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Time-Continuous Quasi-Monte Carlo Ray Tracing

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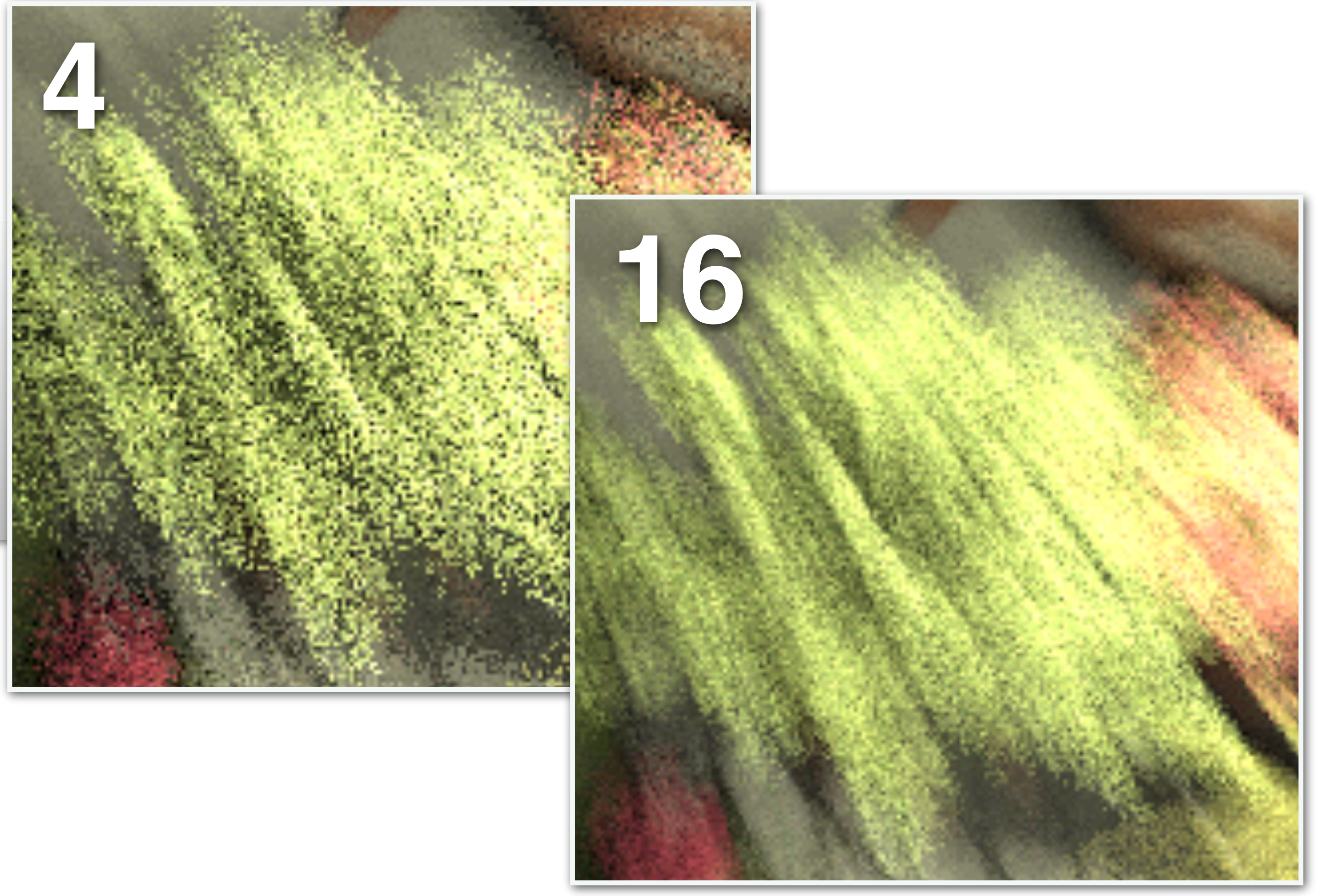
4 / 16 Point Samples
(Multi-Jitter Monte Carlo)



1 Time-Continuous Sample
4 shading samples

Motivation:

Monte Carlo-based ray tracing tends to converge slowly for high-frequent, multi-dimensional inputs

