RadiCal

a radically new approach to model the impact of solar radiation

a physically accurate, flexible and efficient method to model solar-related energy flows

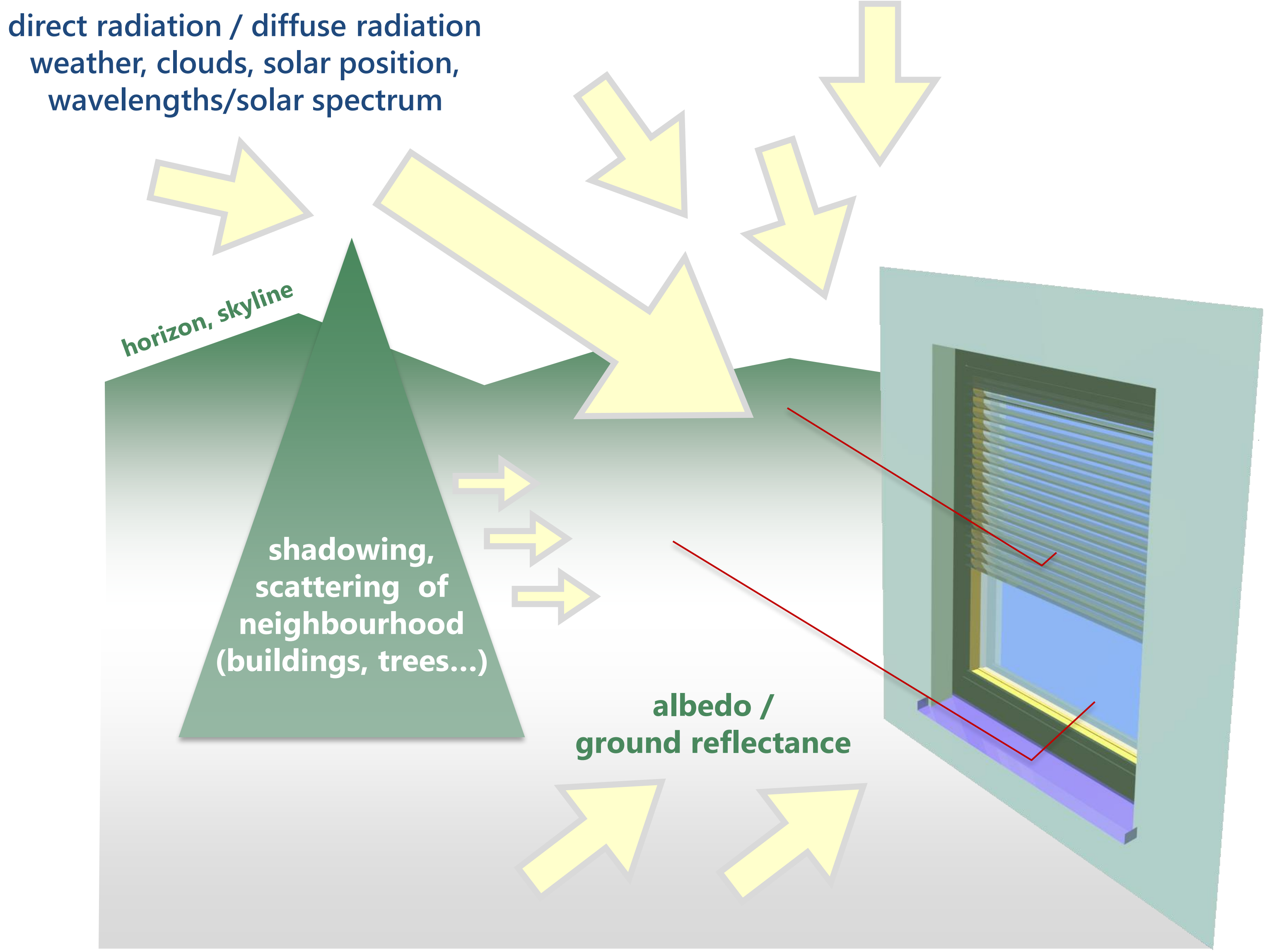
Graz University of Technology

AEE INTEC

Österreichische Forschungsförderungsgesellschaft

What is the problem?

The problem



shades, glazing,
façade, sill,...

complex
Light-surface
interactions

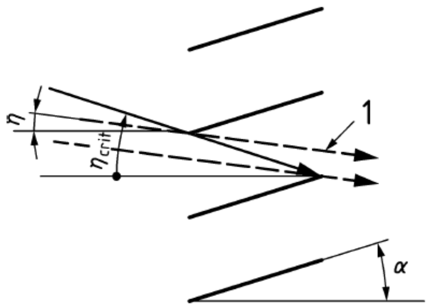
TRANSMISSION
ABSORPTION
REFLECTION

Angular dependency
Complex refractive index
Surface topography
(roughness)
Wavelength dependency
Polarization effects
Diffraction
...

What is the state of the art?

$$\tau_{\text{dir-dif}}(\eta) = \begin{cases} (1-\tau_{dir-dir}).\tau_{S,D}; & \text{if } \eta > -\alpha \\ (1-\tau^*_{dir-dir}).\tau^*_{S,D} & \text{else} \end{cases}$$

$$\rho_{\text{dir-dif}}(\eta) = \begin{cases} (1-\tau_{dir-dir}).\rho_{S,D}; & \text{if } \eta > -\alpha \\ (1-\tau^*_{dir-dir}).\rho^*_{S,D} & \text{else} \end{cases}$$



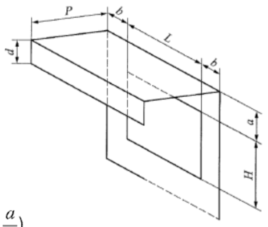


Bild C.2 — Auskragung, Hauptmaße

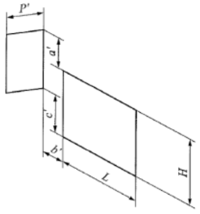


Bild C.3 — Seitenteil, Hauptmaße

$$A_{01} = 0$$

$$A_{02} = H \cdot L$$

$$A_{03} = L(T-a)$$

$$A_{04} = (T-a)\left[L + b - \frac{M\left(1+\frac{a}{T}\right)}{2}\right]$$

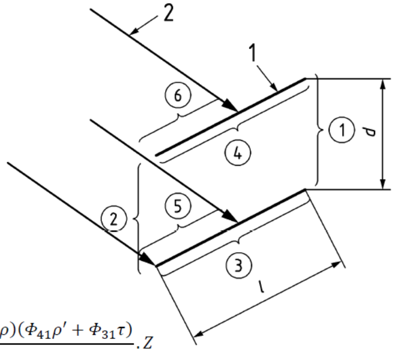
$$A_{05} = H\left\{L - \left[\left(a + \frac{H}{2}\right)\frac{M}{T}\right] + b\right\}$$

$$A_{06} = \left\{\left[(L+b)\frac{T}{M}\right] - a\right\}^2 \left(\frac{M}{2\,T}\right)$$

$$A_{07} = [(T-a)\ L] - \left[(M-b)^2\ \frac{T}{2\ M}\right]$$

$$A_{08} = H\ L - \left\{\left[(H+a)\ \frac{M}{T}\right] - b\right\}^2\ \frac{T}{2\ M}$$

$$A_{09} = L\ \left[\left(b + \frac{L}{2}\right)\frac{T}{M} - a\right]$$

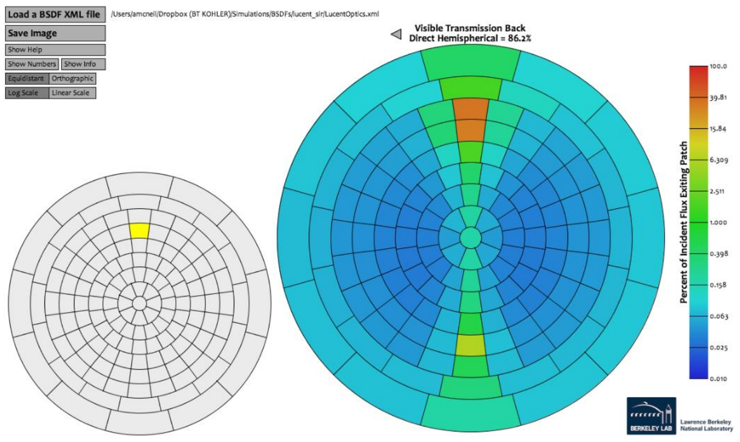


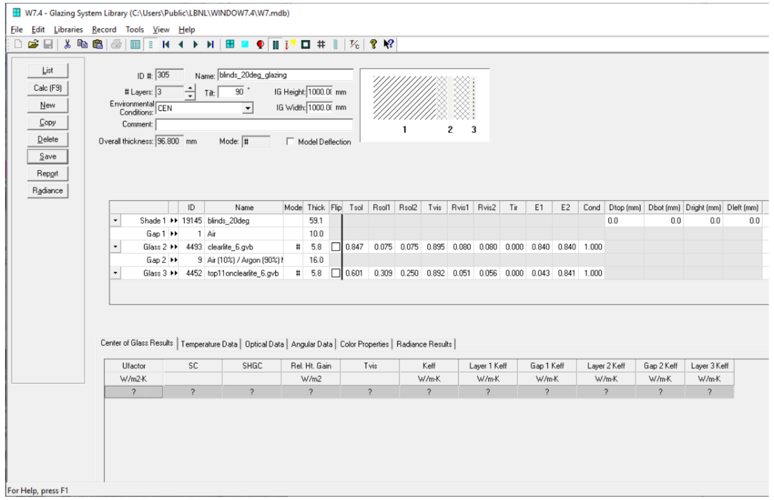
$$\tau_{S,D} = \Phi_{51}\rho + \Phi_{61}\tau + \frac{(Z\Phi_{54}\rho' + \Phi_{63}\tau)(\Phi_{31}\rho + \Phi_{41}\tau) + (Z\Phi_{63}\tau + \Phi_{54}\rho)(\Phi_{41}\rho' + \Phi_{31}\tau)}{\Phi_{34}\rho(1-ZZ')}.Z$$

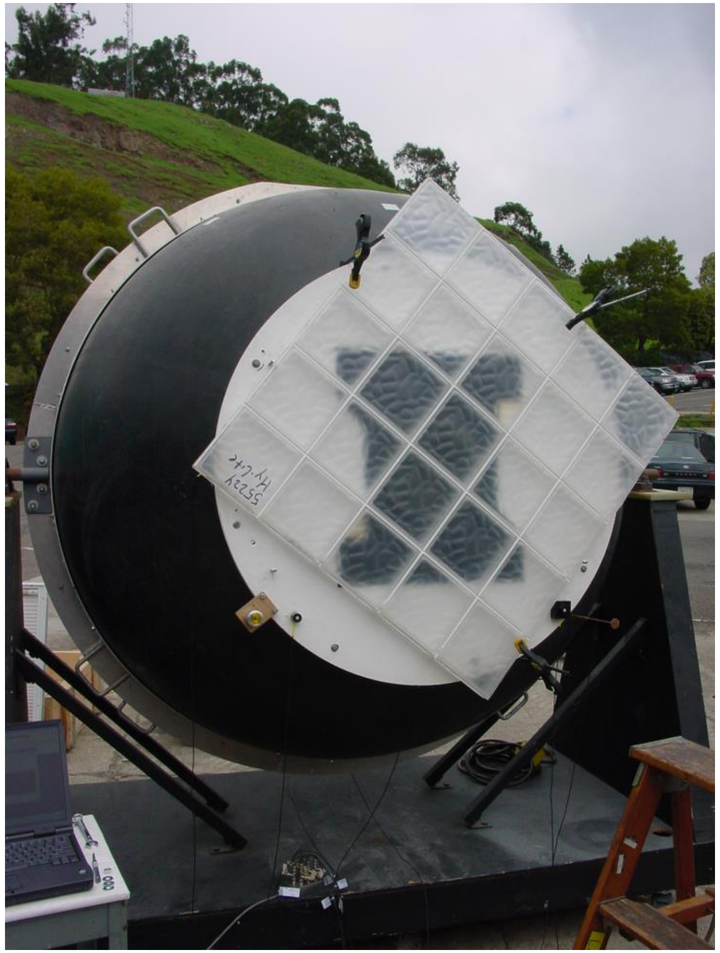
$$\rho_{S,D} = \Phi_{52}\rho + \Phi_{62}\tau + \frac{(Z\Phi_{54}\rho' + \Phi_{63}\tau)(\Phi_{32}\rho + \Phi_{42}\tau) + (Z\Phi_{63}\tau + \Phi_{54}\rho)(\Phi_{42}\rho' + \Phi_{32}\tau)}{\Phi_{34}\rho(1-ZZ')}.Z$$

$$\tau^*_{S,D} = \Phi_{61}\rho' + \Phi_{51}\tau + \frac{(Z'\Phi_{54}\tau + \Phi_{63}\rho')(\Phi_{31}\rho + \Phi_{41}\tau) + (Z'\Phi_{63}\rho + \Phi_{54}\tau)(\Phi_{41}\rho' + \Phi_{31}\tau)}{\Phi_{34}\rho'(1-ZZ')}.Z'$$

$$\rho^*_{S,D} = \Phi_{62}\rho' + \Phi_{52}\tau + \frac{(Z'\Phi_{54}\tau + \Phi_{63}\rho')(\Phi_{32}\rho + \Phi_{42}\tau) + (Z'\Phi_{63}\rho + \Phi_{54}\tau)(\Phi_{42}\rho' + \Phi_{32}\tau)}{\Phi_{34}\rho'(1-ZZ')}.Z'$$







