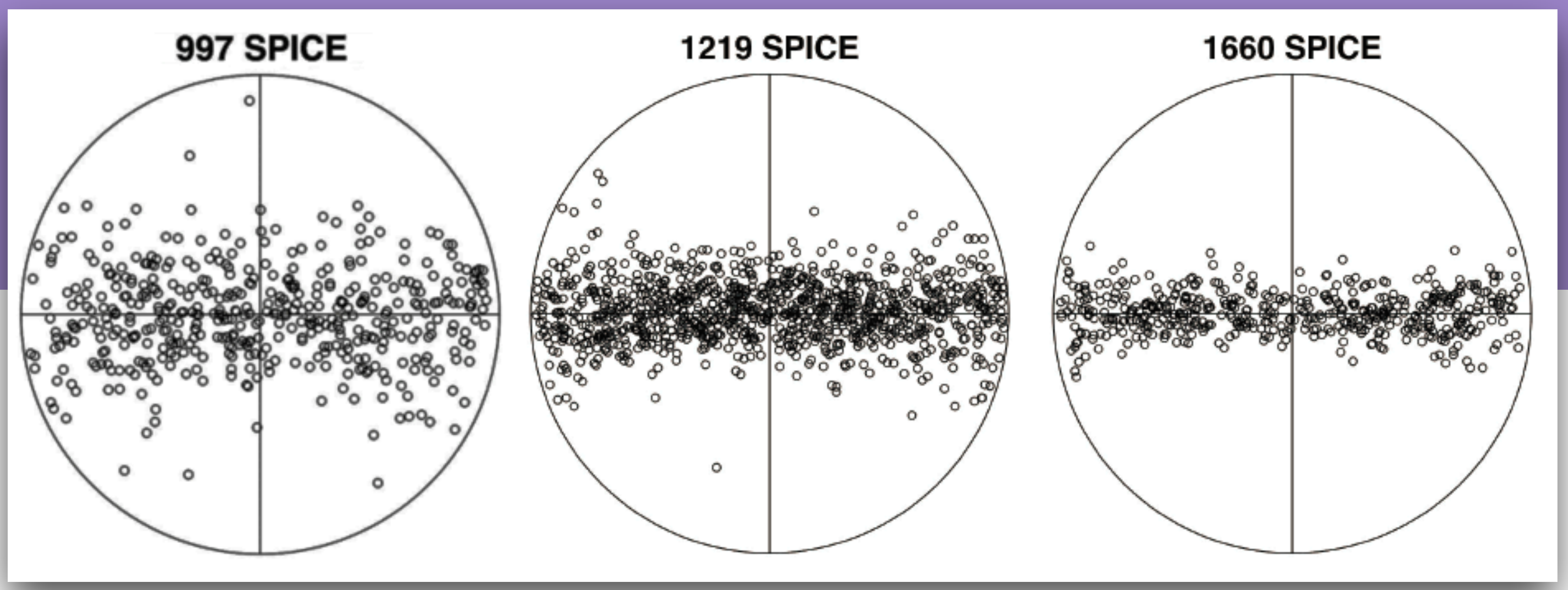
Gray points = each ratio, Blue points are average