- Example: Motion Blur from high velocities

Cook 84
Akenine-Möller et al. 07
Lehtinen et al. 11

Our Proposal:

Integrate the temporal domain on *closed-form*

- Adds complexity, but very fast (“immediate”) convergence
- Not previously done in ray tracing

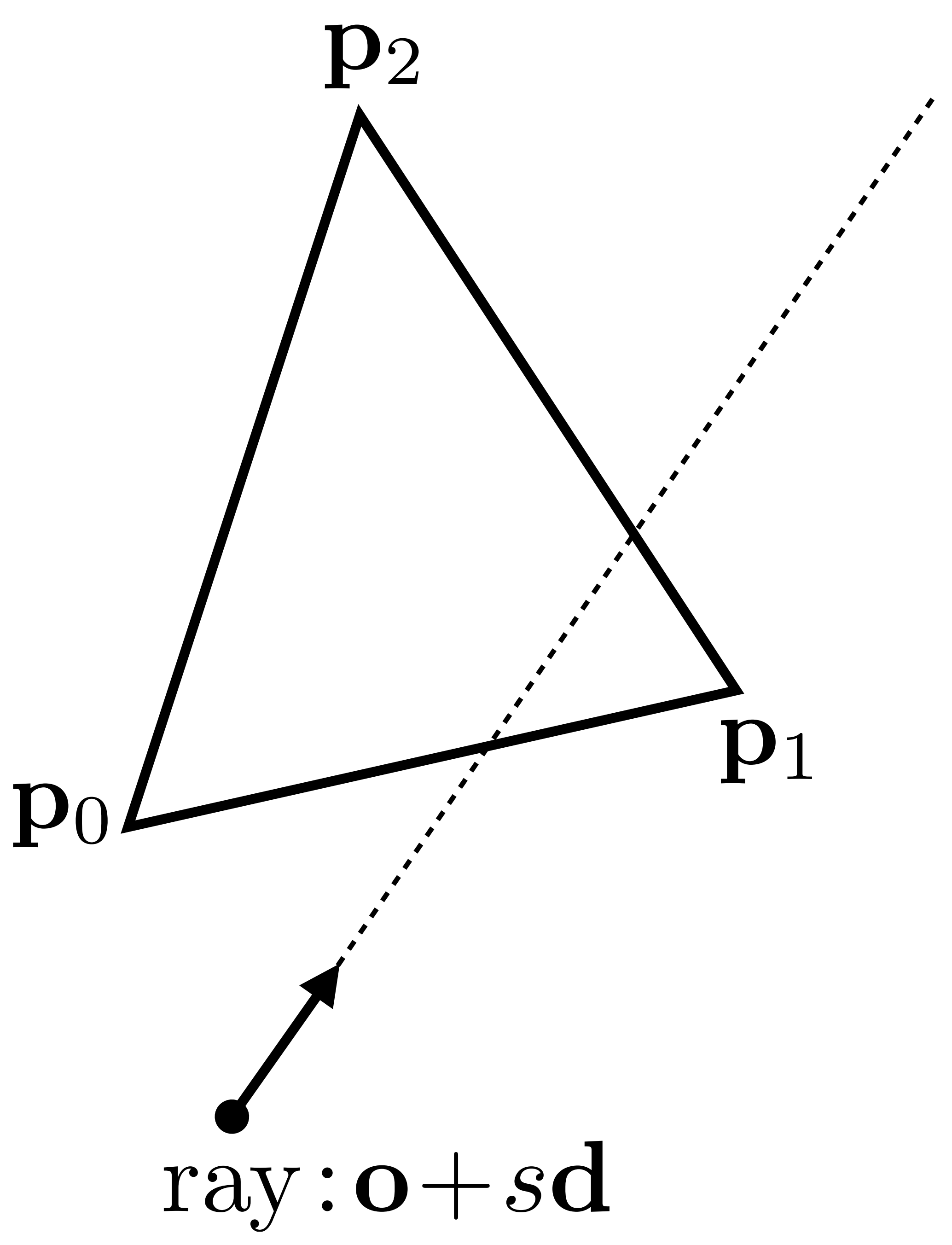
Catmull 78, 84
Sung 02
Gribel et al.10, 11, 12
Tzeng et al. 12
Nowrouzezahrai et al. 13

