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A Case Study of Three-Dimensional Light Flow Expressed Through Volume Photon Mapping

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Overview

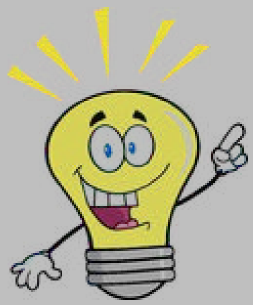
1. Motivation
2. Physical light field simulation with volume photon mapping (“*photon flow*”)
3. Evaluation of cubic illuminance (Cuttle)
4. Case study: Kaze-No-Oka crematorium hall
5. Results
6. Conclusions and future work

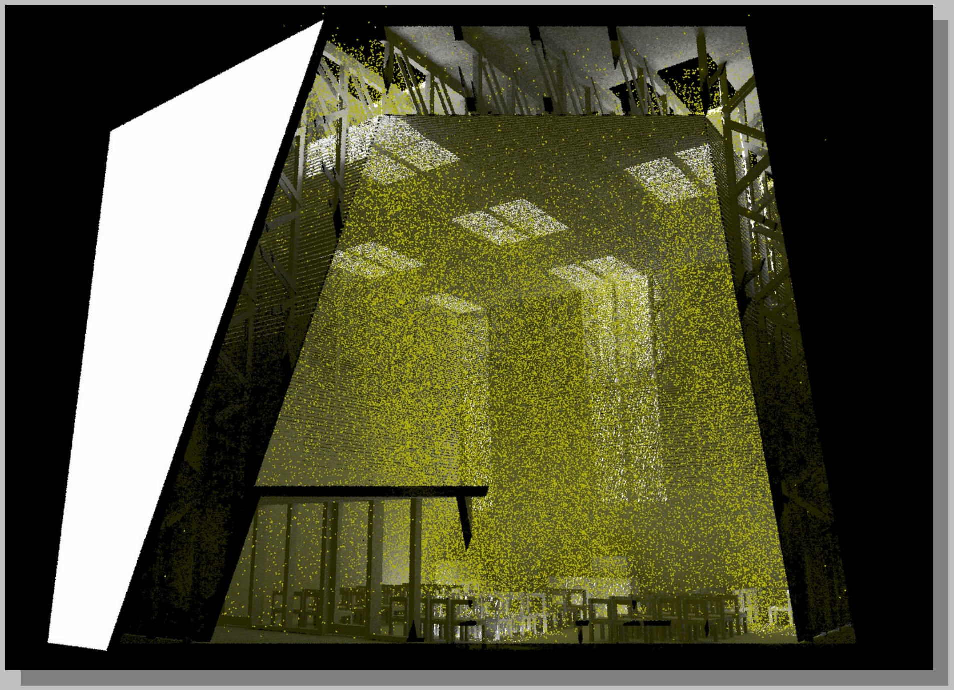
Motivation

Precompute a simulated light field to:

- Gain insight into the light transport process (“light flow”)
- Assess directionality, direct/indirect lighting ratio
- Assess influence of individual fenestrations, skylights, scattering surfaces
- Assess colour bleeding effects from objects in the space
- Evaluate vector illuminance according to various scalar metrics (e.g. mean spherical, cubic, cylindrical, diffuseness ratio…)
- Provide reference for experiments in perception of visual light field

Physical Light Field Simulation with Volume Photon Mapping ("*Photon Flow*")

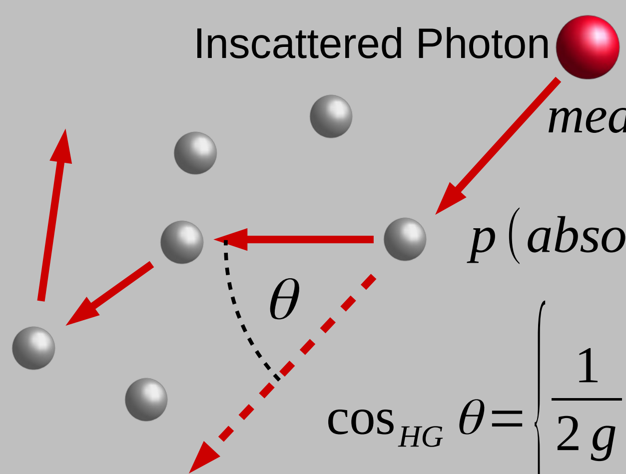




- Directional light distribution as particles (photons) in volume
- Volume photons deposited in nonabsorbing/nonscattering *mist*
- Photons carry RGB flux, direction
- Estimate illuminance on arbitrary surface (≙ photon density)

Volume Photon Scattering in *mist*

- **Extinction $\boldsymbol{\sigma_t}$:** attenuation per unit distance (optical density) → mean free dist between interactions with medium
- **Albedo *α*:** scatter probability when interacting → absorption 1-α
- **Eccentricity *g*:** scattering direction: (-1=bwd, 0=iso, 1=fwd) → angle sampled with phase function (e.g. Henyey-Greenstein)



$$\textit{mean free distance } \bar{s} = -\frac{\log \xi}{\sigma_t}, \quad \textit{random } \xi \in [0,1]$$

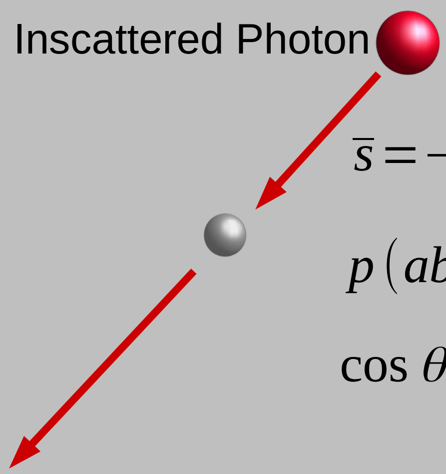
$$p(\textit{absorption}) = 1 - \alpha, \quad \alpha \in [0,1]$$

$$\cos_{HG} \theta = \begin{cases} \dfrac{1}{2g}\left[1 + g^2 - \left[\dfrac{1-g^2}{1+g(2\xi-1)}\right]^2\right], & g \neq 0 \\ 2\xi - 1, & g = 0 \end{cases}, \quad \begin{array}{l} \xi \in [0,1], \\ g \in (-1,1) \end{array}$$

Volume Photon Scattering in Photon Flow

"Hack" *mist* so it does not interfere with photon flow!

