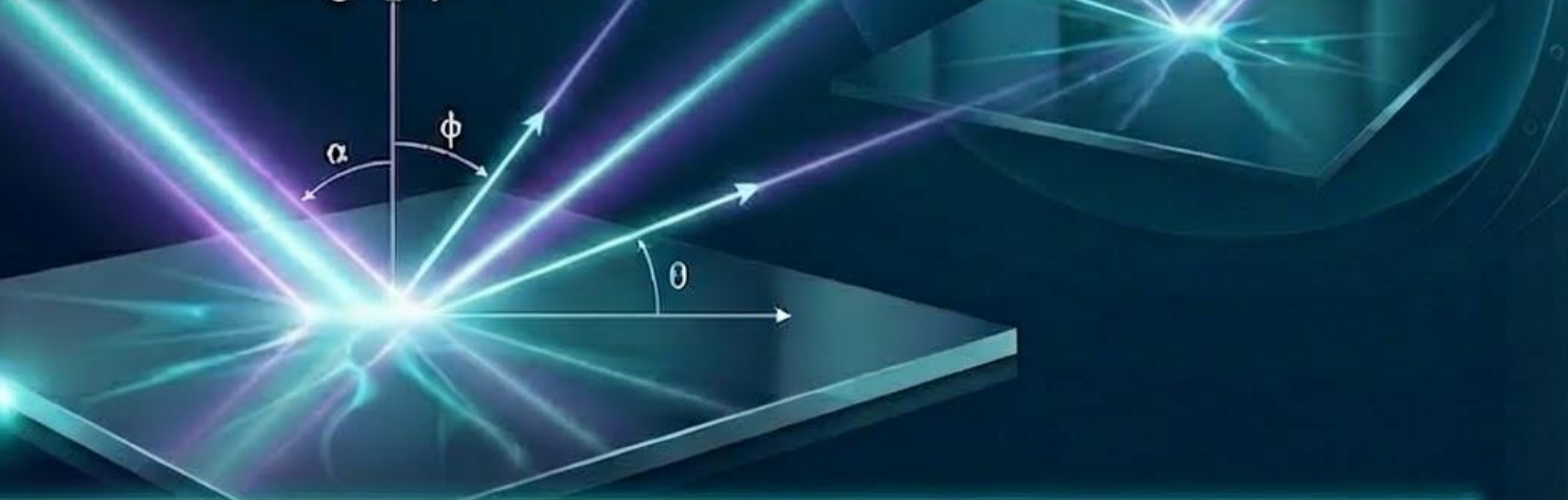
Reflectance Measurements: BRDF fits

Hamza Amar
on behalf of the IFIC-Neutrinos group

March 11th 2026



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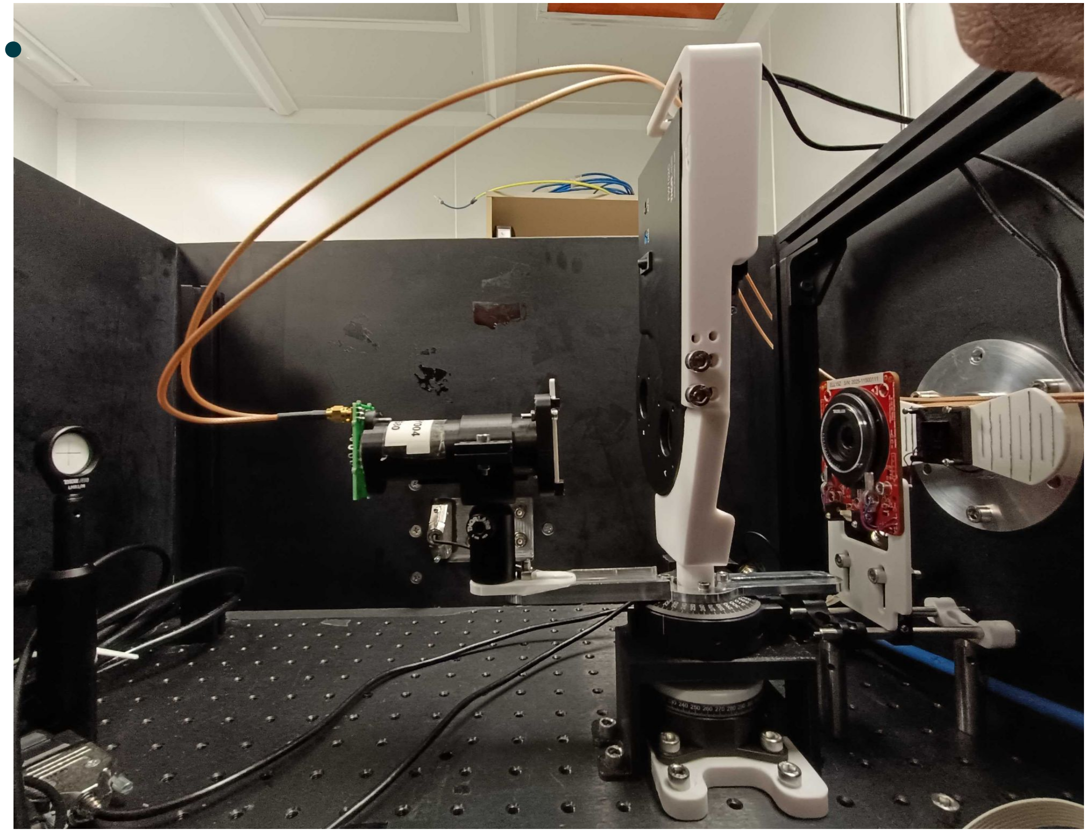
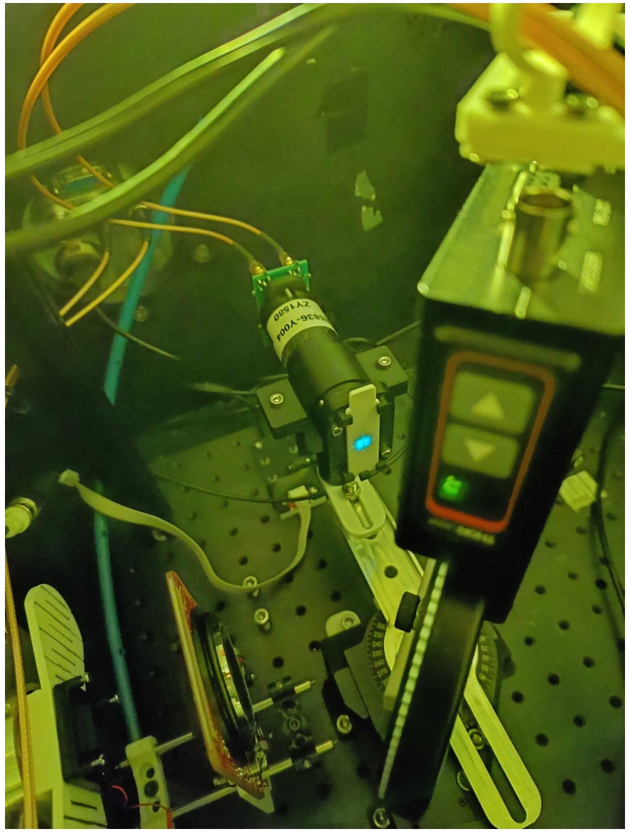
A setup for angular-resolved reflectance measurements

- Motorized **iris aperture**: 2.5 mm. **Distance PMT-sample**: 78.5 mm.
- A **rectangular mask of 2x10 mm^2** is placed over the PMT, to enhance angular resolution through the azimuthal angle ϕ.
- **Samples**: DUNE SS, DUNE Al & 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.