Talk Outline

- Two novel intersection tests, formulated for time-continuity:
  - Ray vs. Moving Triangle
  - Ray vs. Moving AABB
- Prototype Ray Tracer for Time-Continuous Primary Visibility
  - Mixed Sampling of Static and Dynamic Geometry
  - C^1-continuity Guided Shading Filtering
- Results, etc

Ray vs. Static Triangle

- Möller-Trumbore intersection test [Möller and Trumbore 97]
- Allow early-out termination, highly optimizable
- *s* = hit depth, *(u, v)* = barycentric coordinates of hit point

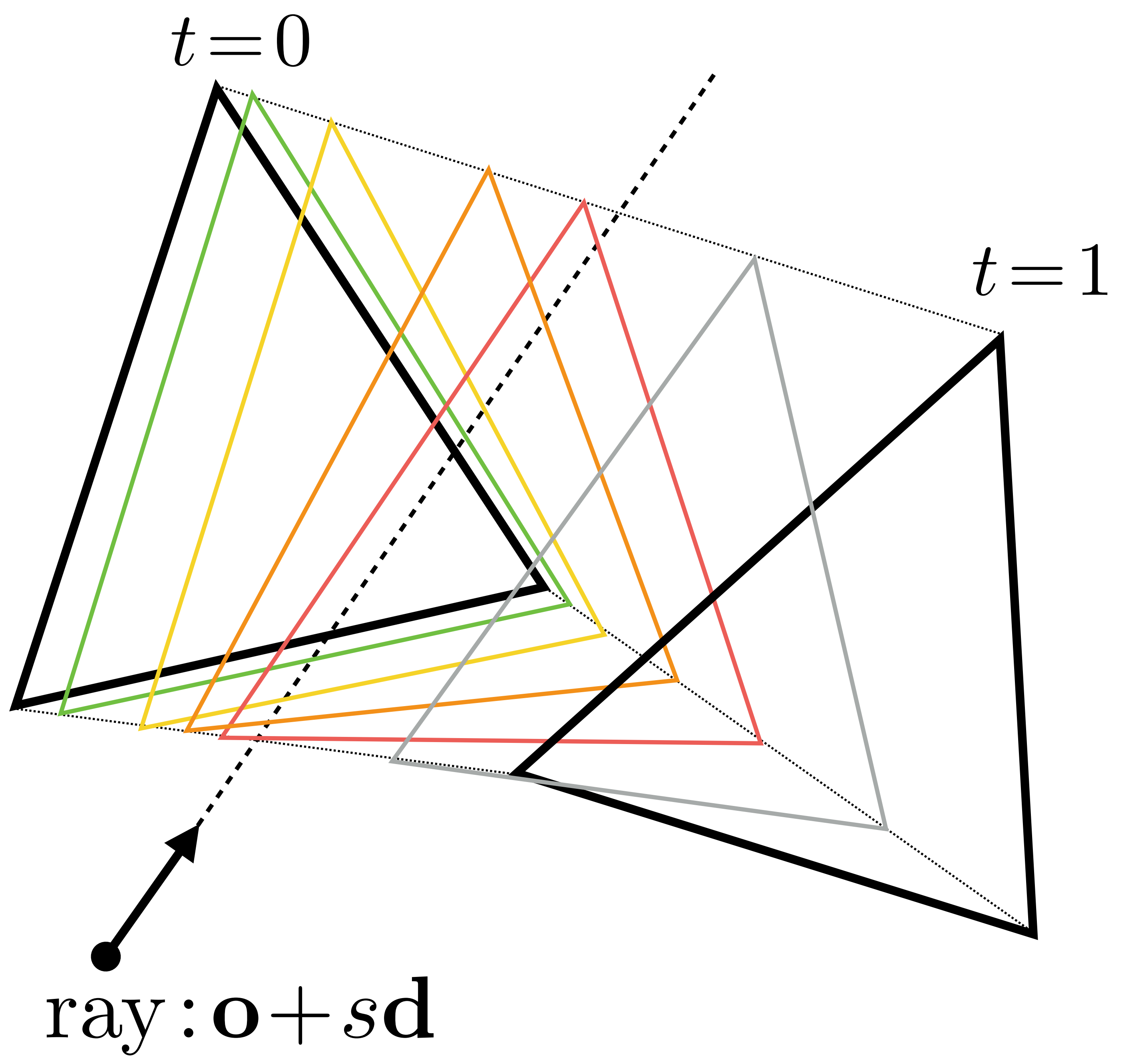


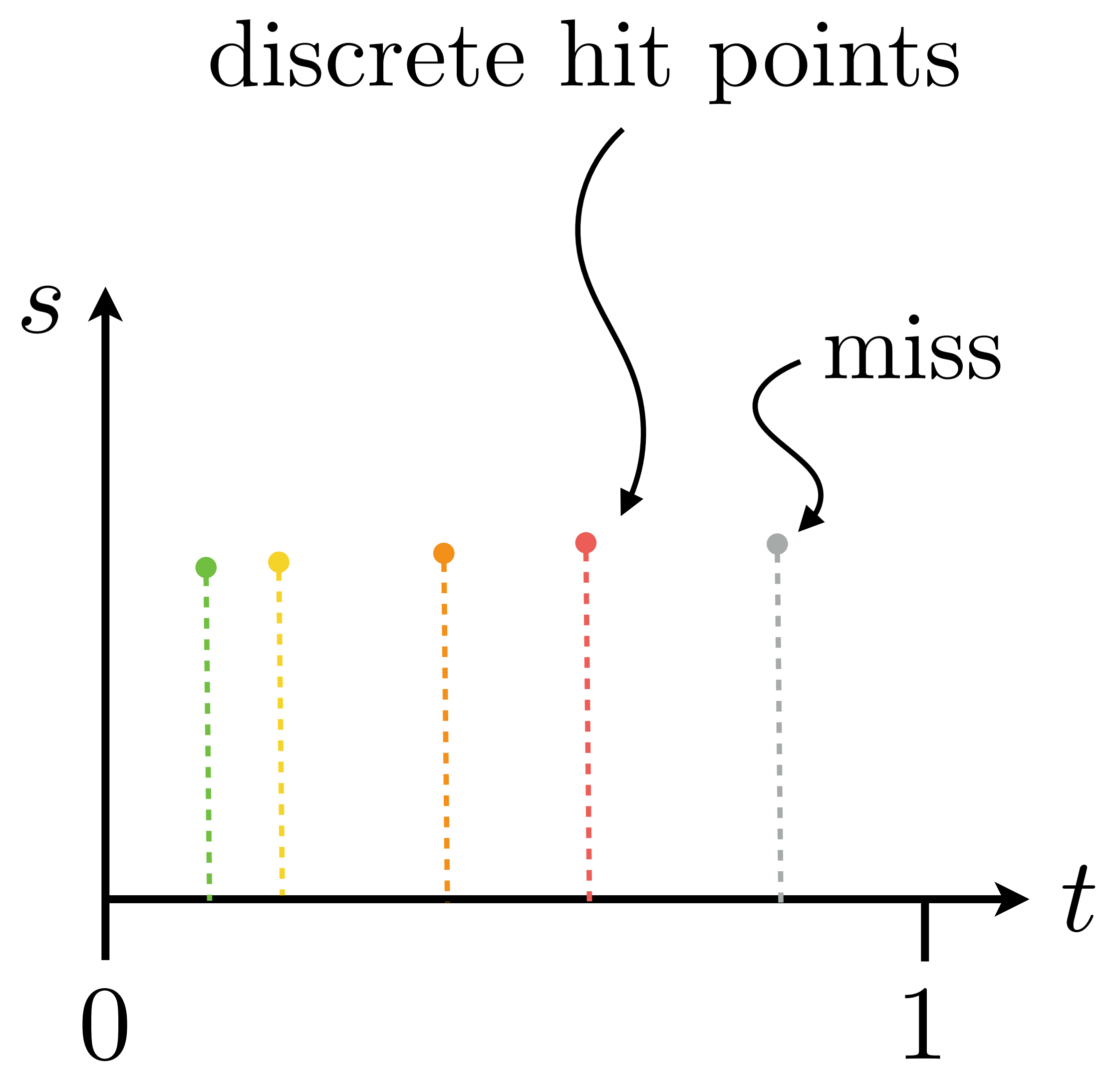
$$\begin{pmatrix} s \\ u \\ v \end{pmatrix} = \begin{pmatrix} -\mathbf{d} \\ \mathbf{p}_1 - \mathbf{p}_0 \\ \mathbf{p}_2 - \mathbf{p}_0 \end{pmatrix}^{-\mathrm{T}} (\mathbf{o} - \mathbf{p}_0)$$

