Real-Time Rendering of Wave-Optical Effects on Scratched Surfaces

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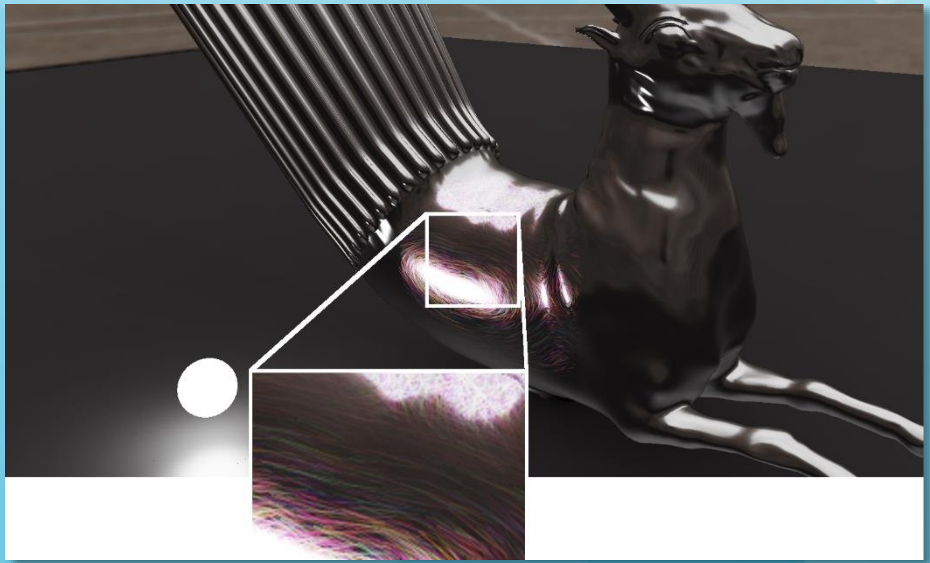


EUROGRAPHICS 2018

Motivation

- Iridescent scratches defined by wave-optical phenomena appear on many everyday items

Related Work

- Scratched surfaces

- Area lighting

Goals

- Area lighting of worn surfaces covered by iridescent scratches
- Anti-aliasing of scratches based on camera pixel footprint
- Everything in real-time with single sample per pixel both in spatial and angular domain

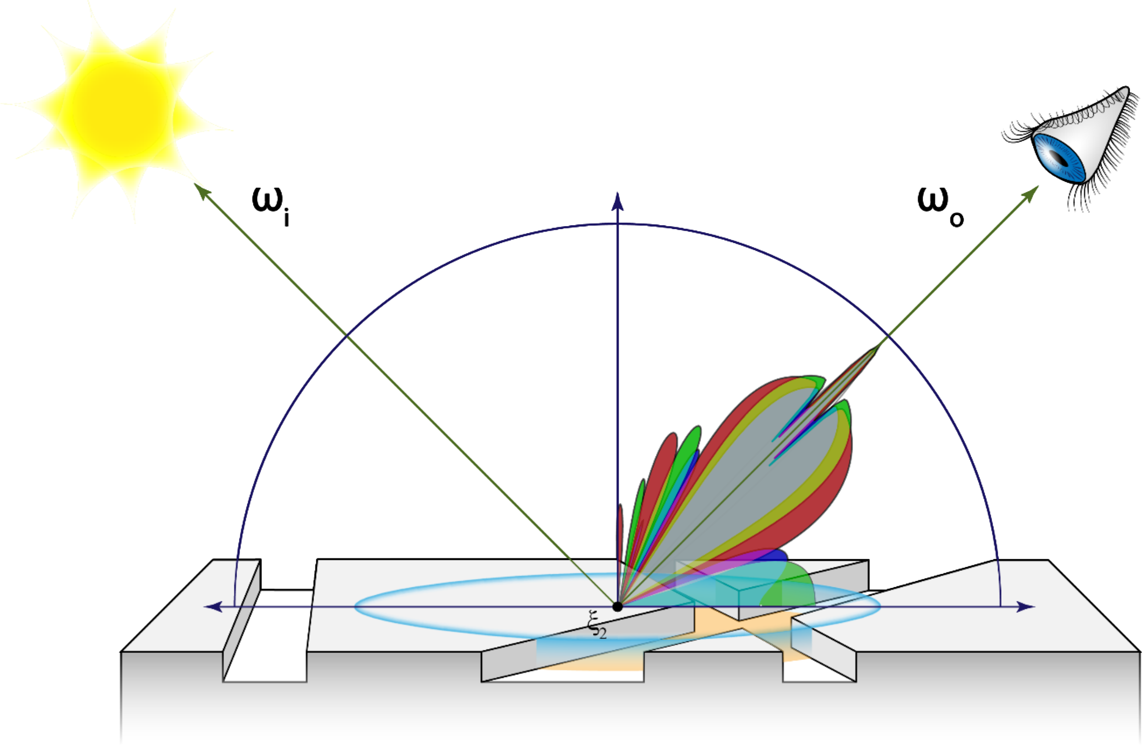
Scratch Iridescence Model

Combined Surface BRDF Model

- Superposition of scratch S and masked base BRDF $\mathcal{B}$ - parameterized by the direction cosine ξ, spatial position $\mathbf{x}$

$$f(\xi, \mathbf{x}) = \frac{1}{\pi\sigma^2} |\mathcal{B}(\xi) - S(\xi, \mathbf{x})|^2$$

- Base BRDF in this case is limited to the smooth coherent model
- Scratch BRDF is defined according to [WVJH17]



Incoherent superposition

- Arbitrary base BRDF is enabled by neglecting interference

$$f(\xi, \mathbf{x}) \approx \frac{1}{\pi\sigma^2}\left(|\mathcal{B}(\xi)|^2 + |S(\xi, \mathbf{x})|^2\right)$$

$$f(\xi, \mathbf{x}) \approx \frac{1}{\pi\sigma^2}\left((1-\rho)|\mathcal{B}(\xi)|^2 + |S(\xi, \mathbf{x})|^2\right)$$

- Masking is performed according to the scratch density ρ

- Separates the base from the scratch response!