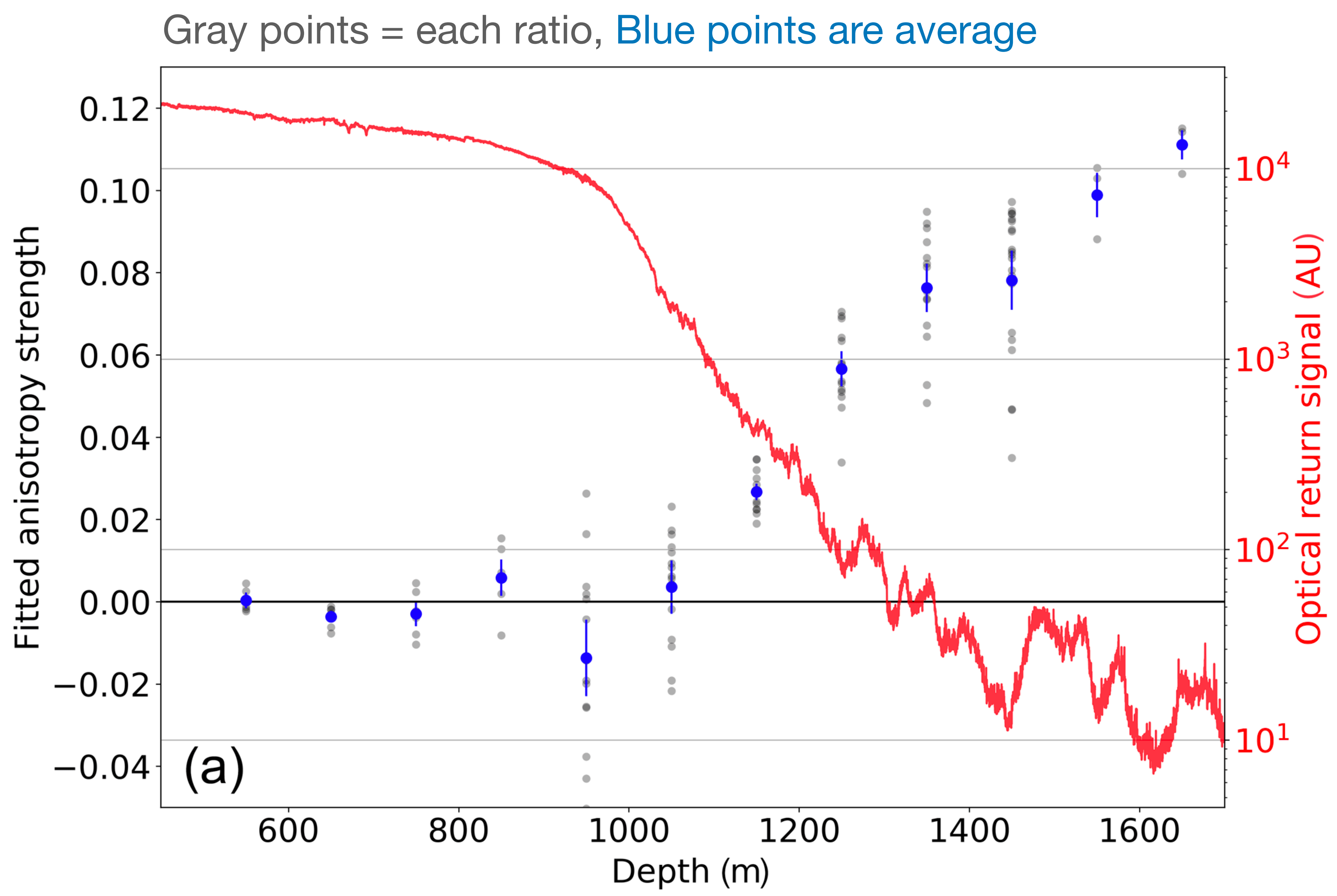
Interpretation

Is this an ice birefringence effect?

SPC14, https://www.usap-dc.org/view/dataset/601057



- From SPICEcore analysis, we know that with increasing depth the ice becomes a girdle fabric
- No signal at ~1000m despite girdle fabric… bubbles to blame?
- Unclear how much of our signal increase with depth is due to increasingly stronger girdle fabric vs decrease in the overall return signal
    - Need simulation to disentangle these effects
- If due to BFR, direction of anisotropy should be correlated with flow direction
    - Currently re-evaluating systematic offsets in measured direction of the effect