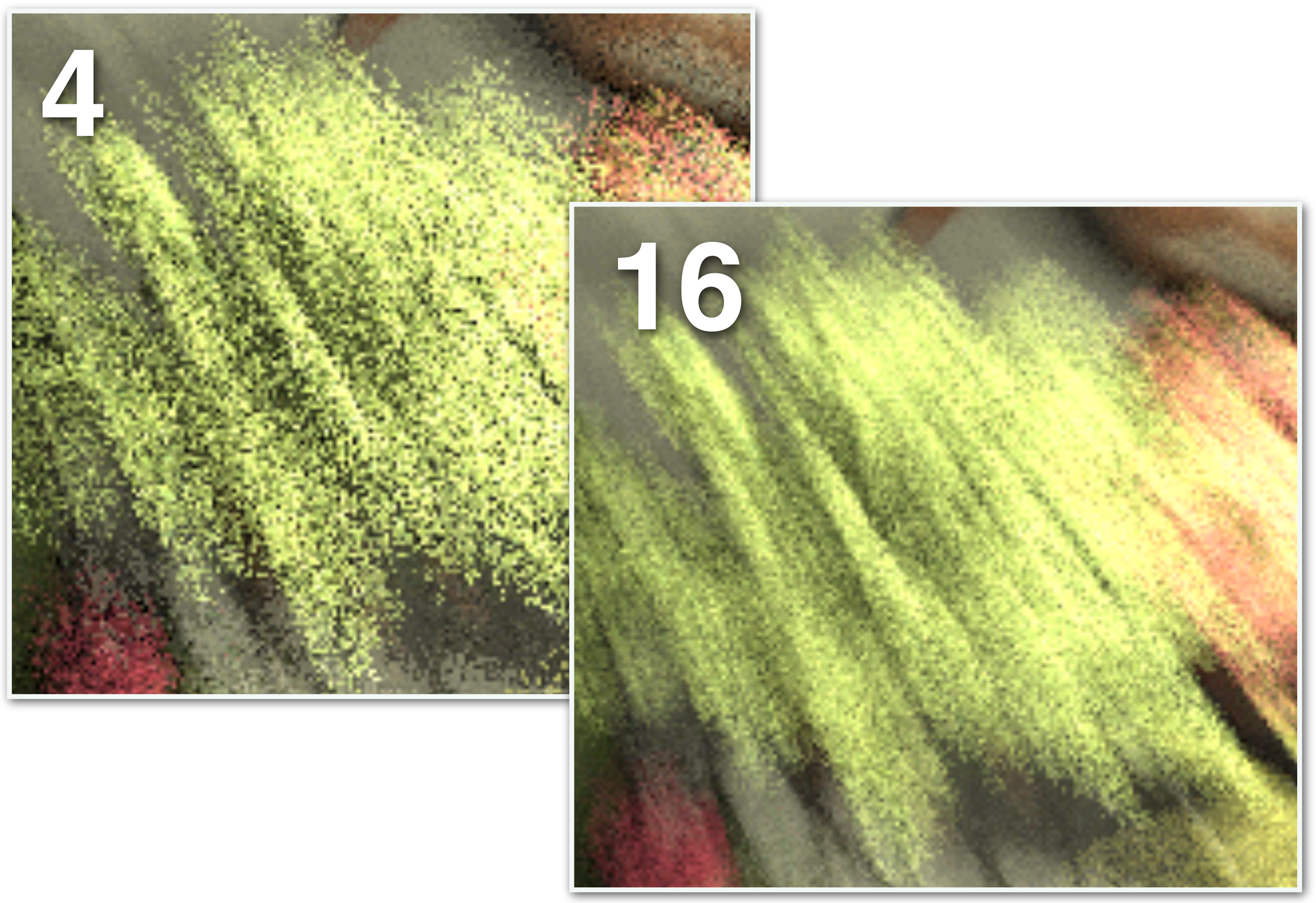
Intersection if $\left.\begin{array}{r} u \\ v \\ 1 - u - v \end{array}\right\} \geq 0$