Scratch BRDF

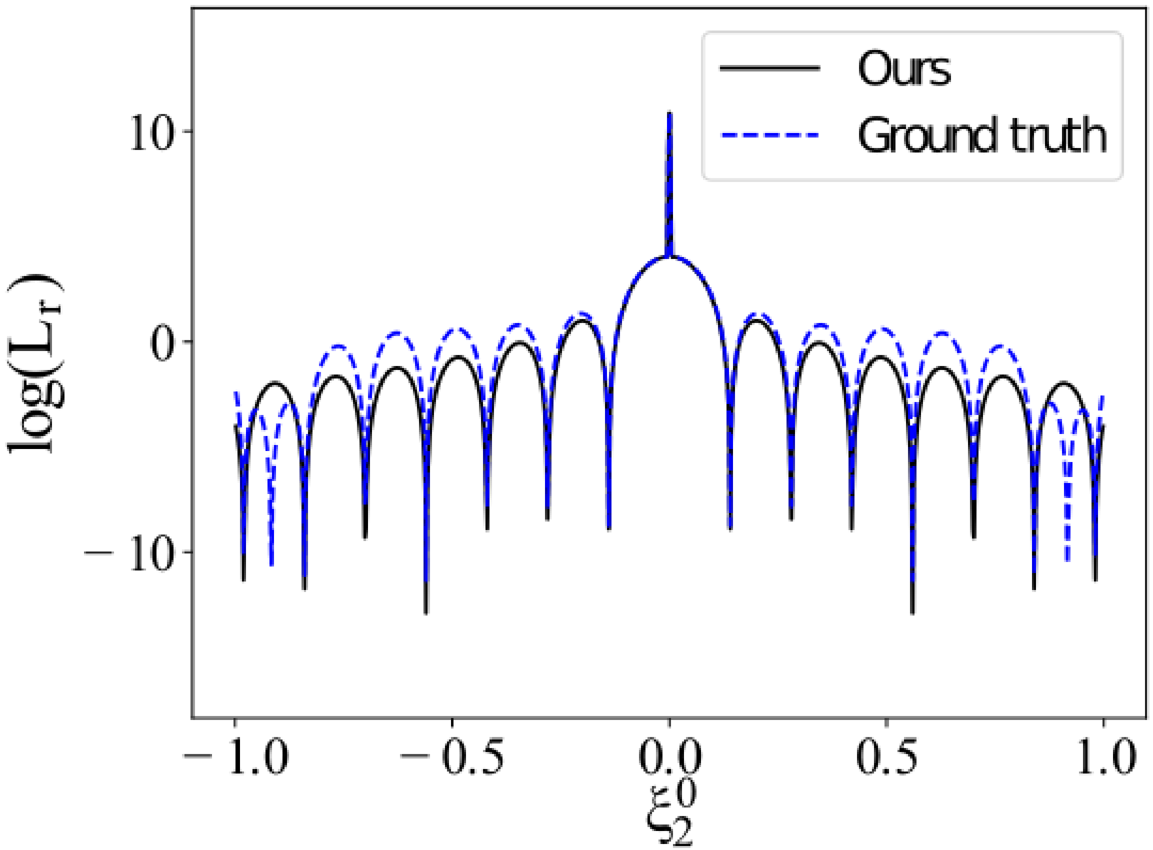
- Defined by width function W across the scratch, depth function D and longitudinal integral term η

$$S(\xi, \mathbf{x}) = W(\xi) \cdot D \cdot \eta(\xi, \mathbf{x})$$
$$= W(\xi) \cdot D \cdot \eta_a(\xi) \cdot \eta_s(\mathbf{x})$$

- We use the small angles approximation

$$D \approx 1 - e^{-i4\pi d/\lambda}$$

- Enables separability in angular domain!



Simplified integration in angular domain

- The separable BRDF in angular domain simplifies integration significantly

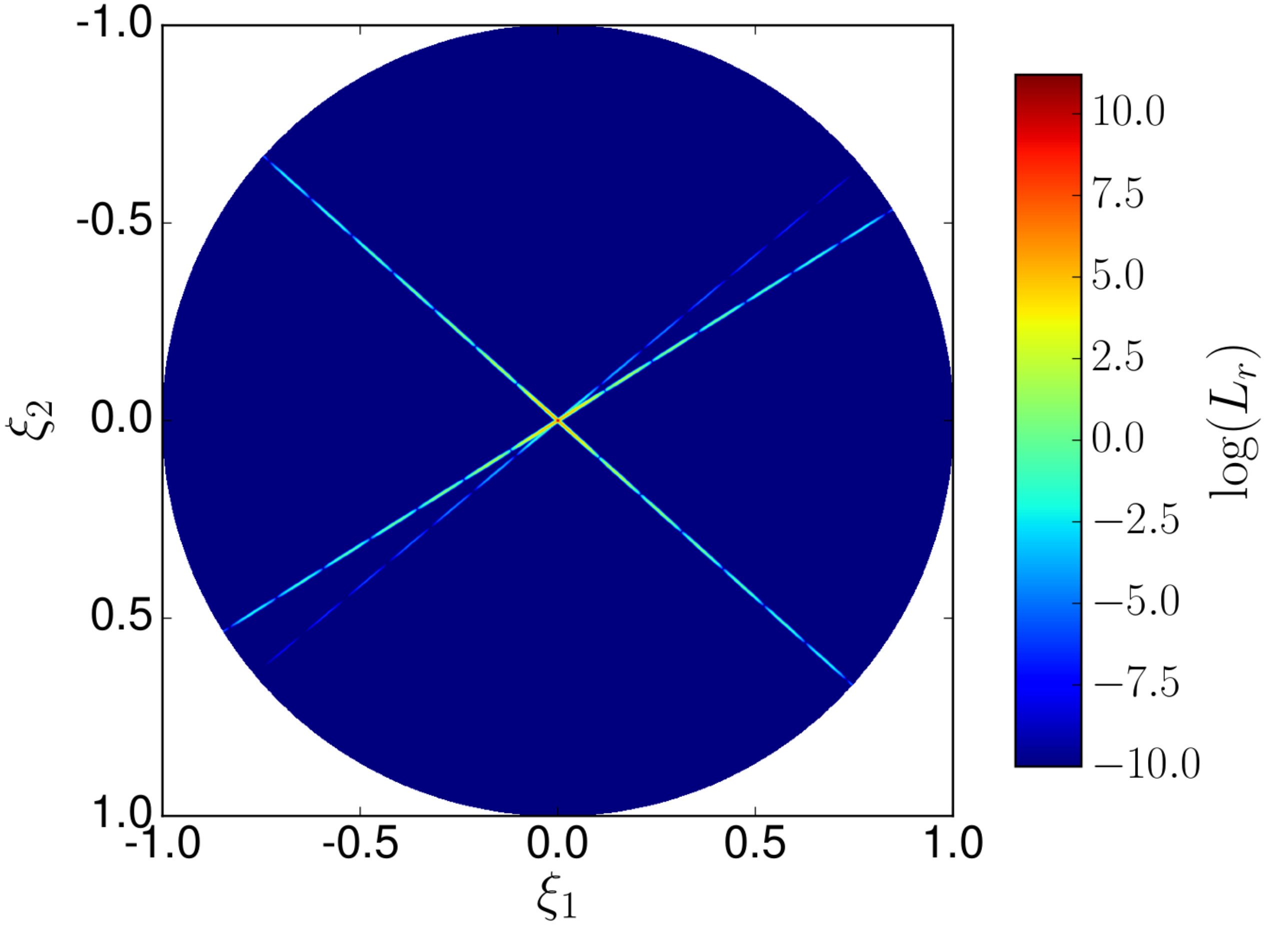
$$\mathrm{L} = \int_{\Omega^+} f(\xi)\, L_i\, d\xi$$

