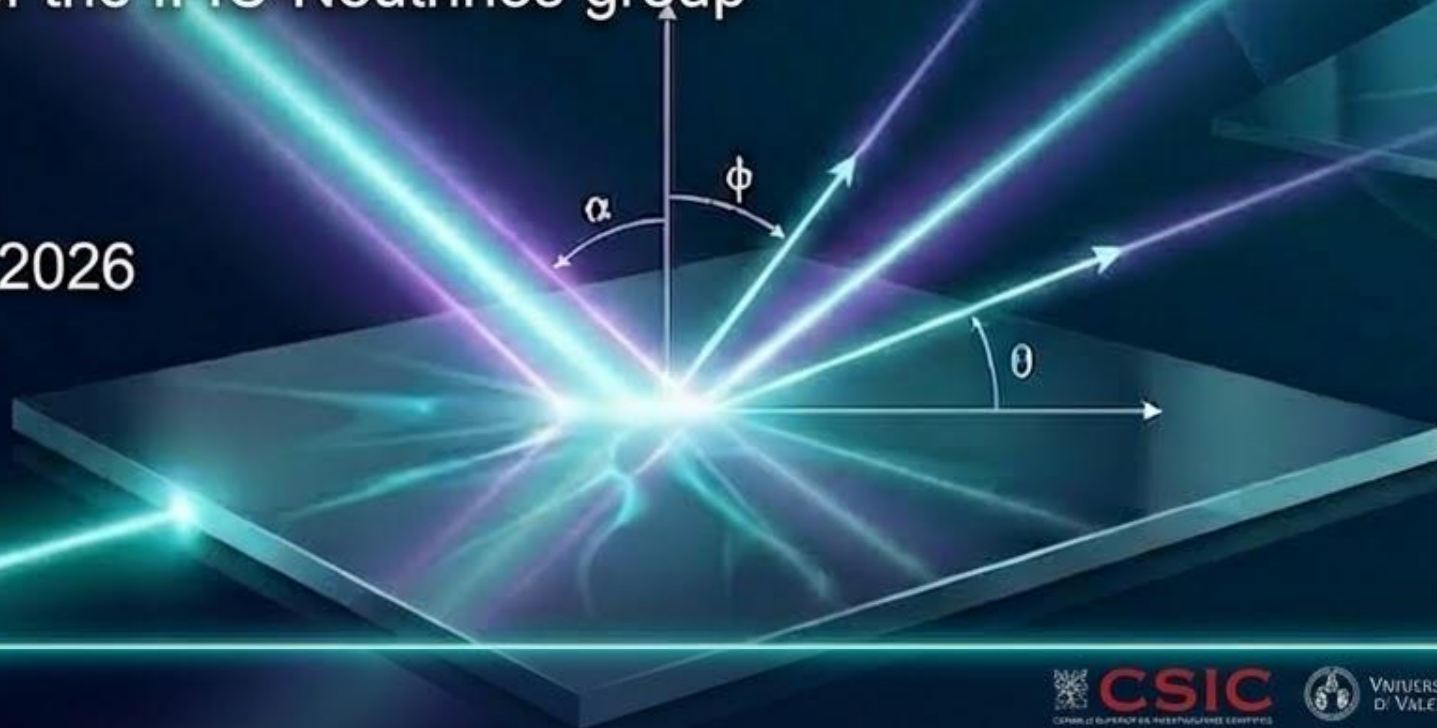


Reflectance Measurements: BRDF fits

Hamza Amar

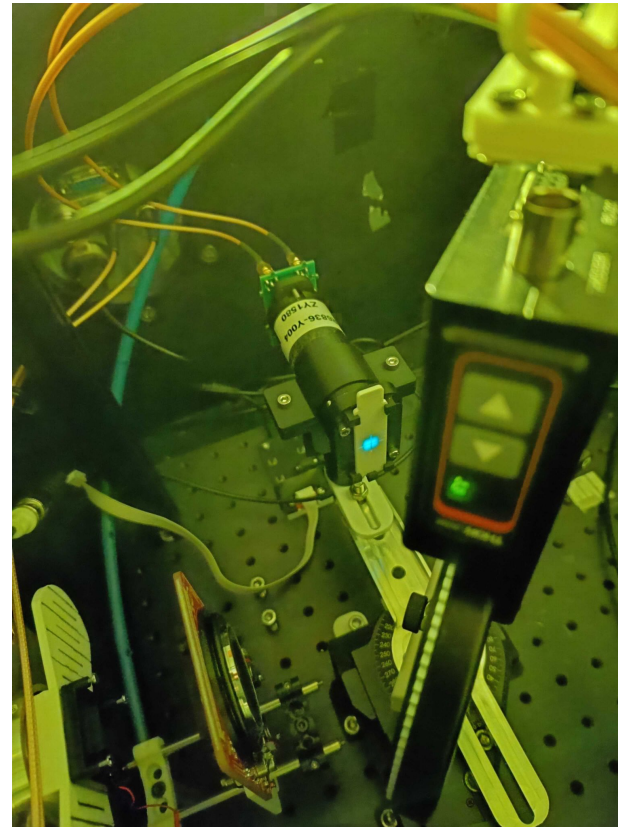
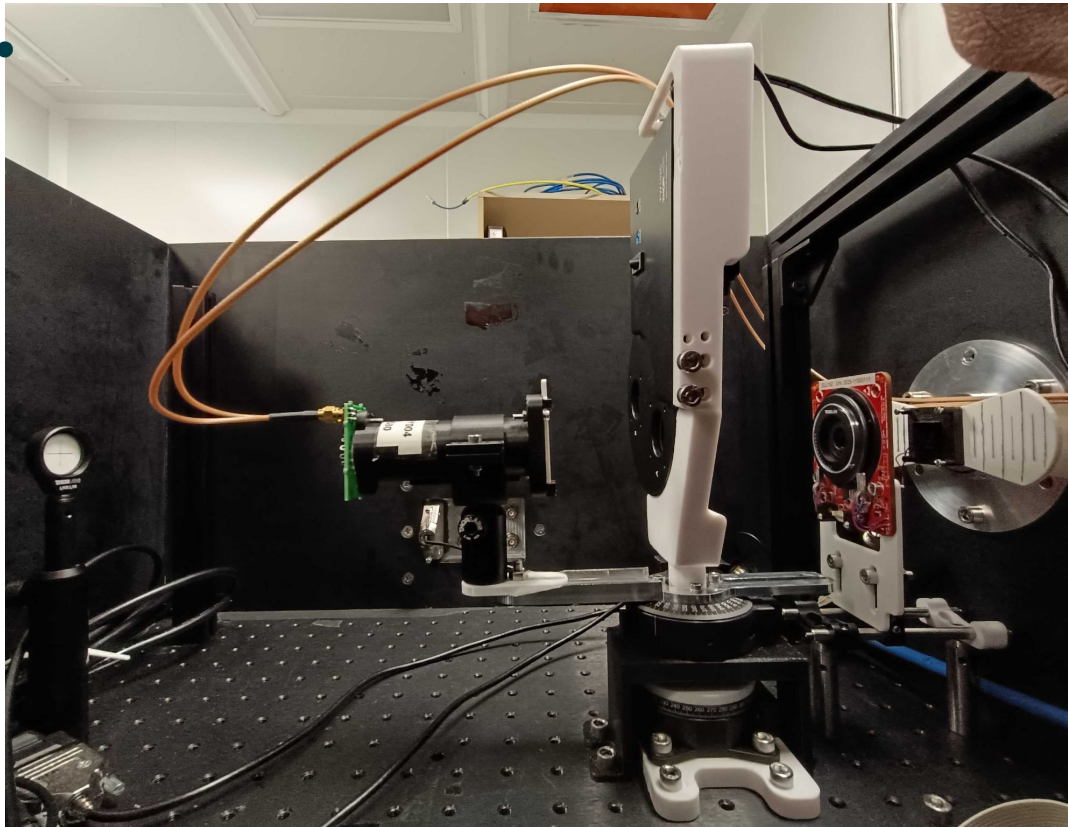
on behalf of the IFIC-Neutrinos group

March 11th 2026



A setup for angular-resolved reflectance measurements

- Motorized iris aperture: 2.5 mm. Distance PMT-sample: 78.5 mm.
- A rectangular mask of $2 \times 10 \text{ mm}^2$ is placed over the PMT, to enhance angular resolution through the azimuthal angle ϕ .
- Samples: DUNE SS, DUNE AI & UV Mirror for alignment purposes. *AOI*: 30, 37.5, 45, 52.5, 60 degrees.