- Extinction σ_t → photon density along path; does not alter <u>overall</u> density, but flux/photon → **needs correction!**
- No absorption: **force albedo α = 1**
- Forward scattering only: **force eccentricity g = 1**



$$\bar{s} = -\frac{\log \xi}{\sigma_t}, \quad random\ \xi \in [0,1]$$

$$p(absorption) = 0 \rightarrow \alpha = 1$$

$$\cos\theta = 1 \rightarrow g = 1$$

Mkpmap Parameters for Photon Flow

Parameter	Description
-apV <pm> <N>	Generate ~N lightflow photons
-me	Extinction σ_t of global *mist*, defines linear photon density along path; implies fwd scattering, no absorption (-mg 1, ma 1 1 1)
-apD	Fraction of photons for prepass; reduce from default .25 to avoid exceeding target N photons with large -me

Example:

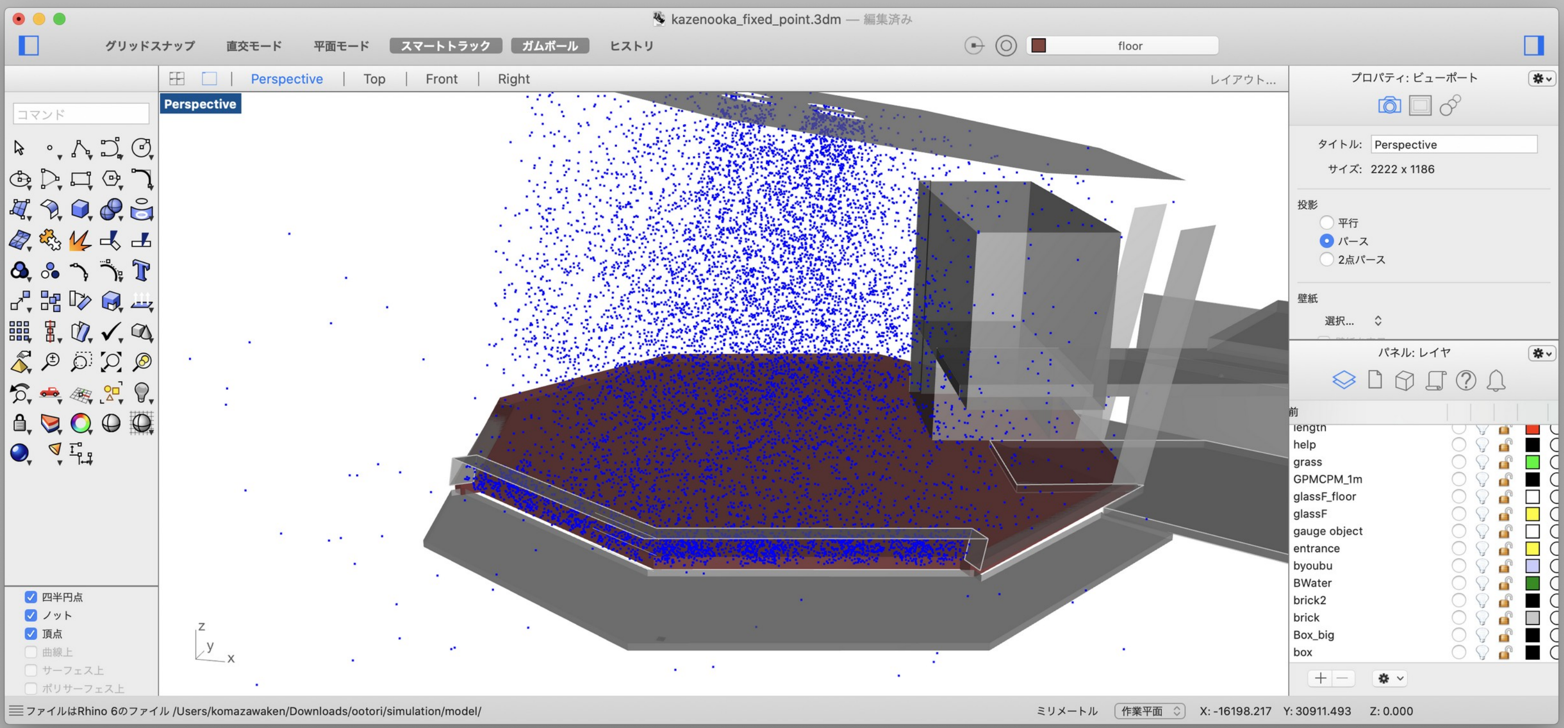
```
mkpmap -me .01 .01 .01 -apD .01 -apV bonzo.Vpm 100m
bonzo.oct
```

Global *mist* → no boundary needed (but not always desirable...)

Photon Flow Visualisation: Point Cloud

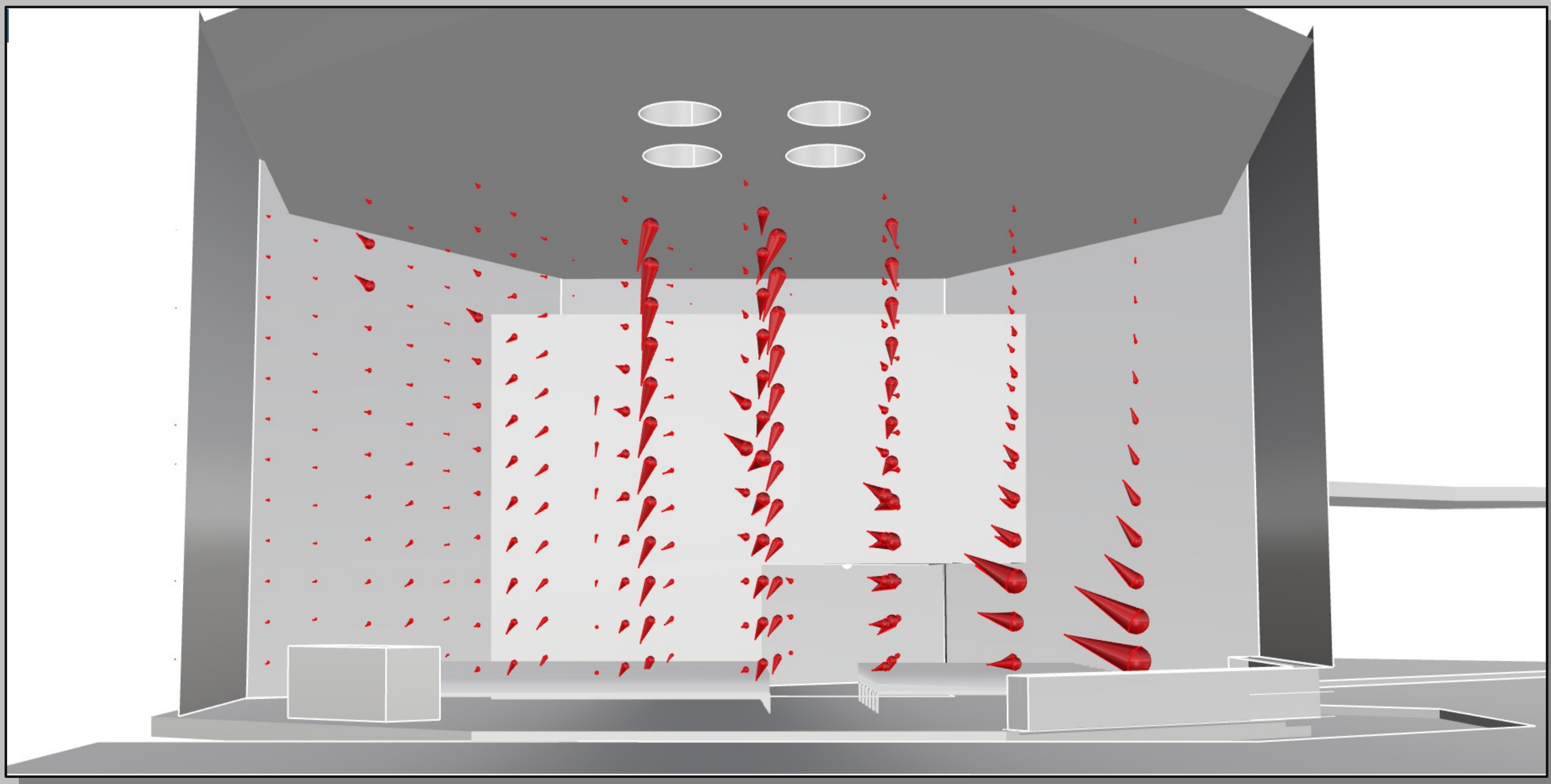
pmapdump can dump photons for import in point cloud viewers:

pmapdump -a -n 100k bonzo.Vpm > bonzo.xyz



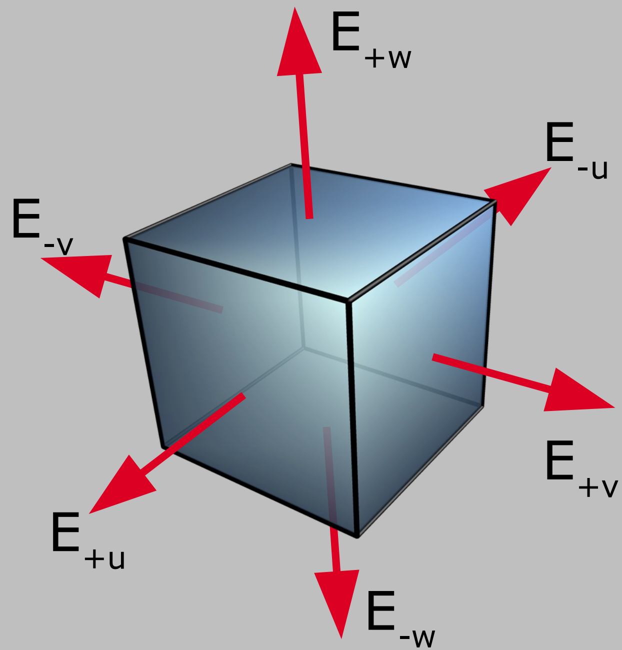
Photon Flow Visualisation: Vectors as Cones

Cones convey relative vector magnitude and direction



Evaluation of Cubic Illuminance (Cuttle)*

Cubic illuminance: approximates scalar illuminance by 6 measurements on cube faces along orthogonal u,v,w axes



$$\textit{Vector illum } \vec{E}_i = E_{+i} - E_{-i}, \quad i \in \{u, v, w\}$$

$$\textit{Symmetric illum } \widetilde{E} = \frac{\widetilde{E}_u + \widetilde{E}_v + \widetilde{E}_w}{3},$$

$$\textit{where } \widetilde{E}_i = \frac{E_{+i} + E_{-i} - |\vec{E}_i|}{2}, \quad i \in \{u, v, w\}$$

$$\textbf{\textit{Scalar illum }} \boldsymbol{E_s = \widetilde{E} + \frac{\|\vec{E}\|}{4}}$$

*C. Cuttle. "Cubic Illumination". *Lighting Research and Technology*, 1997; 29: 1– 14

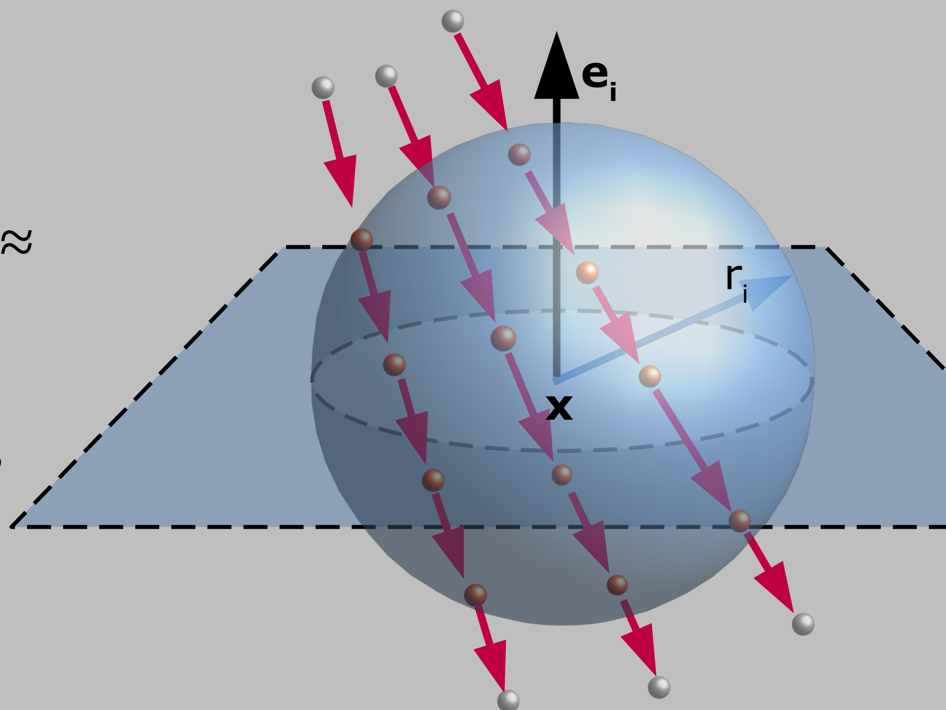
Evaluation of Cubic Illuminance: Spherical Photon Density Estimate