Summary and outlook

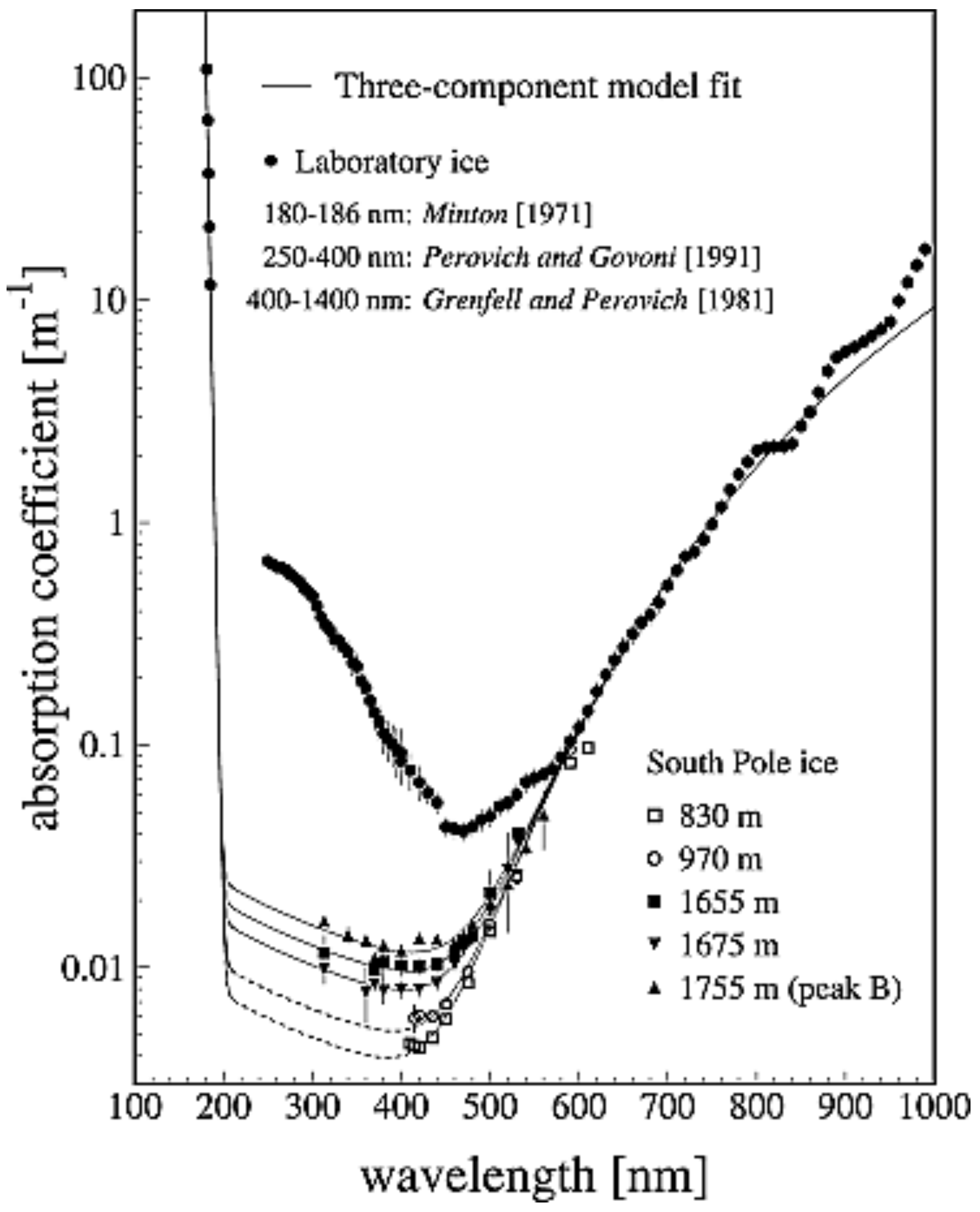
- Analysis of oriented dust logger data provides an independent confirmation of optical anisotropy at the South Pole through photon **backscattering**
- Effect is **potentially consistent** with that expected from birefringent, girdle ice fabric
- Technique provides an opportunity for continuous, in-situ assessment of some ice fabric properties
- **More data** from 2019/20 deployments in SPICEcore available to analyse
- Future deployment in an IceCube Upgrade borehole **will allow measurements down to 2600 m**