Reflectance model: Microfacet theory

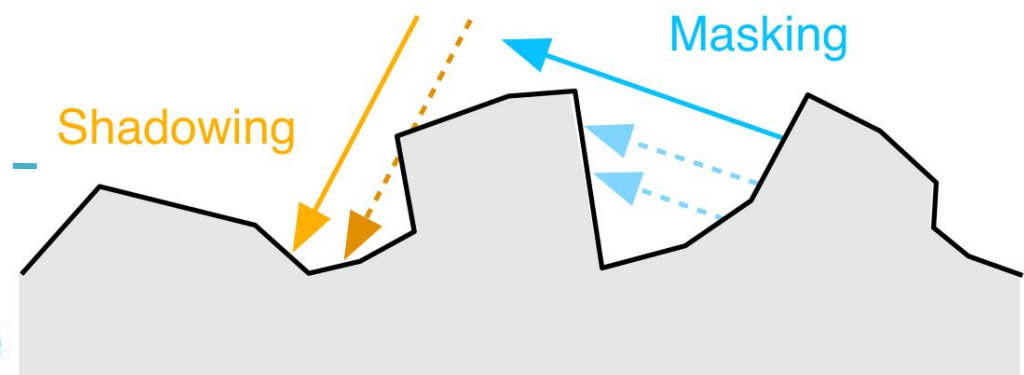
- From this expression, the hemispherical reflectance R can be computed for any angle of incidence.
- Three fit parameters are employed to fully describe a sample: n , κ & γ . Only the refractive index is wavelength dependent.

BRDF from mirror-like microfacets

$$\rho_S(\theta_i, \theta_r, \phi_r; n_0/\tilde{n}, \gamma)$$

$$= \frac{F(\theta'_i, n_0/\tilde{n}) \cdot G(\theta_i, \theta_r, \phi_r; \gamma) \cdot P(\alpha_s; \gamma)}{4 \cos \theta_i \cos \theta_r} \quad R(\theta_i) = \int \rho(\theta_i, \theta_r, \phi_r) \sin \theta_r d\theta_r d\phi_r.$$

Roughness



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BRDF from mirror-like microfacets

$$\rho_S(\theta_i, \theta_r, \phi_r; n_0/\tilde{n}, \gamma) = \frac{\boxed{\text{Fresnel}} \cdot G(\theta_i, \theta_r, \phi_r; \gamma) \cdot P(\alpha_s; \gamma)}{4 \cos \theta_i \cos \theta_r} \quad R(\theta_i) = \int \rho(\theta_i, \theta_r, \phi_r) \sin \theta_r d\theta_r d\phi_r.$$

Roughness ↓

$\tilde{n} = n + i\kappa$

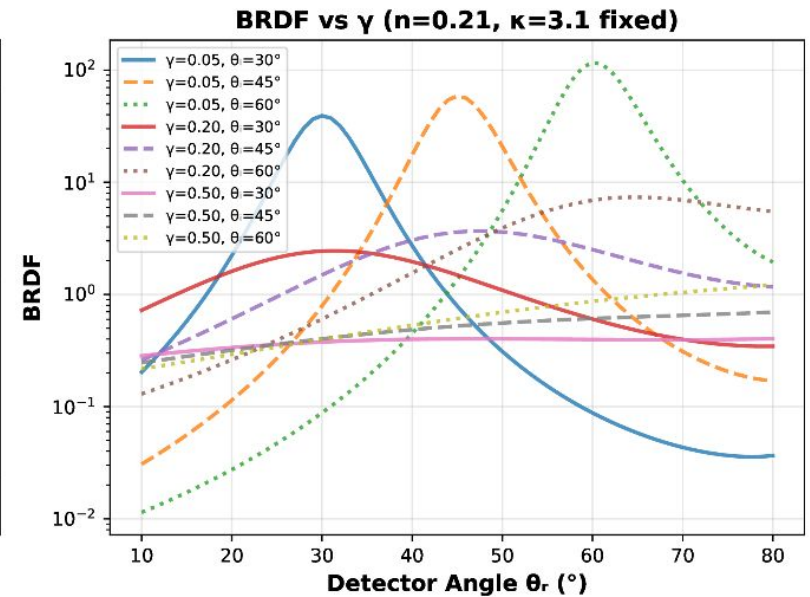
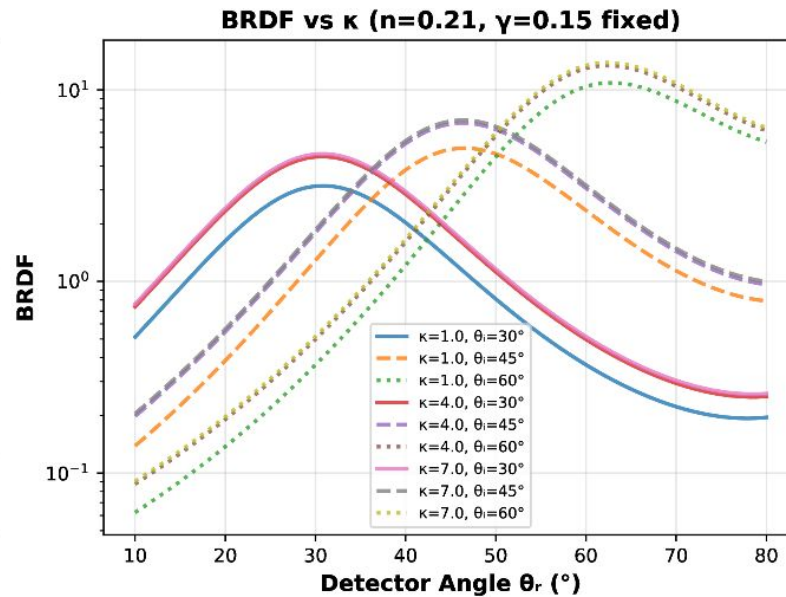
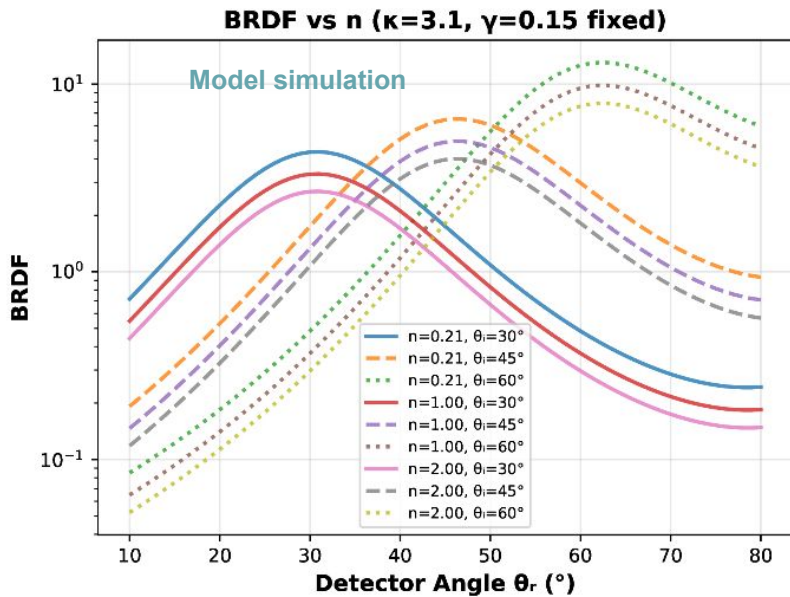
Experimental BRDF

$$\rho(\theta_i, \theta_r, \phi_r) = \frac{d\Phi_r / (d\Omega_r \cos \theta_r)}{\Phi_i}$$

Reflectance model: Sensitivity test

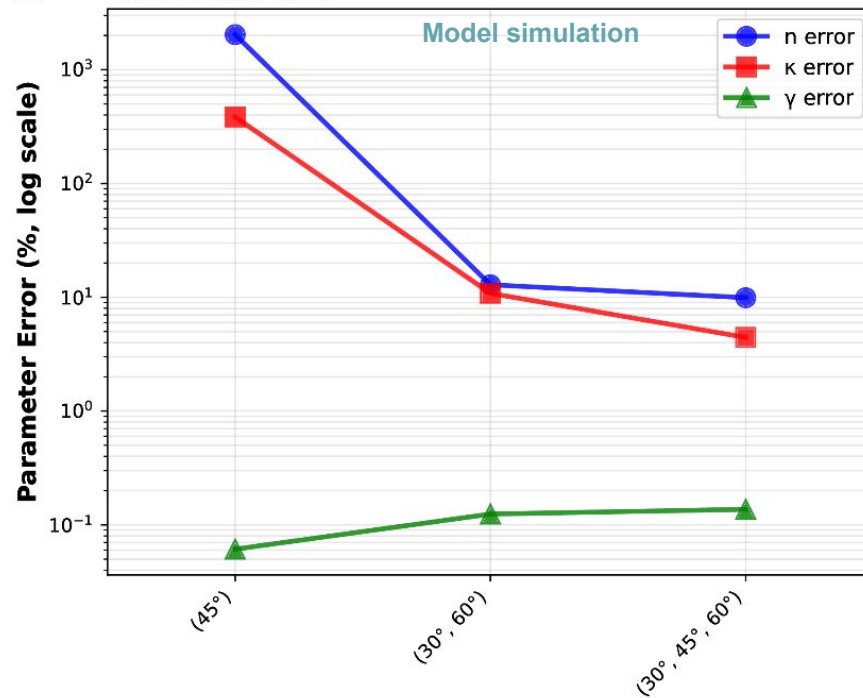
- The significance of the various parameters can be elucidated by holding the other two.
 - Varying either the real or the imaginary part (absorption coefficient) of the refractive index affects the amplitude.
 - Modifying the roughness impacts the specular lobe shape, as well as its amplitude.
 - A lower γ indicates a more specular or smoother surface.