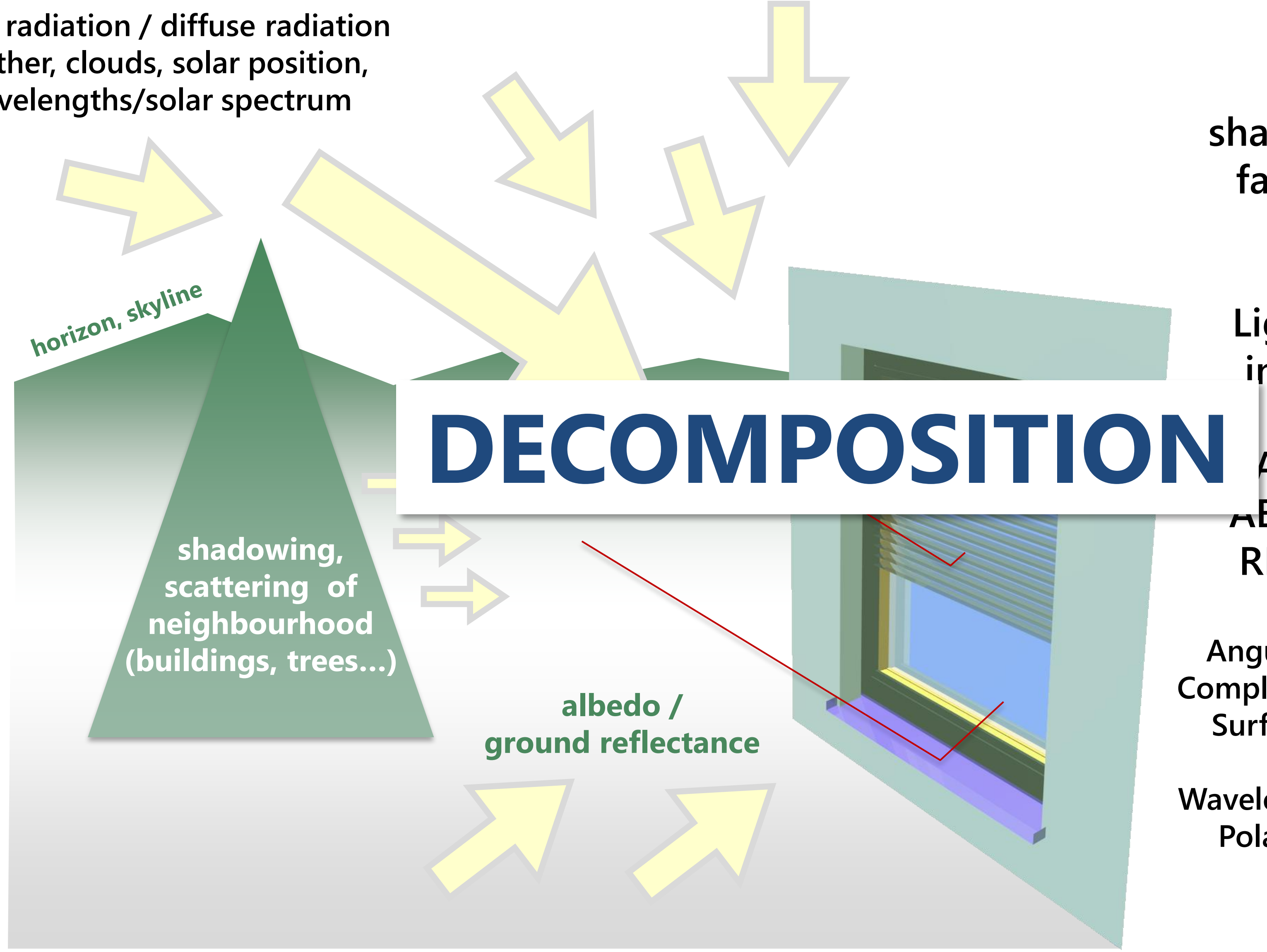
© LBNL - large integrating sphere

© Fraunhofer IBP – sun simulator

What is my solution?

The problem

direct radiation / diffuse radiation
weather, clouds, solar position,
wavelengths/solar spectrum



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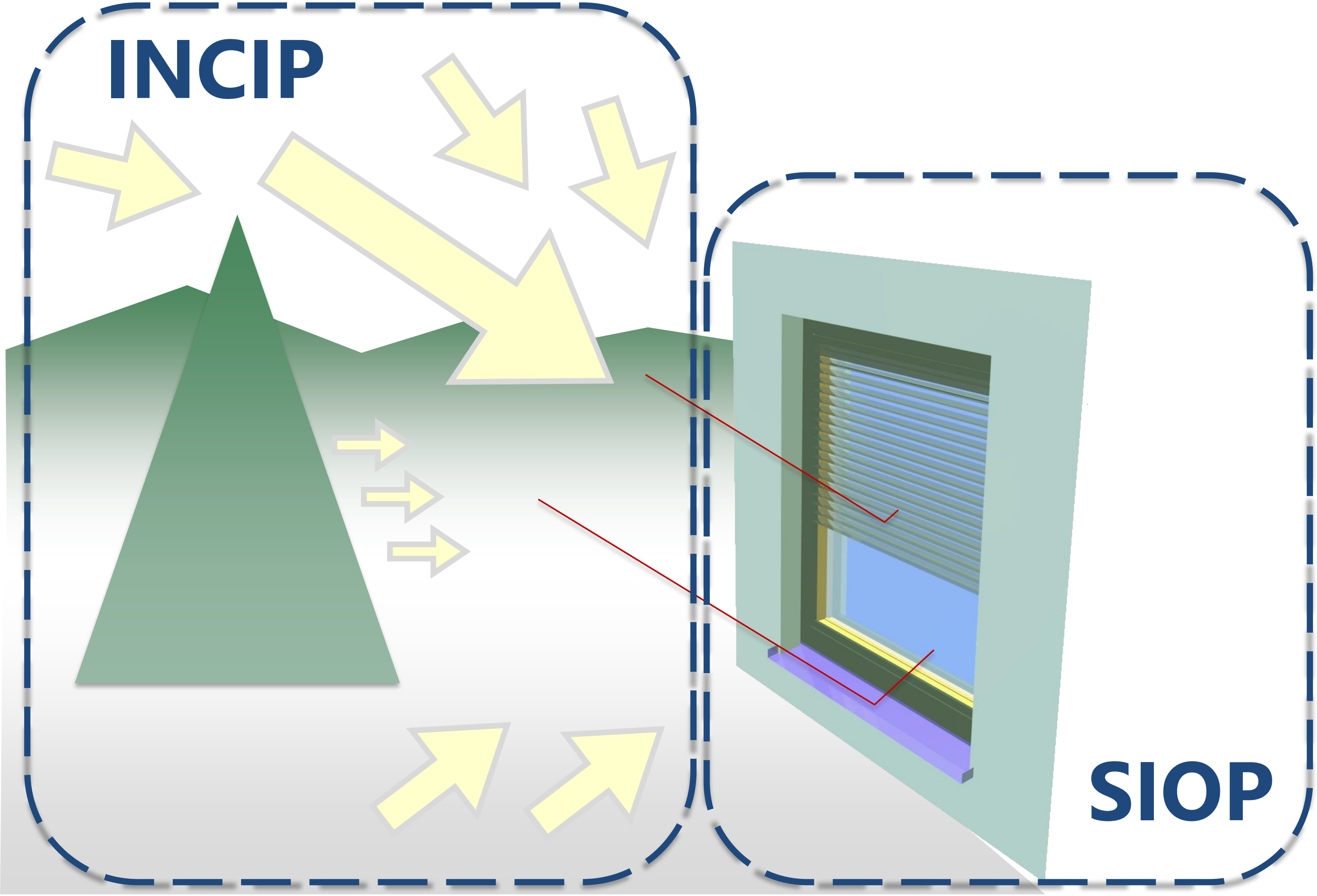
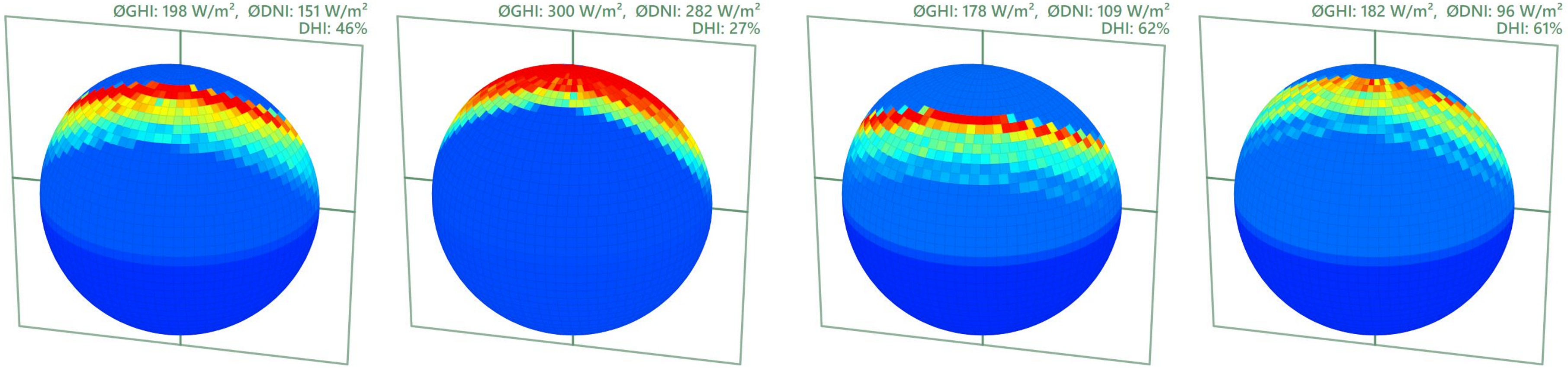
Decomposition SENDER / RECEIVER



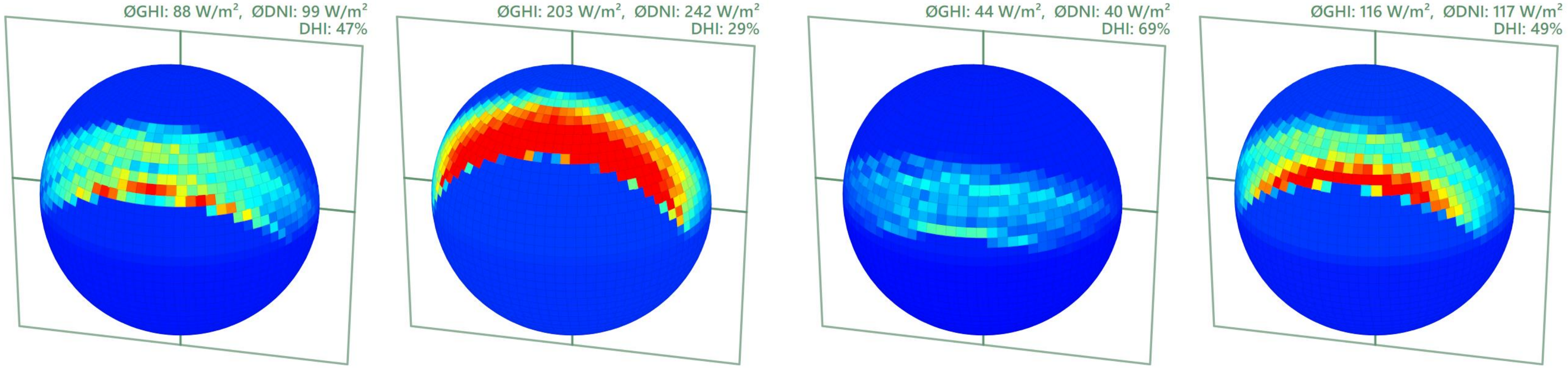
Half-year INCIPs – World (south, clear horizon)

SUMMER



New York | Abu Dhabi | Moscow | Tokyo

WINTER



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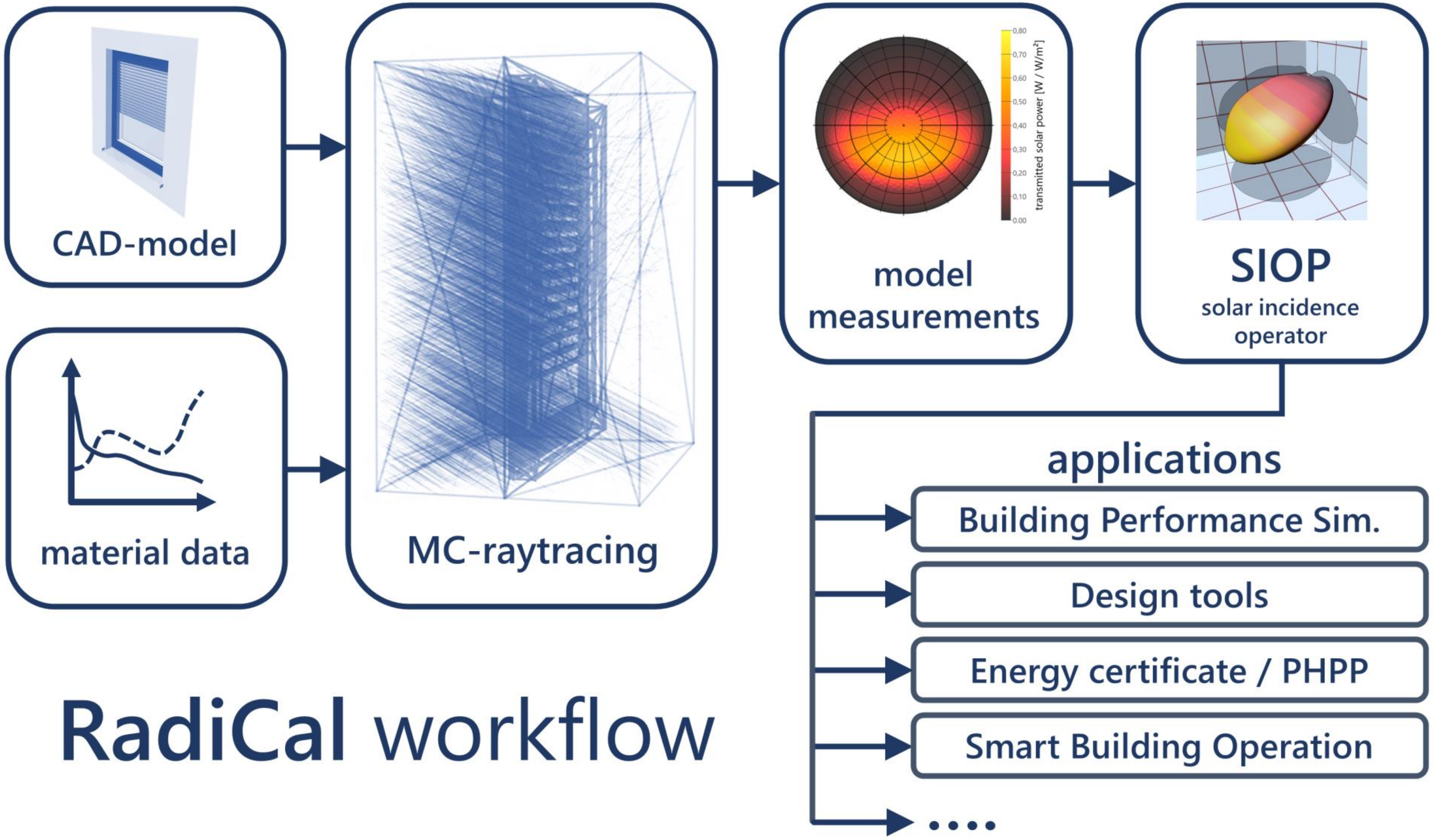
SIOP – Solar Incidence Operator