- Sum flux $\Delta\Phi_p$ from *N* closest photons in sphere around point $\boldsymbol{x}$, ignoring *mist*, normalise by sphere volume and extinction σ_t
- Only accept photons incident from front of axis vector $\boldsymbol{e_i}$

$$E_i(\boldsymbol{x}) = \int_{\Omega_{4\pi}} \frac{d^2\Phi(\boldsymbol{x},\boldsymbol{\omega})(\boldsymbol{e_i}\cdot\boldsymbol{\omega})}{\sigma_t\, d\omega\, dV}\, d\omega \approx$$

$$\frac{3}{4\pi r_i^3} \sum_{p=1}^{N} \frac{\Delta\Phi_p(\boldsymbol{x_p},\boldsymbol{\omega_p})}{\sigma_t} (\boldsymbol{e_i}\cdot\boldsymbol{\omega_p}),$$

$$\{p : \|\boldsymbol{x_p},\boldsymbol{x}\| \le r_i,\ (\boldsymbol{e_i}\cdot\boldsymbol{\omega_p}) > 0\}$$



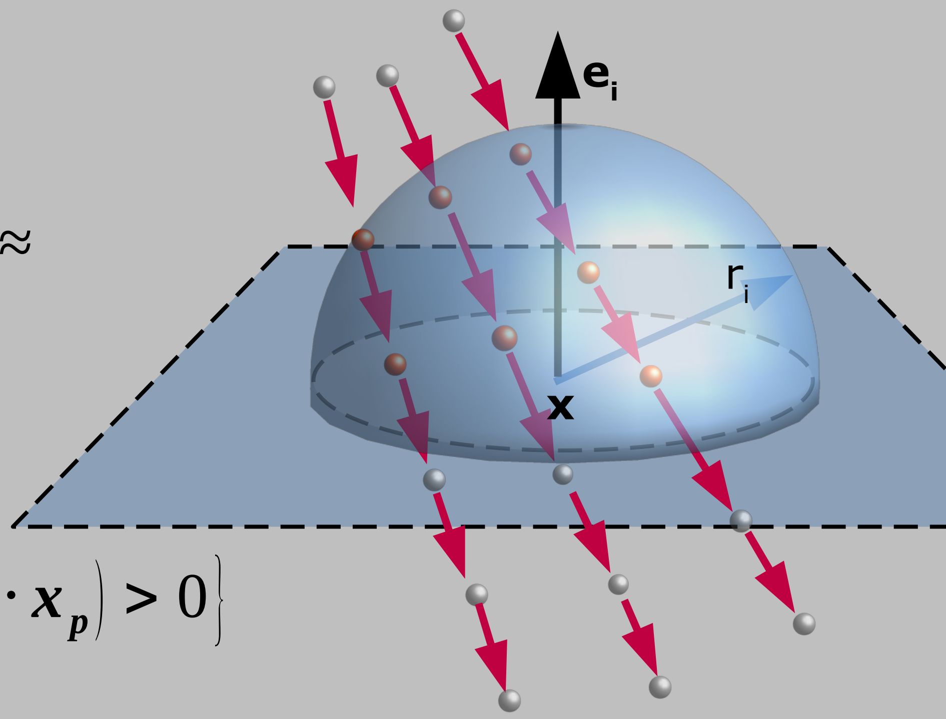
Evaluation of Cubic Illuminance: Hemispherical Photon Density Estimate

- Alternatively, sum only photons located in front
  → Reduce bias near boundaries (solid geometry, scene periphery)

$$E_i(\boldsymbol{x}) = \int_{\Omega_{2\pi}} \frac{d^2\Phi(\boldsymbol{x},\boldsymbol{\omega})(\boldsymbol{e_i}\cdot\boldsymbol{\omega})}{\sigma_t\, d\omega\, dV}\, d\omega \approx$$

$$\frac{3}{2\pi r_i^3} \sum_{p=1}^{N} \frac{\Delta\Phi_p(\boldsymbol{x_p},\boldsymbol{\omega_p})}{\sigma_t} (\boldsymbol{e_i}\cdot\boldsymbol{\omega_p}),$$

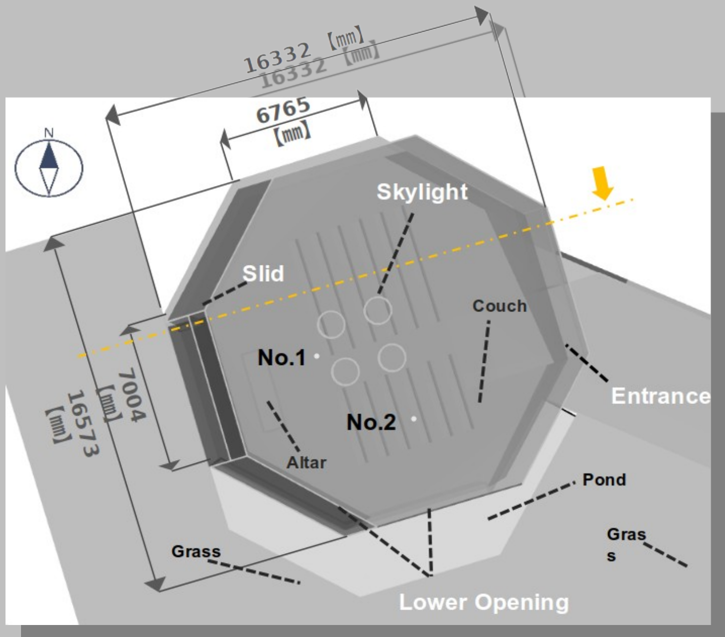
$$\{p : \| \boldsymbol{x_p}, \boldsymbol{x} \| \le r_i, (\boldsymbol{e_i}\cdot\boldsymbol{\omega_p}) > 0, (\boldsymbol{e_i}\cdot\boldsymbol{x_p}) > 0\}$$