Direct BRDF Sensitivity Test: Multiple AOIs (30°, 45°, 60°)



Reflectance model: degeneracy test

- A single angle of incidence introduces a degeneracy in the values of the complex refractive index.
- This degeneracy is resolved by utilizing data from two distinct angles of incidence.



- $n = 0.21$
- $\kappa = 3.10$
- $\gamma = 0.150$

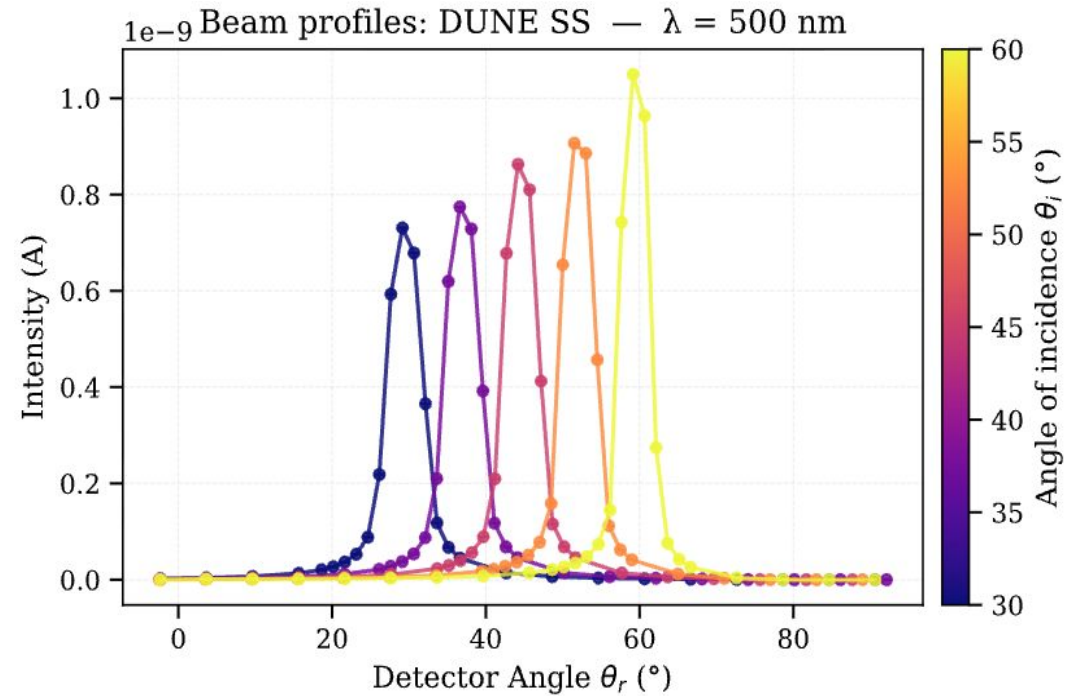
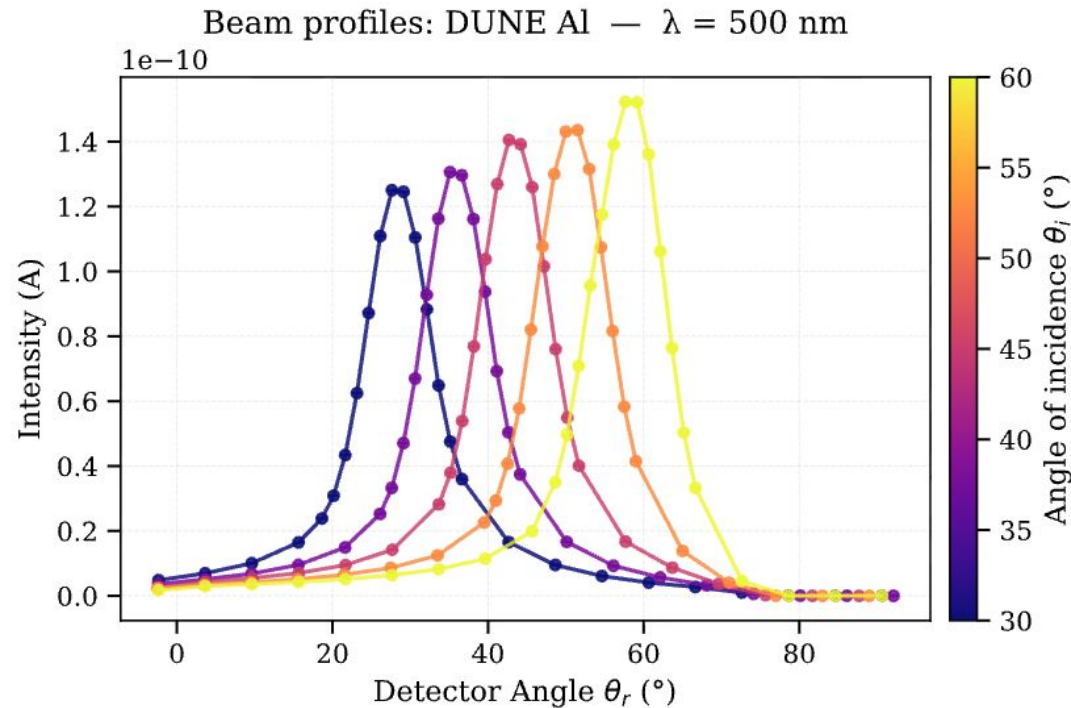
Measurement Setup:

- Detector angles: 13 positions (10°-80°)
- Noise level: 1.0%
- Medium: Vacuum ($n_1 = 1.0$)

A0Is	Points	$\sigma(n)$	$\sigma(\kappa)$	$\sigma(\gamma)$	χ^2/dof
1	12	1.87e+02	2.88e+02	7.10e-04	0.59
2	24	3.02e-02	3.20e-01	3.88e-04	1.09
3	36	2.93e-02	3.00e-01	3.08e-04	0.80

GGX Microfacet Model

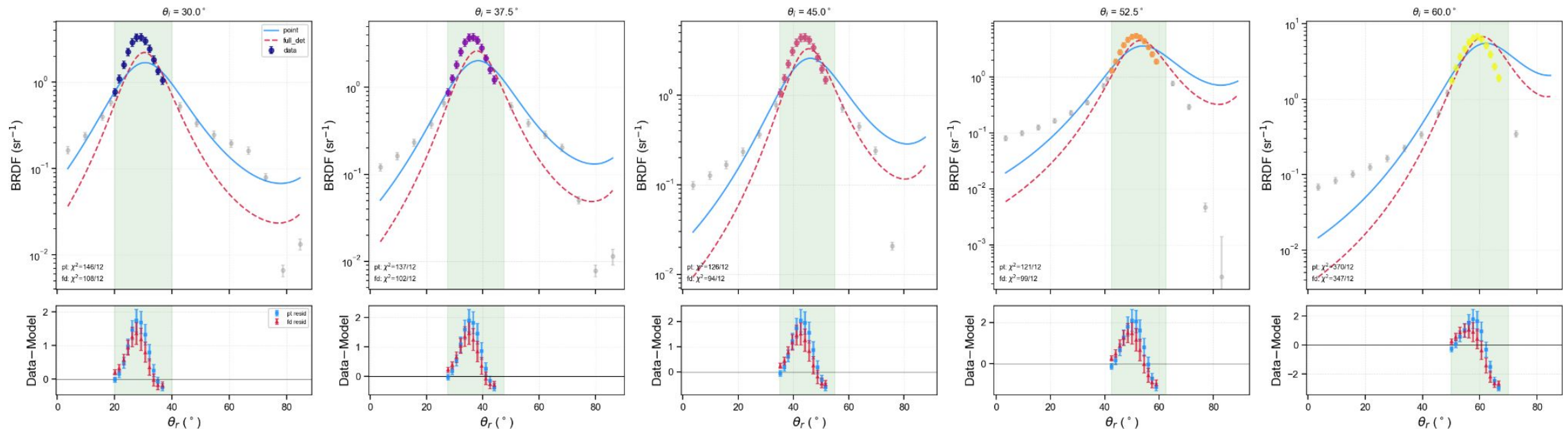
- Single-roughness GGX microfacet model (Trowbridge-Reitz NDF, Smith G, exact Fresnel).
- 3 free parameters for metals: n , κ & γ .
- Multi-AOI pipeline with detector-angle correction from mirror reference. Full-detector averaging and point-mode fitting.