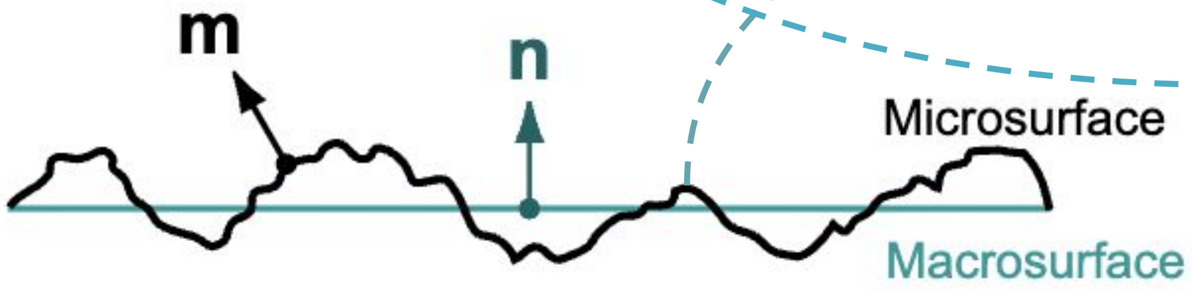
BRDF from mirror-like microfacets

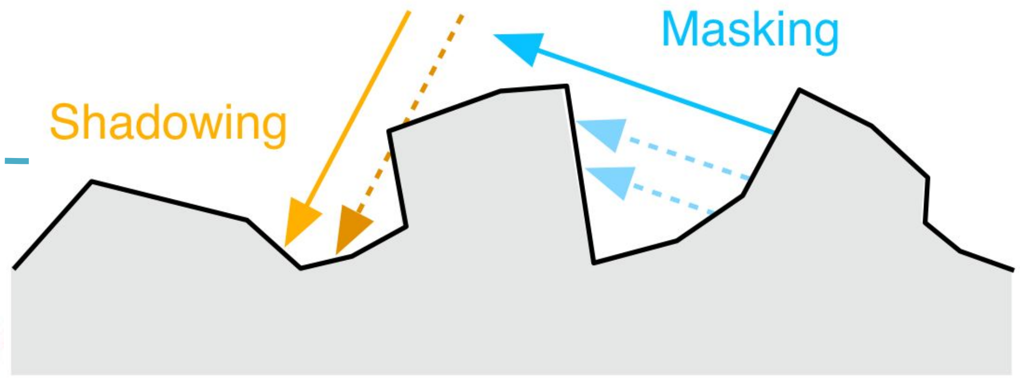
Roughness

$$\varrho_S(\theta_i, \theta_r, \phi_r; n_0/\tilde{n}, \gamma) = \frac{F(\theta_i', n_0/\tilde{n}) \cdot G(\theta_i, \theta_r, \phi_r; \gamma) \cdot P(\alpha_s; \gamma)}{4 \cos\theta_i \cos\theta_r}$$

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

$$R(\theta_i) = \int \varrho(\theta_i, \theta_r, \phi_r) \sin\theta_r d\theta_r d\phi_r .$$





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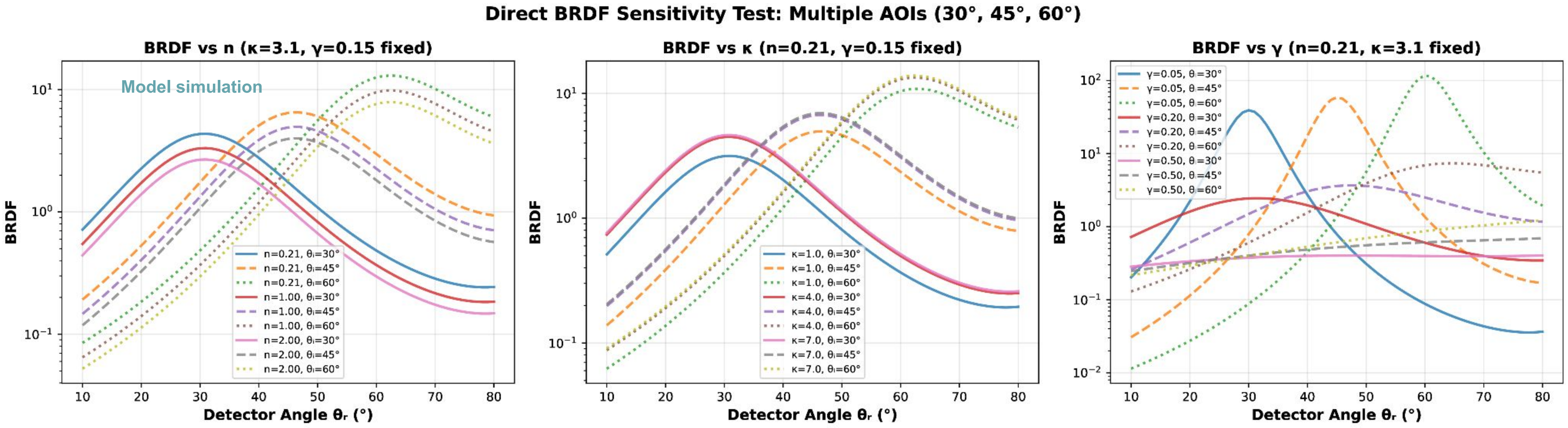
Experimental BRDF

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

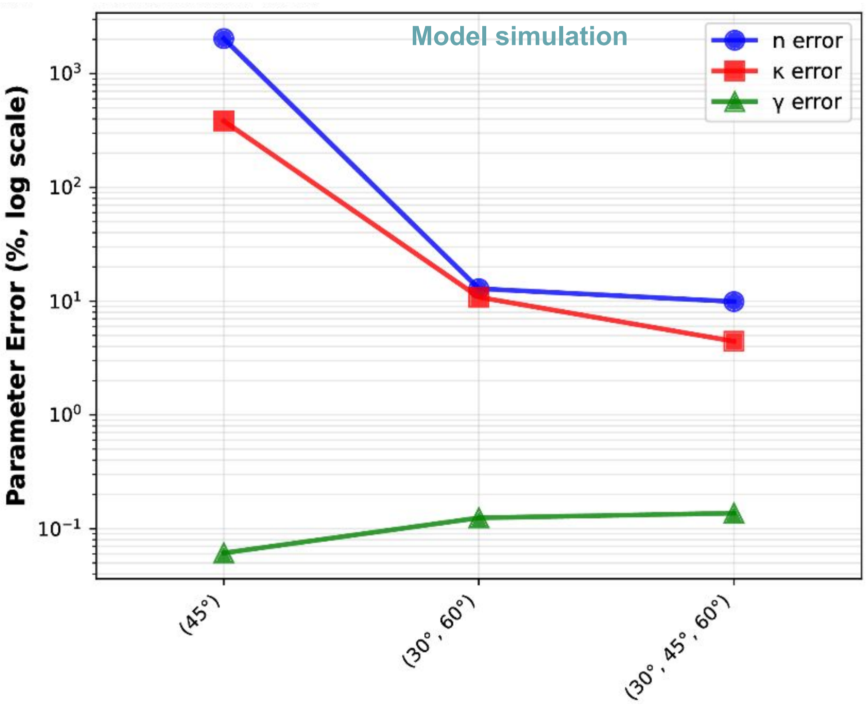
Reflectance model: Sensitivity test

- 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.