- used to evaluate the effect of a INCIP on the target (window, façade,…)

- can describe various physical quantities of interest:
  - **transmitted power (energy)**
  - **absorbed power (energy)**
  - reflected power
  - spectral power
  - light engineering params (illuminance, lum. intensity)
  - glare
  - directional information
  - …

RadiCal workflow and SIOP

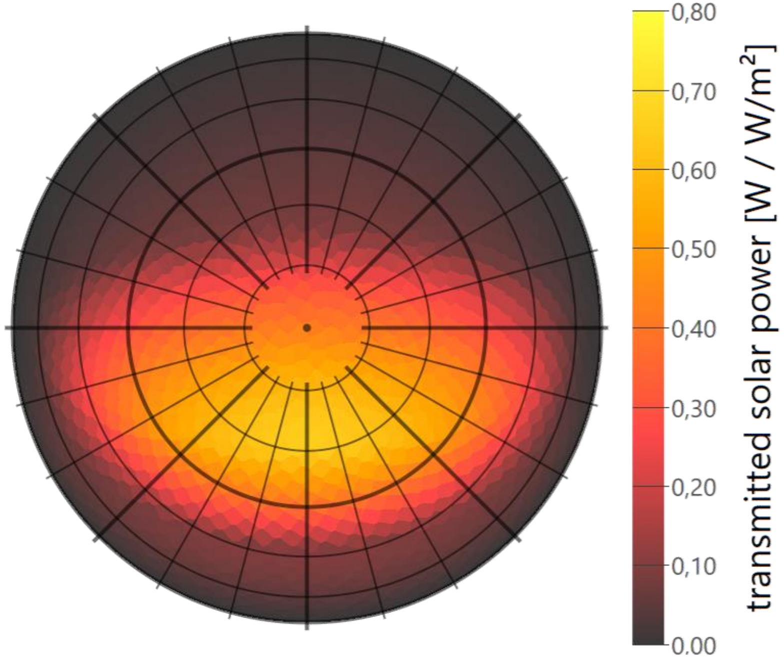


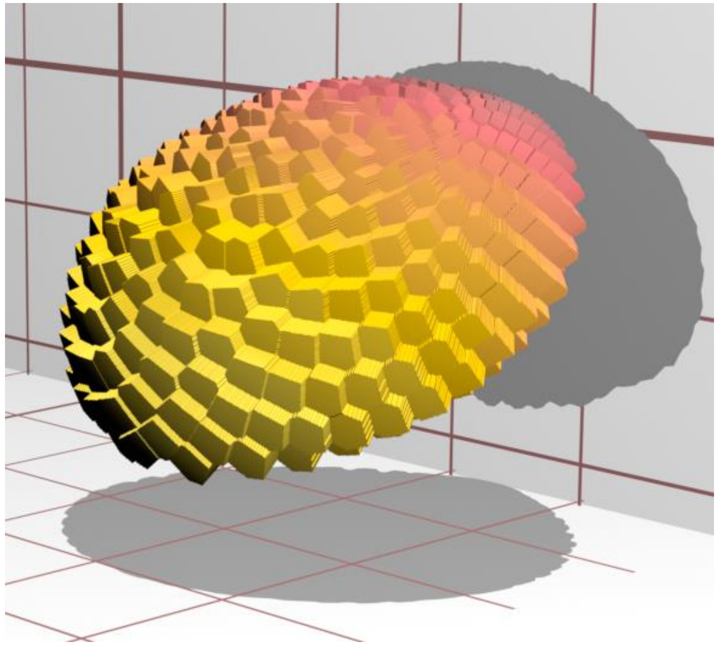
How is it different?

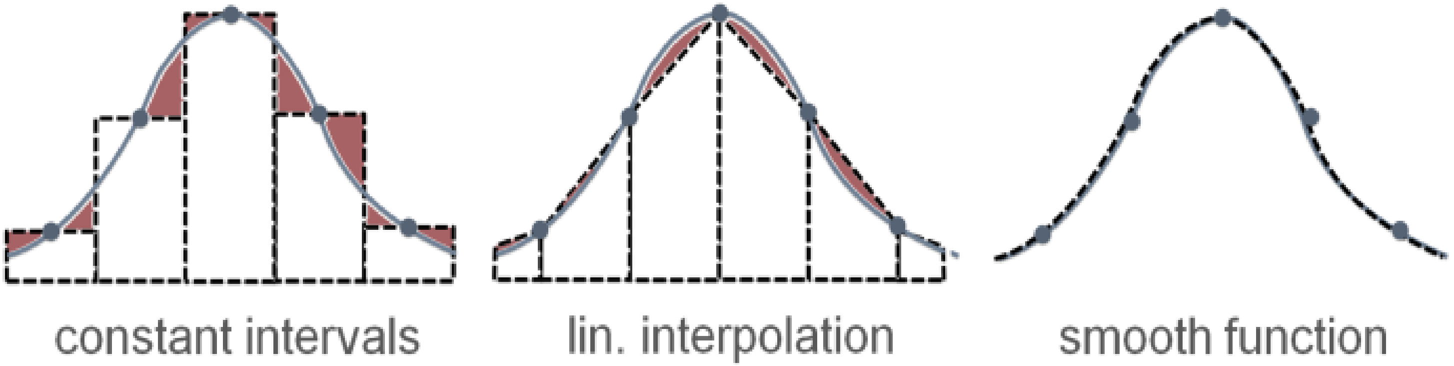
→ Physically based raytracing

→ SIOP - functional form

SIOP – raw data







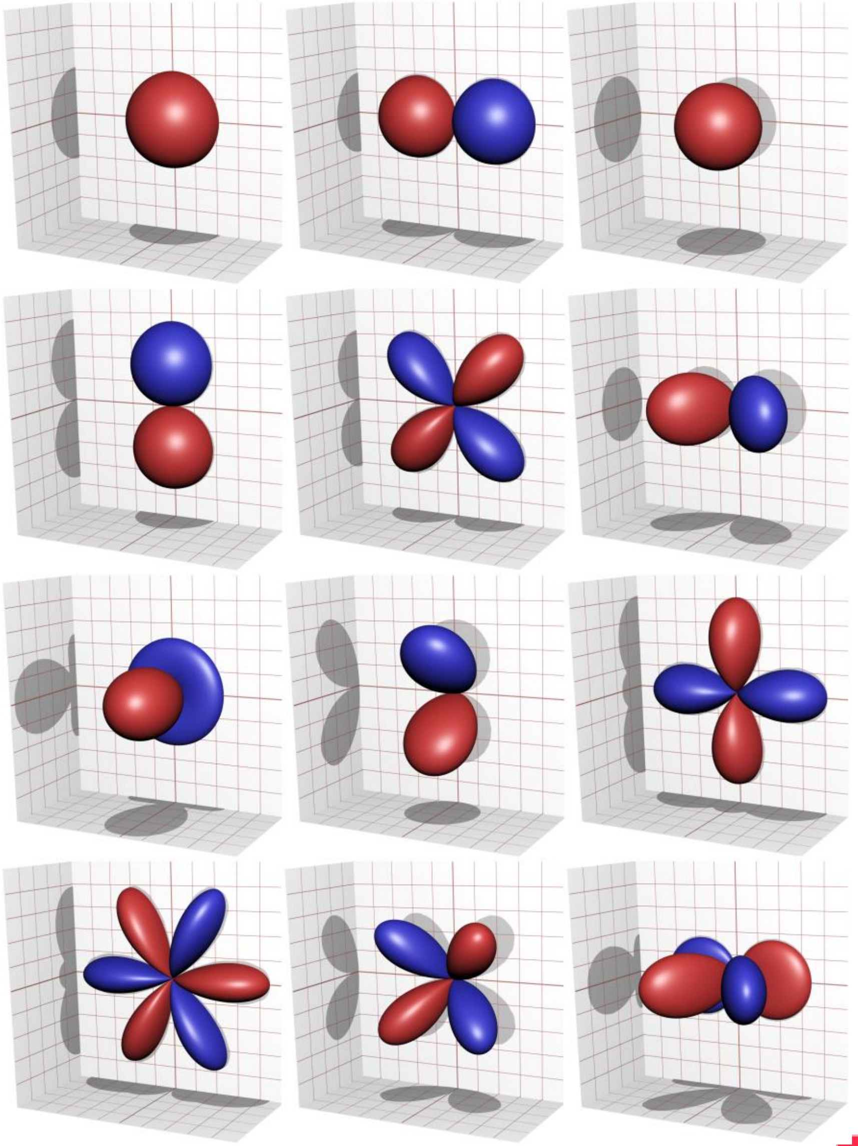
SIOP – functional form

spherical harmonics expansion

$$Y_{lm}(\theta,\varphi) = C_l^m \cdot P_l^m(\cos\theta) \cdot e^{im\varphi}$$

$$C_l^m = \sqrt{\frac{2l+1}{4\pi}\frac{(l-m)!}{(l+m)!}}$$

$$SIOP(\theta,\varphi) = \sum_{j=0}^{jmax} s_j\, YR_j(\theta,\varphi)$$

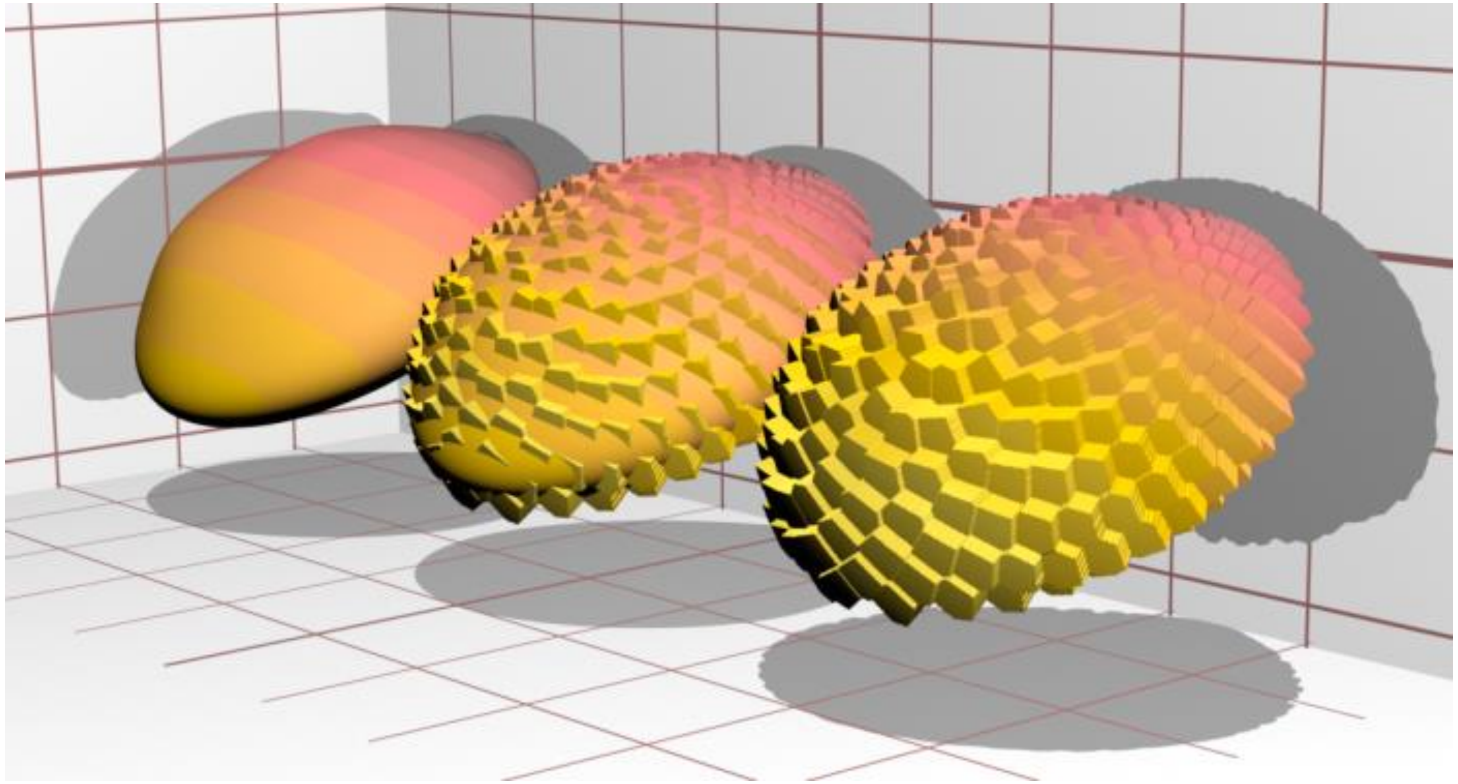


deployment (e.g. XML):