Ray vs. Moving Triangle

- Monte Carlo Motion Blur: Assign discrete times to each ray
- In effect: interpolate triangle, intersect as if it were static

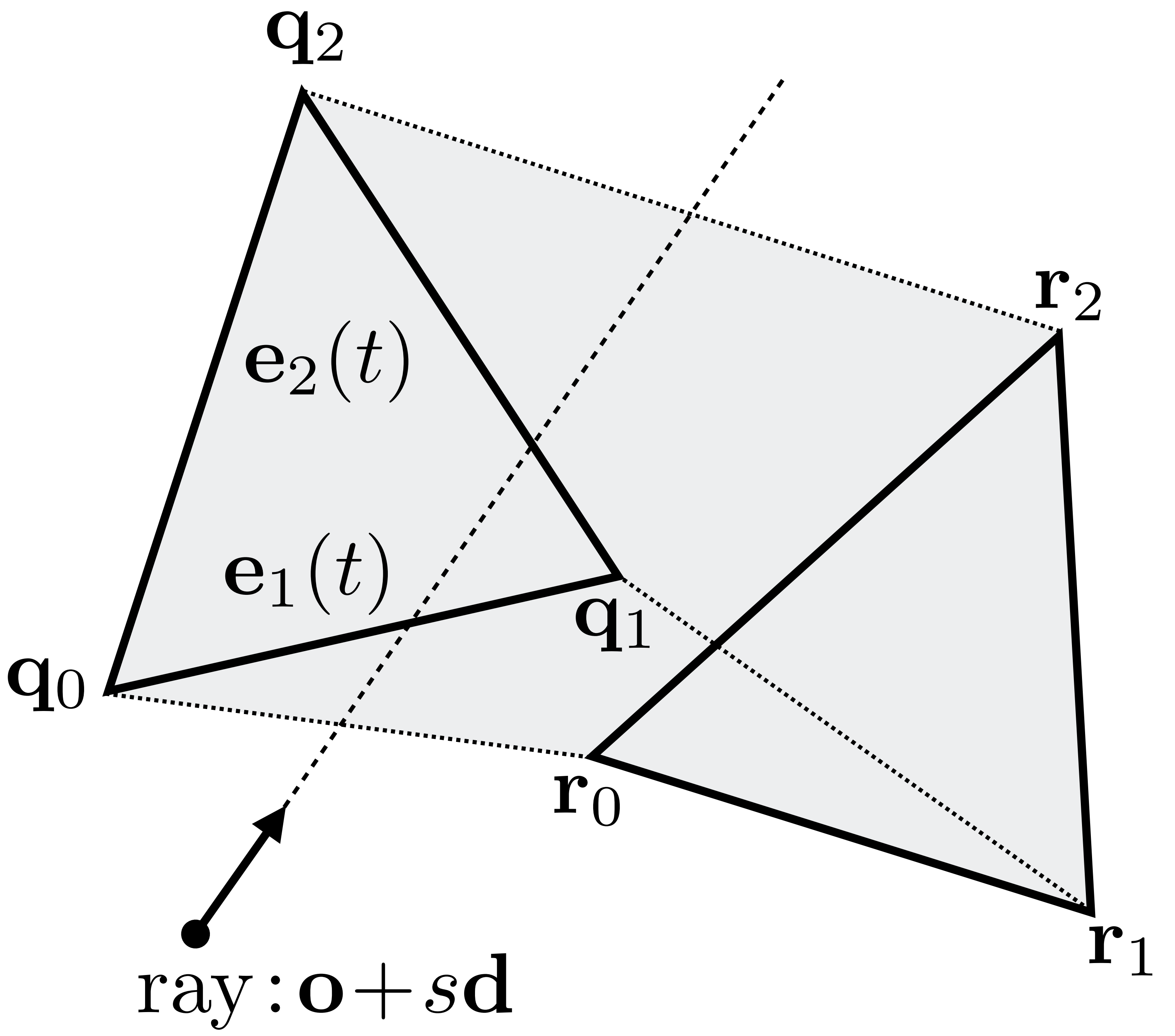