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
- κ = 3.10
- γ = 0.150

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

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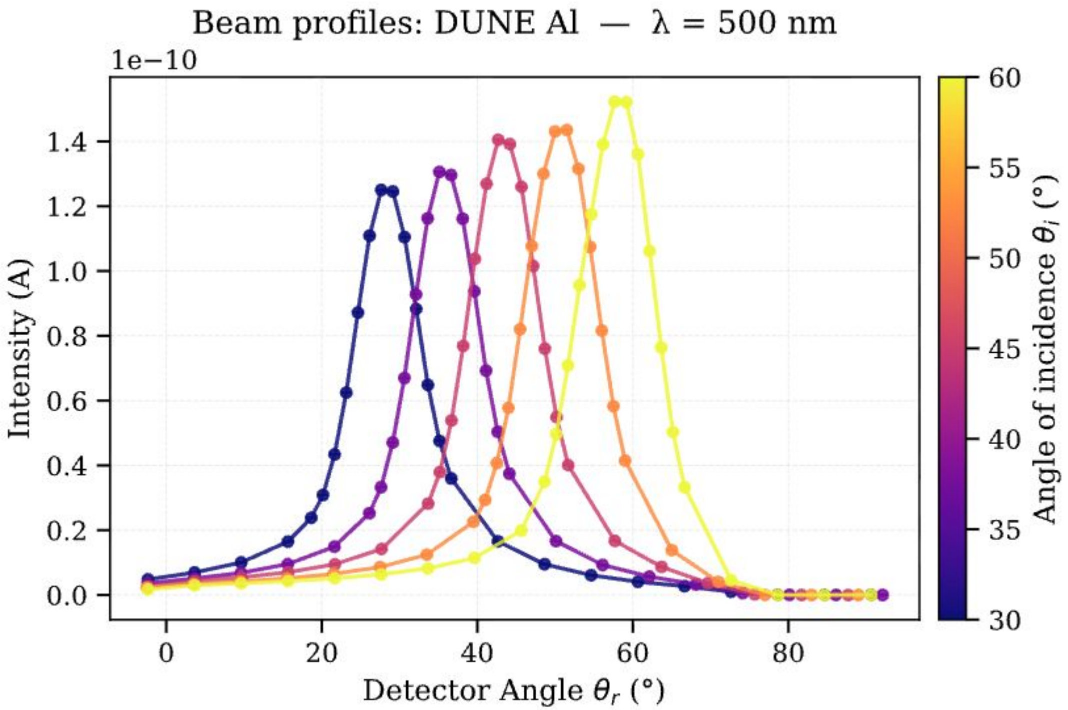
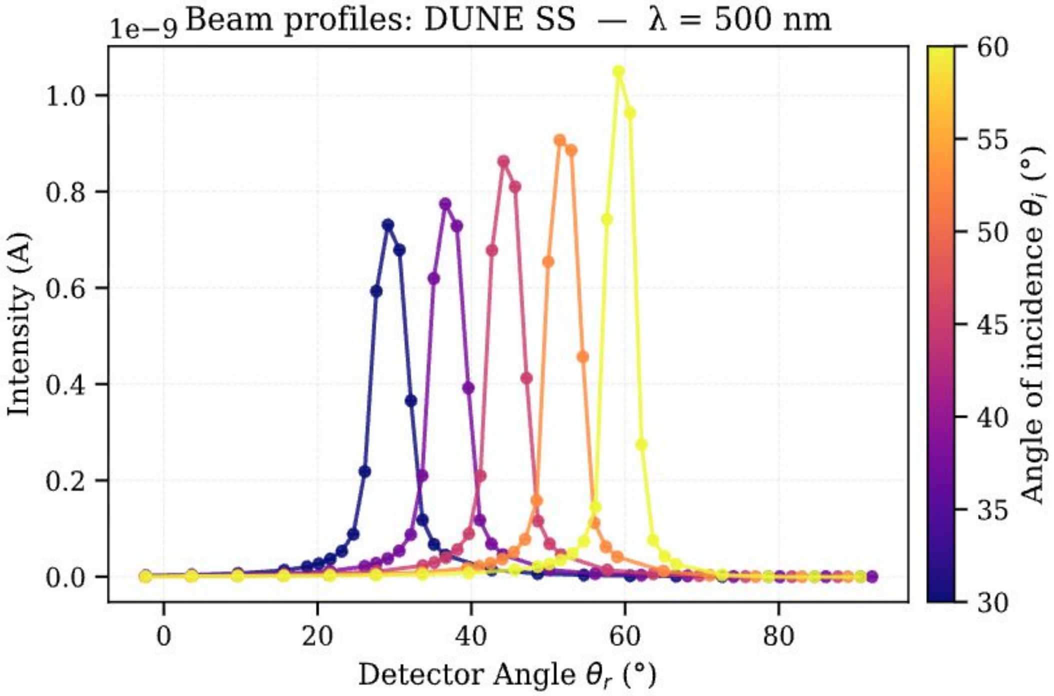
AOIs	Points	σ(n)	σ(κ)	σ(γ)	χ^2/dof
1	12	1.87e+02	2.88e+02	7.10e-04	0.59
2	24	3.02e-02	3.20e-01	3.88e-04	1.09
3	36	2.93e-02	3.00e-01	3.08e-04	0.80

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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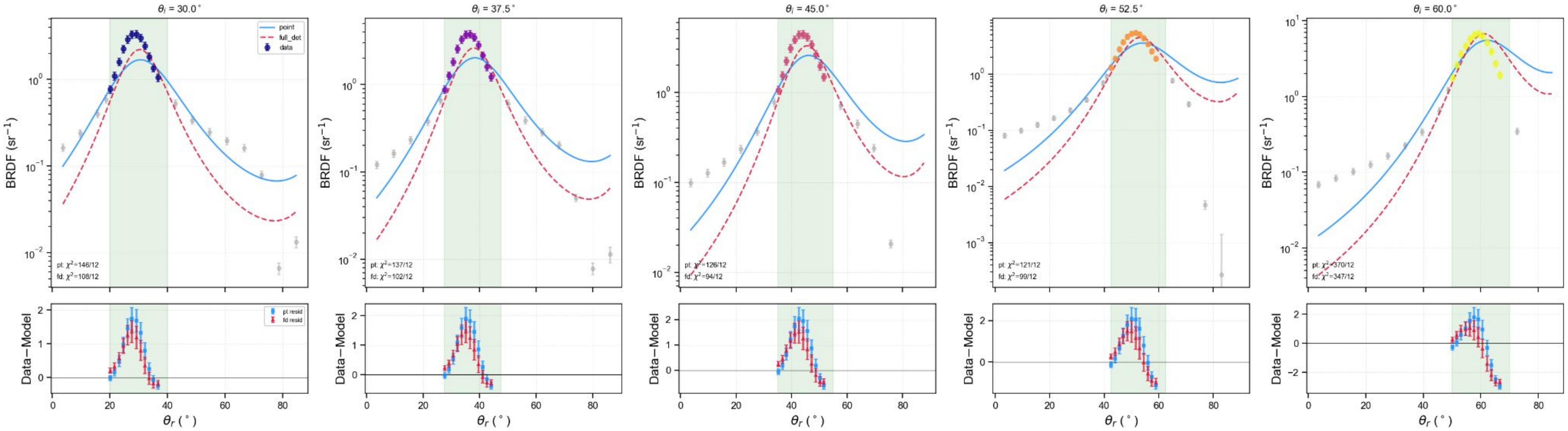
DUNE Al --- λ = 500 nm
Point: n=2.500 κ=1.329 γ=0.1344 χ^2/dof=15.8 R^2=0.344
Full det: n=2.500 κ=0.100 γ=0.0895 χ^2/dof=13.2 R^2=0.552

- The best fit from a pool of 10 initial seeds!!! Changing the boundaries was proven ineffective: convergence to the boundaries.



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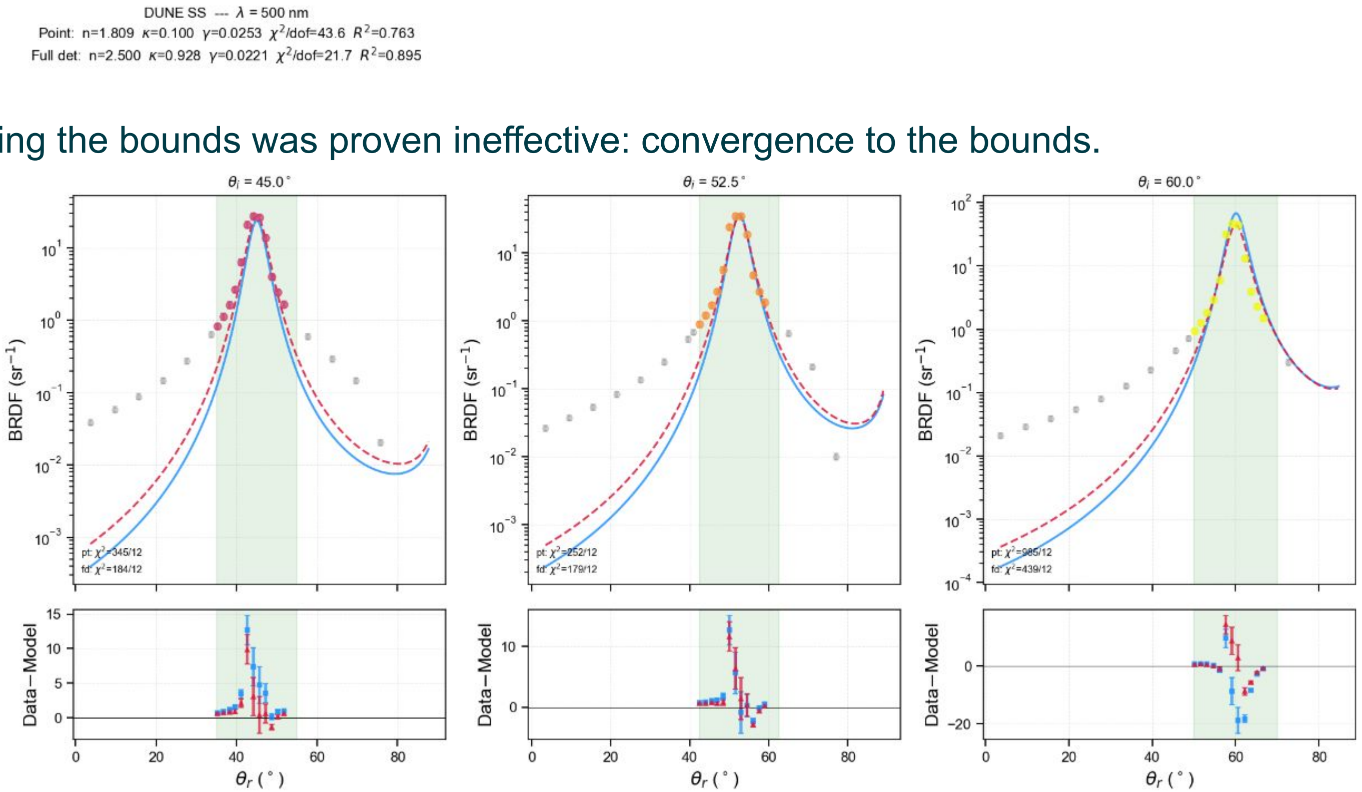