$$SIOP = \{\, (j_1, c_1), (j_2, c_2) \ldots (j_n, c_n)\}$$

SIOP functional form

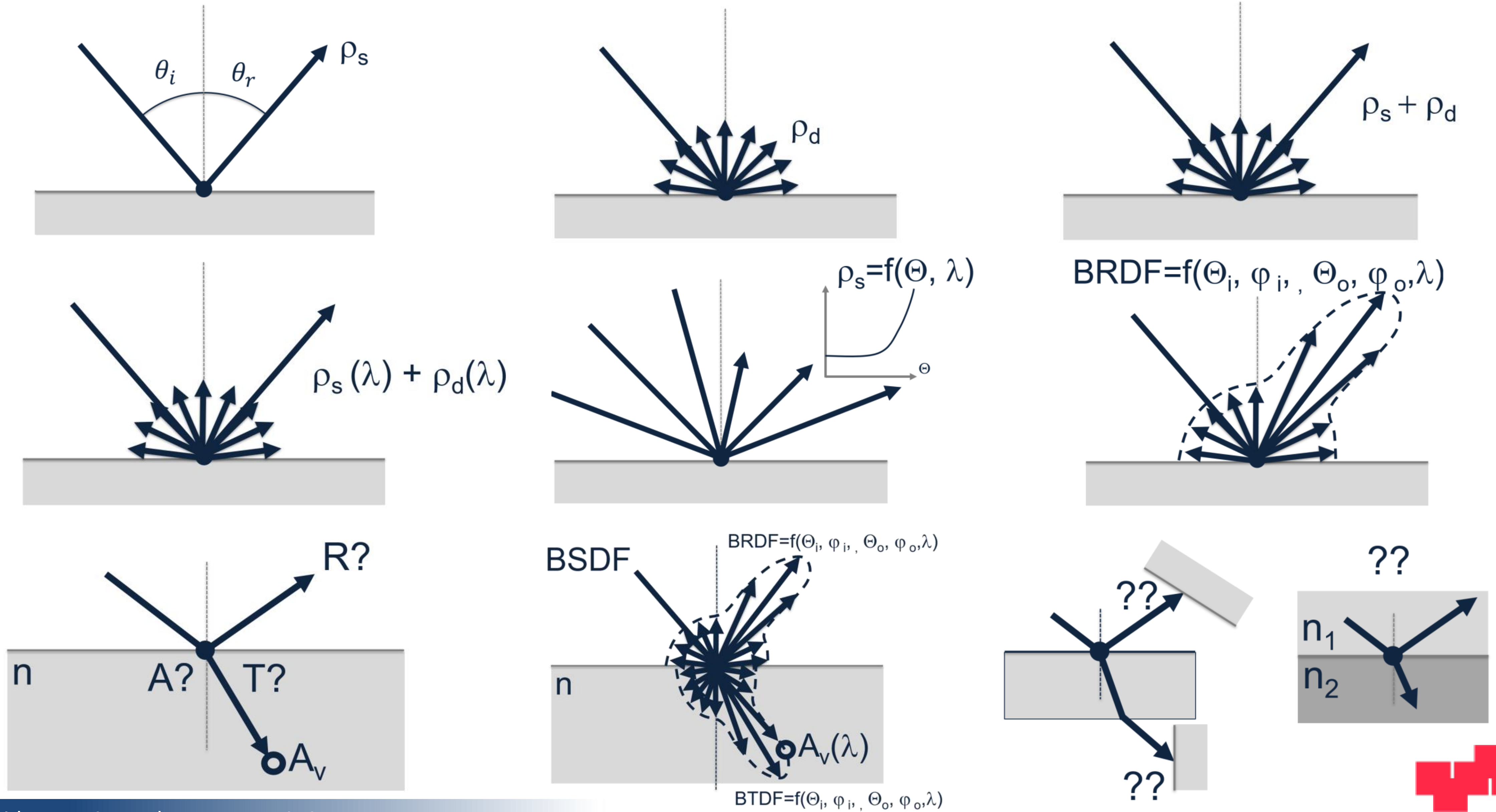
coefficients are determined **by non-linear optimization**



smooth form

1440(!) samples/
discrete directions

Empirical scattering models

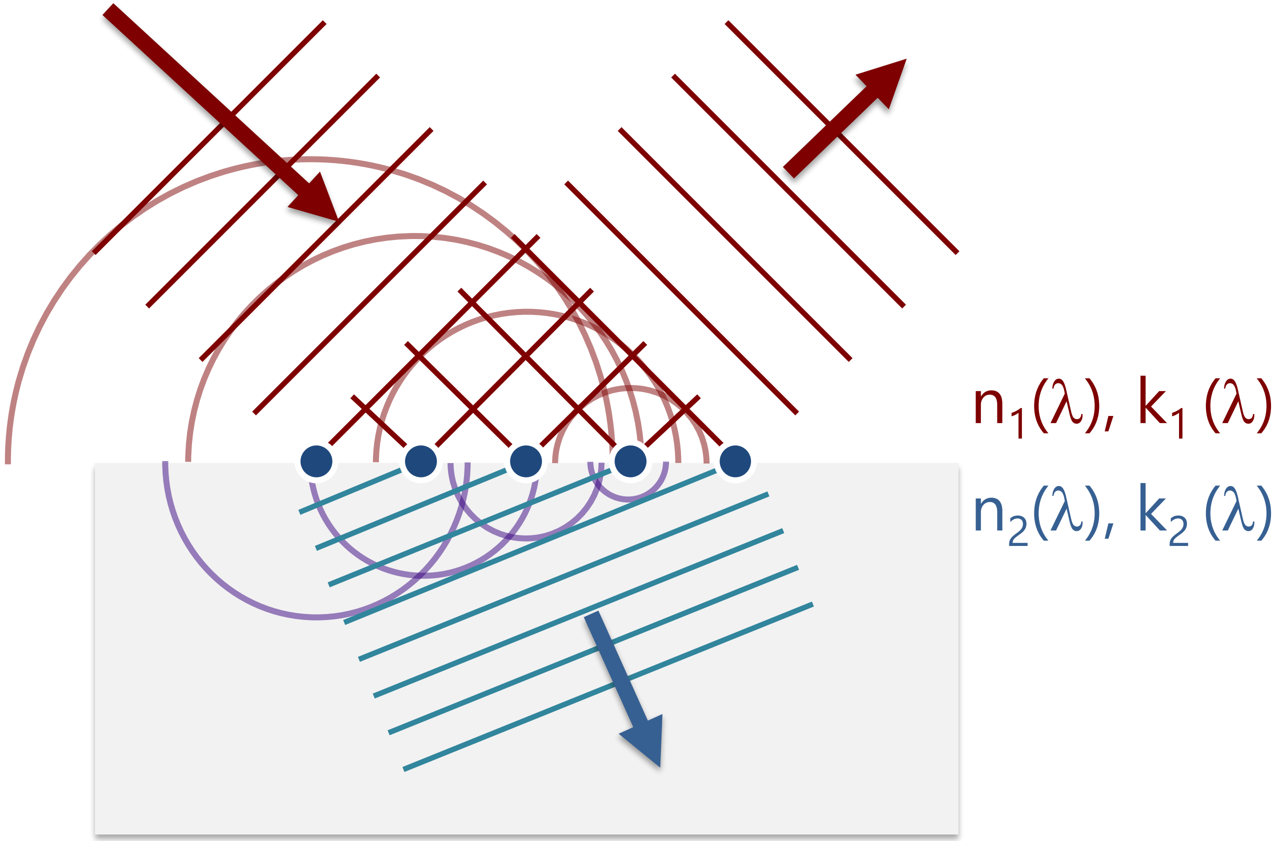


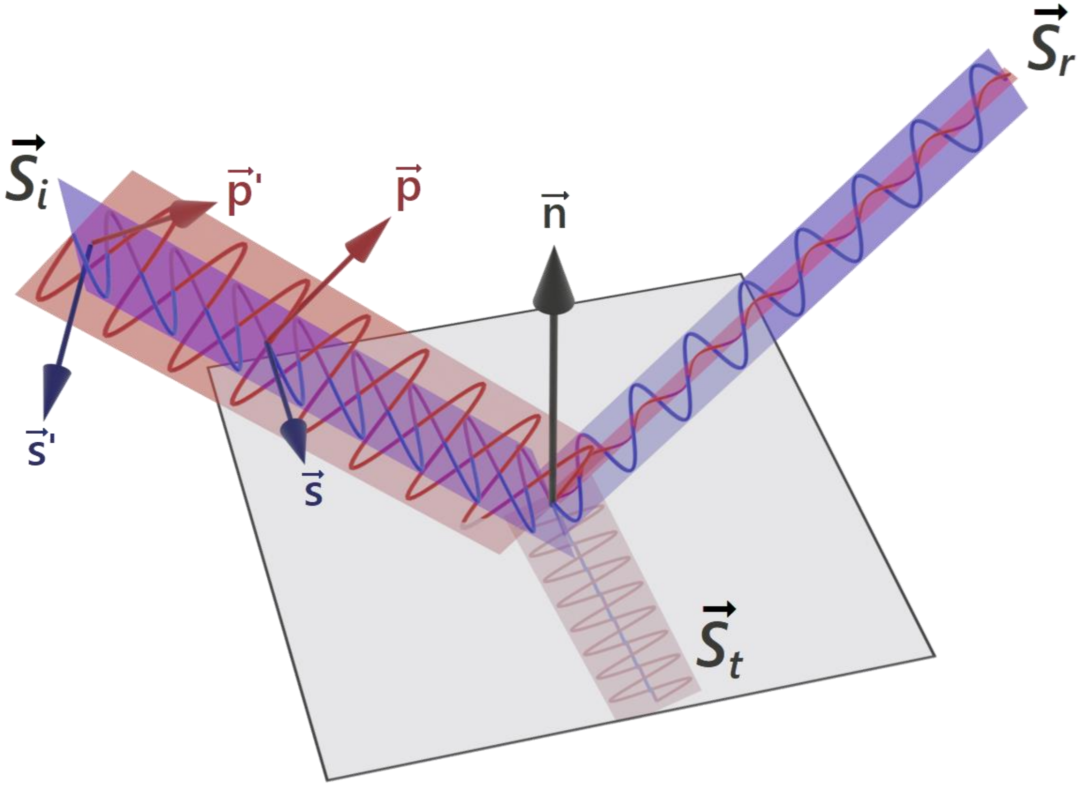
Scattering of light – empirical models

→ Empirical models quickly „explode“
They get too complex and require too many parameters and patches (i.e. additional models)

→ Check underlying physics and
create a physically-based model that can cover „most“ cases

Electrodynamics – physical optics

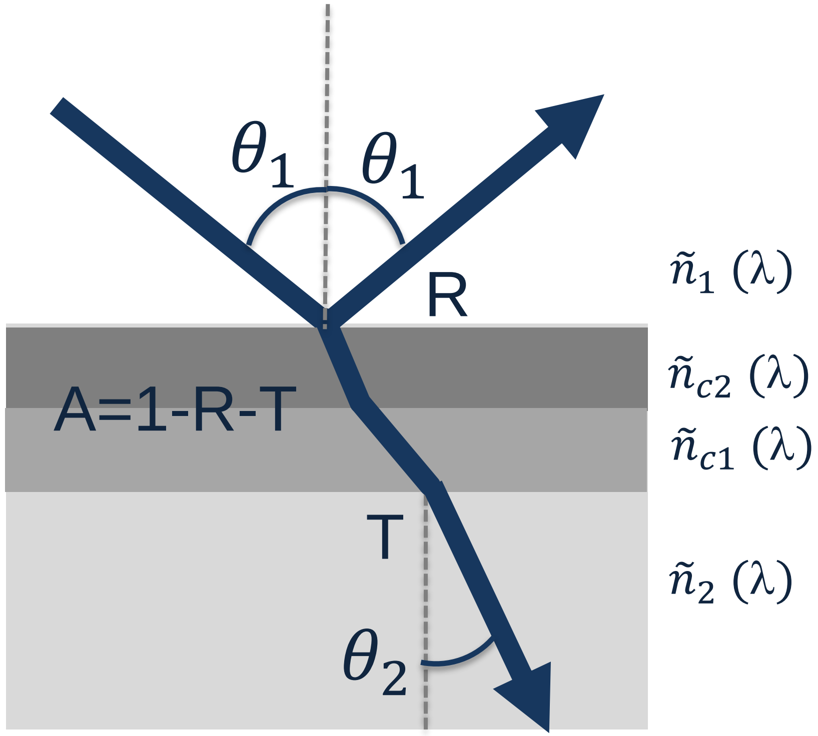




Electrodynamics – physical optics

→ many effects arise naturally now:

- → R, T, A intensities
- → angle of refraction
- → volumetric absorption
- → wavelength dependencies
  (entire global radiation spectrum
  is simulated!)
- → angular dependencies
- → polarisation effects



Complex-valued Fresnel equations

$$\tilde{n}_i(\lambda) = n_i(\lambda) - i \cdot k_i(\lambda)$$

$$sin(\tilde{\theta}_2) = \frac{\tilde{n}_1}{\tilde{n}_2} sin(\tilde{\theta}_1)$$

$$\tilde{\eta}_i^{\,s} = \tilde{n}_i \, cos(\tilde{\theta}_i) \qquad \tilde{\eta}_i^{\,p} = \frac{\tilde{n}_i}{cos(\tilde{\theta}_i)}$$

$$\tilde{r}_{1\to 2}^{\,s,p} = \frac{\tilde{\eta}_1^{\,s,p}\,\tilde{E}_1^{\,s,p} - \tilde{H}_1^{\,s,p}}{\tilde{\eta}_1^{\,s,p}\,\tilde{E}_1^{\,s,p} + \tilde{H}_1^{\,s,p}}$$

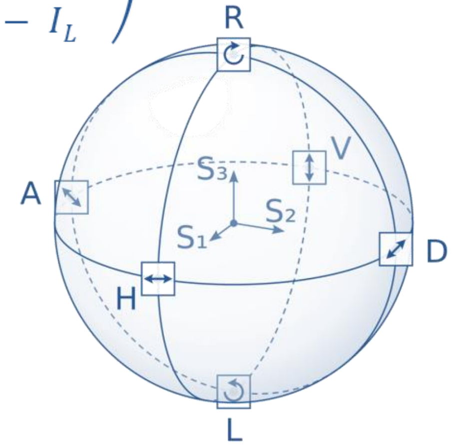
$$\tilde{t}_{1\to 2}^{\,s,p} = \frac{2\tilde{\eta}_1^{\,s,p}}{\tilde{\eta}_1^{\,s,p}\,\tilde{E}_1^{\,s,p} + \tilde{H}_1^{\,s,p}}$$

$$T_{1\to 2}^{s,p} = \left|\tilde{t}_{1\to 2}^{\,s,p}\right|^2 \qquad \epsilon_{t1\to 2}^{s,p} = arg\left(\tilde{t}_{1\to 2}^{\,s,p}\right)$$

$$R_{1\to 2}^{s,p} = \left|\tilde{r}_{1\to 2}^{\,s,p}\right|^2 \qquad \epsilon_{r1\to 2}^{s,p} = arg\left(\tilde{r}_{1\to 2}^{\,s,p}\right)$$