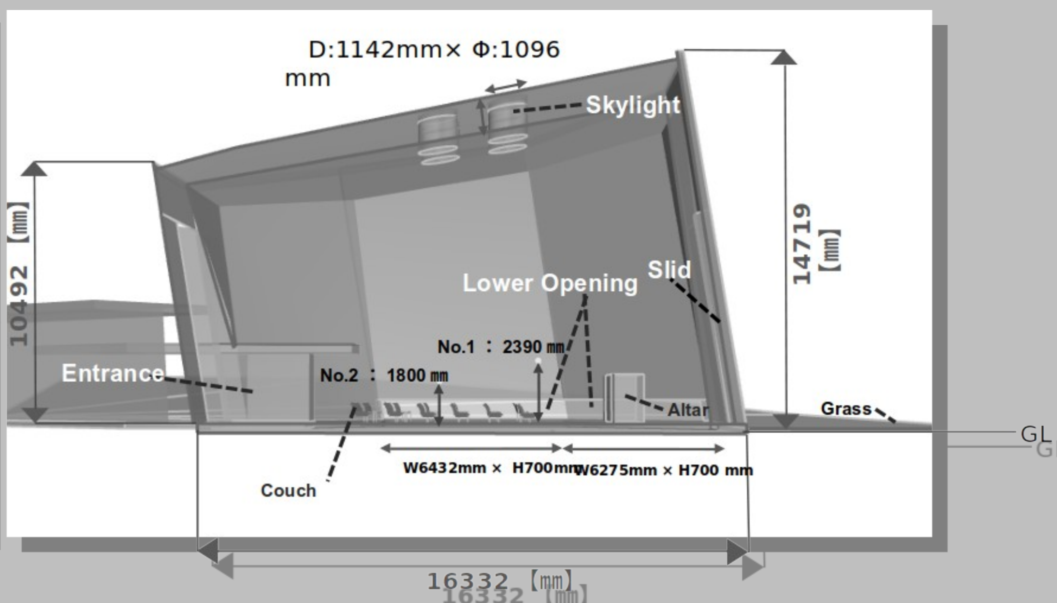


Case Study: Kaze-No-Oka Crematorium Hall

- Designed by Fumihiko Maki, built 1995-97 in Nakatsu, Japan
- HDR capture of sky and interior under stable conditions (fluctuations < 10%), calibration by luxmetre
- Interior indirectly lit from skylights, fenestration at floor level, external reflection from pond

Case Study: 3D Model

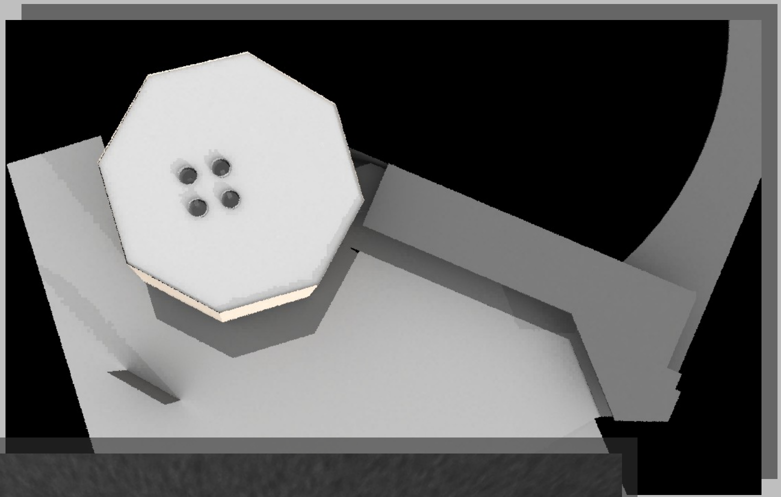


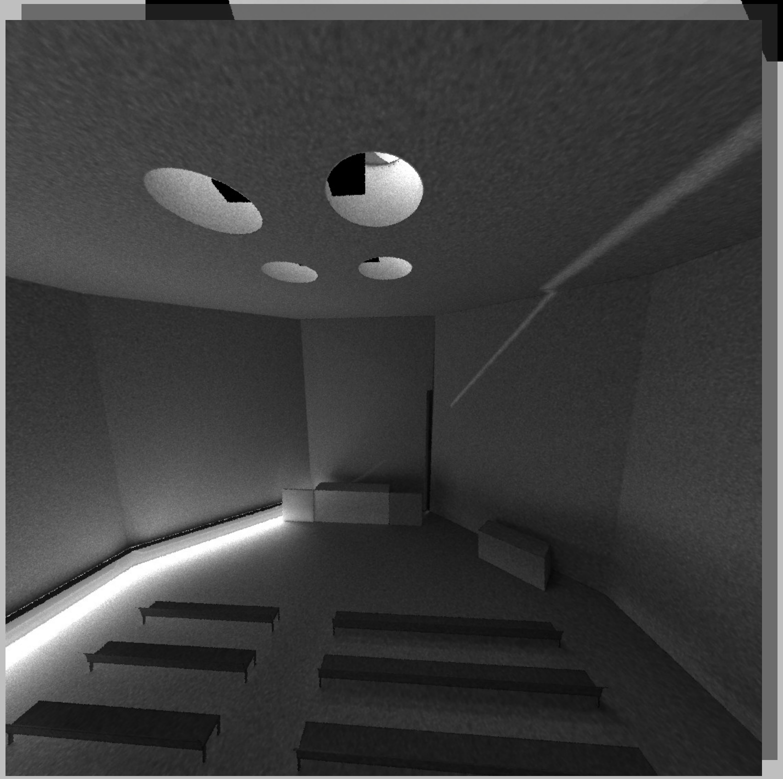


- Geometry from floor plan, height/elevation from measurements
- Materials estimated from measurements or literature

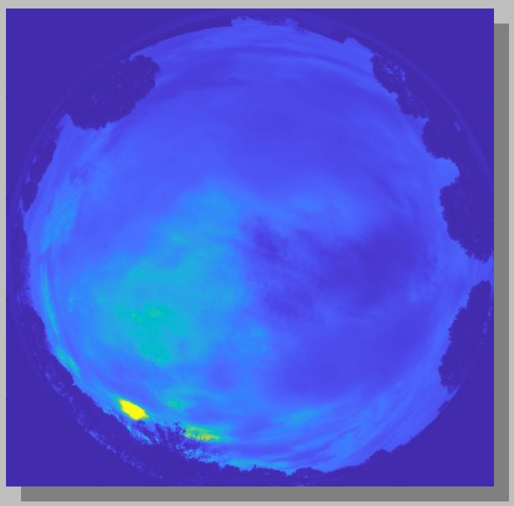
Case Study: 3D Model

- Sky modelled from HDR capture as *brightfunc*
- Skylights, side window, pond as photon ports → accelerates photon emission
- Grid of ca. 300 sensor positions spaced ca. 2.5m

