# A Statistical Approach to Modelling the Optical Scattering Calibration System in SNO+

Daniel Cookman, on behalf of the SNO+ Collaboration

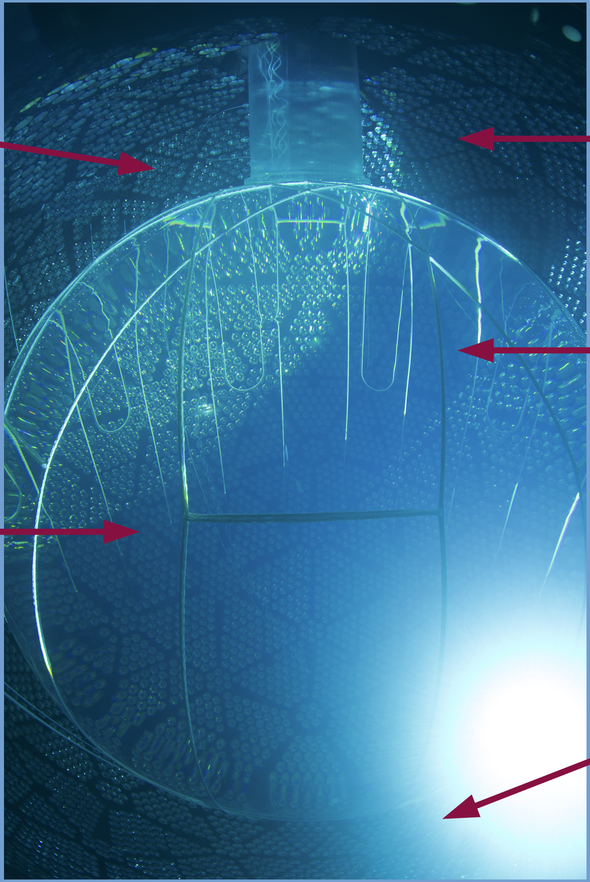
IOP HEPP & APP Annual Conference 2022

UNIVERSITY OF OXFORD

# The SNO+ Detector: *A Multi-purpose Neutrino Detector*

Cavity Filled with Ultra Pure Water

12m diameter Acrylic Vessel (AV), holding 780 tonnes of Liquid Scintillator (LS)



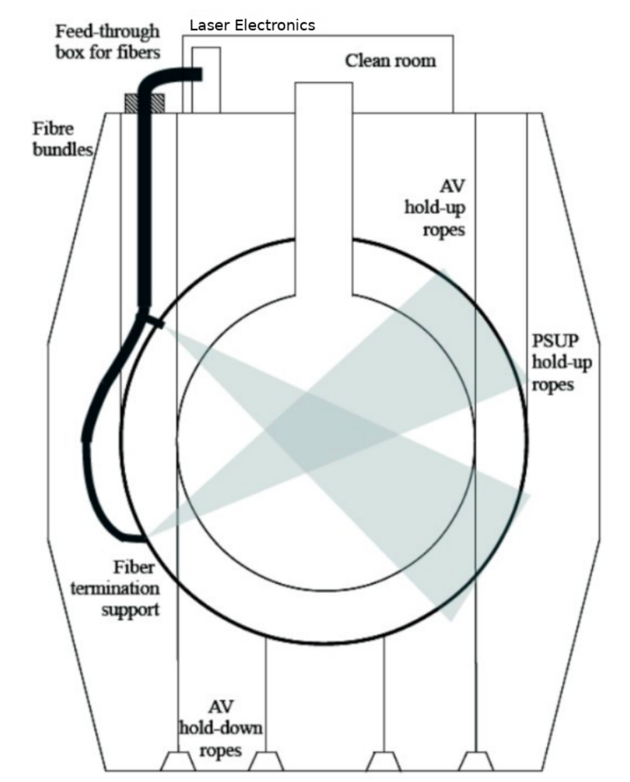
Located 2km underground in SNOLAB

Hold-up & hold-down ropes for AV support

>9000 PMTs giving ≃4π coverage at 50% area on stainless steel support structure (PSUP)