Stokes formalism

$$\vec{S} = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} = \begin{pmatrix} \langle E_x^2 \rangle + \langle E_y^2 \rangle \\ \langle E_x^2 \rangle - \langle E_y^2 \rangle \\ \langle 2E_x E_y cos\delta \rangle \\ \langle 2E_x E_y sin\delta \rangle \end{pmatrix} = \begin{pmatrix} I_{0^\circ} + I_{90^\circ} \\ I_{0^\circ} - I_{90^\circ} \\ I_{45^\circ} - I_{135^\circ} \\ I_R - I_L \end{pmatrix}$$



$$\vec{S} = \vec{S}' \cdot R(\varphi) = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(2\varphi) & \sin(2\varphi) & 0 \\ 0 & -\sin(2\varphi) & \cos(2\varphi) & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\vec{S}_t = \vec{S}_i \cdot M_T = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} \begin{pmatrix} 1/2\,(T_s + T_p) & 1/2\,(T_s - T_p) & 0 & 0 \\ 1/2\,(T_s - T_p) & 1/2\,(T_s + T_p) & 0 & 0 \\ 0 & 0 & \sqrt{T_p T_s}\,cos(\epsilon_p - \epsilon_s) & \sqrt{T_p T_s}\,sin(\epsilon_p - \epsilon_s) \\ 0 & 0 & -\sqrt{T_p T_s}\,sin(\epsilon_p - \epsilon_s) & \sqrt{T_p T_s}\,cos(\epsilon_p - \epsilon_s) \end{pmatrix}$$

$$\vec{S}_r = \vec{S}_i \cdot M_R = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} \begin{pmatrix} 1/2\,(R_s + R_p) & 1/2\,(R_s - R_p) & 0 & 0 \\ 1/2\,(R_s - R_p) & 1/2\,(R_s + R_p) & 0 & 0 \\ 0 & 0 & -\sqrt{R_p R_s}\,cos(\epsilon_p - \epsilon_s) & -\sqrt{R_p R_s}\,sin(\epsilon_p - \epsilon_s) \\ 0 & 0 & \sqrt{R_p R_s}\,sin(\epsilon_p - \epsilon_s) & -\sqrt{R_p R_s}\,cos(\epsilon_p - \epsilon_s) \end{pmatrix}$$

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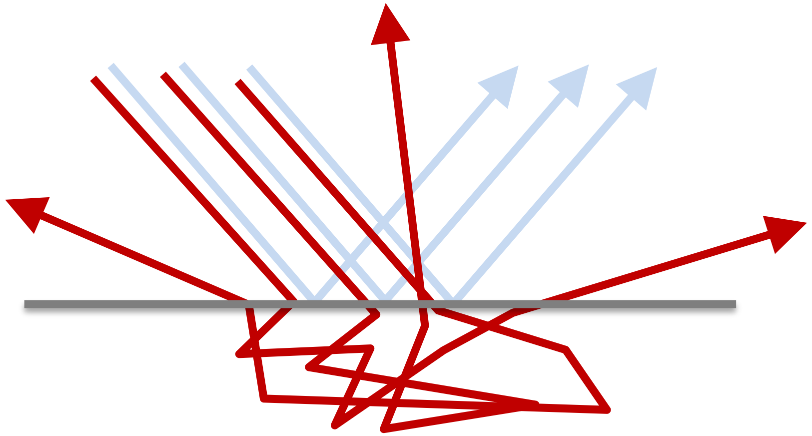
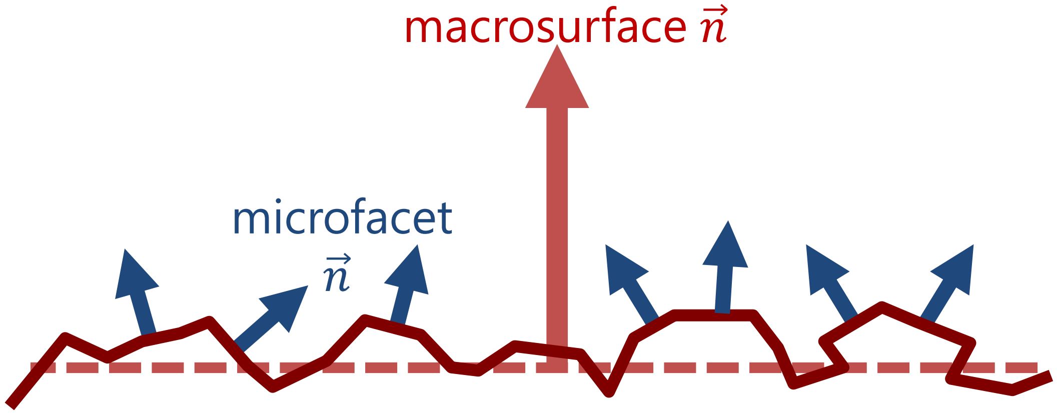
Additonally required models

sub-surface scattering



roughness microfacet-theory



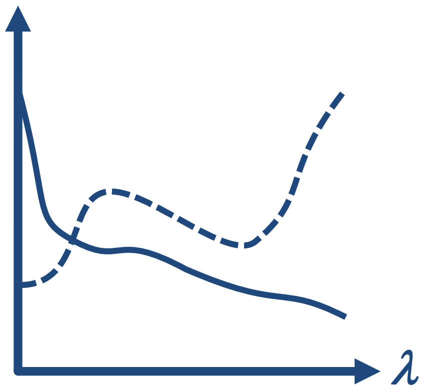
The LSISRoughPol model

generic, physically based light-surface interaction model for many opaque and transparent materials.

simply defined by:

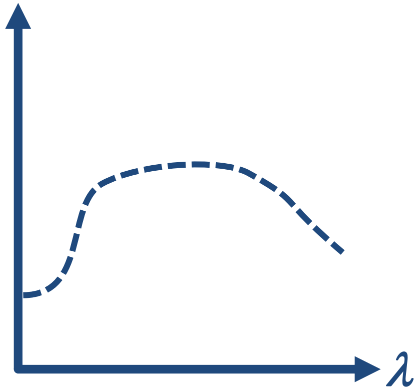
index of refraction complex-valued

$\tilde{\boldsymbol{n}}(\lambda) = \boldsymbol{n}(\lambda) - \boldsymbol{i}\,\boldsymbol{k}(\lambda)$



diffuse subsurface refl.

$\rho(\lambda)$

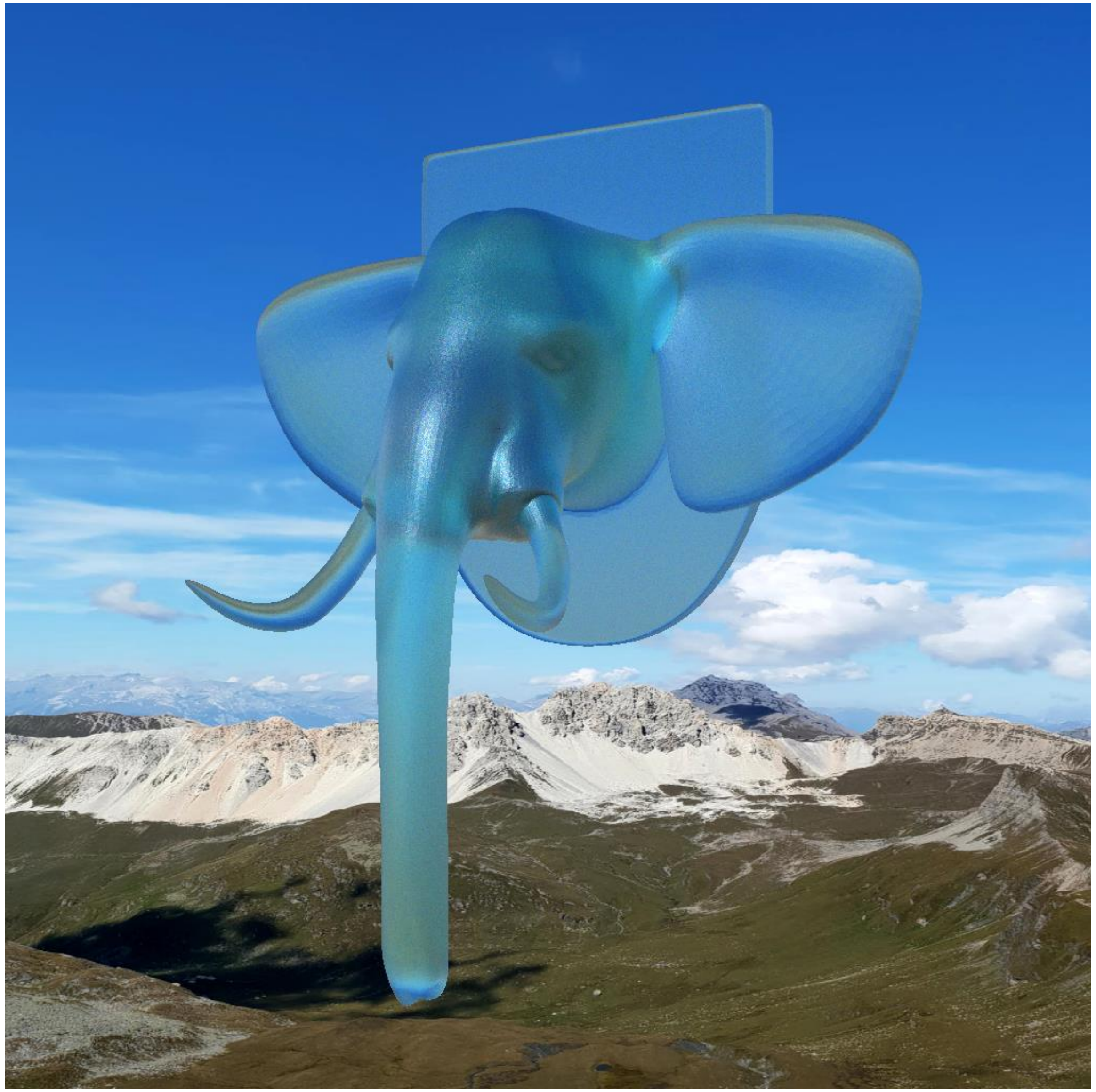


surface roughness

α

0..1

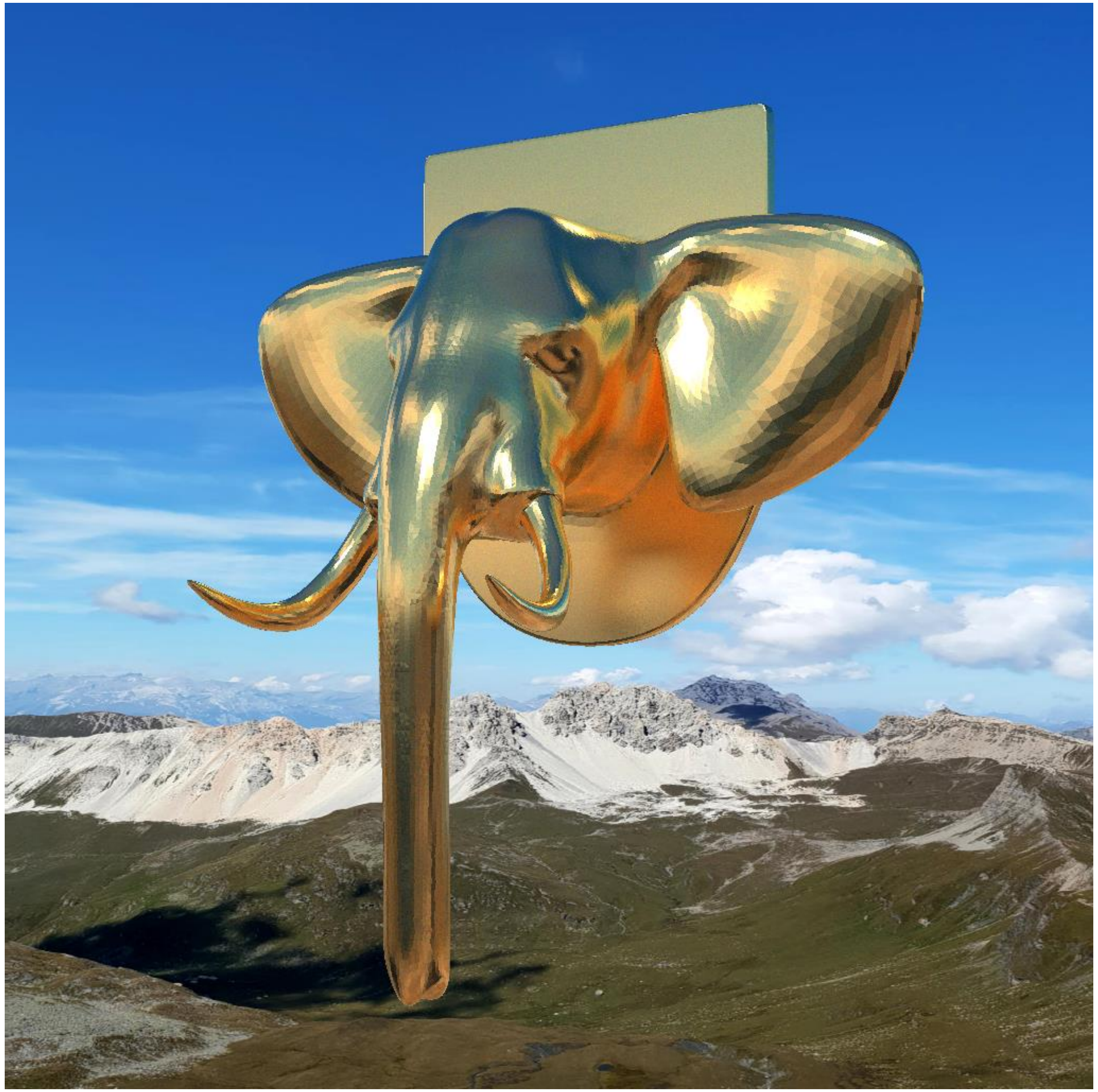
Generic material model demo – surface roughness variation