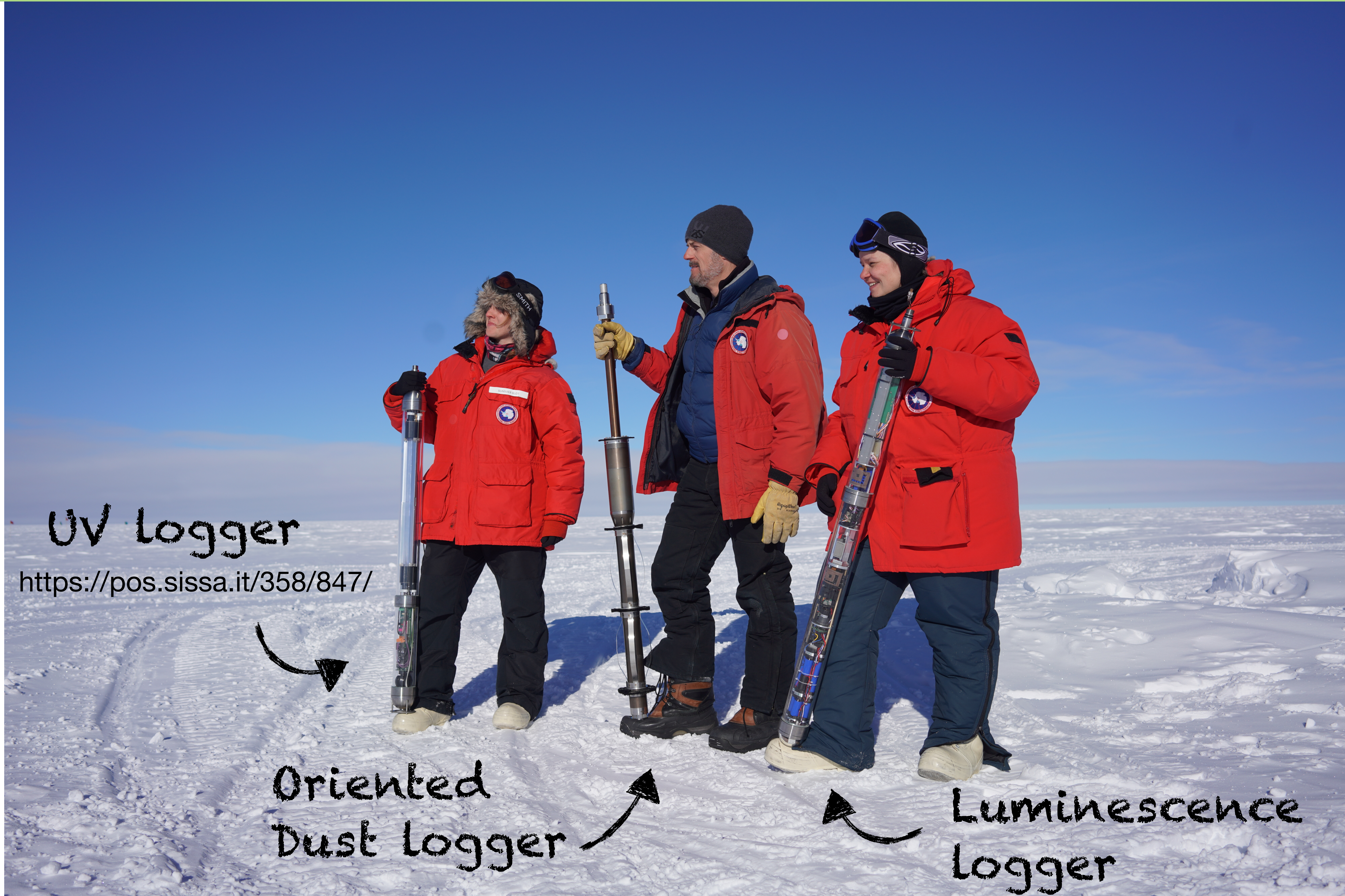
More information and discussion can be found in The Cryosphere, 14, 2537–2543, 2020