Photograph of the detector, taken November 2021

# The SMELLIE Calibration System



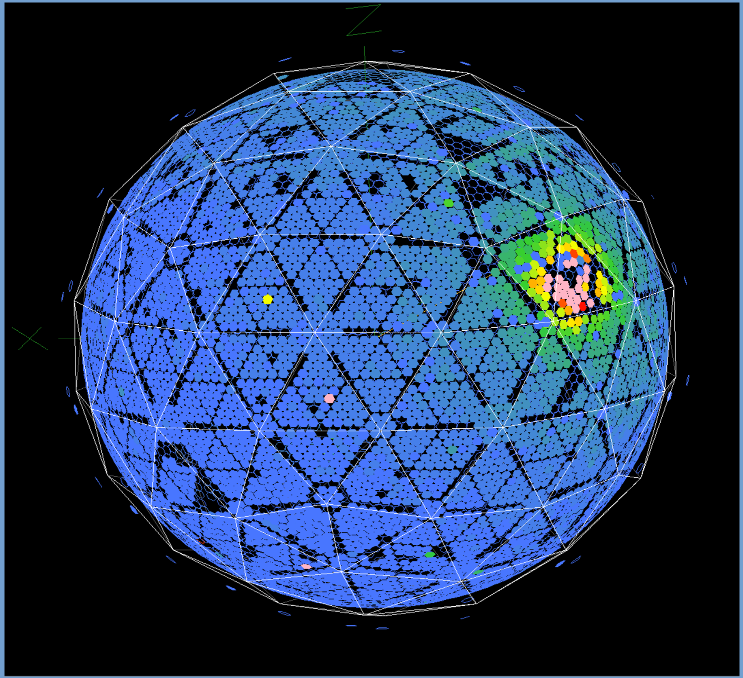

***S**cattering **M**odule for the **E**mbedded **L**ED/**L**aser **L**ight **I**njection **E**ntity*

5 diode lasers:

- 375 nm, 407 nm, 446 nm, 495 nm
- 400-700 nm “Super-Continuum” laser (continuously-tunable)

15 optical fibres with collimators attached to PSUP

Can trigger detector asynchronously



Raw SMELLIE PMT hit distribution from data

# The SMELLIE Calibration System

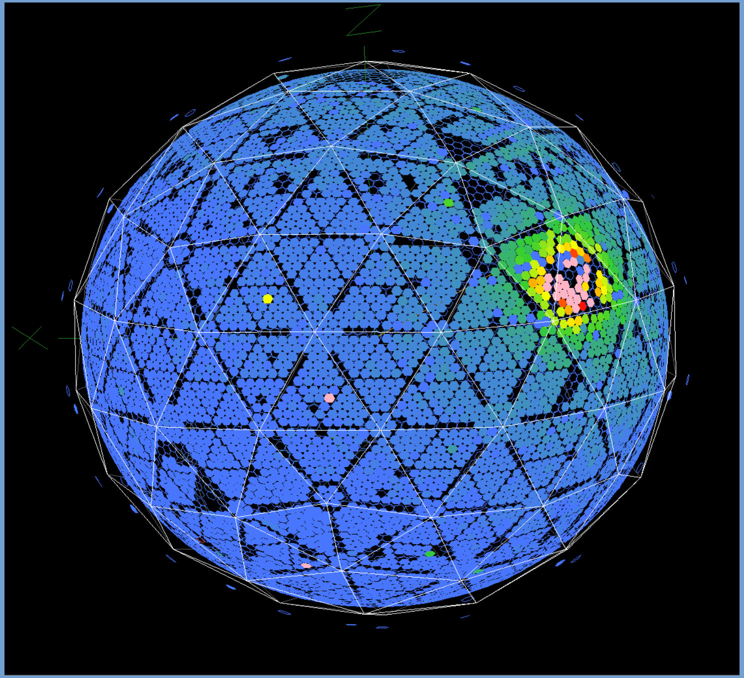
Goals:

A) **Monitor** relative changes in scintillator’s optical **scattering & extinction** over time.

B) **Measurement of scattering cross-section** in scintillator, including angle, wavelength & time-dependence.