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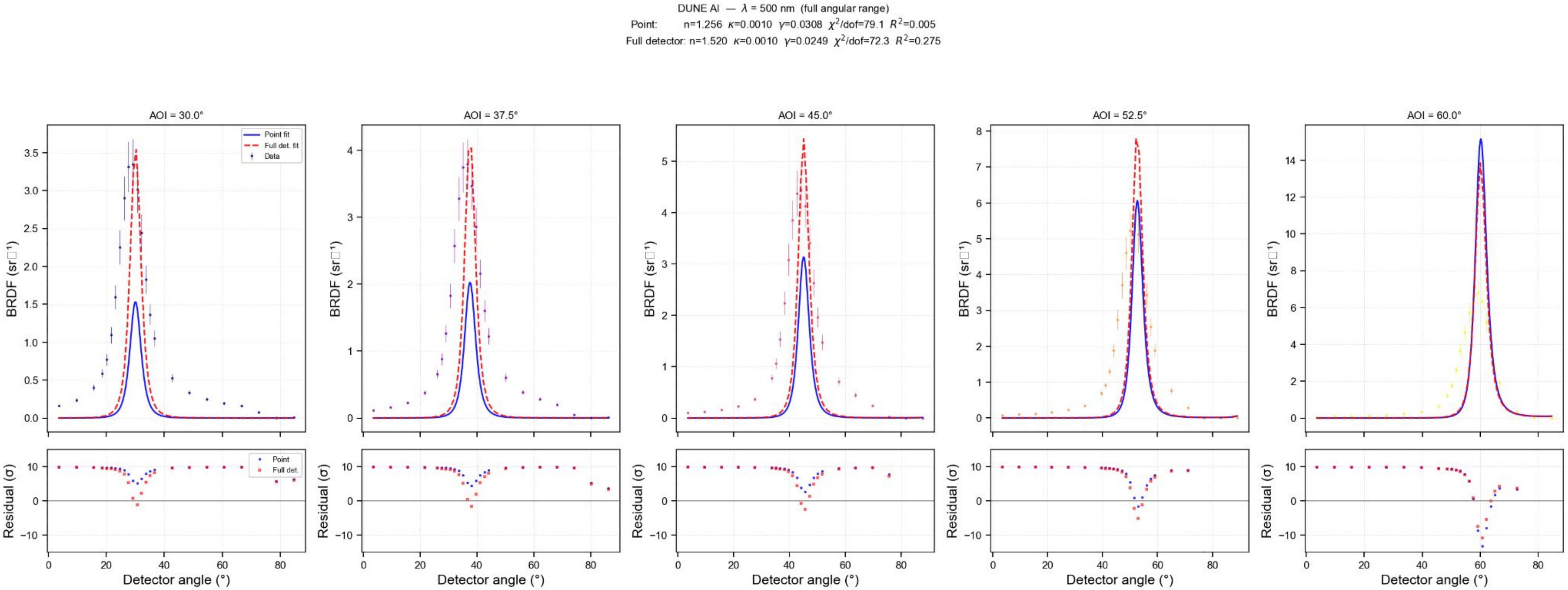

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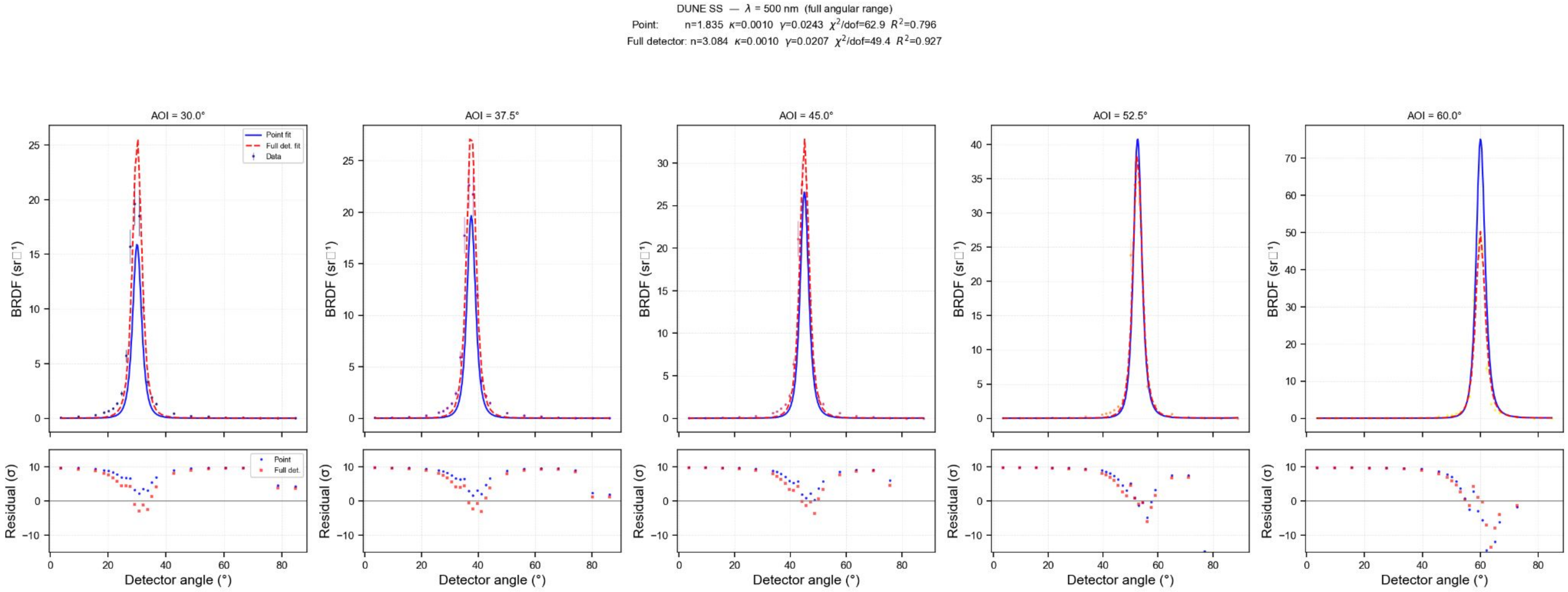