$$\xi = \omega_{i,t} + \omega_{o,t}$$

- The projected outgoing direction $\omega_{o,t}$ acts as offset of the light source projection defined by the projected incident direction $\omega_{i,t}$

Approximation motivation

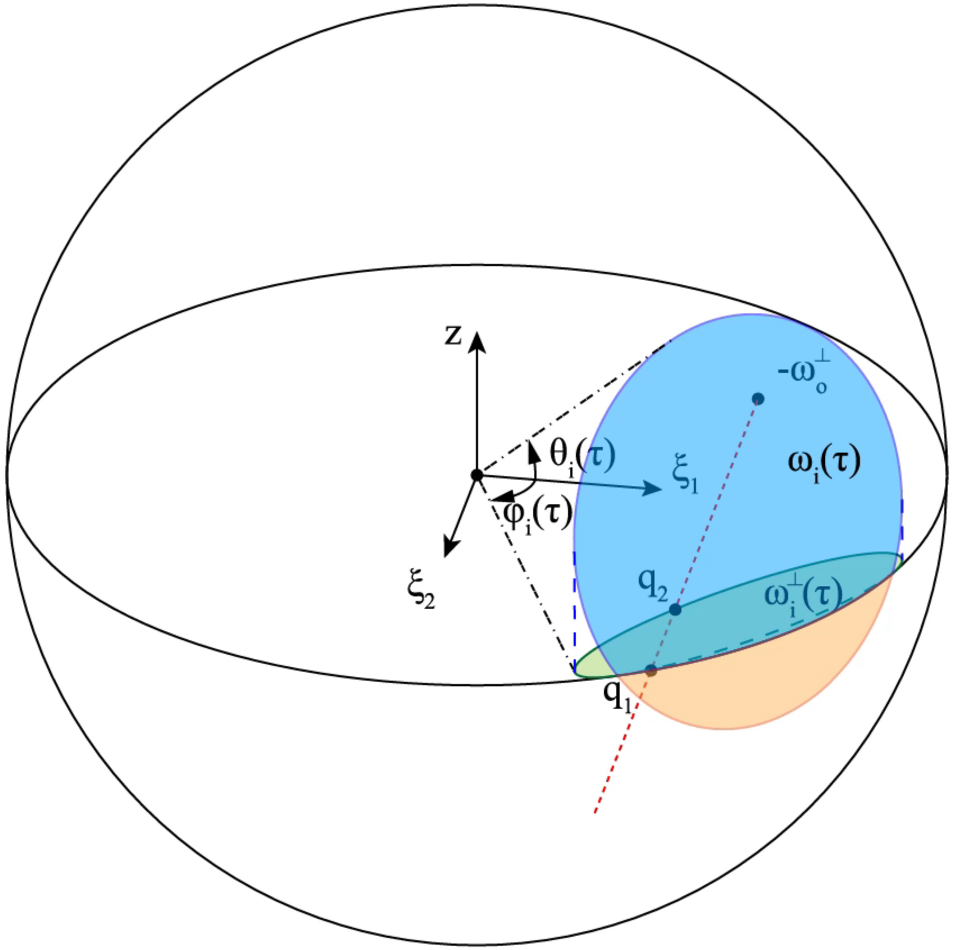
- Response by three scratches in direction cosine domain



Spherical Light Sources

Spherical Light Source

1. *Check* for sphere underneath horizon
2. *Project* disk in direction cosine domain
3. *Intersect* horizon arc, if needed
4. *Intersect* projected ellipse
5. *Assemble* line segment
6. *Evaluate* integral and superimpose on *Spherical Pivot Transformed Distribution* (SPTD) [DHB17]