# Calibrating SMELLIE

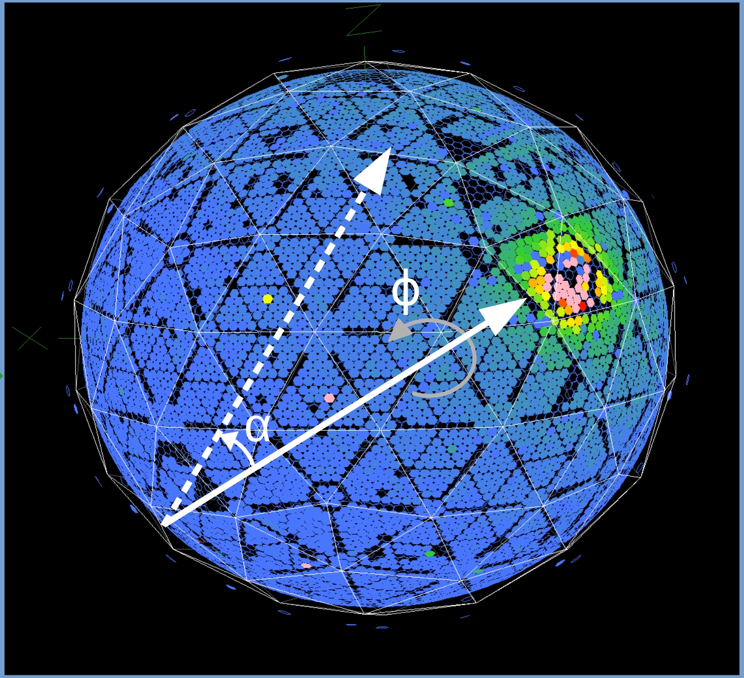
- Require accurate simulation of SMELLIE events!
- Parameters to model:
  - Fibre emission positions
  - Laser timing & wavelength distributions
  - Emission pulse energy
  - Angular emission distributions ("beam profiles")



Raw SMELLIE PMT hit distribution from data

# Calibrating SMELLIE

- Require accurate simulation of SMELLIE events!
- Parameters to model:
  - Fibre emission positions ✓
  - Laser timing & wavelength distributions ✓
  - Emission pulse energy ✓
  - **Angular emission distributions ("beam profiles")**



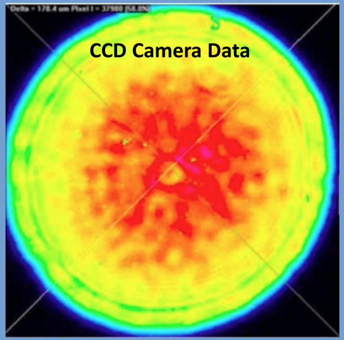
# Why Care about Beam Profiles?

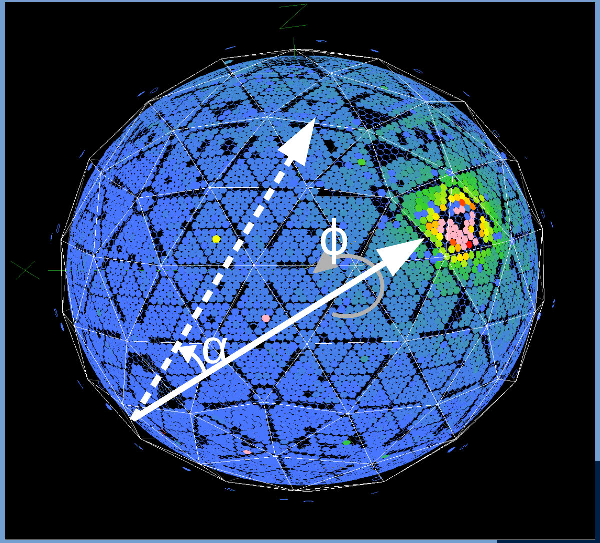
- Historically found to be the **dominant source of uncertainty** in SMELLIE analysis!

- Understanding beam profiles necessary for accurate scattering measurements.

# Modelling Beam Profiles

- Simple 1D Gaussian approach fails to capture beam profile shape sufficiently – evidence of "speckle pattern"
- Generate full 2D beam profiles, varying in ϕ as well as α!
- Assume each fibre has associated beam profile; wavelength-independent
- Assume that at sufficiently-long wavelengths, scattering in water is negligible
- **Challenge**: obtain sufficient statistics from data to have 2D profile accurately-modelled



# Data used

- Water-phase SMELLIE data taken in 2018 used for generation of beam profiles
- Data taken over wavelengths 490-600 nm & through all fibres, at a number of intensities, 10k shots each
- **How to combine data sets together to get beam profile per fibre?**

# Modelling Light Emission → PMT

Mean number of photoelectrons (p.e.s) produced in PMT $i$ during data run $j$: **what we derive from measured occupancy!**

| | |
|---|---|
| PMTs: | index $i$ |
| Data runs: | index $j$ |

$$\mu_{ij} = I_j b_i f_i$$

Mean number of photons generated from fibre in data run $j$: "**Intensity**".