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- 3 free parameters for metals: n , κ & γ .
- Multi-AOI pipeline with detector-angle correction from mirror reference. Full-detector averaging and point-mode fitting.
- $n = 2.5$ & $\kappa = 0.1$ are fit parameter bounds.
- The best fit from a pool of 10 initial seeds!!! Changing the boundaries was proven ineffective: convergence to the boundaries.

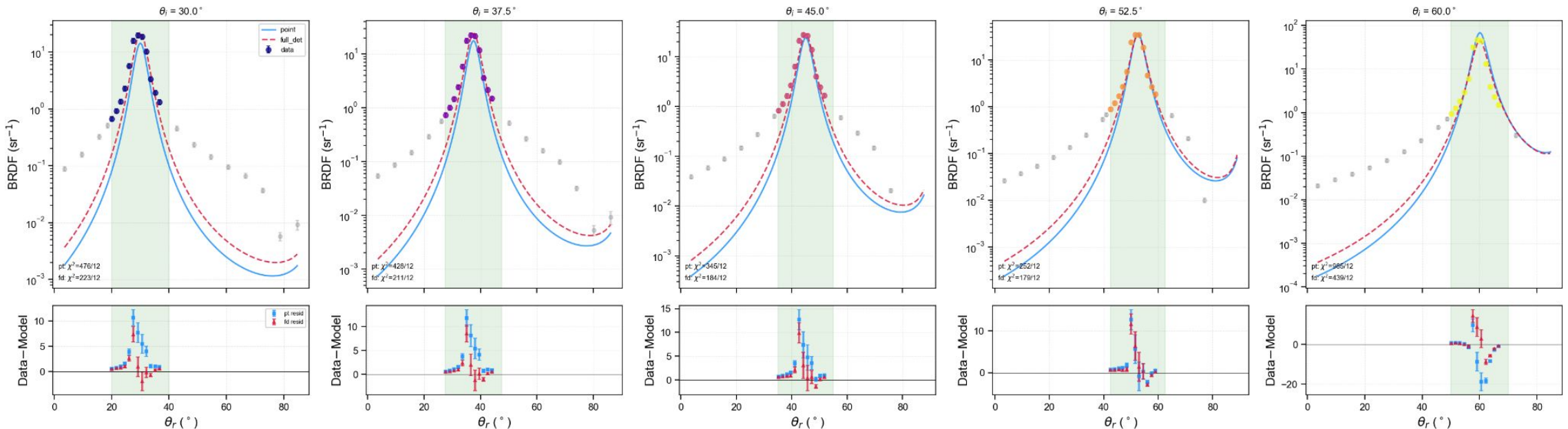
DUNE Al $\lambda = 500$ nm
 Point: $n=2.500$ $\kappa=1.329$ $\gamma=0.1344$ $\chi^2/\text{dof}=15.8$ $R^2=0.344$
 Full det: $n=2.500$ $\kappa=0.100$ $\gamma=0.0895$ $\chi^2/\text{dof}=13.2$ $R^2=0.552$



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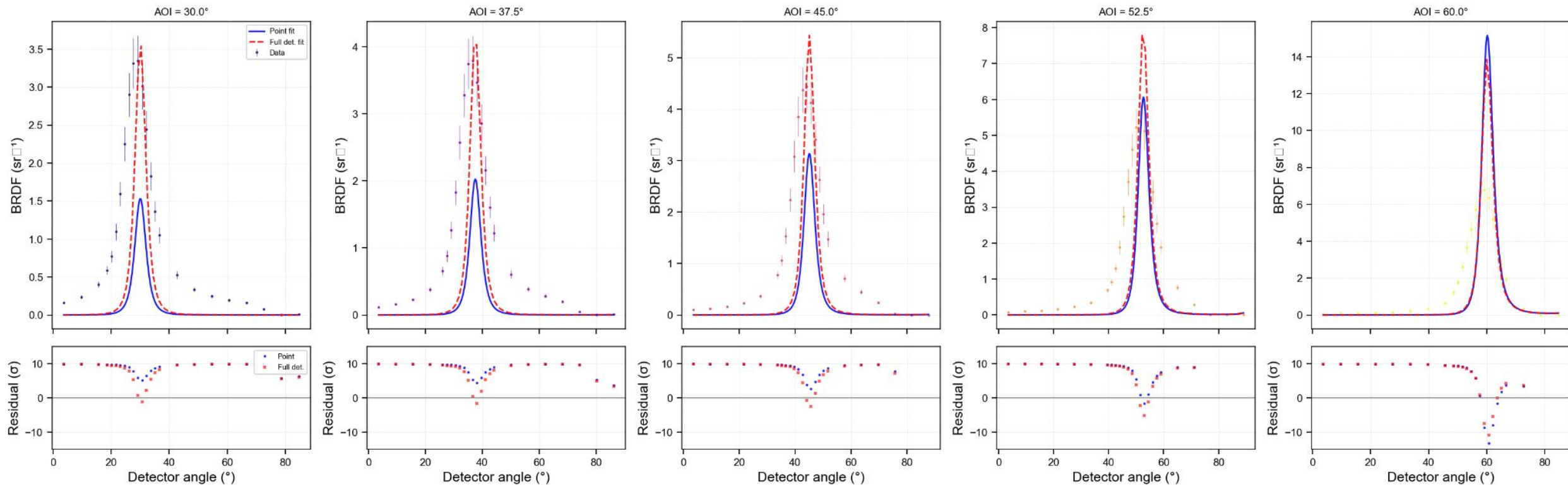
DUNE SS --- $\lambda = 500$ nm
 Point: $n=1.809$ $\kappa=0.100$ $\gamma=0.0253$ $\chi^2/\text{dof}=43.6$ $R^2=0.763$
 Full det: $n=2.500$ $\kappa=0.928$ $\gamma=0.0221$ $\chi^2/\text{dof}=21.7$ $R^2=0.895$



GGX Microfacet Model

- Fitting the full range does not yield a better data-model match.

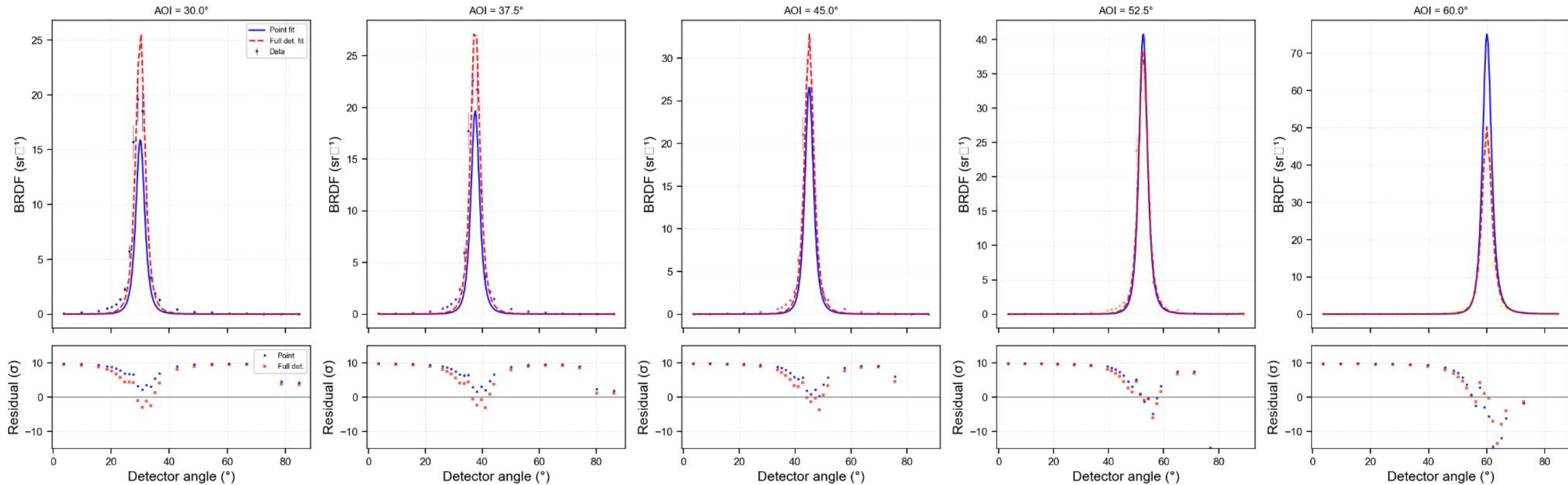
DUNE Al — $\lambda = 500$ nm (full angular range)
 Point: $n=1.256$ $\kappa=0.0010$ $\gamma=0.0308$ $\chi^2/\text{dof}=79.1$ $R^2=0.005$
 Full detector: $n=1.520$ $\kappa=0.0010$ $\gamma=0.0249$ $\chi^2/\text{dof}=72.3$ $R^2=0.275$



GGX Microfacet Model

- Fitting the full range does not yield a better data-model match.