Bonus material

IceCube increasingly interested in fundamental ice properties

https://doi.org/10.1029/2005JD006687





Bonus material

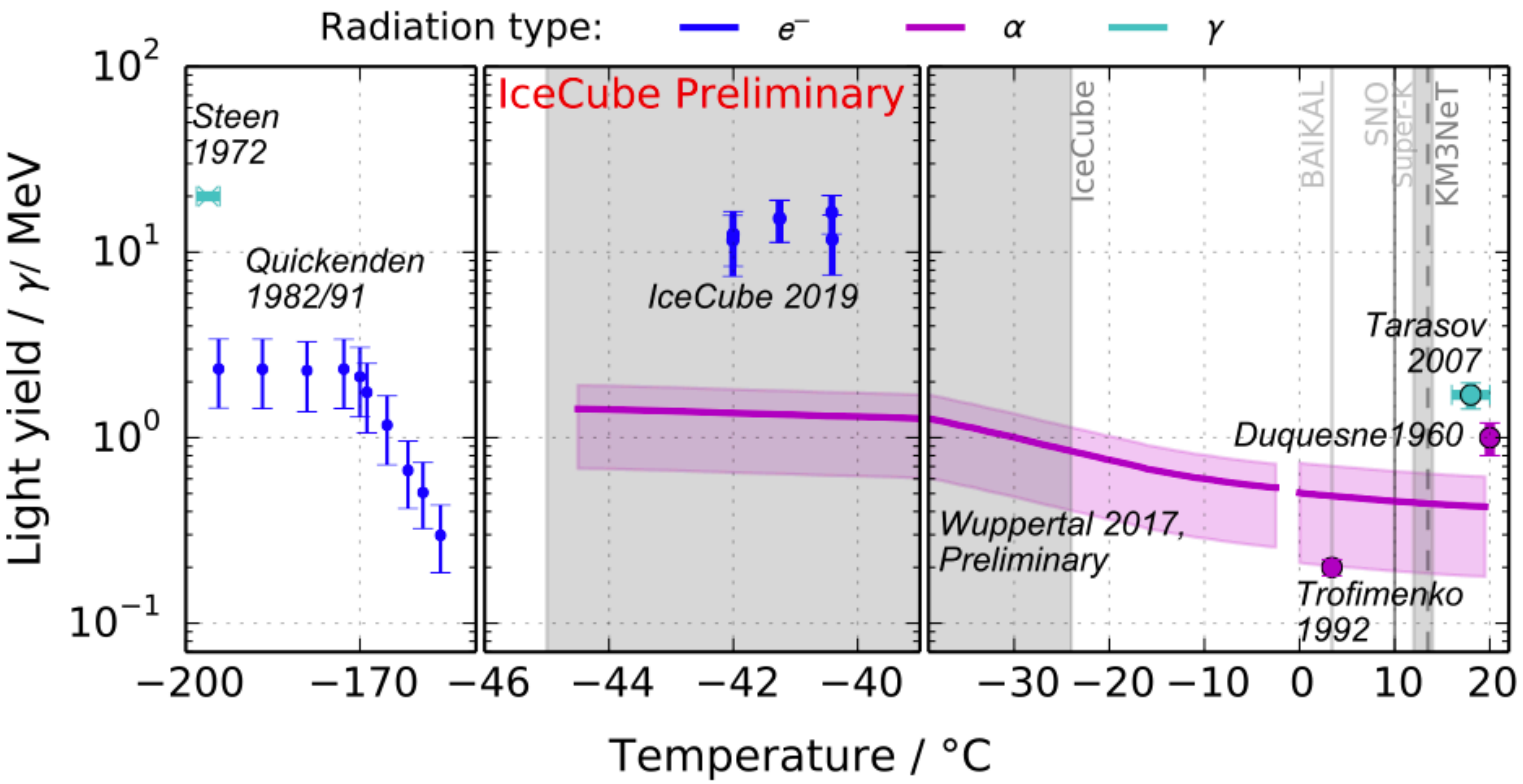
Luminescence logger

Credit to **Anna Pollmann, U. Wuppertal**

More details in proceedings to ICRC 2019
https://arxiv.org/pdf/1908.07231.pdf

- Ice luminescence caused when ionising radiation passes through, exciting atoms
  - Relaxation of electrons releases isotropic light whose properties are characteristic of the medium

- β-emitter (^{36}Cl) and PMT equipped on logger and deployed in the SPICEcore
- Extract measurement of luminescence light yield for several depths
  - Use simulation to decouple Cherenkov light yield from luminescence
  - Find around 10 γ/MeV at -41°C



Thank you for your attention

Questions?