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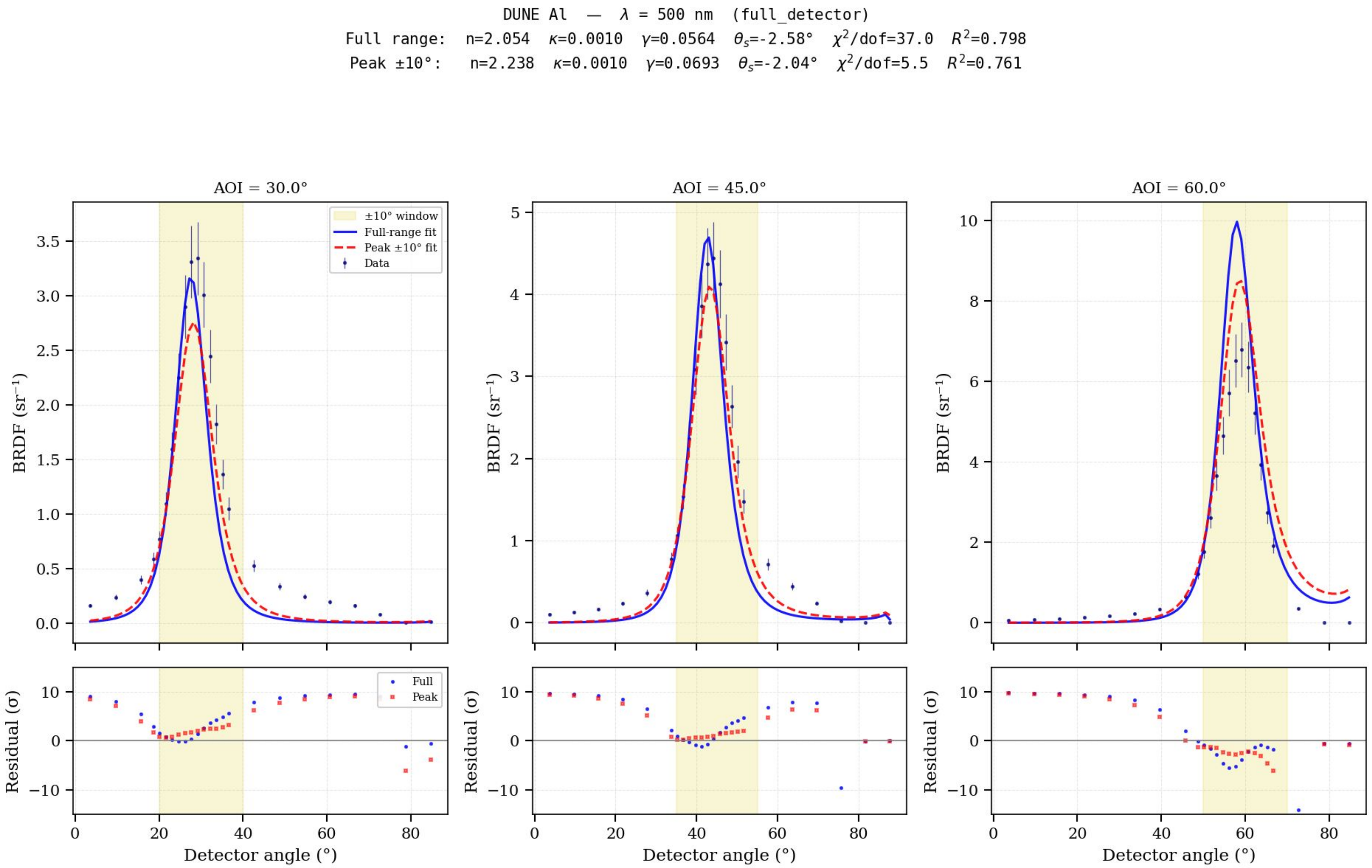
- $n = 2.5$ & $\kappa = 0.1$ are fit parameter bounds.
- The best fit from a pool of 10 initial seeds!!! Changing the bounds was proven ineffective: convergence to the bounds.
- **Finding**:
  - n and κ are fundamentally unidentifiable from angular BRDF data — Fresnel varies only ~3% across 30°–60° for 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.



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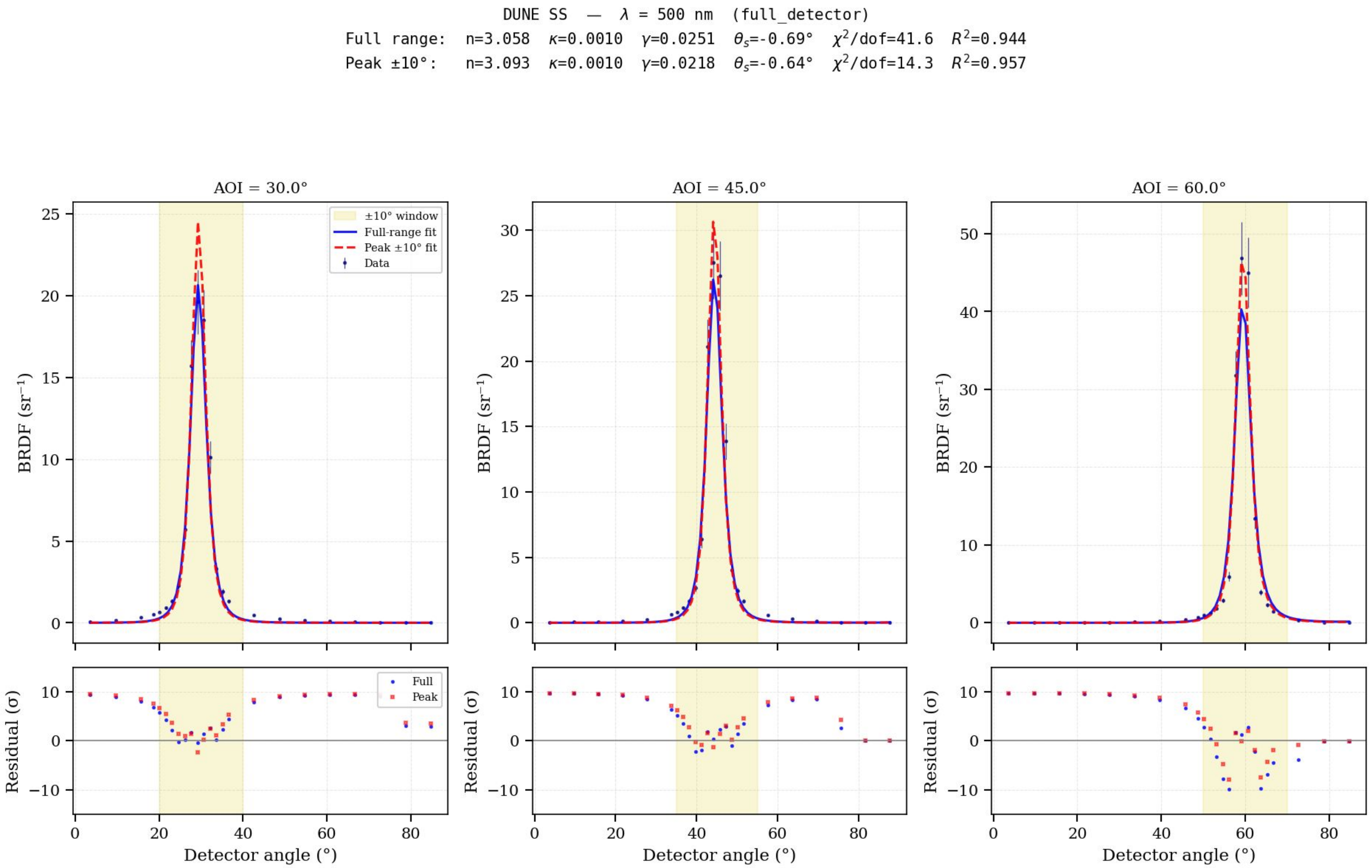