DUNE SS — $\lambda = 500 \text{ nm}$ (full angular range)
Point: $n=1.835$ $\kappa=0.0010$ $\gamma=0.0243$ $\chi^2/\text{dof}=62.9$ $R^2=0.796$
Full detector: $n=3.084$ $\kappa=0.0010$ $\gamma=0.0207$ $\chi^2/\text{dof}=49.4$ $R^2=0.927$



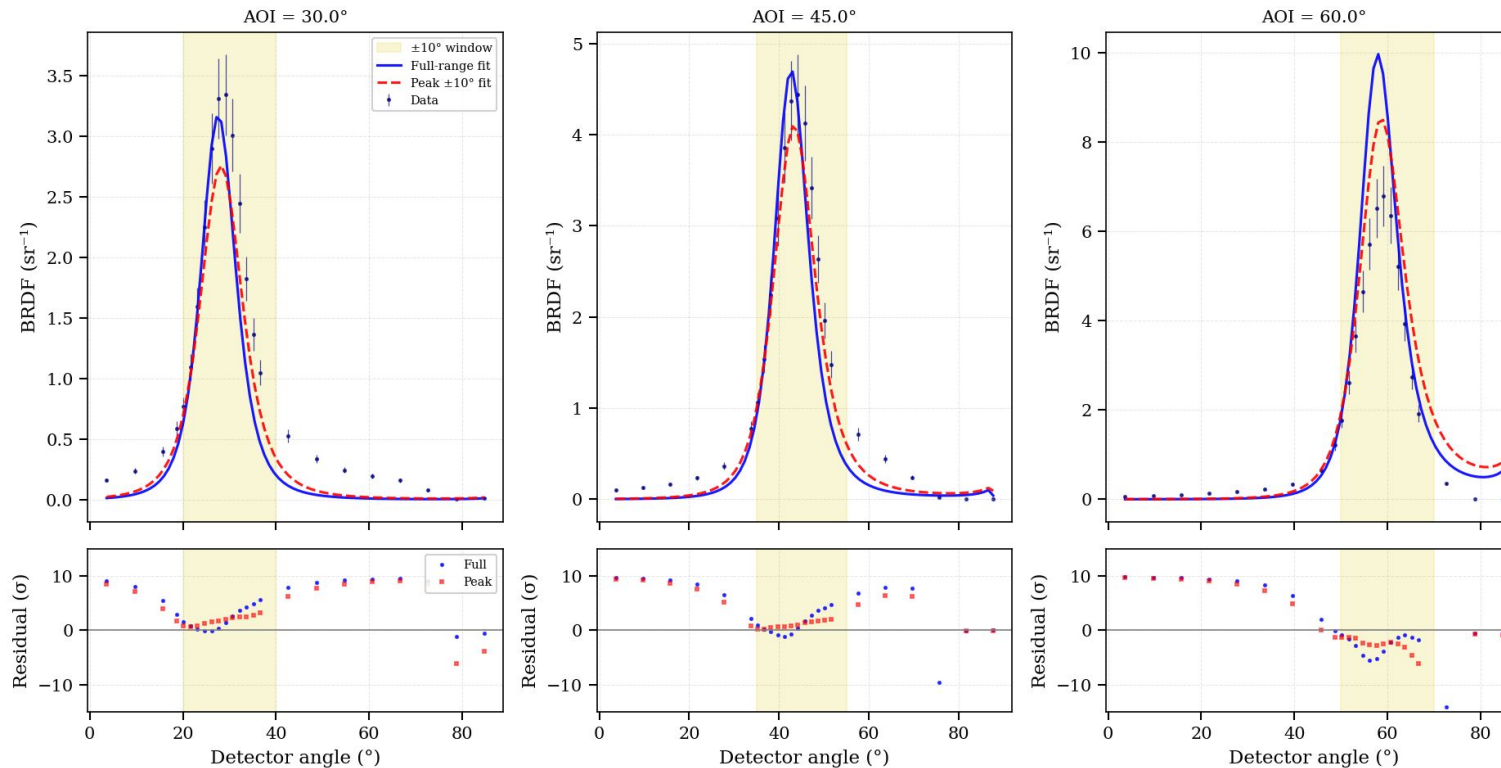
GGX Microfacet Model

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- 3 free parameters for metals: n , κ & γ .
- Multi-AOI pipeline with detector-angle correction from mirror reference. Full-detector averaging and point-mode fitting.
- $n = 2.5$ & $\kappa = 0.1$ are fit parameter bounds.
- The best fit from a pool of 10 initial seeds!!! Changing the bounds was proven ineffective: convergence to the bounds.
- **Finding:**
 - n and κ are fundamentally unidentifiable from angular BRDF data — Fresnel varies only ~3% across 30°–60° for metals.
 - Optimizer drives $\kappa \rightarrow 0$ in point mode because the model peak overshoots the measured BRDF (detector convolution needed)
- **Proposal:** new fit parameters.
 - θ_s : peak angular shift. Boundaries: ± 5.73 degrees.
 - Amplitude factor A , instead of Fresnel. Boundaries: $[0, 10]$.

GGX Microfacet Model: θ_s

- Model underestimates the tails: multiscattering yields a lambertian contribution to the BRDF.

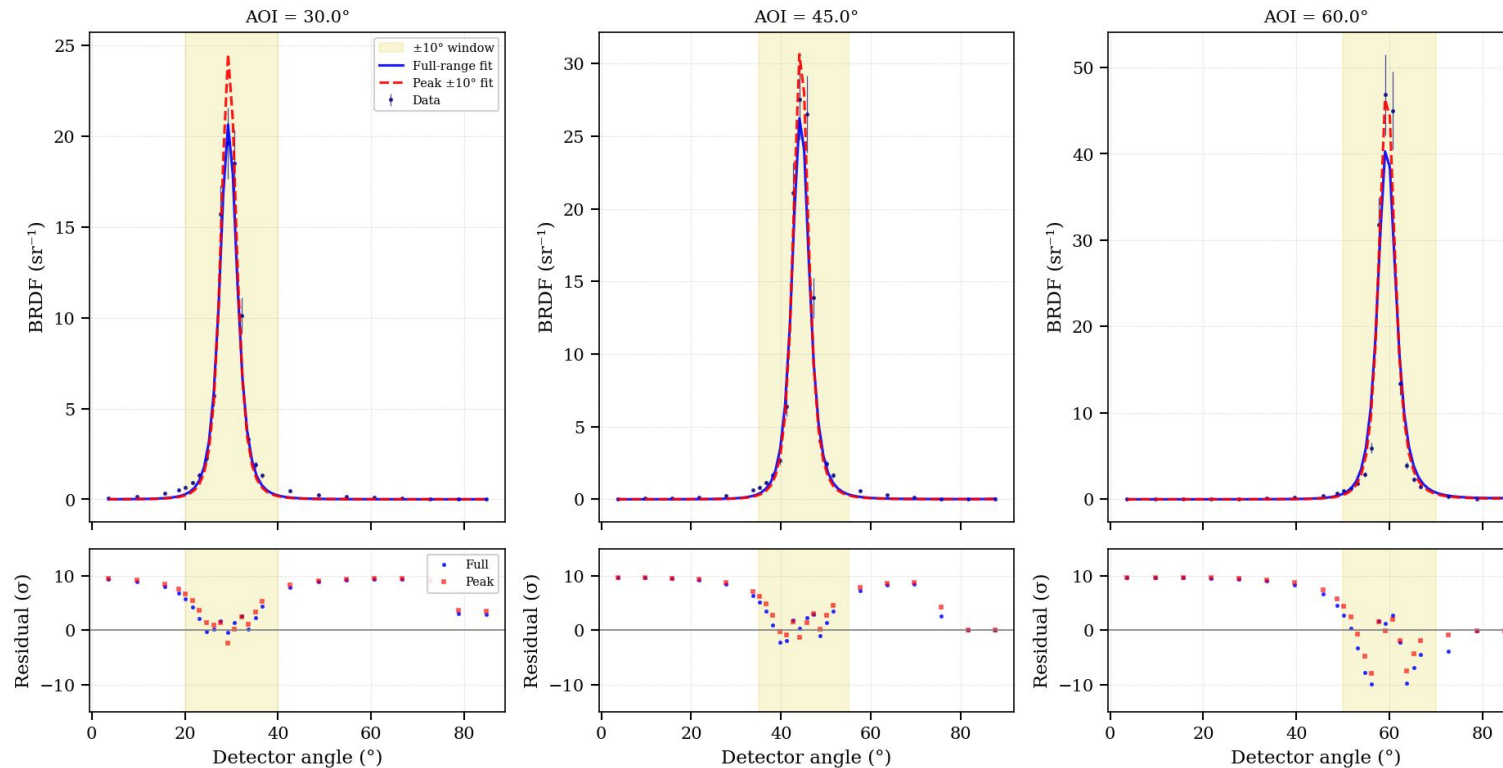
DUNE A1 — $\lambda = 500$ nm (full_detector)
 Full range: $n=2.054$ $\kappa=0.0010$ $\gamma=0.0564$ $\theta_s=-2.58^\circ$ $\chi^2/\text{dof}=37.0$ $R^2=0.798$
 Peak $\pm 10^\circ$: $n=2.238$ $\kappa=0.0010$ $\gamma=0.0693$ $\theta_s=-2.04^\circ$ $\chi^2/\text{dof}=5.5$ $R^2=0.761$