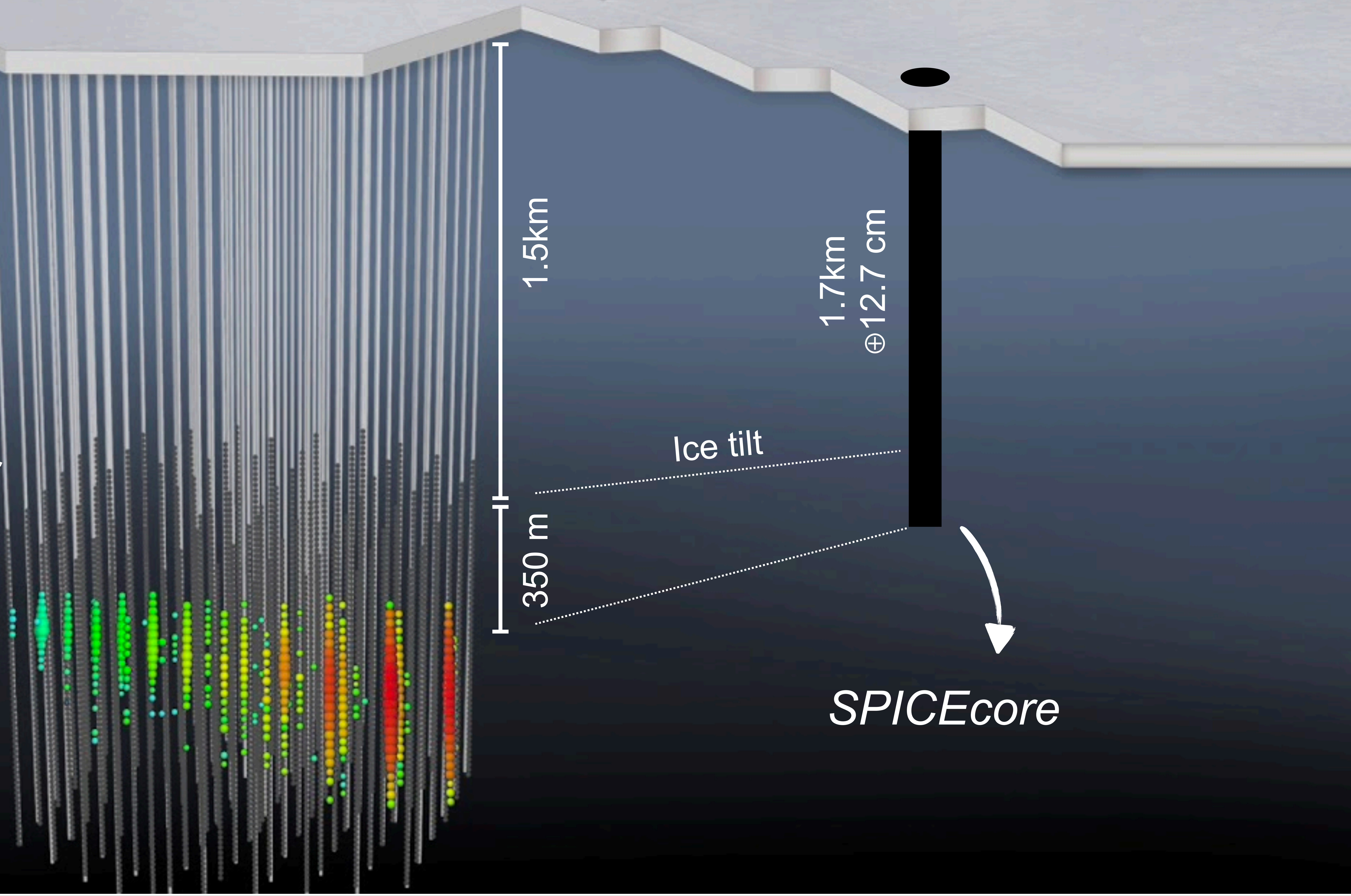
Backup

SPICEcore

- Located ~1 km from IceCube
- 12.7 cm diameter, 1700 m depth
- Drilled mechanically - cores transported North for analysis
- Filled with Estisol to preserve borehole access and allow measurements