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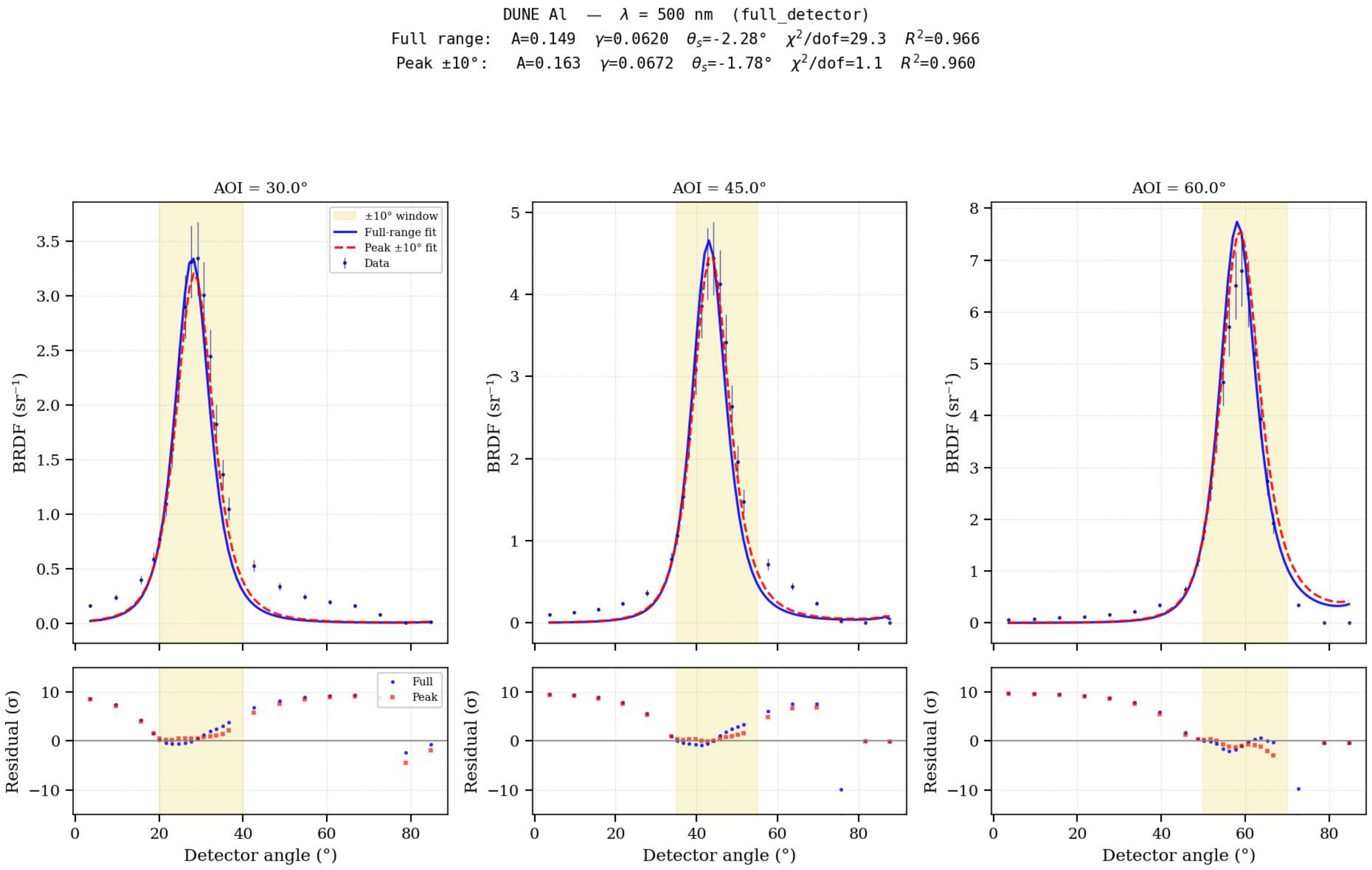

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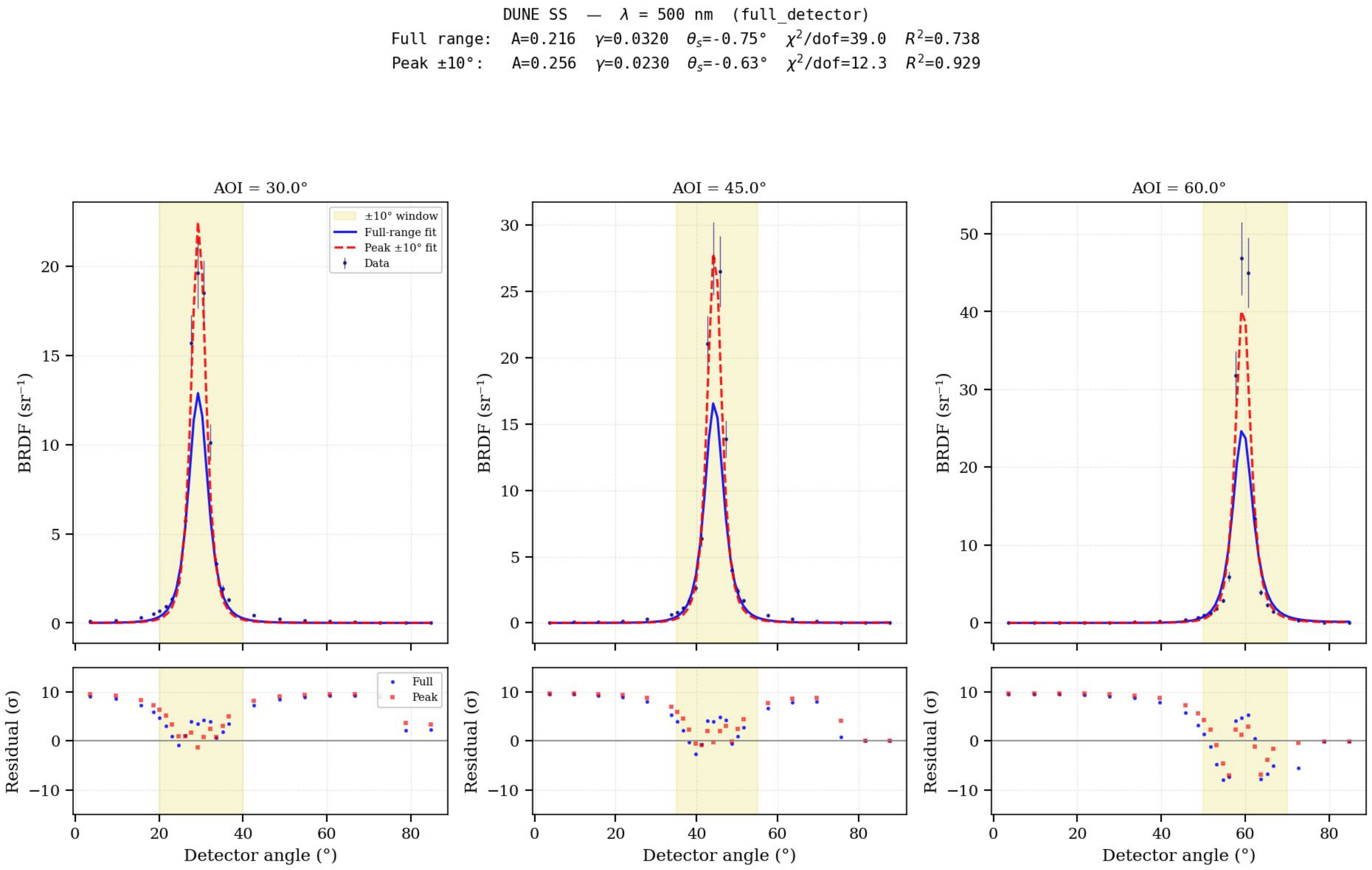
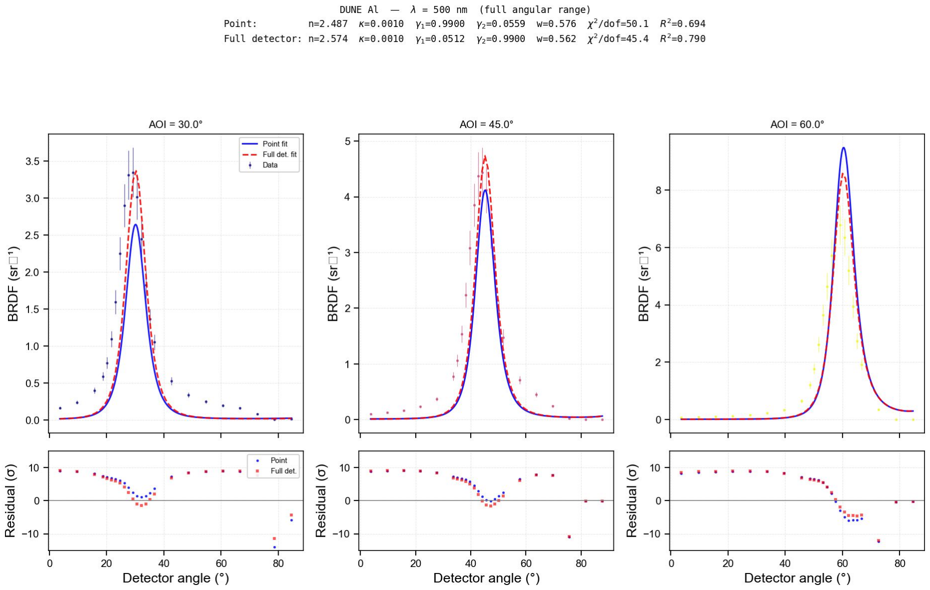
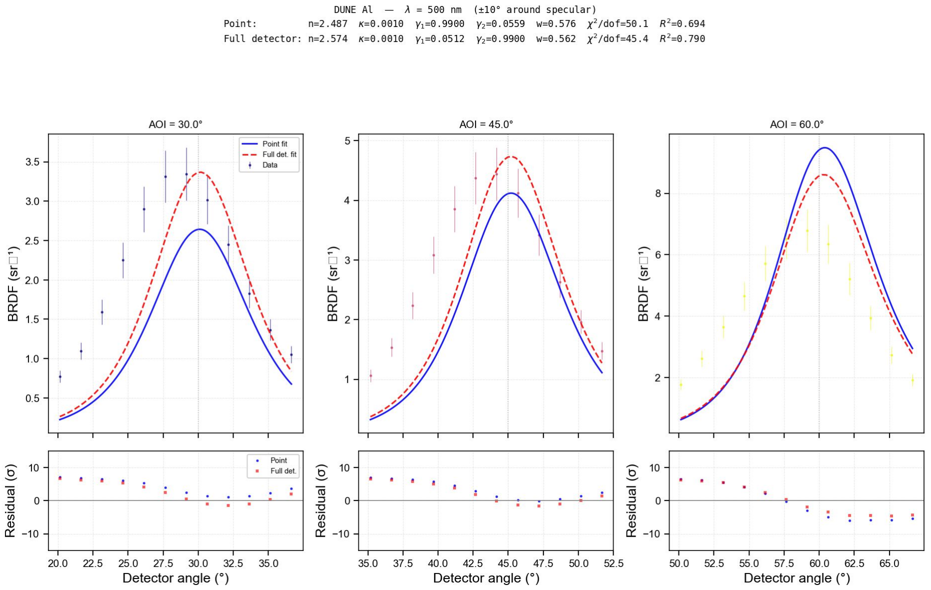