GGX Microfacet Model: θ_s

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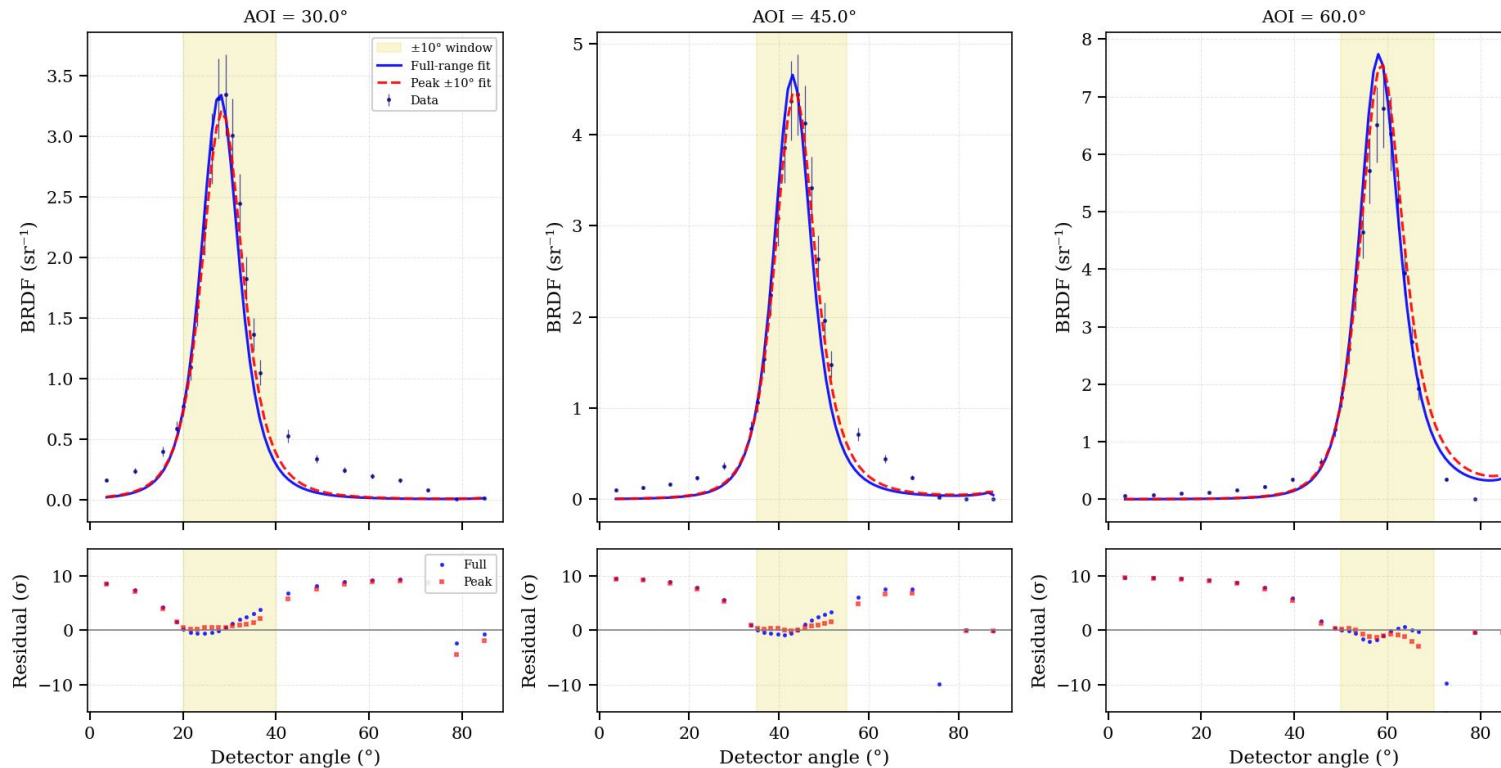
DUNE SS — $\lambda = 500$ nm (full_detector)
Full range: $n=3.058$ $\kappa=0.0010$ $\gamma=0.0251$ $\theta_s=-0.69^\circ$ $\chi^2/\text{dof}=41.6$ $R^2=0.944$
Peak $\pm 10^\circ$: $n=3.093$ $\kappa=0.0010$ $\gamma=0.0218$ $\theta_s=-0.64^\circ$ $\chi^2/\text{dof}=14.3$ $R^2=0.957$



GGX Microfacet Model: θ_s & Amplitude

- Model underestimates the tails: multiscattering yields a lambertian contribution to the BRDF.

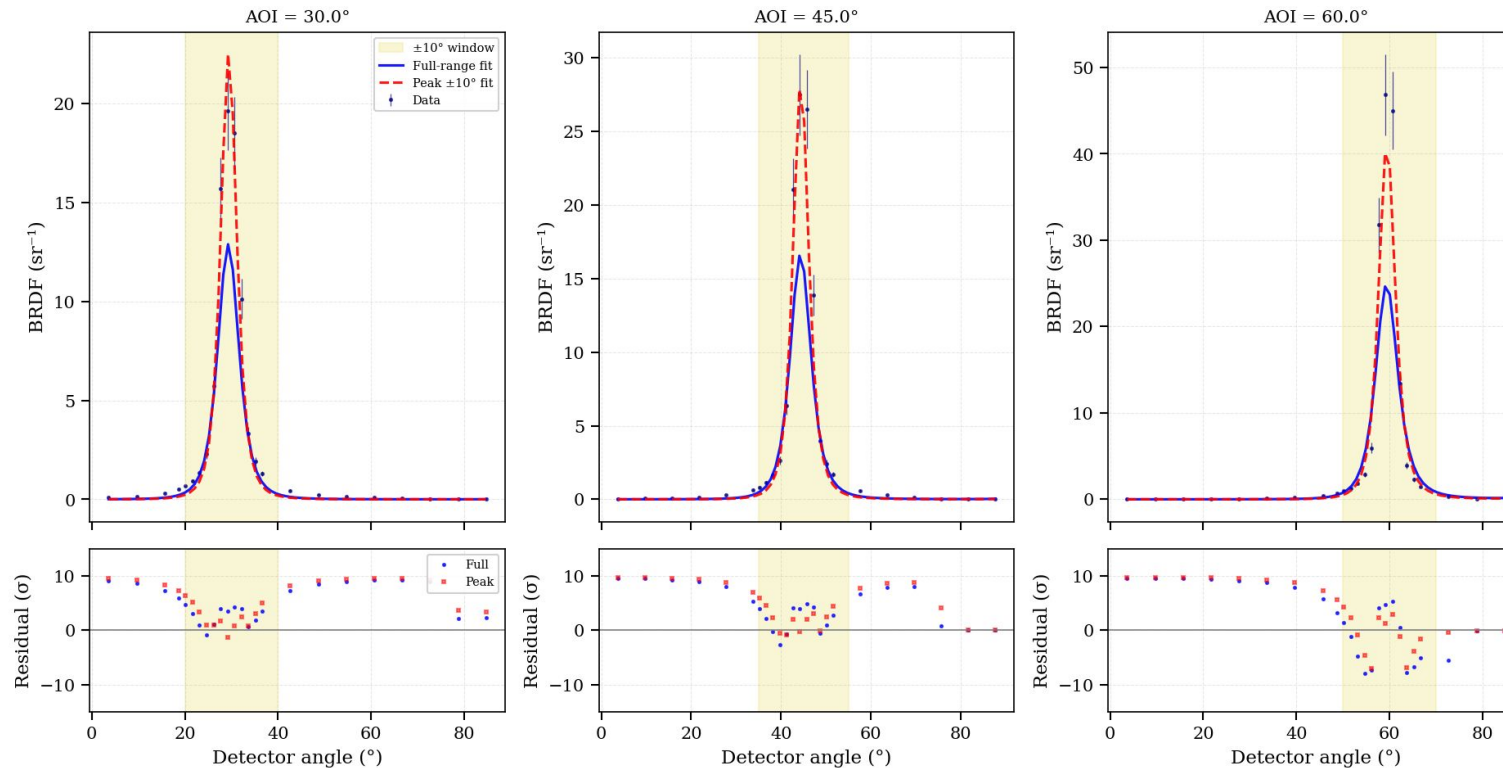
DUNE A1 — $\lambda = 500$ nm (full_detector)
 Full range: $A=0.149$ $\gamma=0.0620$ $\theta_s=-2.28^\circ$ $\chi^2/\text{dof}=29.3$ $R^2=0.966$
 Peak $\pm 10^\circ$: $A=0.163$ $\gamma=0.0672$ $\theta_s=-1.78^\circ$ $\chi^2/\text{dof}=1.1$ $R^2=0.960$