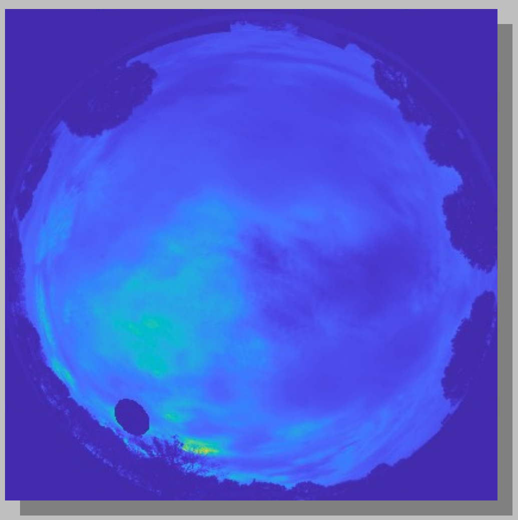




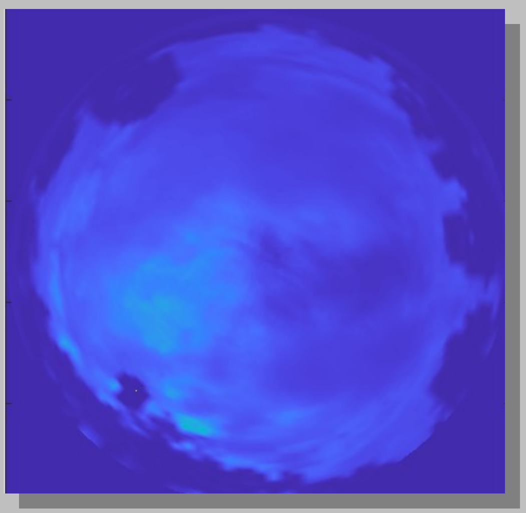
Case Study: HDR Sky Capture



実測そのまま
(Measured sky luminance)

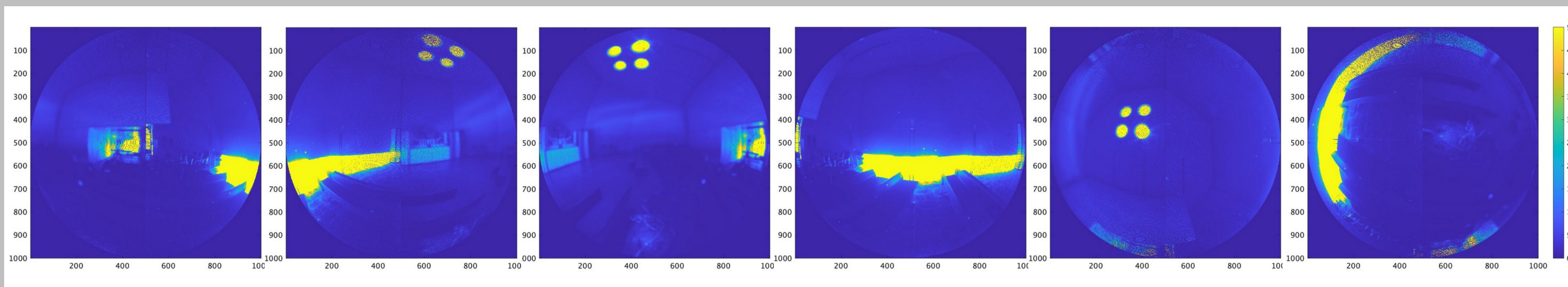


実測遮蔽後
(Measured sky luminance with shielded sun)

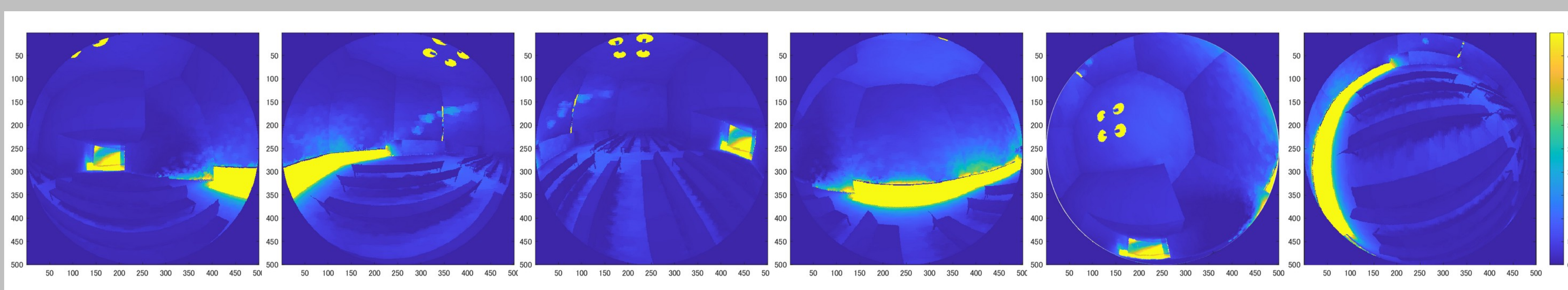


シミュレーション天空
(Simulated sky as *brightfunc*)

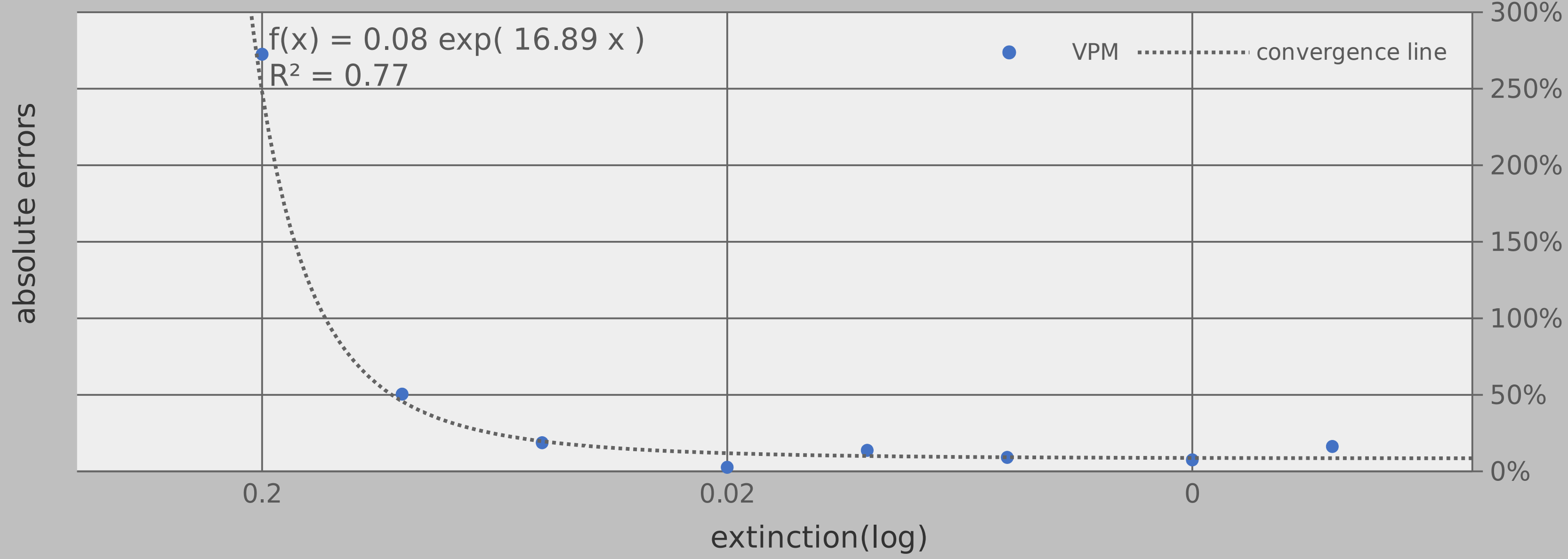
Case Study: HDR Interior Capture vs. Simulation (top resp. bottom row)