Backup

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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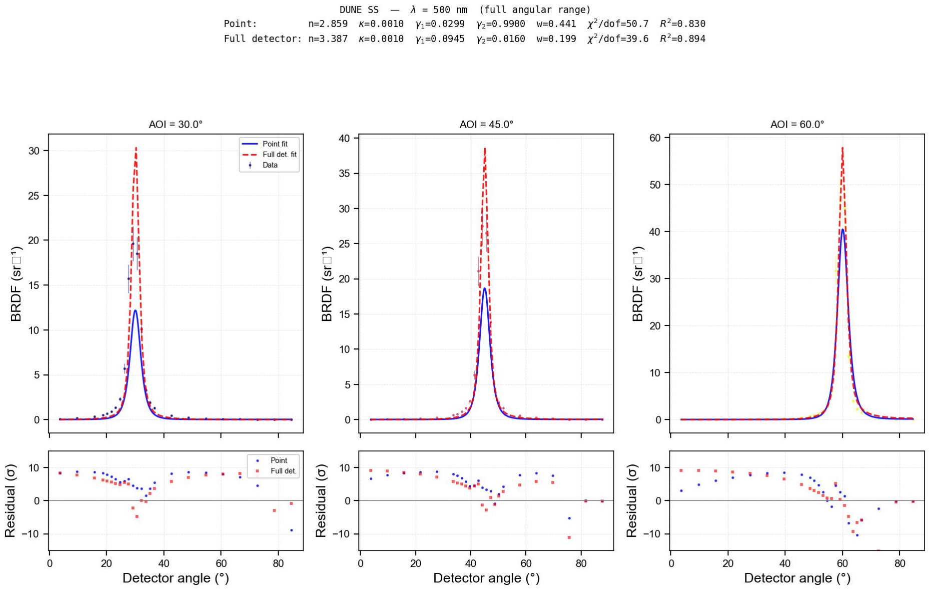

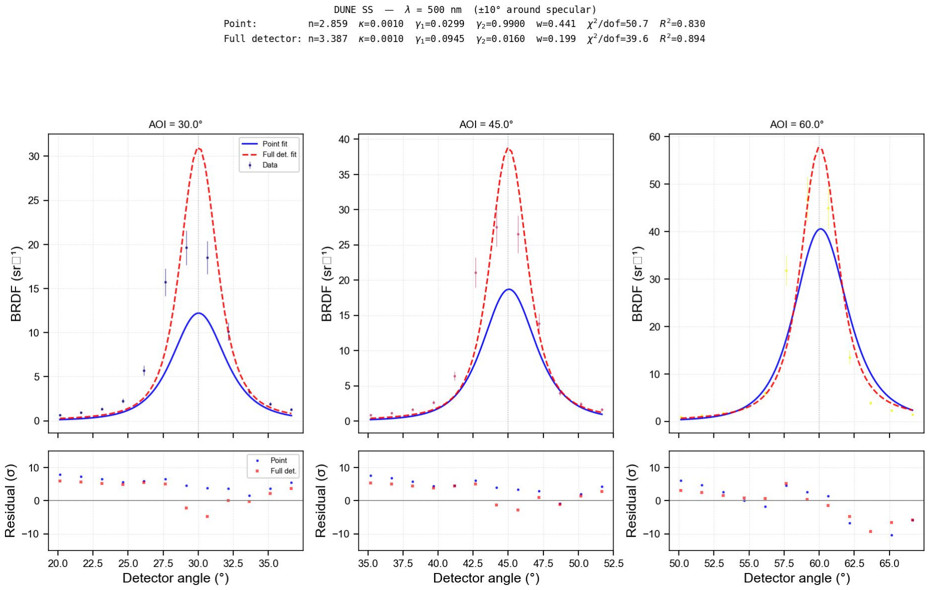

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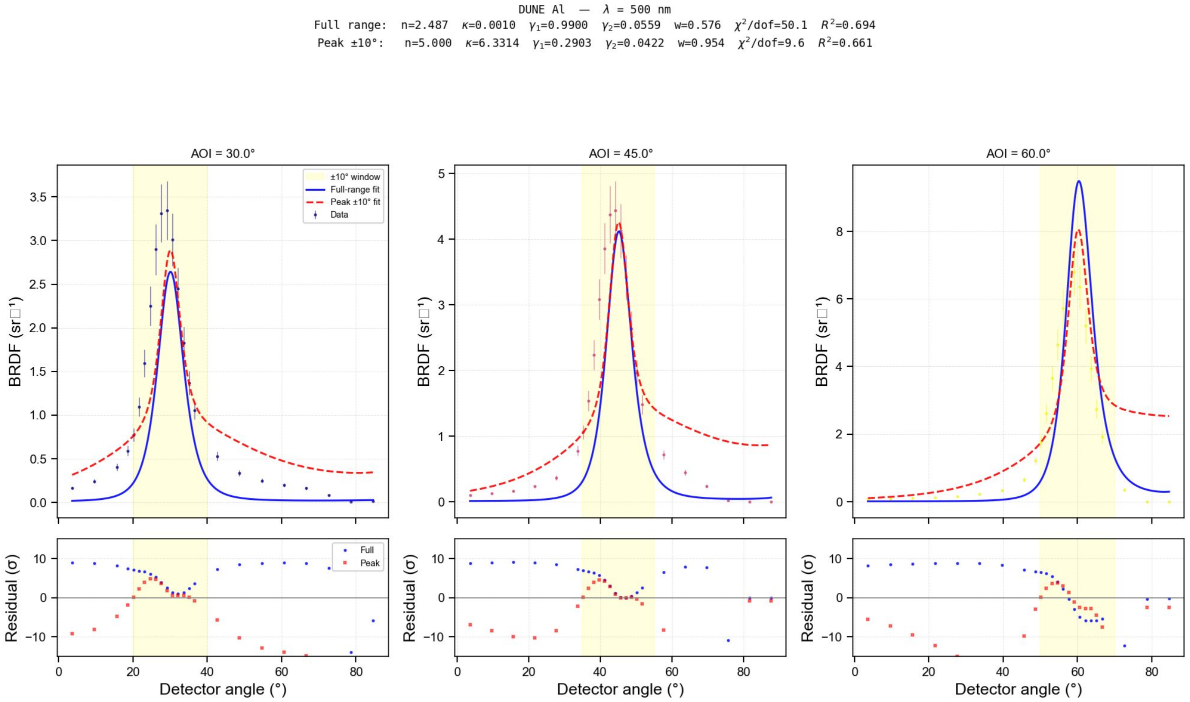
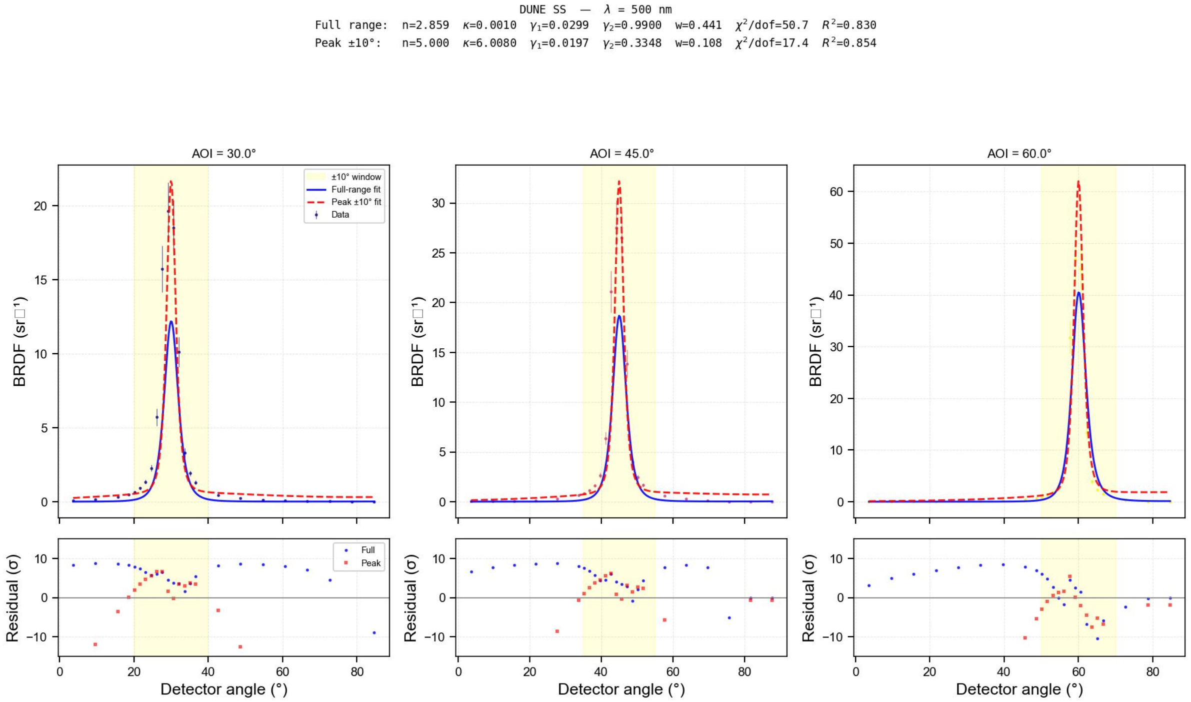
- Tails contain the missing energy: multiscattering. This is not predicted by the model.
- Scratches are not isotropic, which is a model requirement.