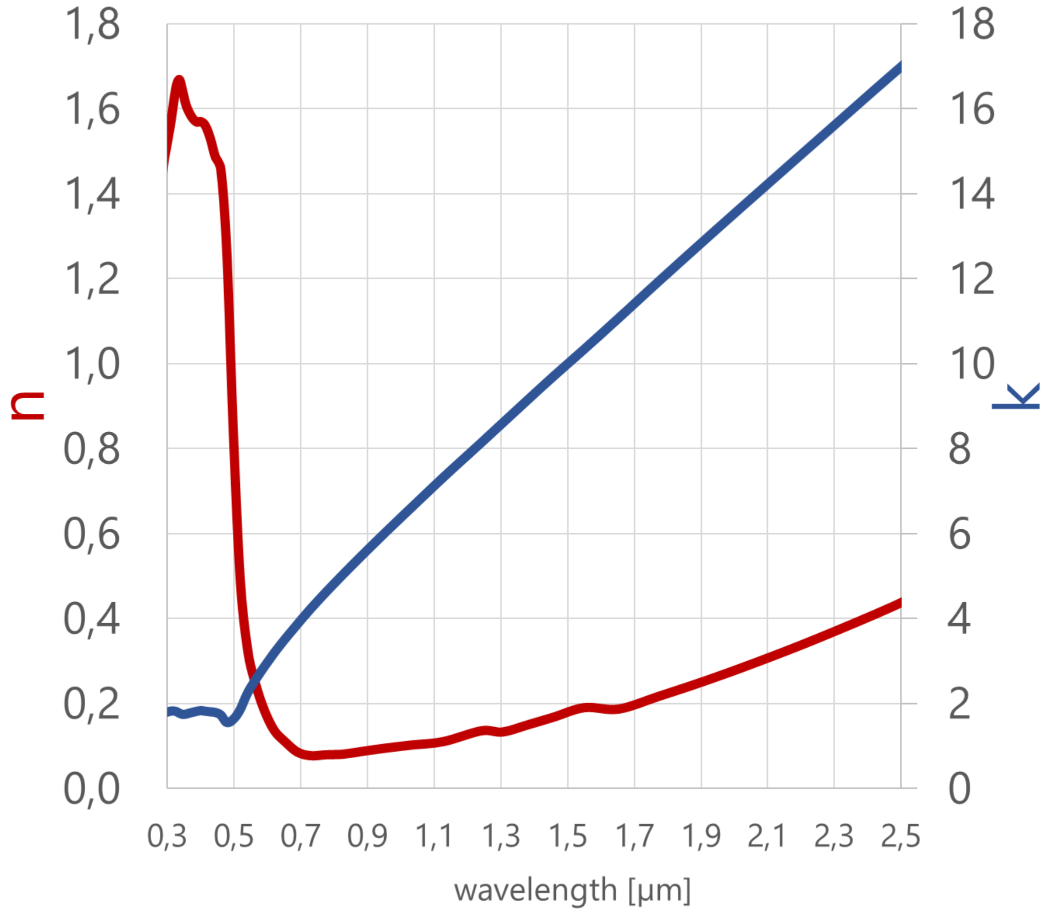


α = **0,20**

n(λ), k (λ) = **float glass**

Generic material model demo – refractive index variation



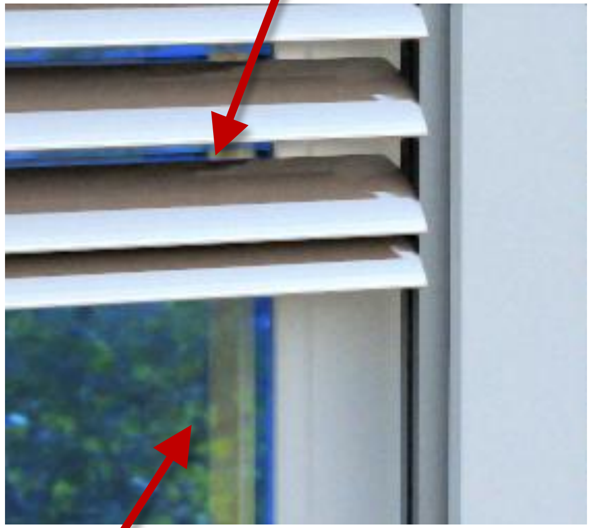


$n(\lambda)$, $k(\lambda)$ = **gold**

α = **0,05**

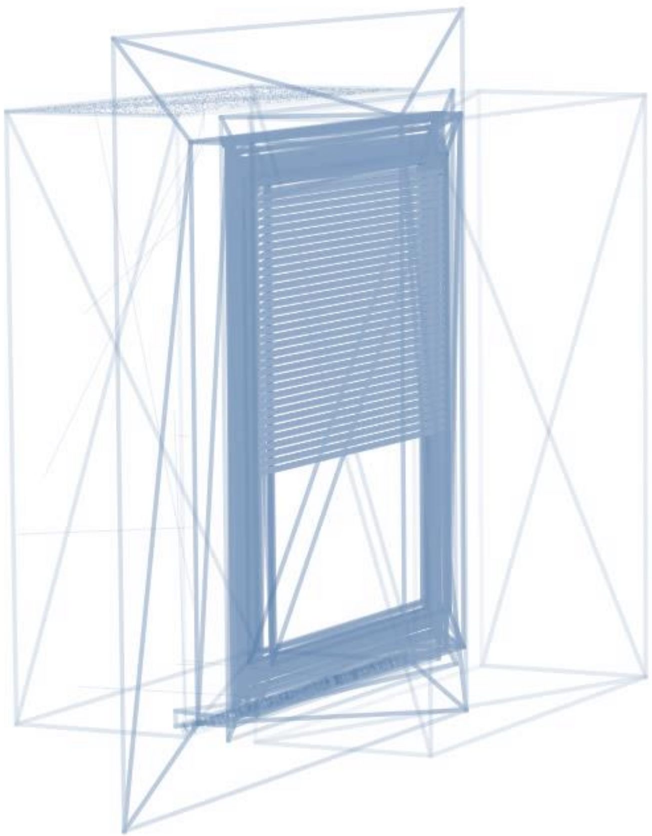
Demo Renderings
using RadiCal in backward-raytracing mode

interreflections

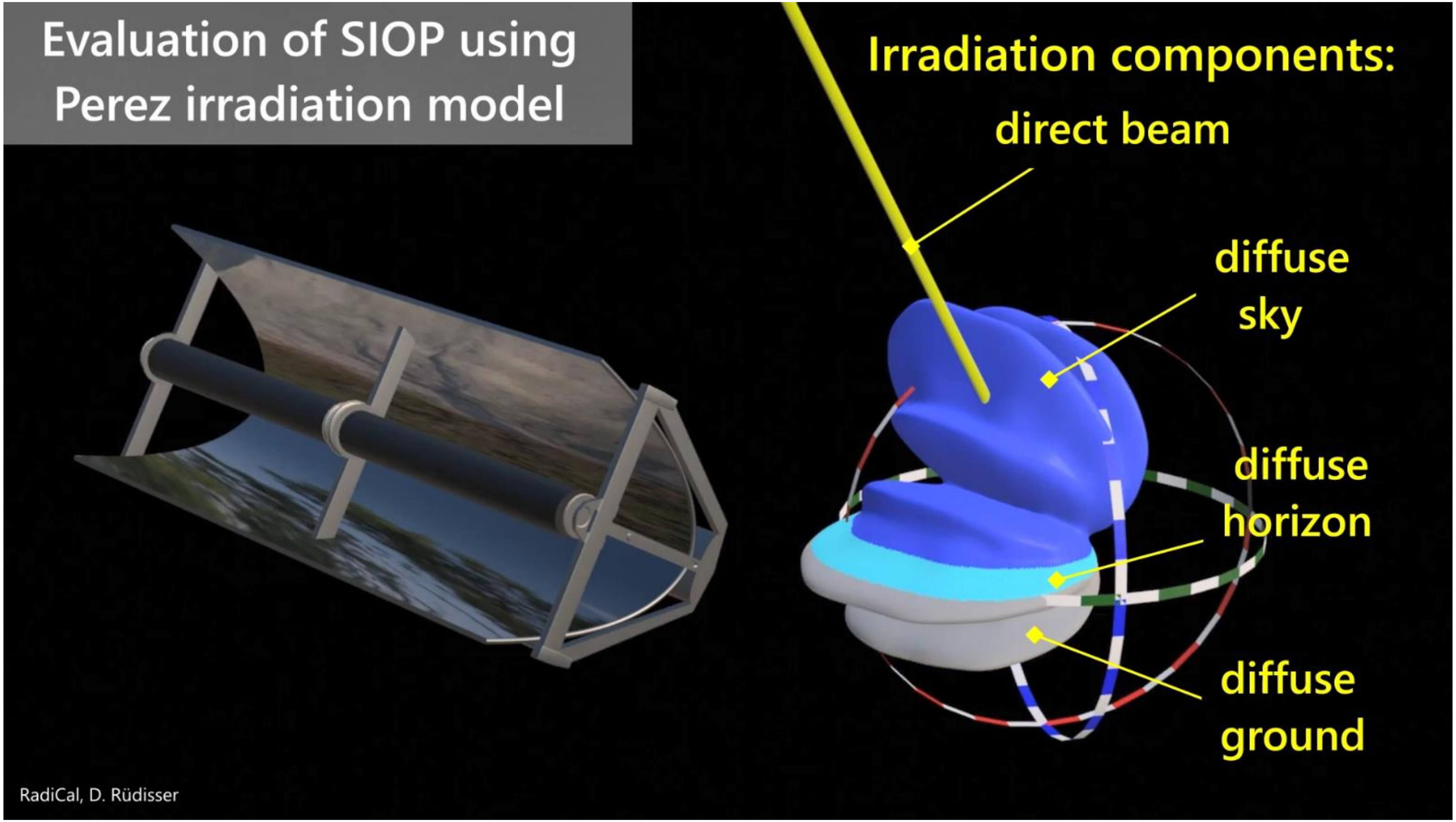


Accurate modeling of
coated triple glazing

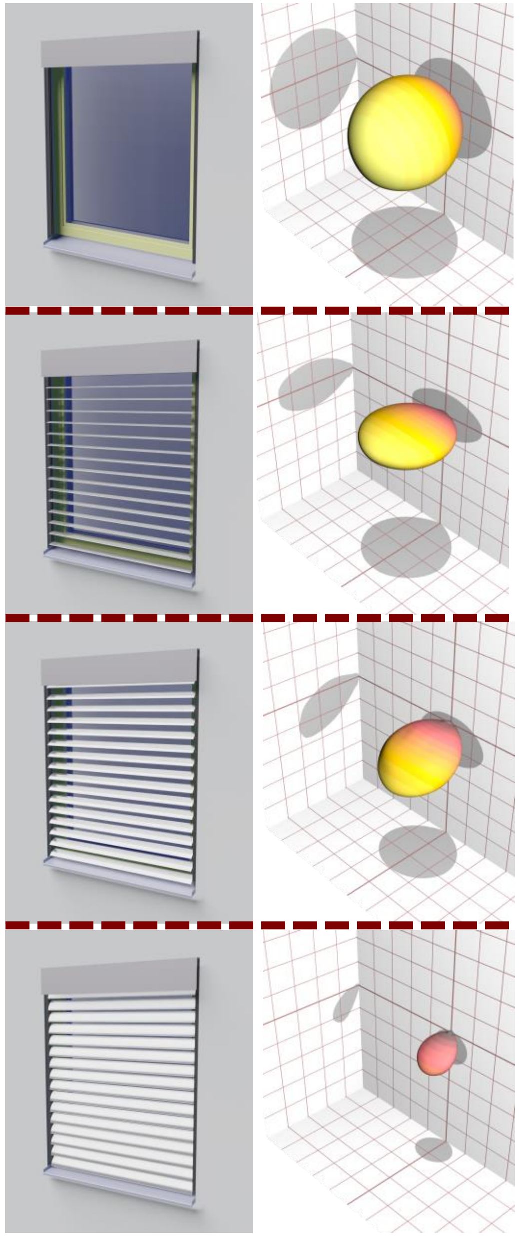
MC-Raytracer – sampling SIOP data

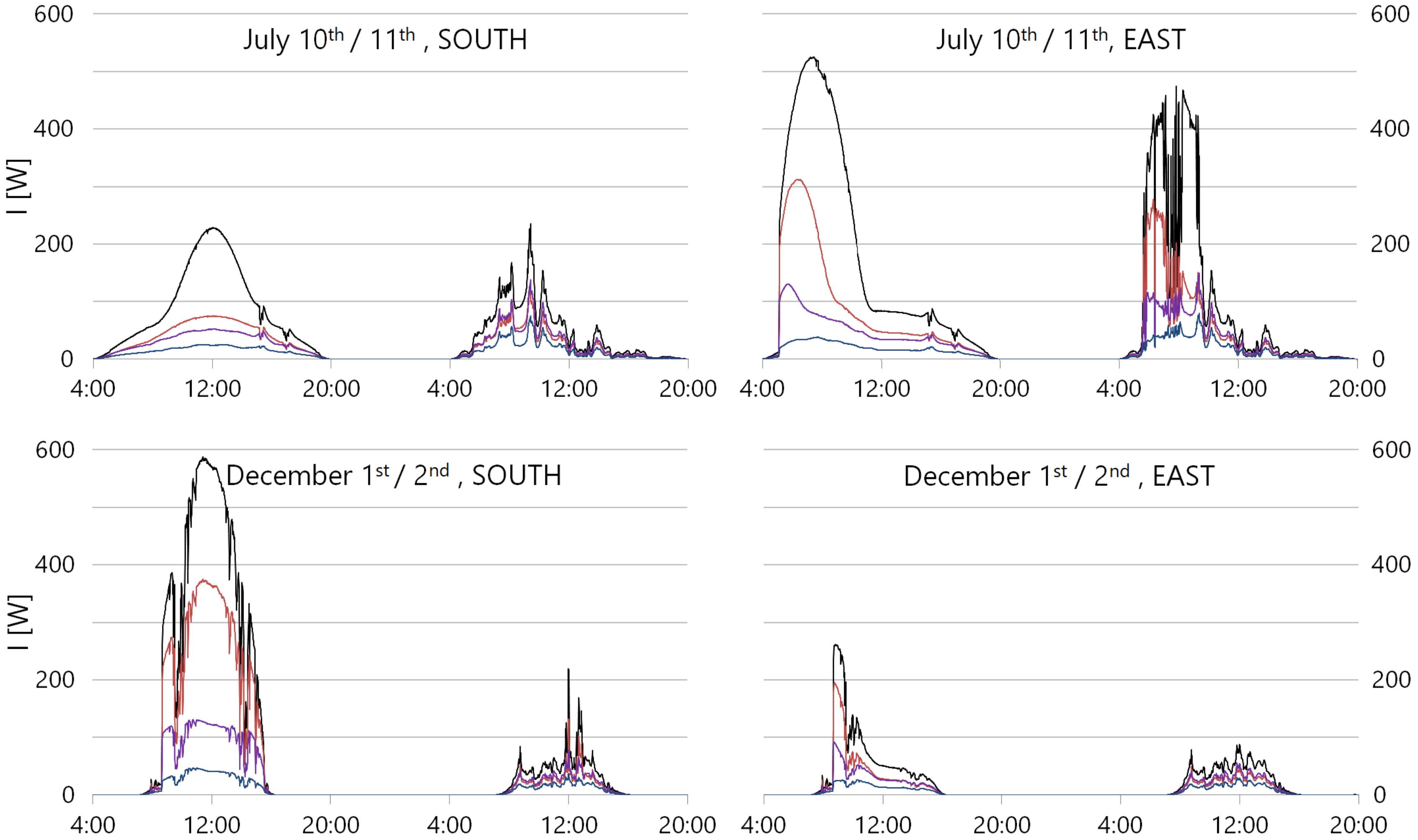


- stochastic simulation method – very EFFICIENT
- using random numbers / probability distribution functions to model physical processes
- energy conservation trivial: follow one ray sample from craddle to grave
- error-estimator: central limit theorem