GGX Microfacet Model: θ_s & Amplitude

- Model underestimates the tails: multiscattering yields a lambertian contribution to the BRDF.

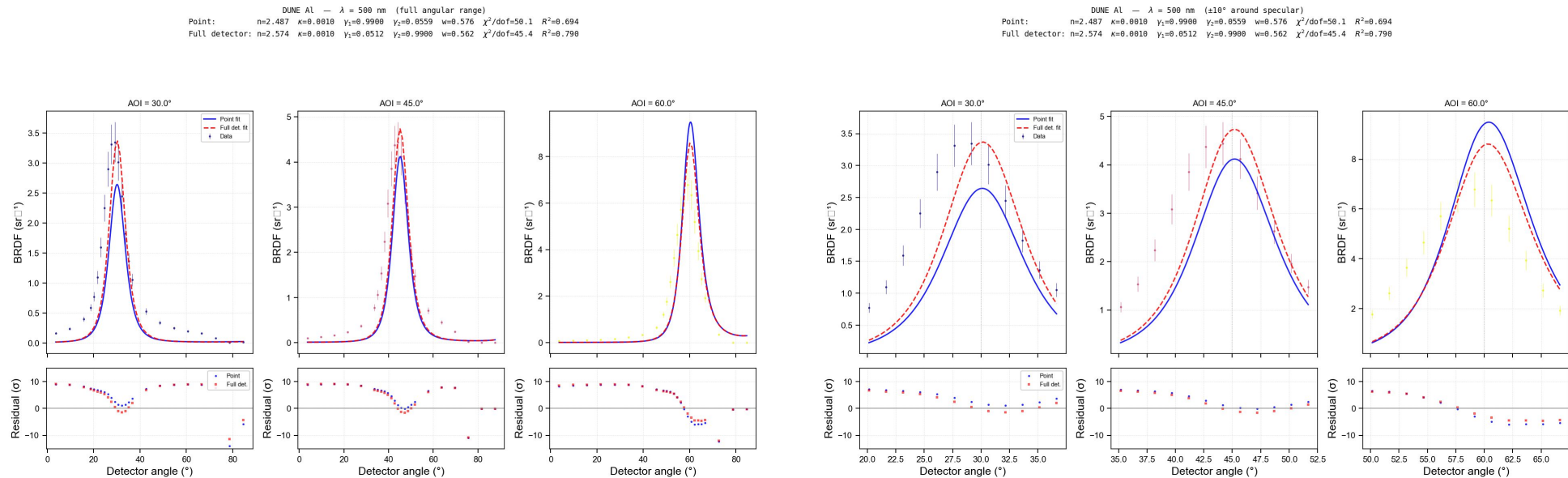
DUNE SS — $\lambda = 500$ nm (full_detector)
 Full range: $A=0.216$ $\gamma=0.0320$ $\theta_s=-0.75^\circ$ $\chi^2/\text{dof}=39.0$ $R^2=0.738$
 Peak $\pm 10^\circ$: $A=0.256$ $\gamma=0.0230$ $\theta_s=-0.63^\circ$ $\chi^2/\text{dof}=12.3$ $R^2=0.929$



Backup

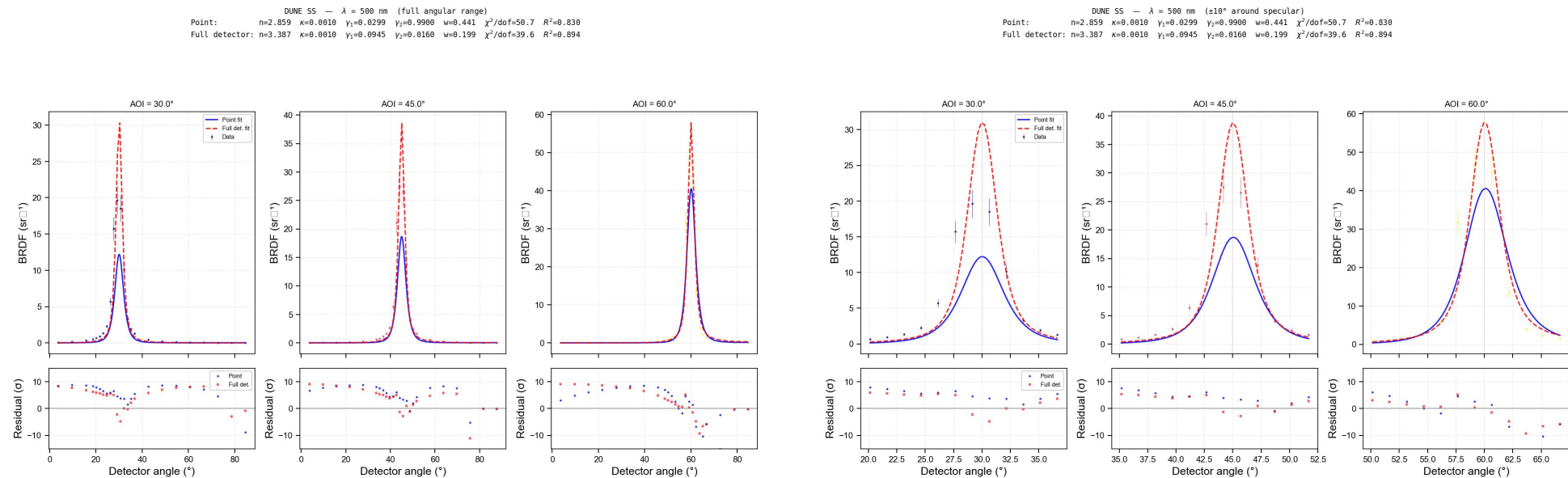
GGX Microfacet Model: Multiroughness

- Two-roughness mixture model.
- 5 parameters: n , κ , γ_1 , γ_2 , ω .
- Mixes a narrow specular lobe (γ_1) with a broad scattered component (γ_2).
- **Finding:**
 - Better tail fitting than single-roughness, but n/κ degeneracy persists.
 - Adding a second roughness lobe doesn't resolve the fundamental Fresnel identifiability problem.



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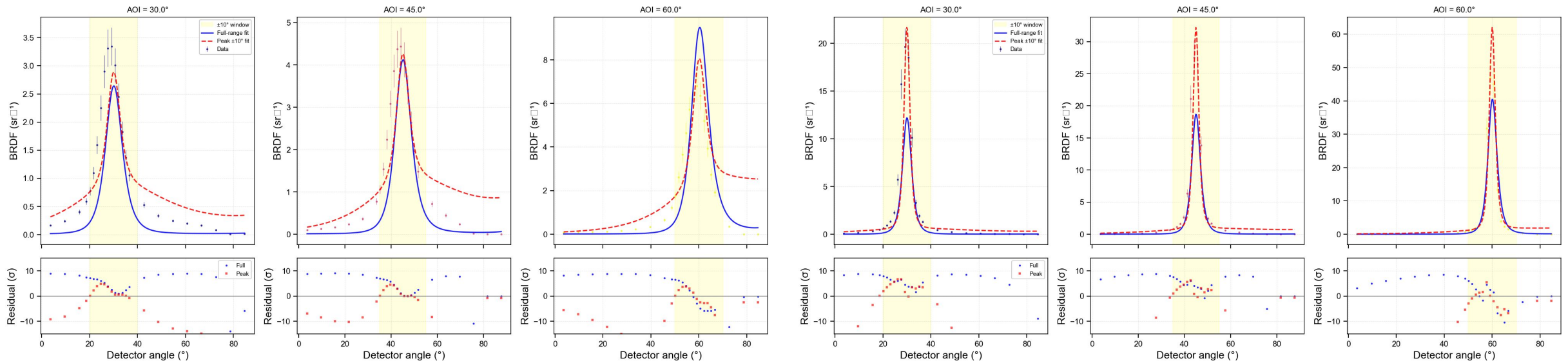


GGX Microfacet Model: Multiroughness

- Fitting the full range or fixing the refractive index does not help.
- Tails contain the missing energy: multiscattering. This is not predicted by the model.
- Scratches are not isotropic, which is a model requirement.