East West North South Up Down

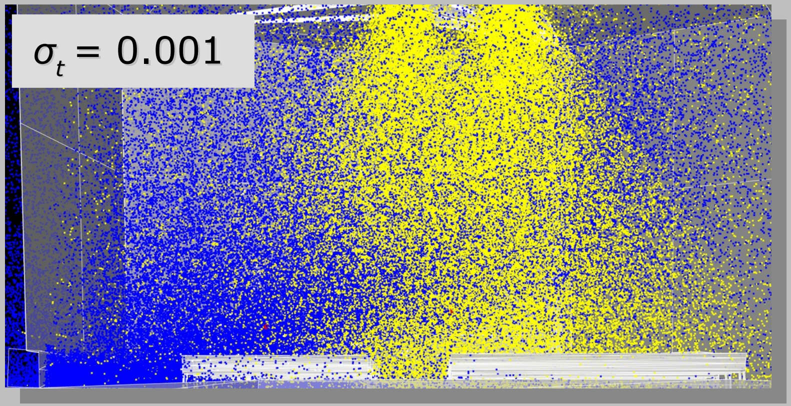


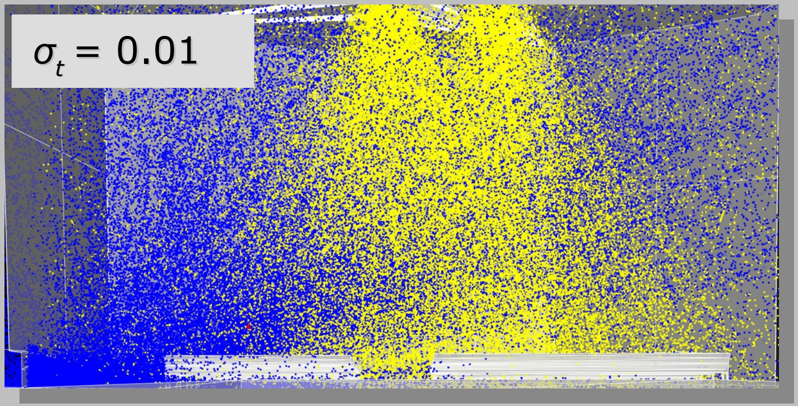
Case Study: Extinction Parameter

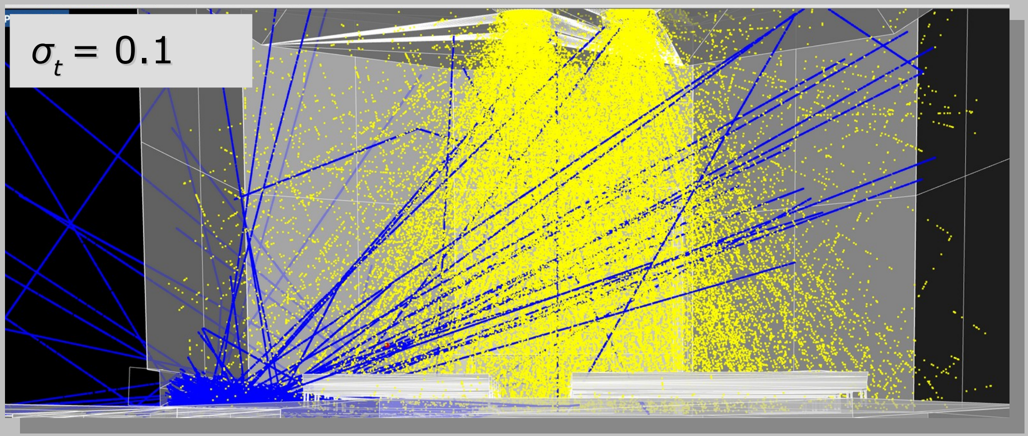


- Extinction determines linear photon density along paths
- Too high → “ray effect” (linear clustering) and bias
- Too low → *mkpmap* slow, as more photons emitted
- Adapt to num photons N_p and max extent d_{max} of scene geometry: $\sigma_t \propto N_p / d_{max}$ (?)