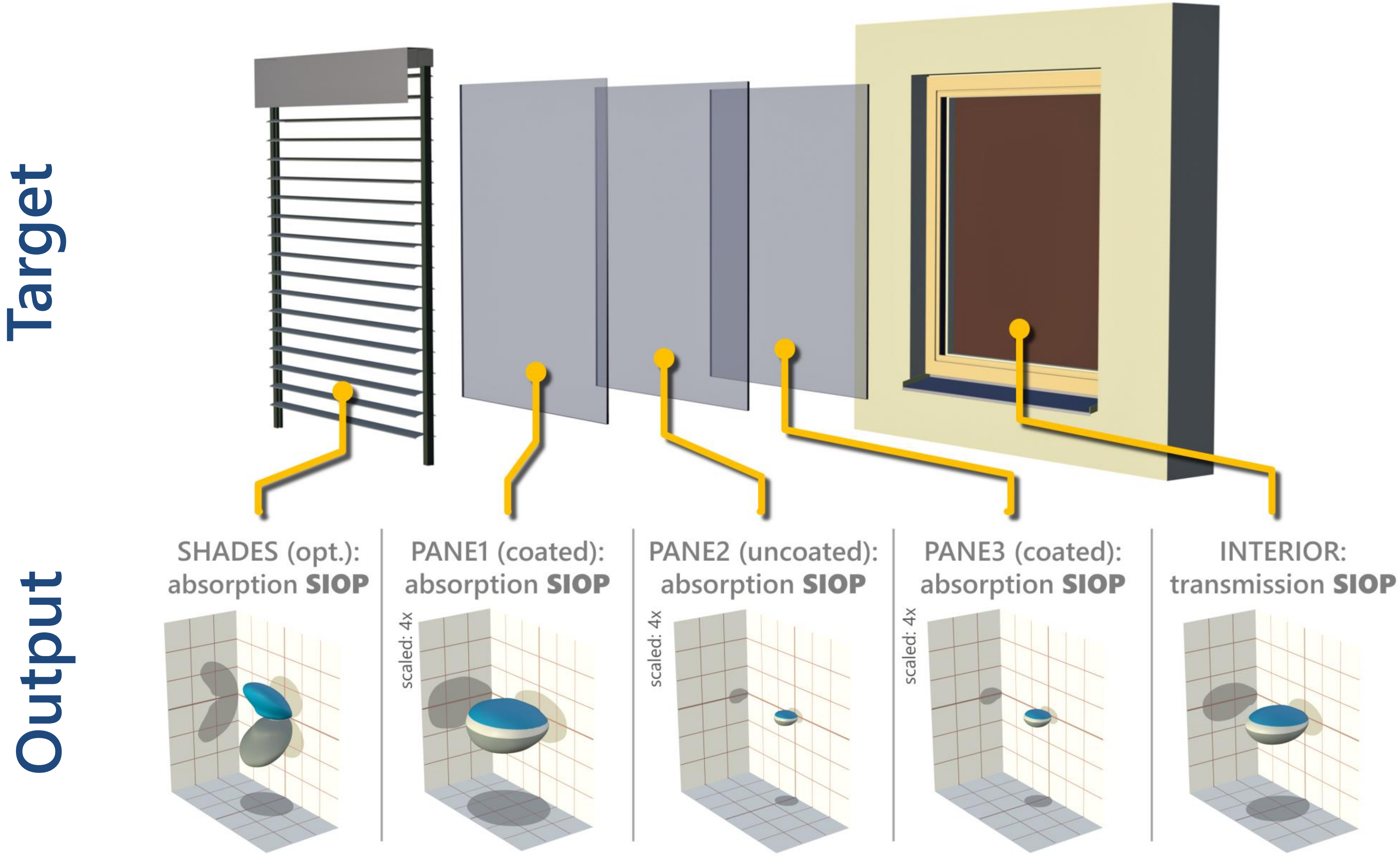

Evaluation of SIOP using
Perez irradiation model
Irradiation components:
direct beam
diffuse
sky
diffuse
horizon
diffuse
ground
RadiCal, D. Rüdisser

Evaluation of SIOP - time series





Application example



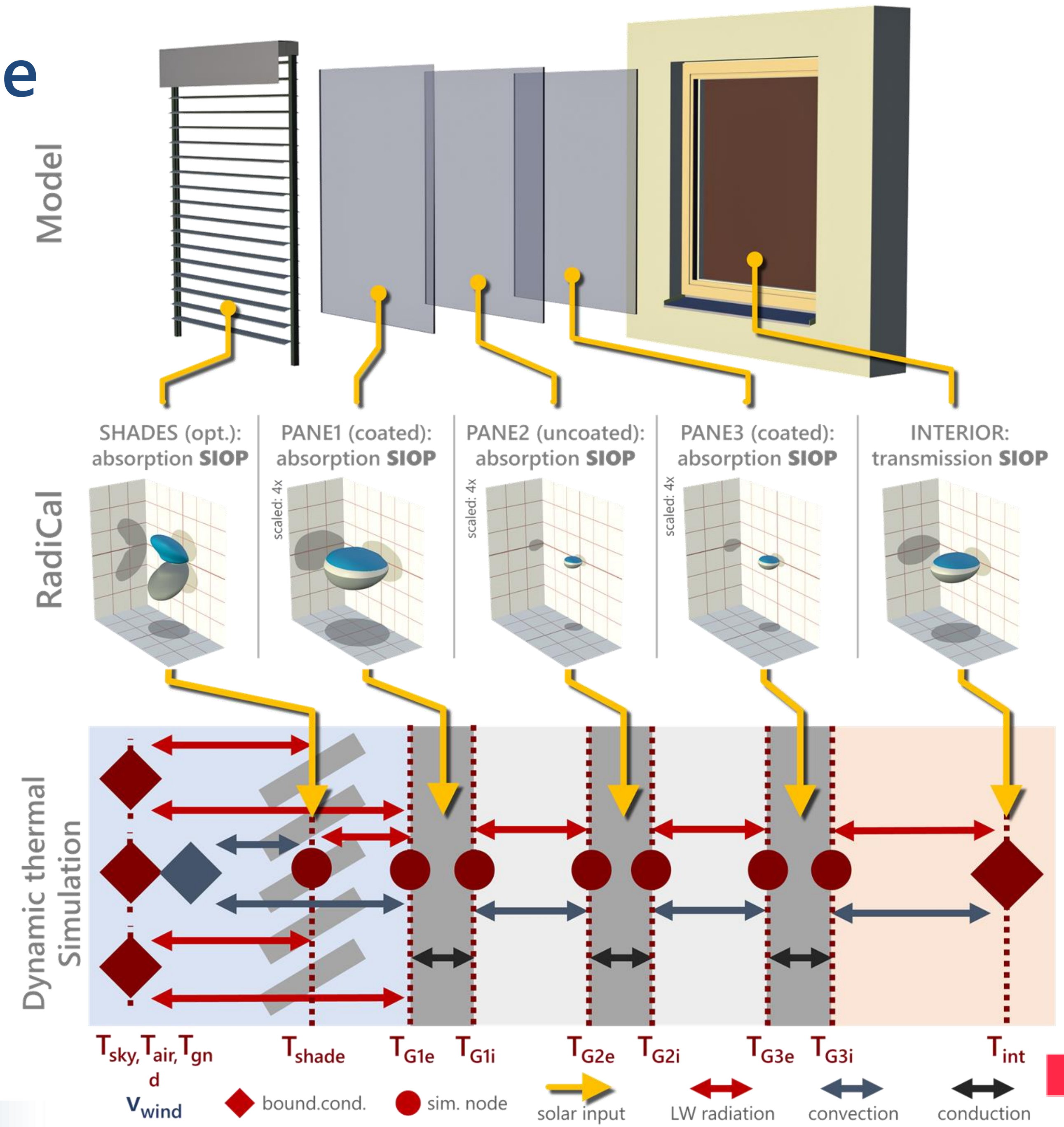
Application example

accurate dynamic thermal simulation of glazings and facades

Preprint

BauSIM 2022 in Weimar

ibpsa



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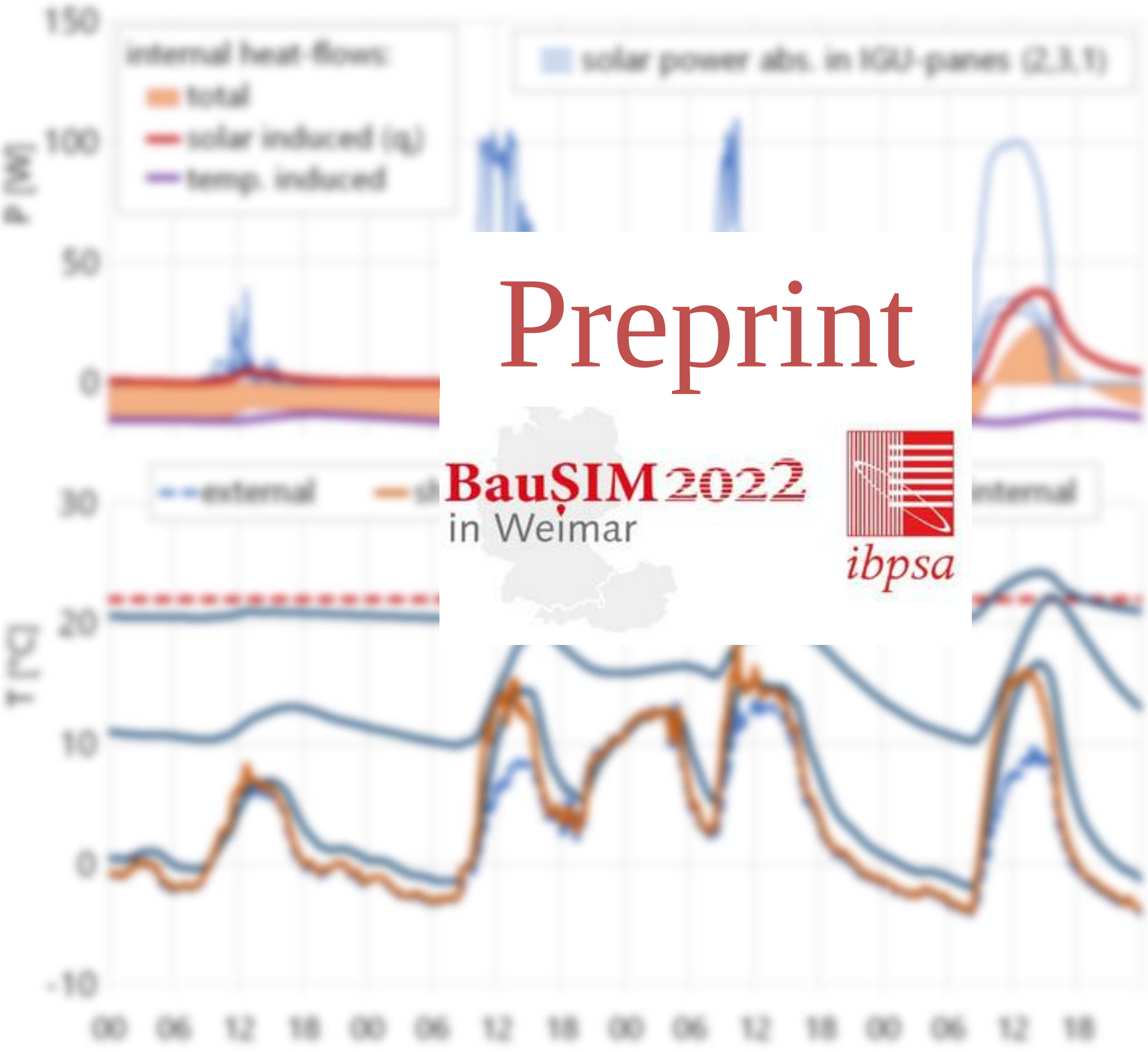
Application example

- Presumably most accurate dynamic simulation currently available.
- Includes all thermal masses.
- Simulation time for one year (min-resolution): <1s