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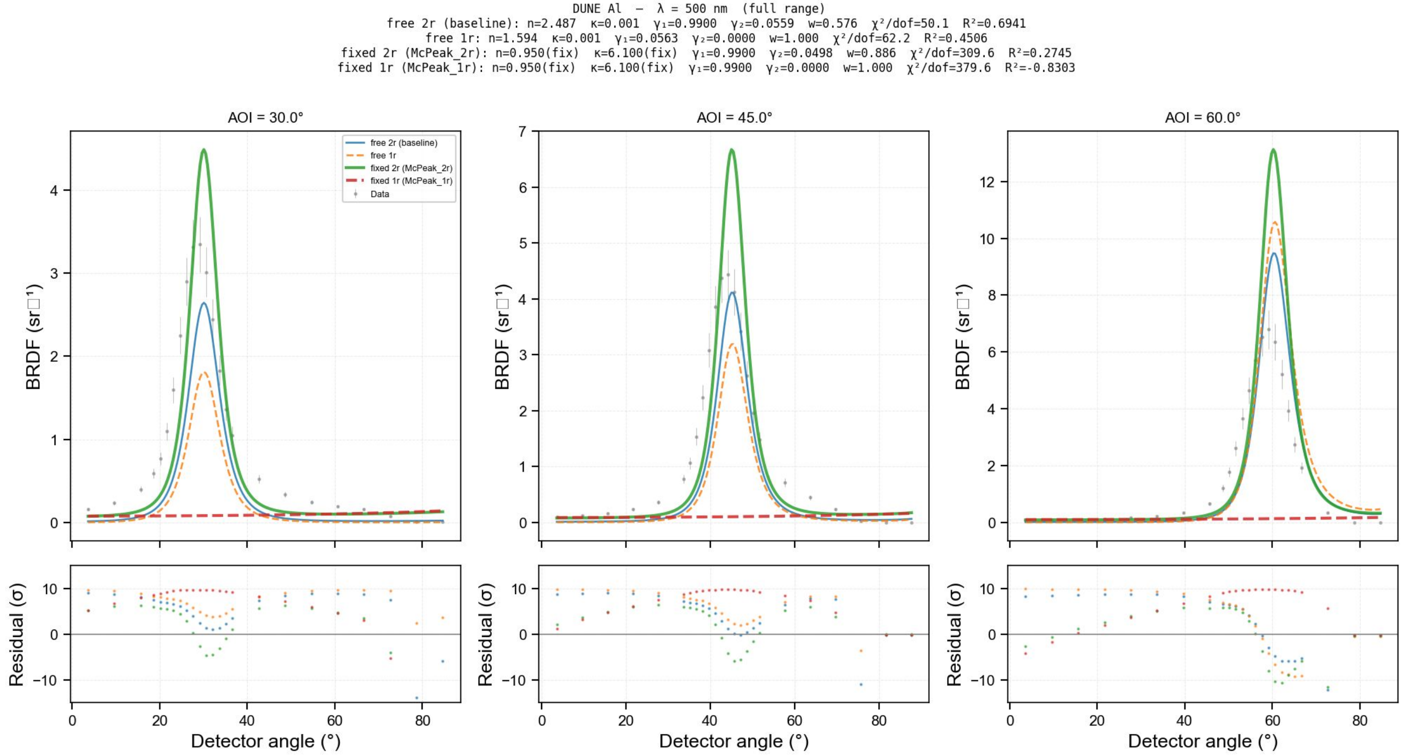

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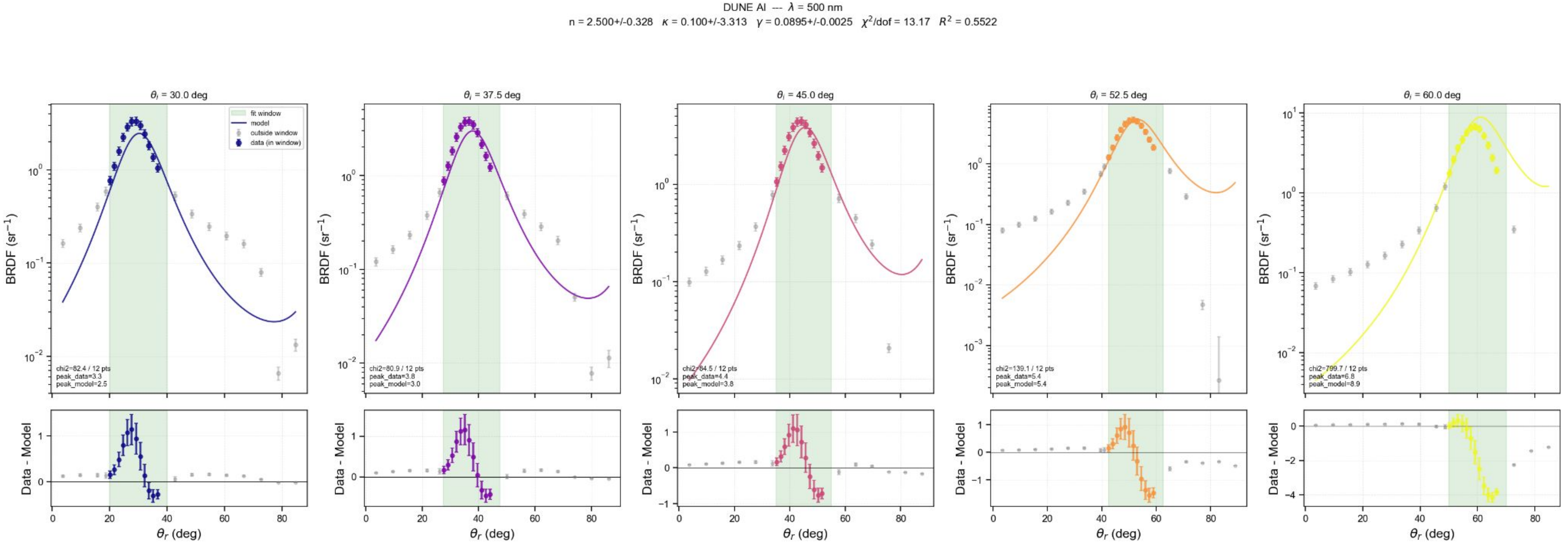

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