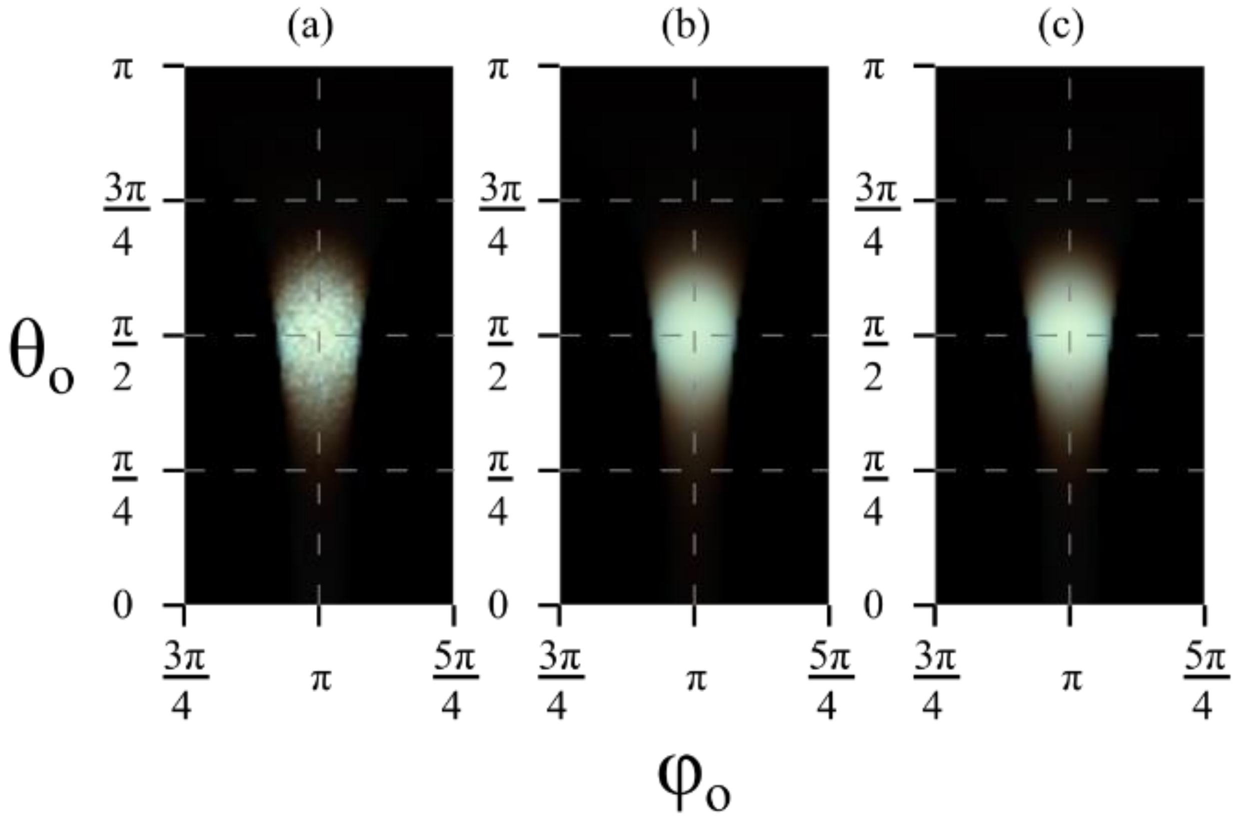


Approximation Comparison

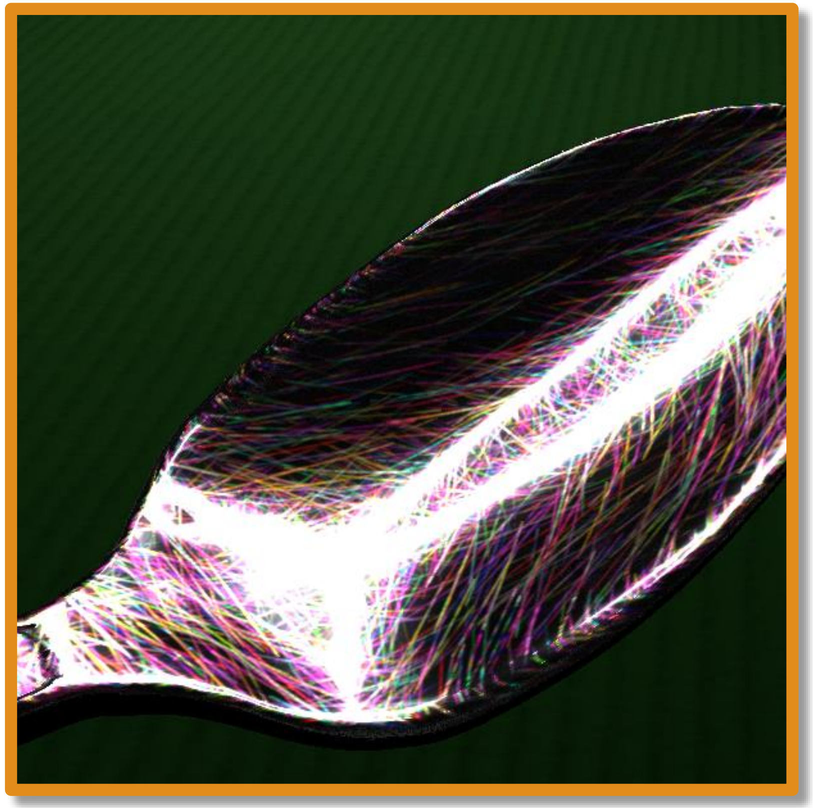
a) Monte Carlo

b) Ours (Approximate Si)