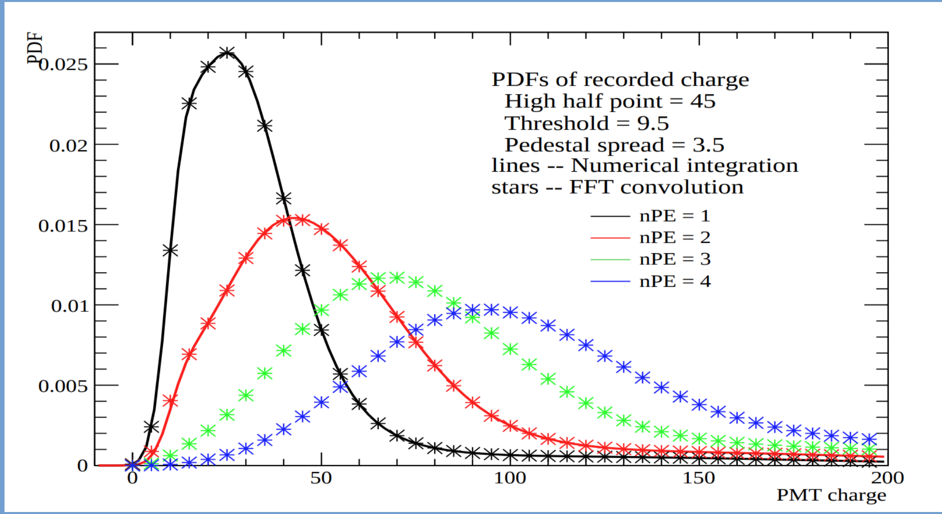
Probability a given ɣ at fibre source points in direction of PMT $i$: the **beam profile!**

Probability that correctly-pointed ɣ *actually makes it*: shadowing; also includes solid angle factor. Estimated via MC. "**Geometric factor**"

# Inferring $\mu_{ij}$ from PMT hits

- Charge collected on detector PMTs is a poor n.p.e. discriminator
- PMT “hit” when ≥1 n.p.e. generated
- Assume Poisson statistics for the n.p.e. generation
- Probability of observing a hit is:

$$p_{ij} := P\left(\text{hit}|\mu_{ij}\right) = P\left(\text{npe} \geq 1|\mu_{ij}\right)$$
$$= 1 - P\left(\text{npe} = 0|\mu_{ij}\right) = 1 - e^{-\mu_{ij}}$$




Example charge spectra for SNO+ PMT (W. Heintzelman)

# Inferring $\mu_{ij}$ from PMT hits

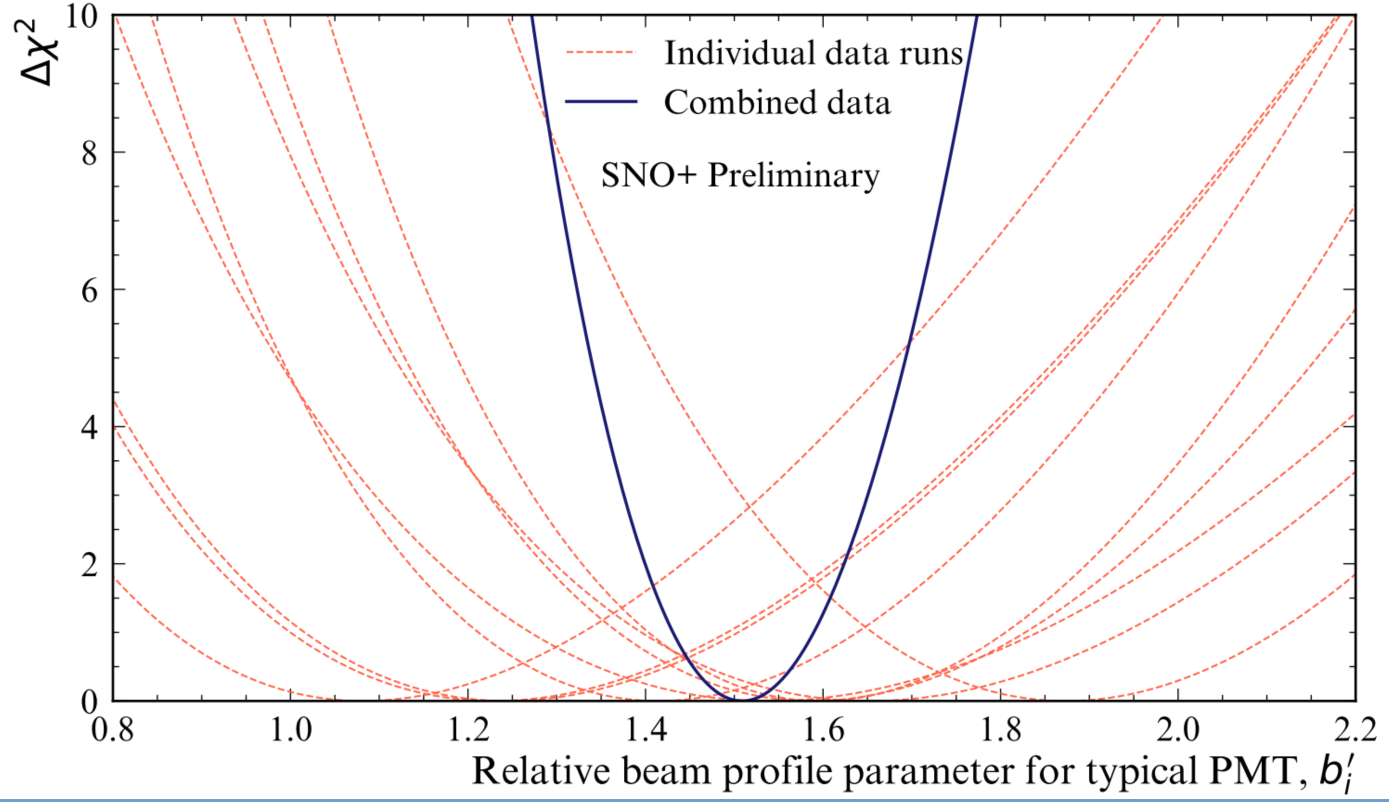
- For each PMT $i$ in data run $j$, likelihood for mean number of photoelectrons incident per triggered event, $\mu_{ij}$, given $m_{ij}$ hits observed out of $N_j$ events given by **Binomial** distribution:

$$P(m_{ij}|\mu_{ij}) = L(\mu_{ij}|m_{ij}) = \binom{N_j}{m_{ij}} p_{ij}^{m_{ij}} (1 - p_{ij})^{N_j - m_{ij}} = \binom{N_j}{m_{ij}} \left(1 - e^{-\mu_{ij}}\right)^{m_{ij}} e^{-\mu_{ij}(N_j - m_{ij})}$$

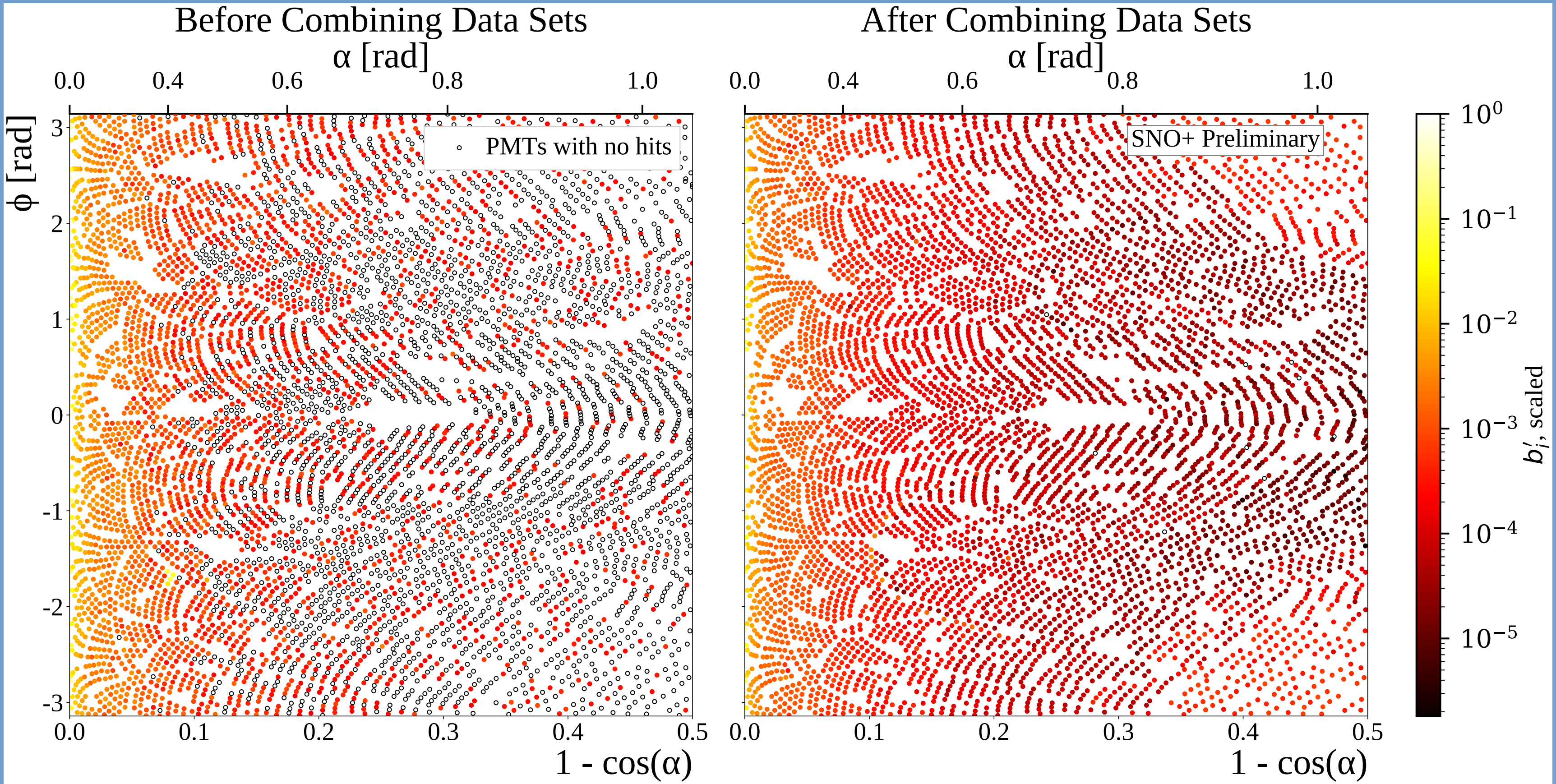
- **Combining multiple data runs** $j$ with different intensities $I_j$, the log-likelihood is the sum over each data run's log-likelihood:

$$\mathcal{L}\left(b_i | \{m_{ij}\}, \{I_j\}, f_i\right) = \sum_j \left[\ln\left({}^{N_j}C_{m_{ij}}\right) + m_{ij} \ln\left(1 - e^{-I_j b_i f_i}\right) - I_j b_i f_i \left(N_j - m_{ij}\right)\right]$$

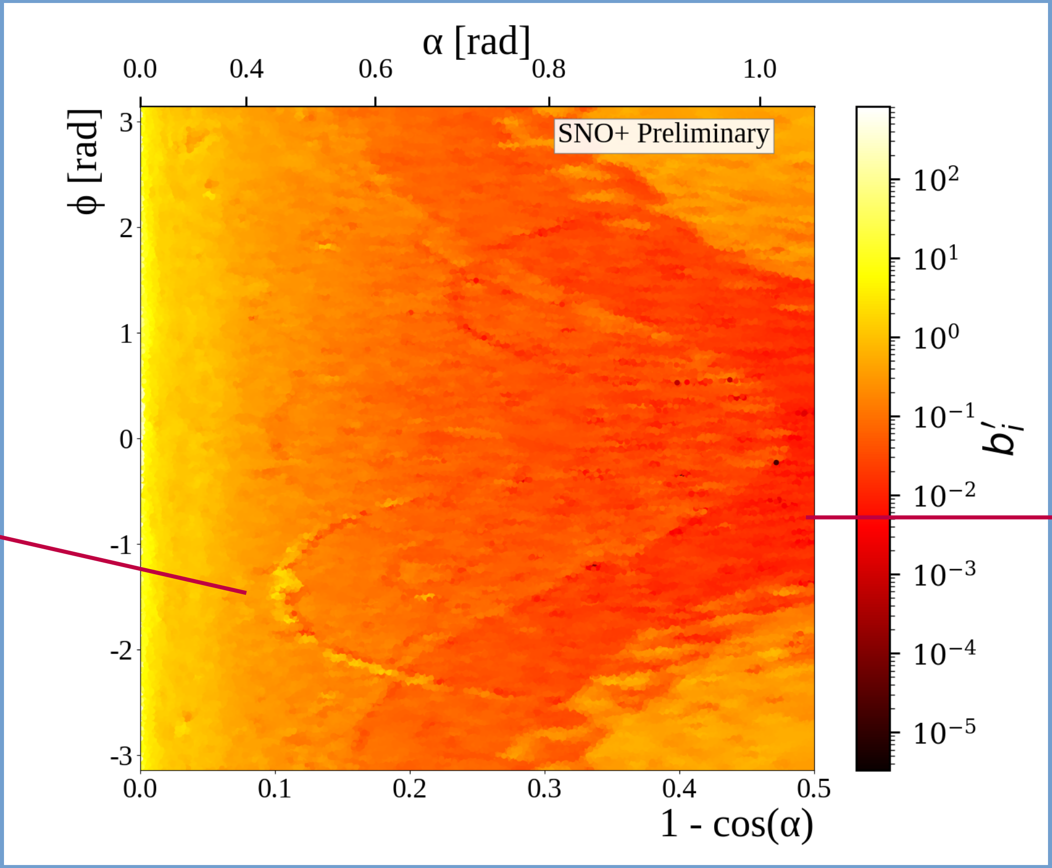
# Beam Profile Parameter Estimation



# Old vs. New Beam Profiles



# Sampling 2D space




Colour axis: relative beam profile values after interpolation

Arcs due to misalignment of rope shadows in simulation

Large discontinuous band likely due to AV attenuation/reflection modelled too low