Preprint
BauSIM2022
in Weimar
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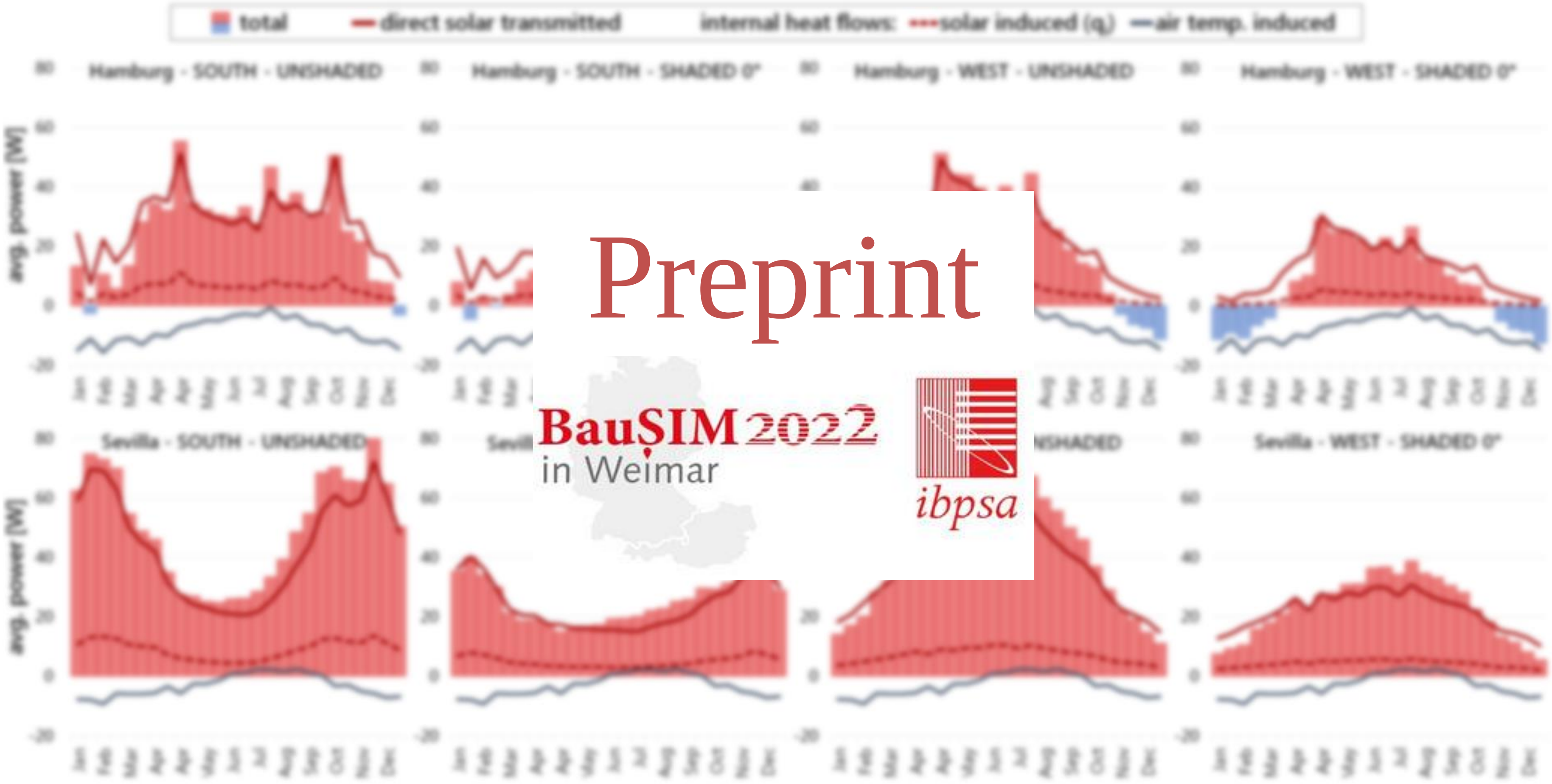
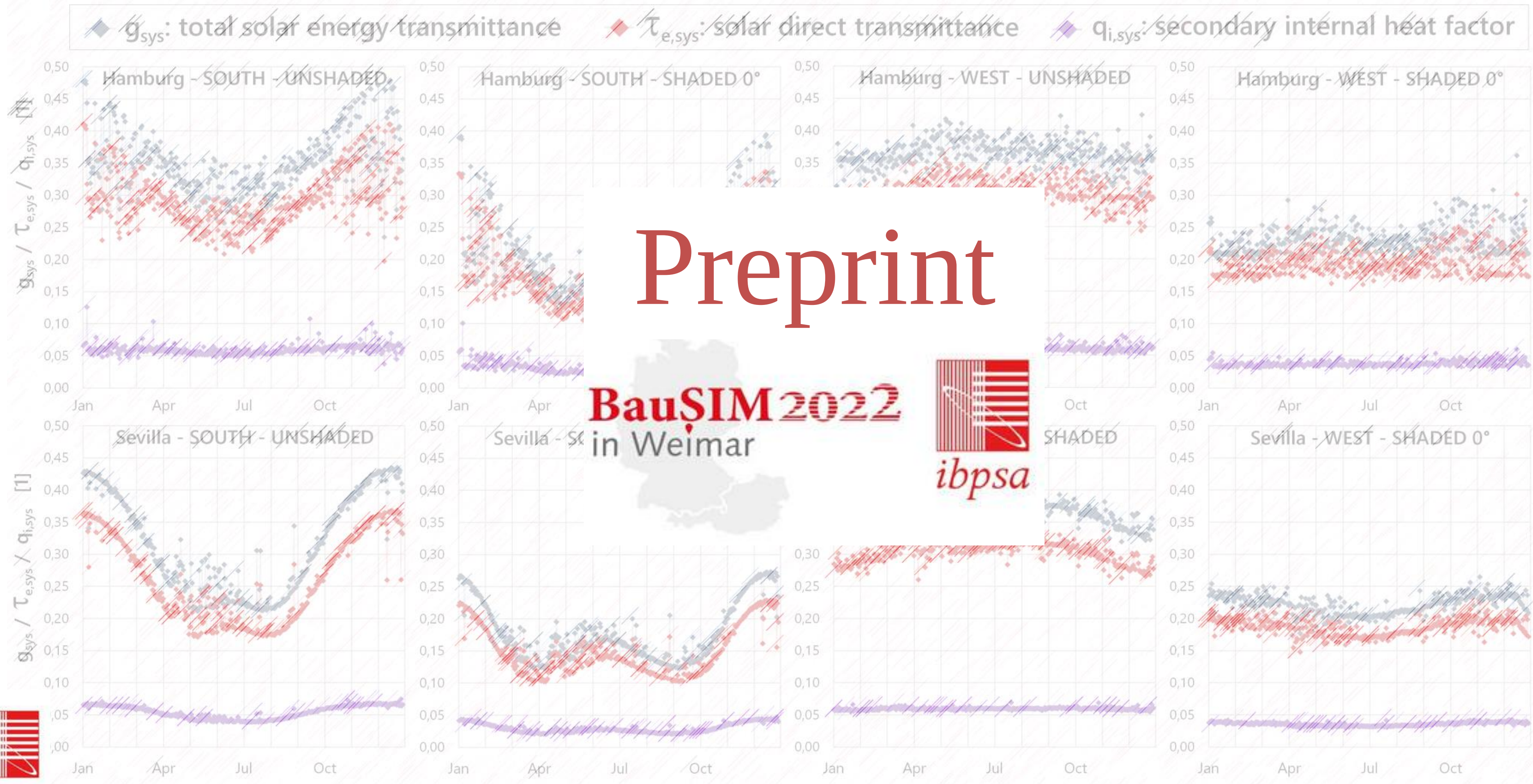
Application example – annual energy balance

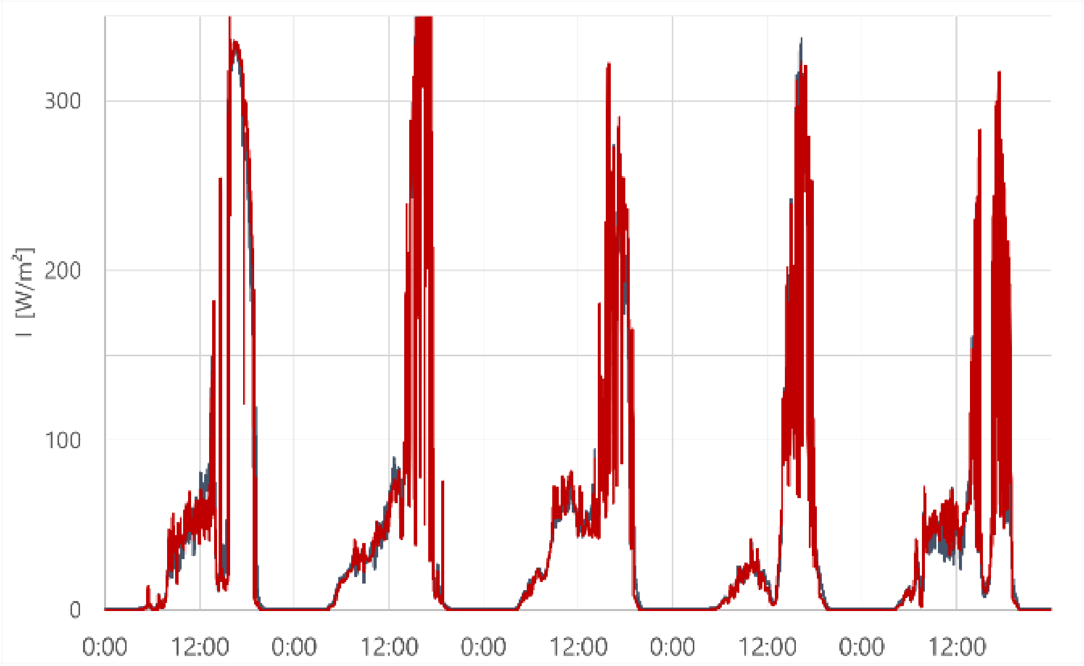


Application example – real-world key figures

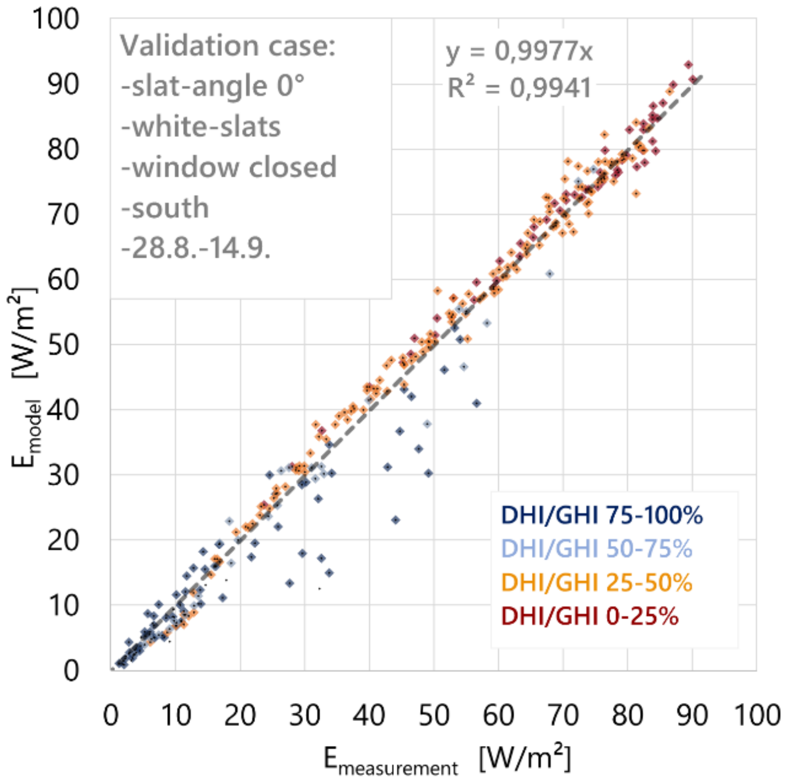


Validation measurements - PyroScanner

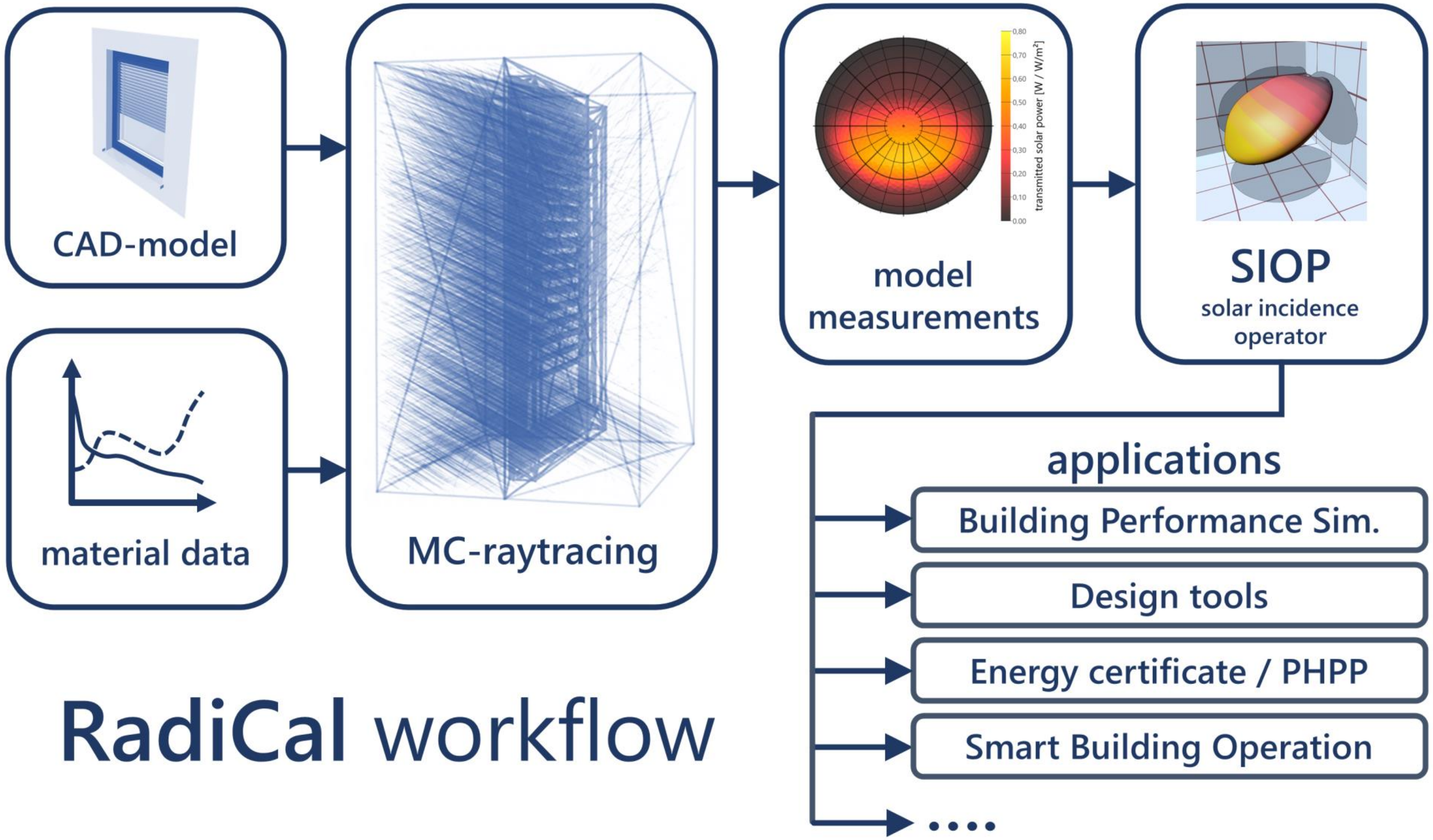
Validation results - examples



Irradiation behind unshaded, west-oriented triple-glazed window model (red) vs. measurement (blue)



Irradiation behind shaded, south-oriented triple-glazed window model (Y-axis) vs. measurement (X-axis)



RadiCal workflow

RadiCal

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