c) Exact analytic approximation

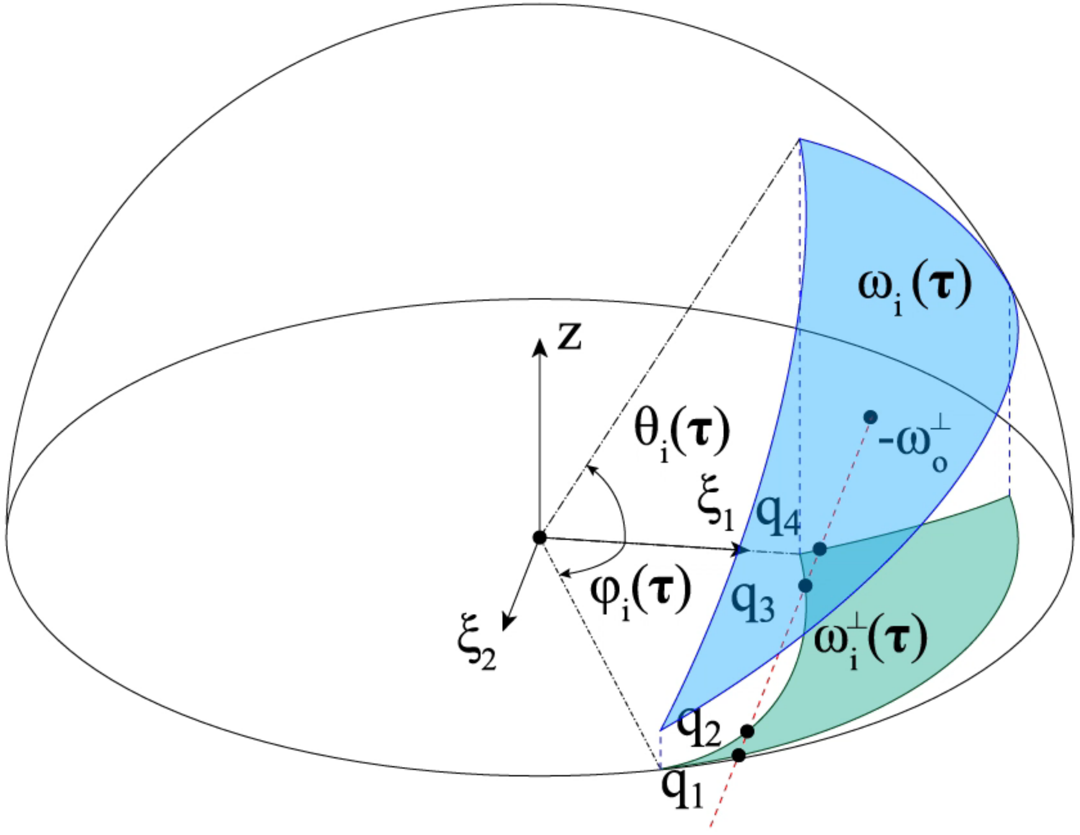


Polygonal Light Sources



Polygonal Light Source Algorithm

1. *Clip* (split) triangle to the upper hemisphere
2. *Project* triangle into direction cosine domain as arcs
3. *Intersect* arcs with reflected band
4. *Cull* points outside of a triangle
5. *Sort* intersection points with bitonic sort and assemble line segments
6. *Evaluate* integral and superimpose on *Linearly Transformed Cosines* (LTC) [HDHN16]



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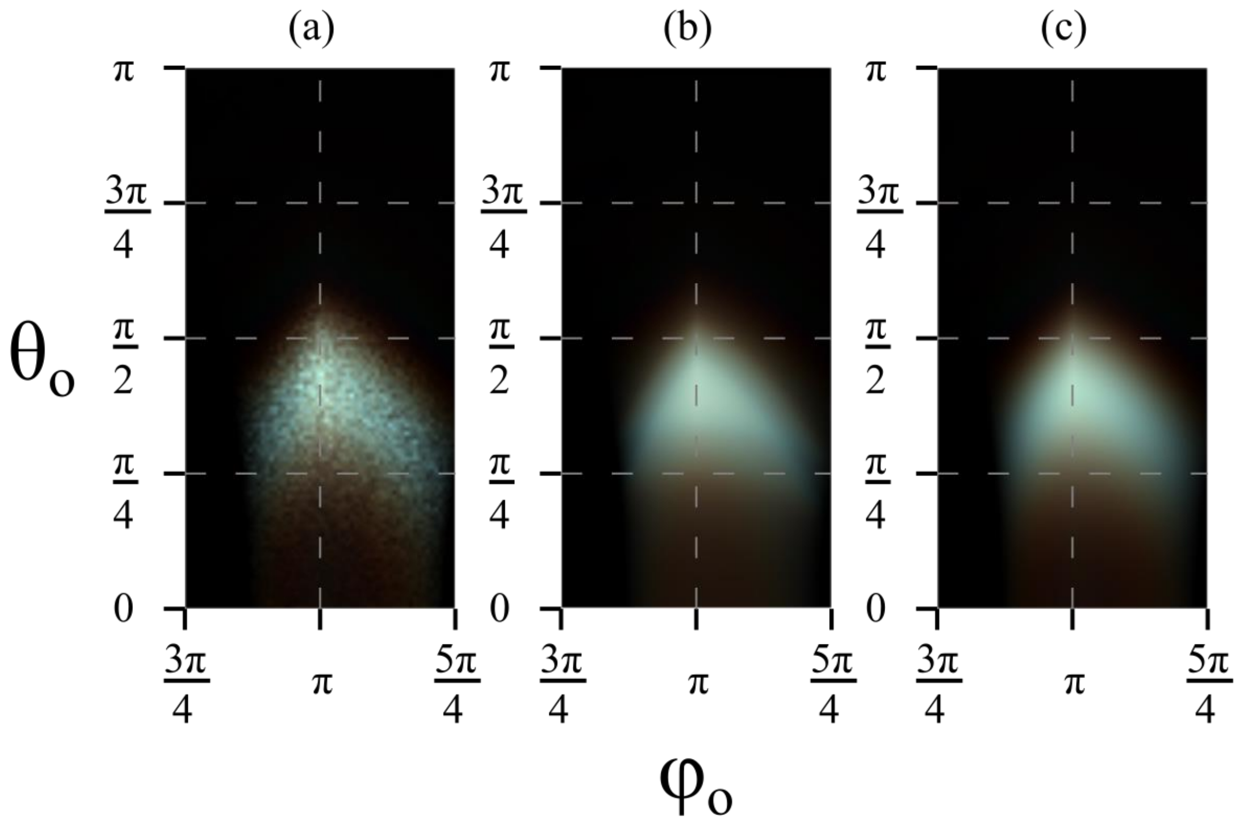
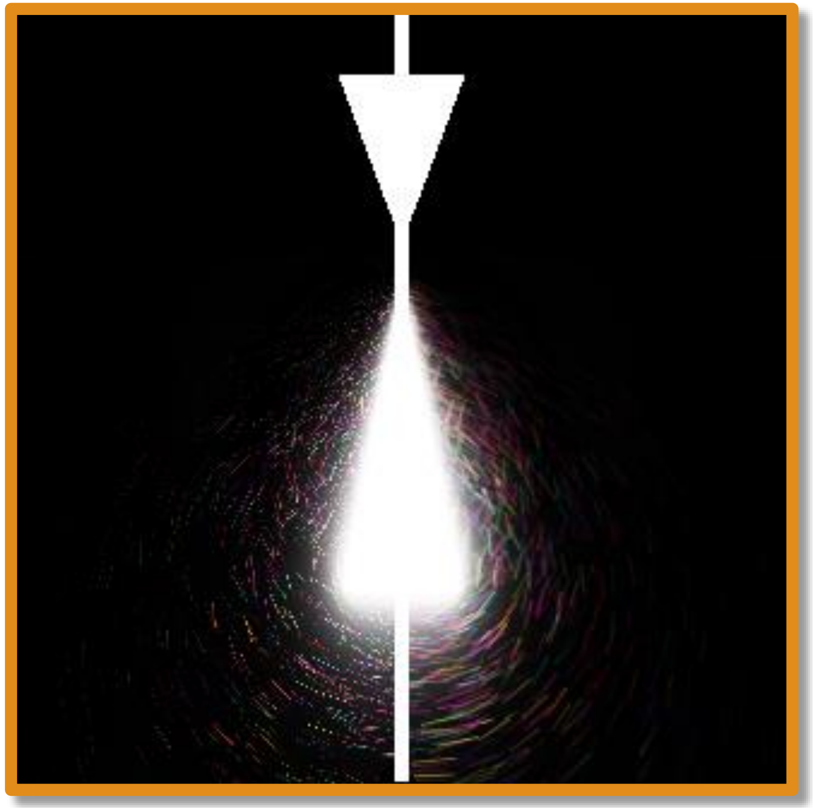