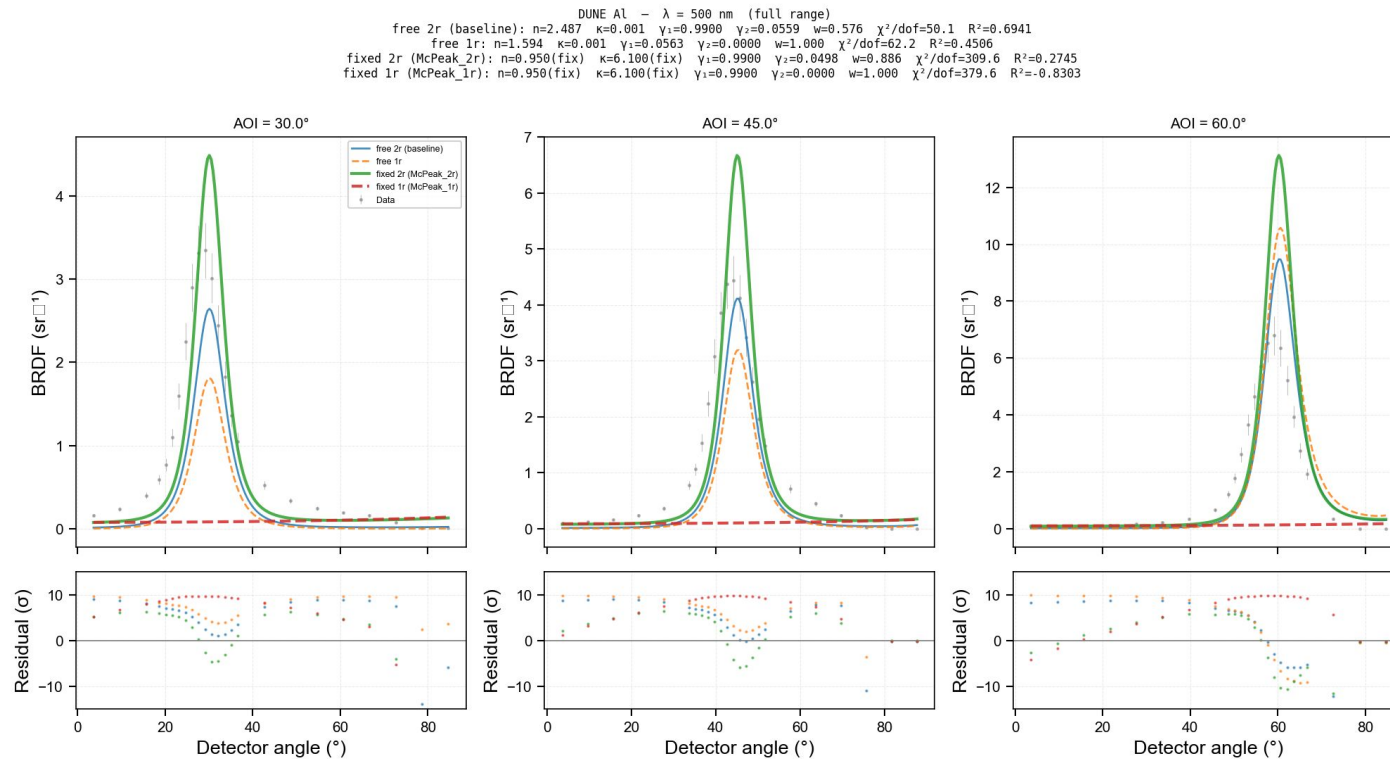
DUNE A1 — $\lambda = 500 \text{ nm}$
 Full range: $n=2.487$ $k=0.0010$ $\gamma_1=0.9900$ $\gamma_2=0.0559$ $w=0.576$ $\chi^2/\text{dof}=50.1$ $R^2=0.694$
 Peak $\pm 10^\circ$: $n=5.000$ $k=6.3314$ $\gamma_1=0.2903$ $\gamma_2=0.0422$ $w=0.954$ $\chi^2/\text{dof}=9.6$ $R^2=0.661$

DUNE S5 — $\lambda = 500 \text{ nm}$
 Full range: $n=2.859$ $k=0.0010$ $\gamma_1=0.0299$ $\gamma_2=0.9900$ $w=0.441$ $\chi^2/\text{dof}=50.7$ $R^2=0.830$
 Peak $\pm 10^\circ$: $n=5.000$ $k=6.0080$ $\gamma_1=0.0197$ $\gamma_2=0.3348$ $w=0.108$ $\chi^2/\text{dof}=17.4$ $R^2=0.854$



GGX Microfacet Model: Multiroughness

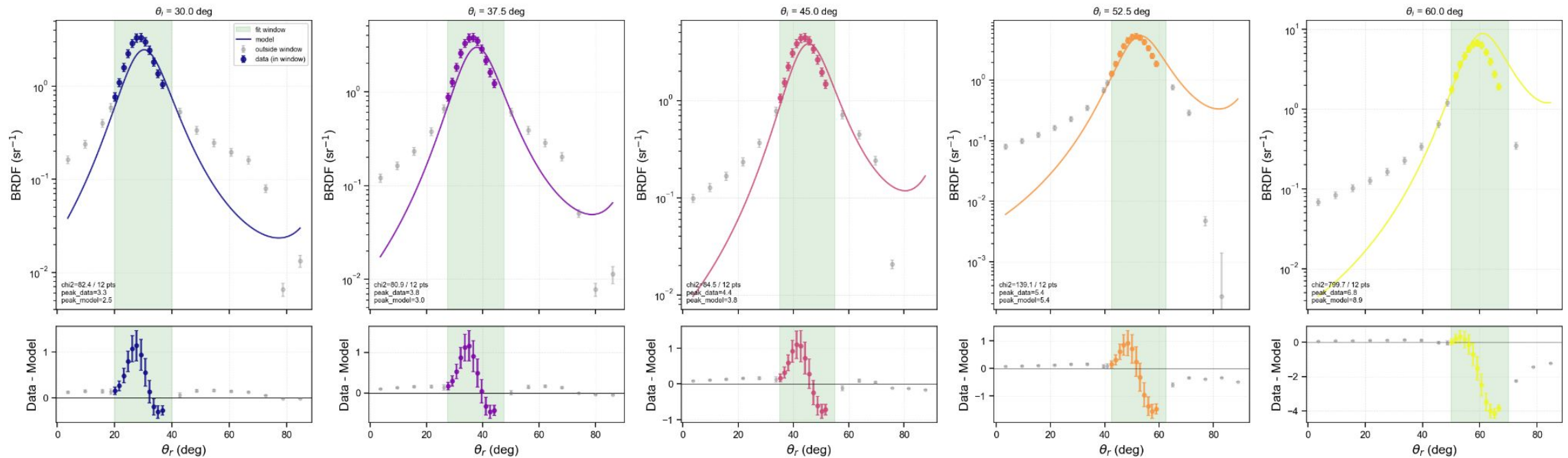
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- 3 free parameters for metals: n , κ & γ .
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DUNE Al $\lambda = 500$ nm
 $n = 2.500 \pm 0.328$ $\kappa = 0.100 \pm 3.313$ $\gamma = 0.0895 \pm 0.0025$ $\chi^2/\text{dof} = 13.17$ $R^2 = 0.5522$



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- 3 free parameters for metals: n , κ & γ .
- Multi-AOI pipeline with detector-angle correction from mirror reference. Full-detector averaging and point-mode fitting.

DUNE SS --- $\lambda = 500$ nm
 $n = 2.500 \pm 0.455$ $\kappa = 0.928 \pm 0.400$ $\gamma = 0.0221 \pm 0.0004$ $\chi^2/\text{dof} = 21.68$ $R^2 = 0.8945$