UNIVERSITY OF OXFORD

# Summary

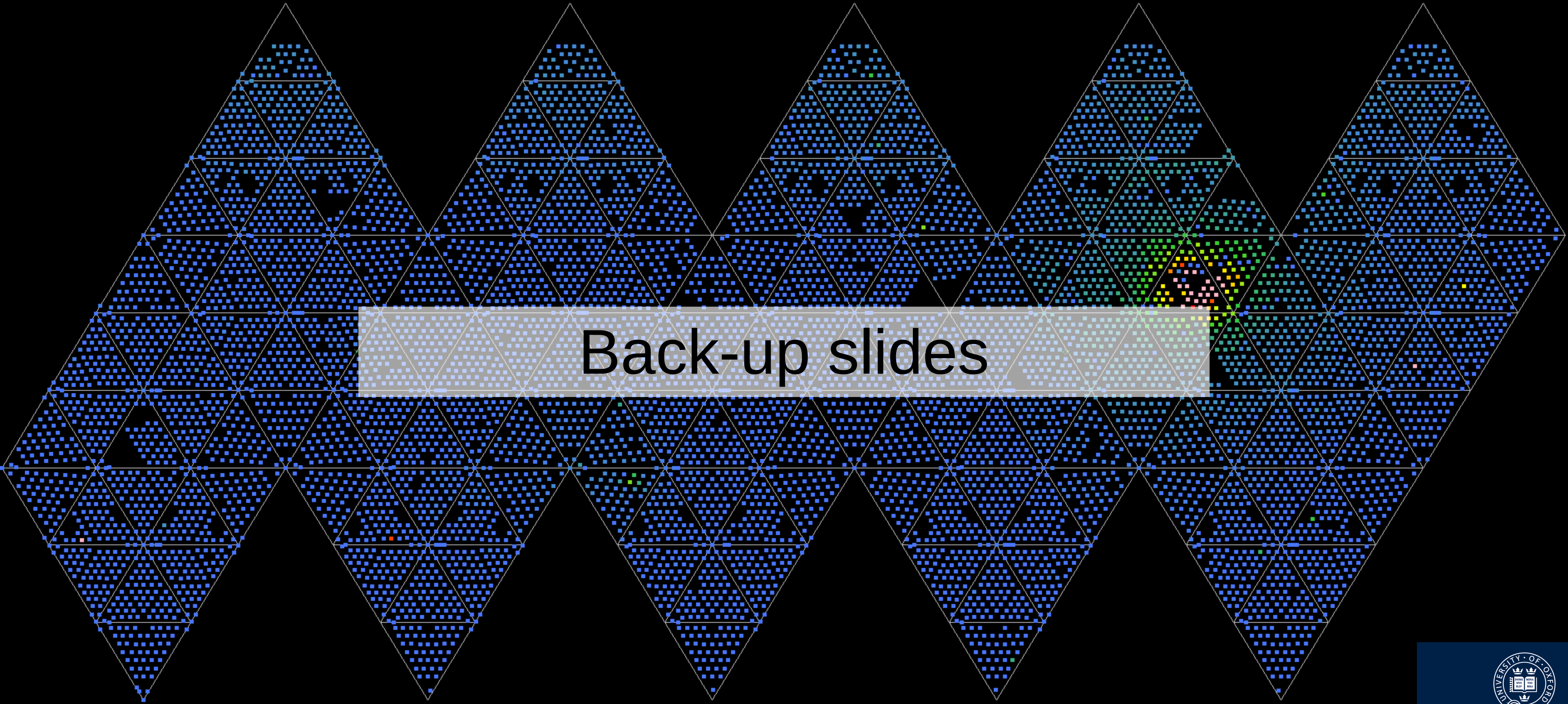
- SMELLIE is an *in-situ* attenuation & scattering calibration system for the SNO+ detector
- Beam profiles are critical for accurate SMELLIE analysis
- Statistical model built and used to combine SMELLIE data for extraction of beam profile parameters
- Method allows for improved modelling of detector beyond just SMELLIE!