Anti-Aliasing and Scratch Density



Anti-Aliasing and Base Masking

- Taking the limit and correcting for small pixel footprint is good enough to approximate the integral in spatial domain

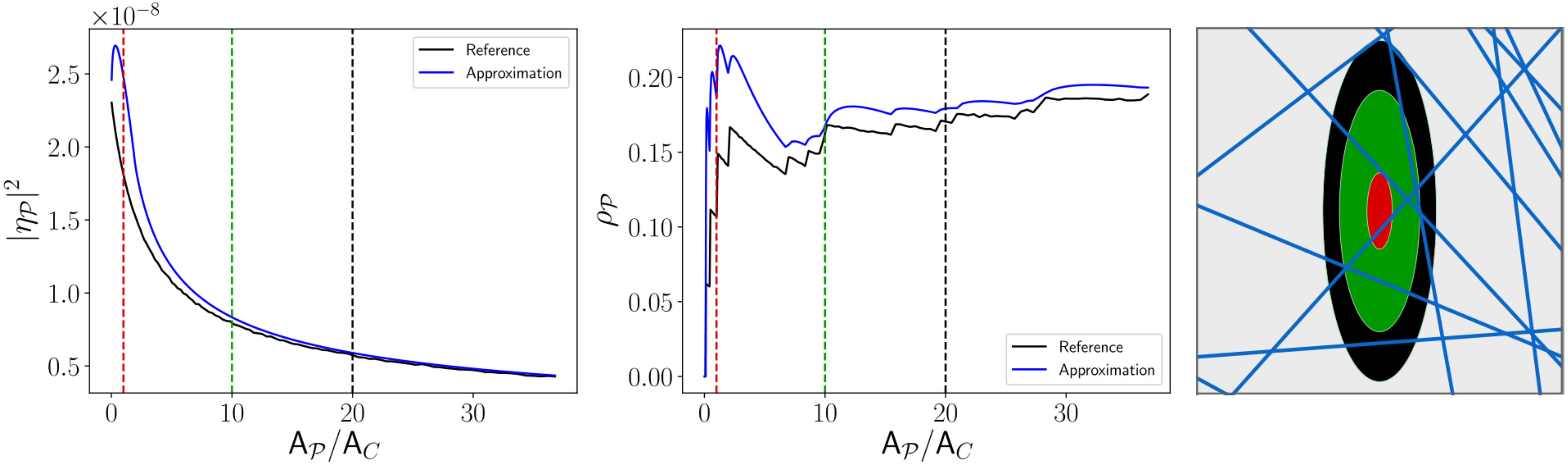
$$\alpha = \min\left(\frac{1}{2}\frac{A_{\wp}}{A_C}, 1\right)$$

$$|\eta_{\wp}|^2 \approx \alpha \int_{-\infty}^{+\infty} \int_{s_1}^{s_2} |\eta_s|^2 \, dx \, dy + (1-\alpha) A_{\wp} |\eta_s|^2$$

- Scratch density is similarly approximated

$$\rho_{\wp} \approx \frac{2}{A_{\wp}} \sum_m W^{(m)} l_{contained}^{(m)}$$

Anti-Aliasing and Base Masking (Error)



Anti-Aliasing

No Anti-Aliasing | Anti-Aliasing (Ours) | Monte Carlo (Box)

Implementation and Results

Data Structure

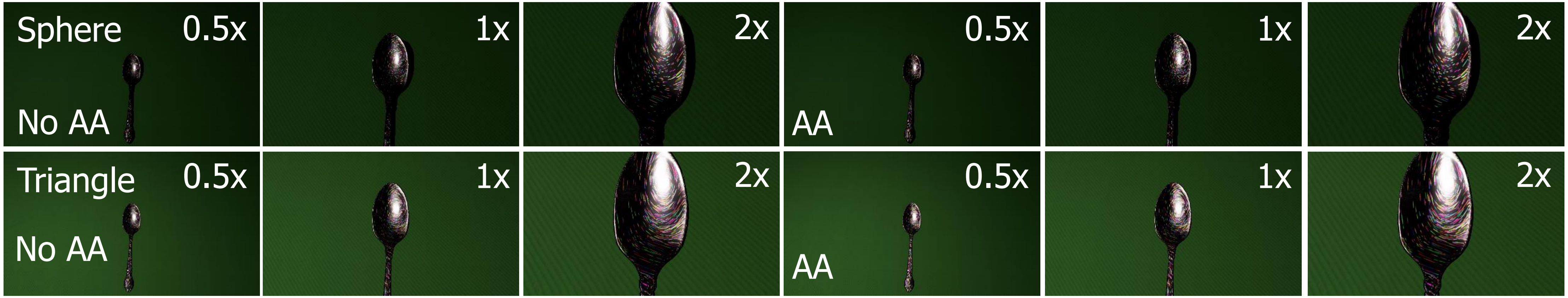
- Bounding Volume Hierarchy – threaded BVH with skip pointers [Smi98] – simplified compared to the DAG data structure from original paper [WVJH17]