Case Study: Extinction Parameter & "Ray Effect"*

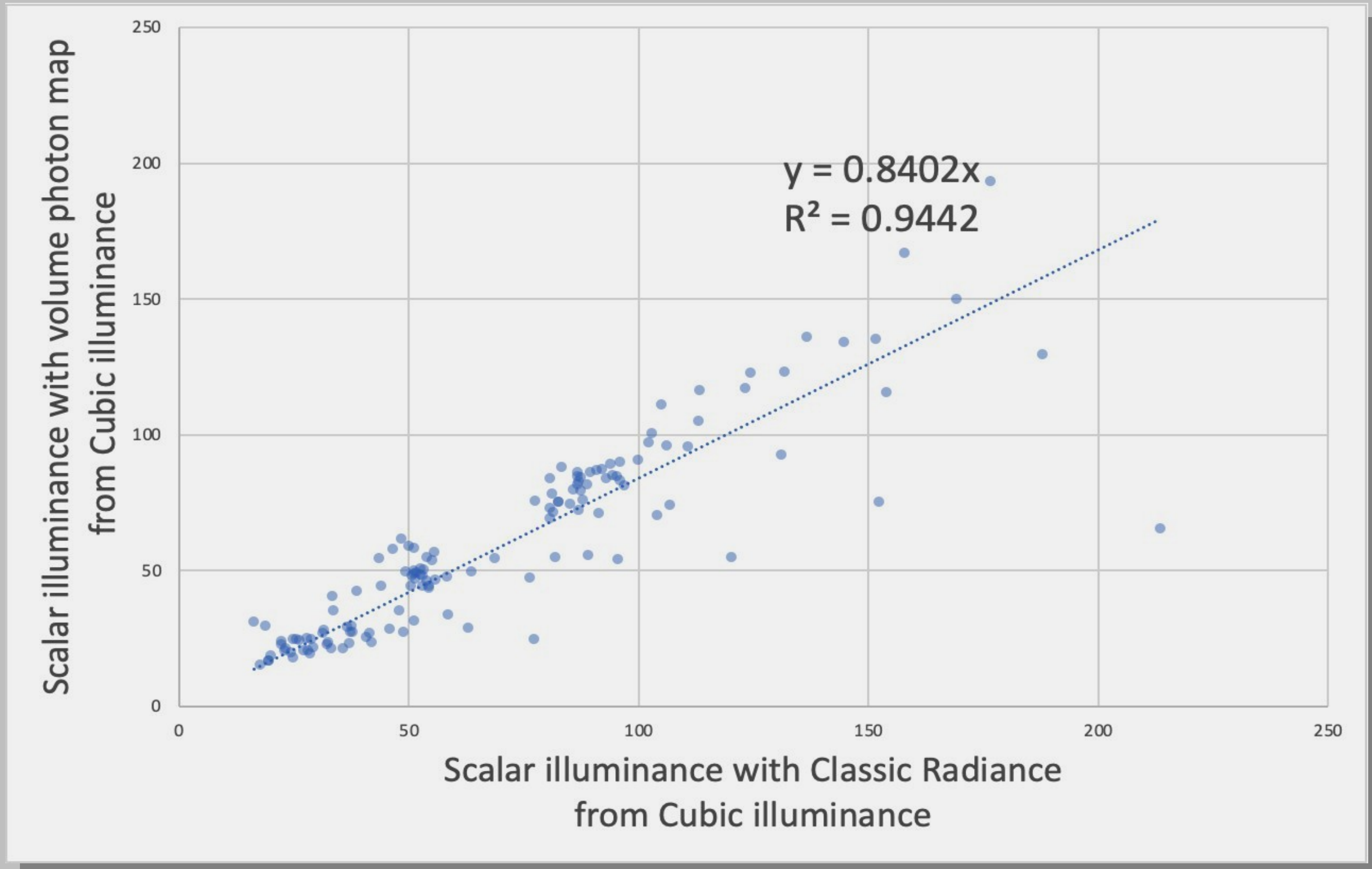






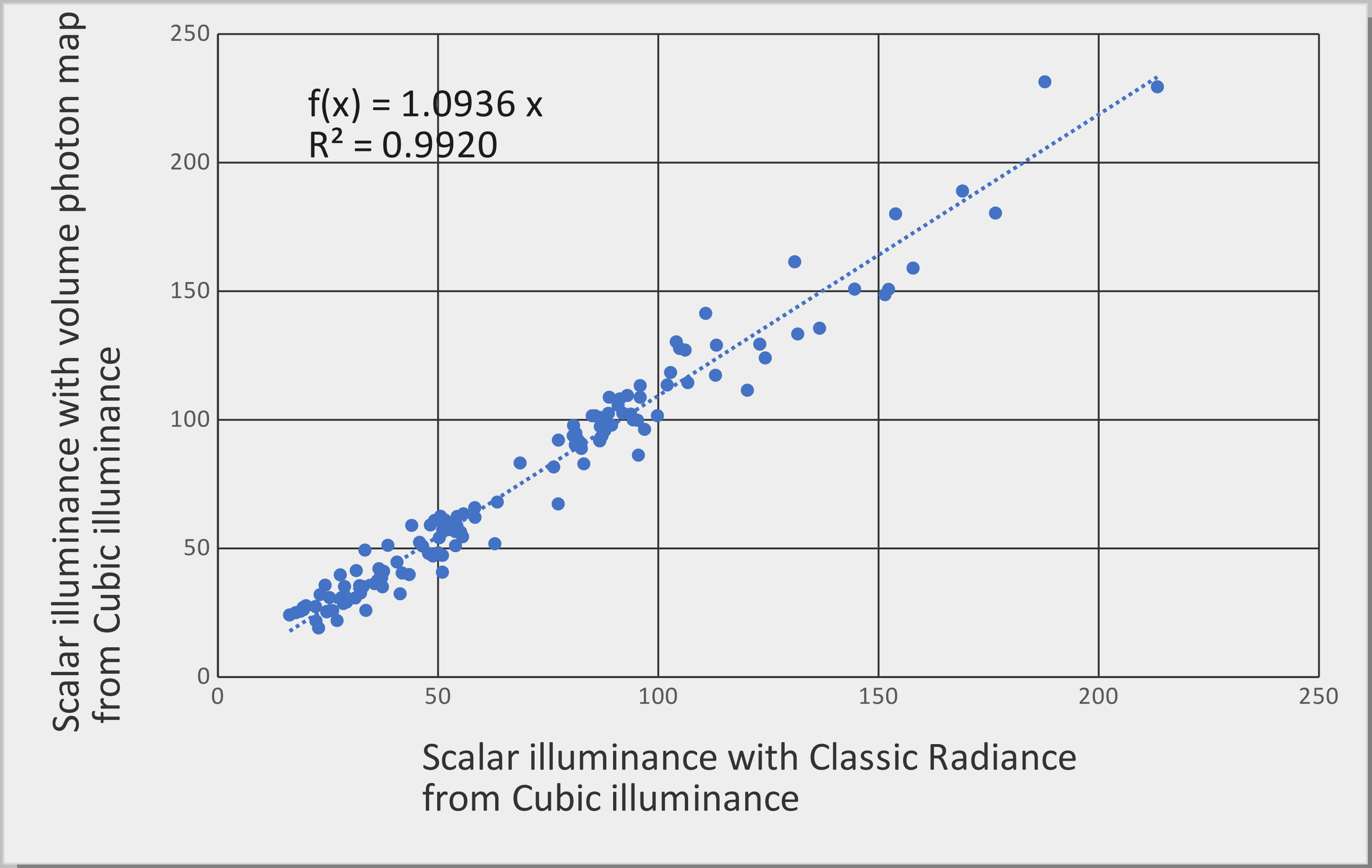
*Lathrop, K.D. "Ray Effects in Discrete Ordinates Equations", *Nuclear Science and Engineering*; 32:3, pp. 357–369, 1968

Case Study: RADIANCE Classic vs. Photon Flow (with Photon Ports)



Photon map + photon ports underpredicts due omitted external reflections?

Case Study: RADIANCE Classic vs. Photon Flow (without Photon Ports)



Better, but **SLOOOW**! :^(

Conclusions and Future Work

- Case study revealed:
  - Photon flow concept and cubic illuminance evaluation is valid
  - Issues with photon emission from non-quadrilateral ports
    → added triangular sampling [thanks, Greg!]
  - Issues with missing external reflections using photon ports
    → emit photons from *illum* or backward raytrace from port?
  - Photon flow sensitive to extinction σ_t (ray effect vs. long computation) → optimal value?
- Make code available in official distro; include in default build?
- Paper to appear in *Lighting Research and Technology*!

Thank You for Your Attention!

Project log: https://www.researchgate.net/project/3D-Light-Flow

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