SPICEcore

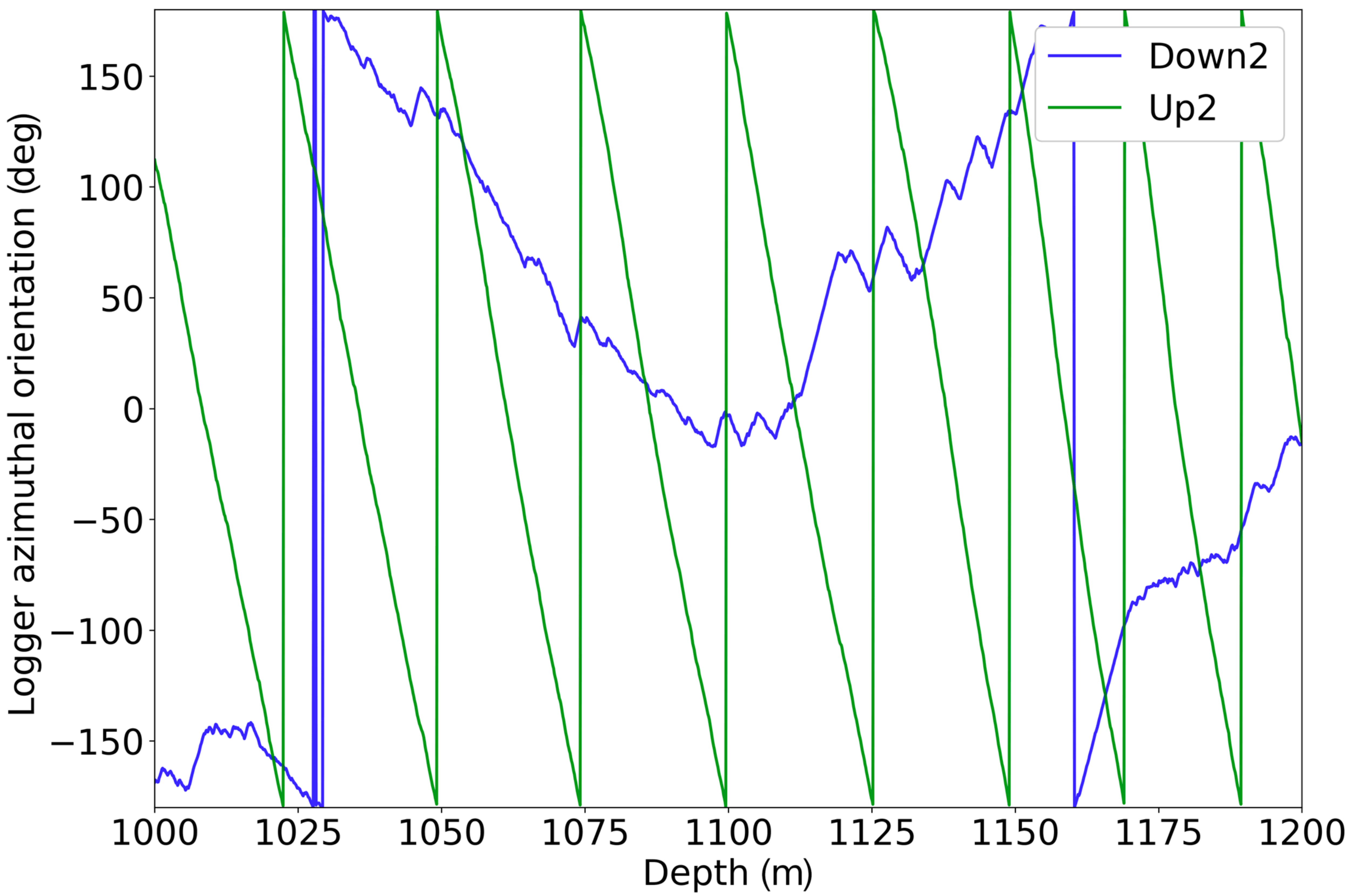
Many devices:
Dust logger
UV logger
Luminescence logger
Camera logger



Backup

Logger rotation ascent vs. descent

- Smoother rotation on ascent compared to descent
- Most likely due to sticking and then slippage on descent



Backup

Example polynomial corrections