- Per Triangle Array
  - Traversed by using PrimitiveID from Visibility Buffer
  - Requires covering scratches associated with nearby triangles that fall within the coherence area
  - Similarly applicable in regular path tracing

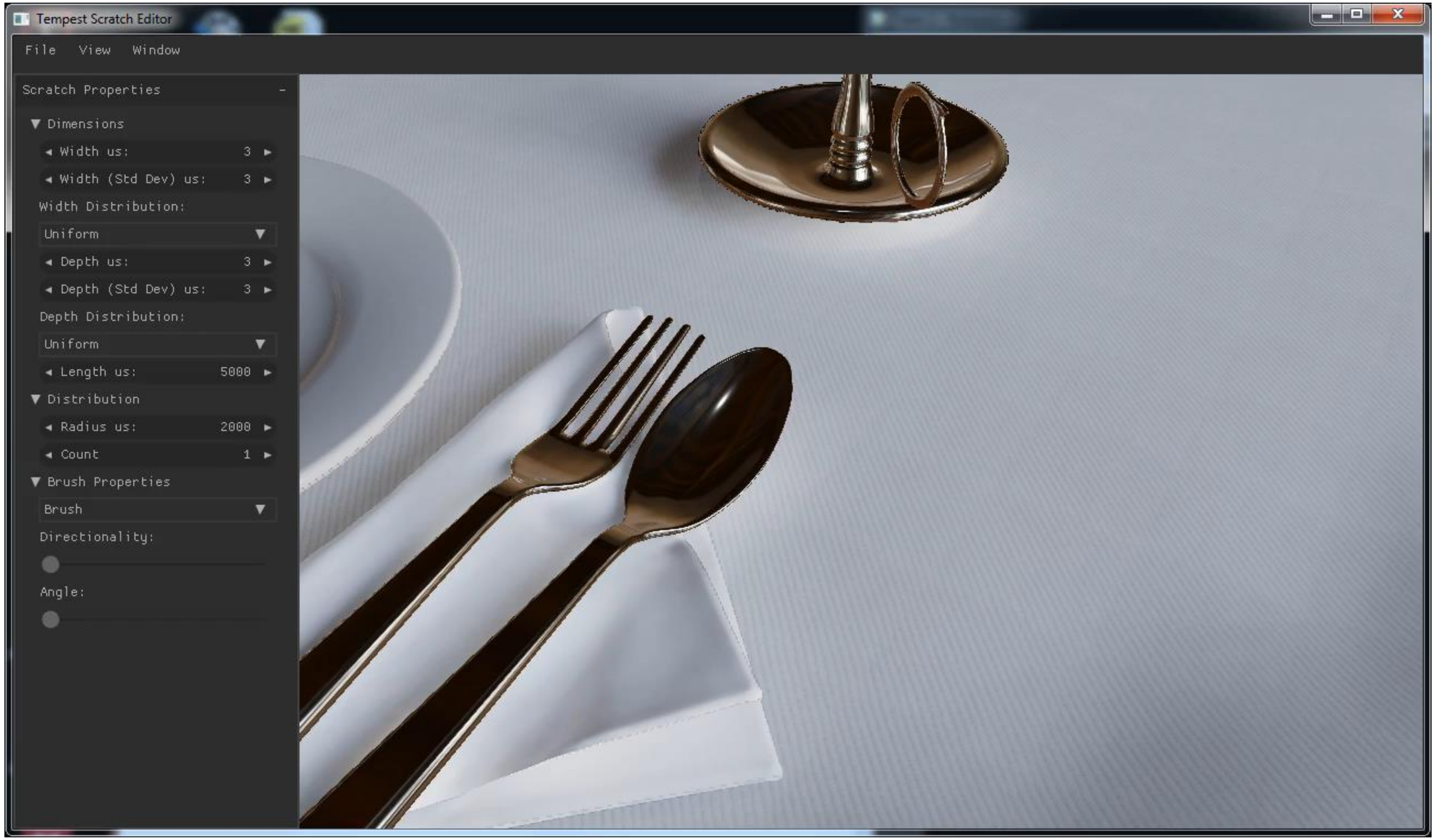
Data Structure (Benchmark)

Benchmark was performed on NVIDIA GTX 970M

	AA disabled						**AA enabled**		
Type	BVH			Per Triangle Array			BVH		
Zoom-In	0.5x	1x	2x	0.5x	1x	2x	0.5x	1x	2x
Intersection Only	4.1ms	4.4ms	5.5ms	2.9ms	3.5ms	3.8ms	18.1ms	17.5ms	15.5ms
Sphere	4.5ms	6.3ms	12.8ms	3.9ms	4.7ms	8ms	27.3ms	31.7ms	36.3ms
Triangle	13.9ms	26.5ms	60.6ms	12.5ms	21.1ms	43.4ms	48.5ms	60.3ms	94.1ms