# Thank You! Any Questions?

SNO+

UNIVERSITY OF OXFORD

# Back-up slides

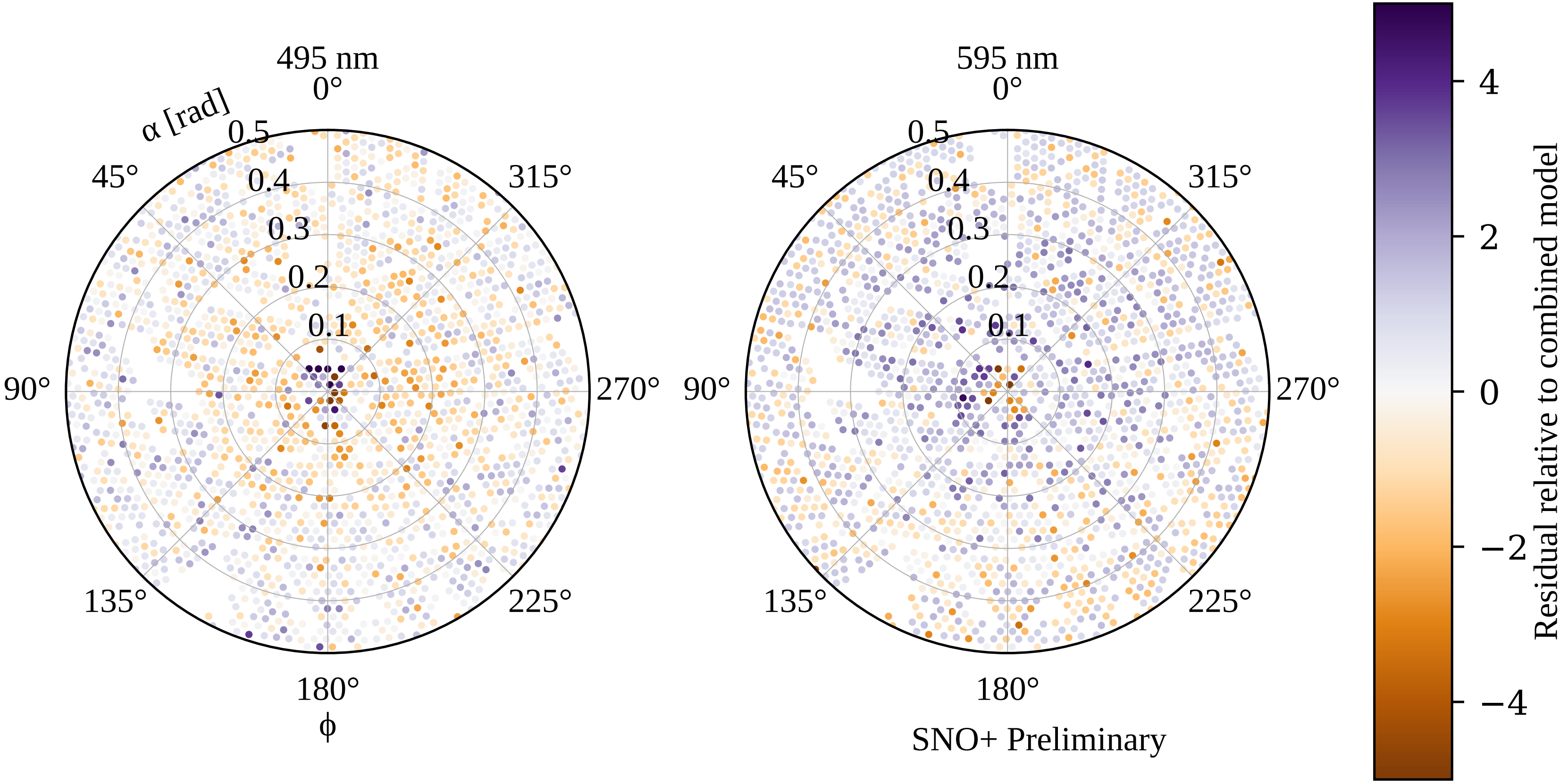


# Handling $I_j$ & $f_i$

- $I_j$ proportional to average npe summed over all PMTs (that are "good" in all the subruns of interest)
- $f_i$ calculated by performing same analysis on isotropically-emitted MC, for which $b_i$ is just constant

# Wavelength-dependence of beam profiles

Process combined data from different wavelengths. Are they consistent?



# Data-MC comparison