Interactive editing with complete model



Summary

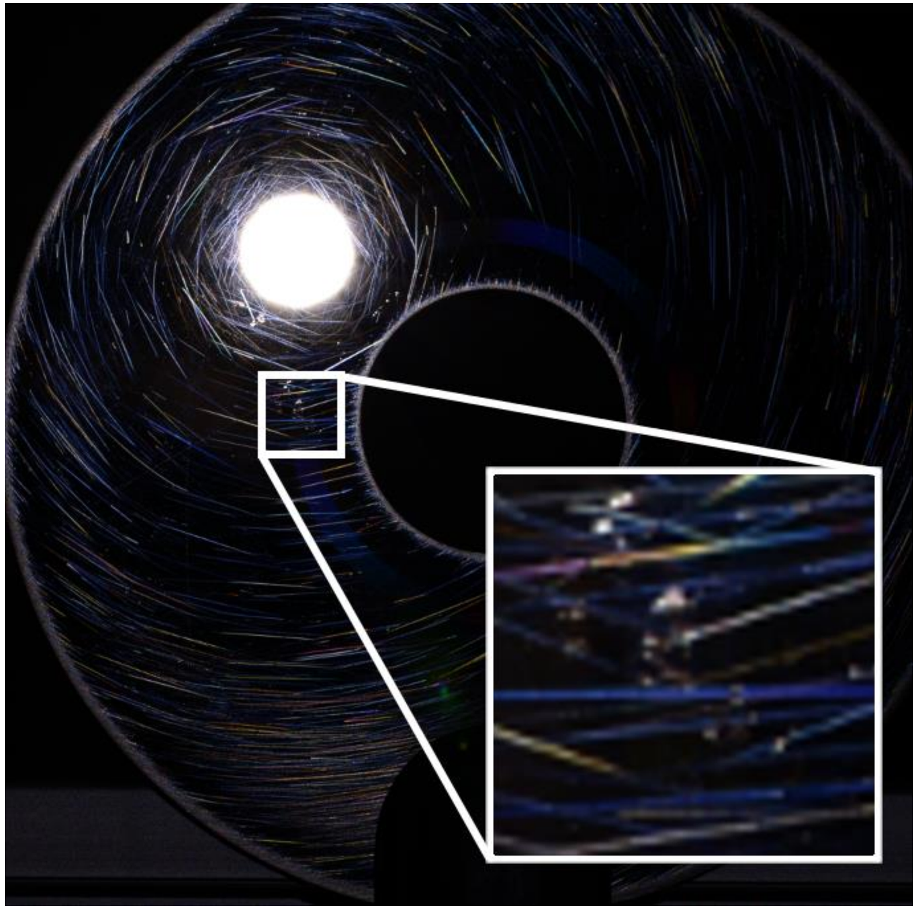
- Improved performance several orders of magnitude compared to [WVJH17] and enabled real-time performance
  - Polygonal and sphere light sources with potential for generalizing to more simple shapes
  - Anti-aliasing through approximate integration in spatial domain
  - More performant specialized data structure which are also compatible with original model

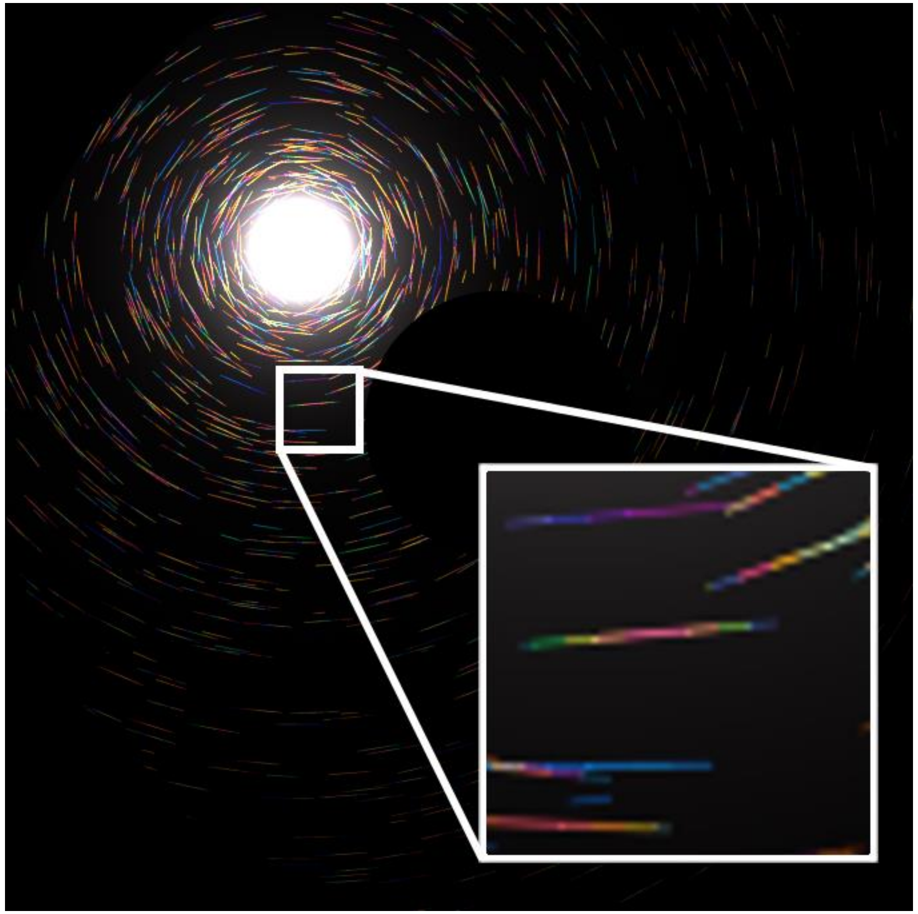
- Properties of the original model are preserved by approximations

Thank you

Source Code:
http://3dgraphics.guru/code/TempestRenderer-EG2018.zip

Ground truth





Complete BRDF + Light Source Line Integral

$$f(\xi, \mathbf{x}) \approx \frac{1}{\pi\sigma^2}\left((1-\rho)|\mathcal{B}(\xi)|^2 - |\mathrm{S}(\xi, \mathbf{x})|^2\right)$$

$$S(\xi|q_1, q_2) = W^{(m)^2} D^{(m)^2} \eta_s^{(m)^2} \left(\aleph^{(m)}(\xi, q_1) - \aleph^{(m)}(\xi, q_0)\right)$$

$$\aleph^{(m)}(\xi, q) = \frac{\sqrt{\pi}}{\sigma\pi}\left(2\frac{\mathrm{Si}\left(kW^{(m)}q\right)}{kW^{(m)}} - 4\frac{\sin^2\left(kW^{(m)}q/2\right)}{k^2 W^{(m)^2} q}\right)$$