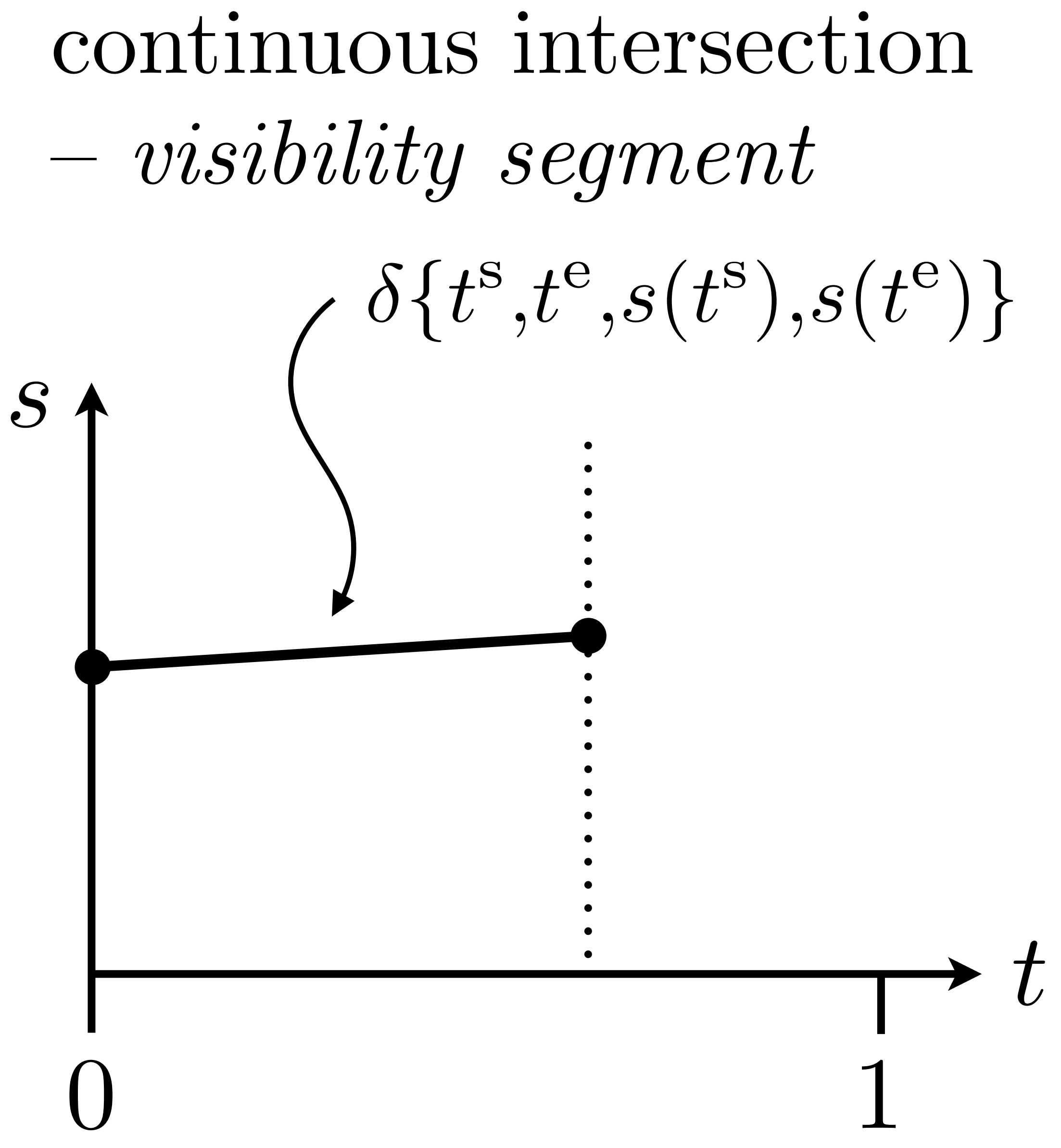




Ray vs. Moving Triangle

- Our approach: **reformulate & solve for *continuous* intersection**
- Interval of intersection – *visibility segment*





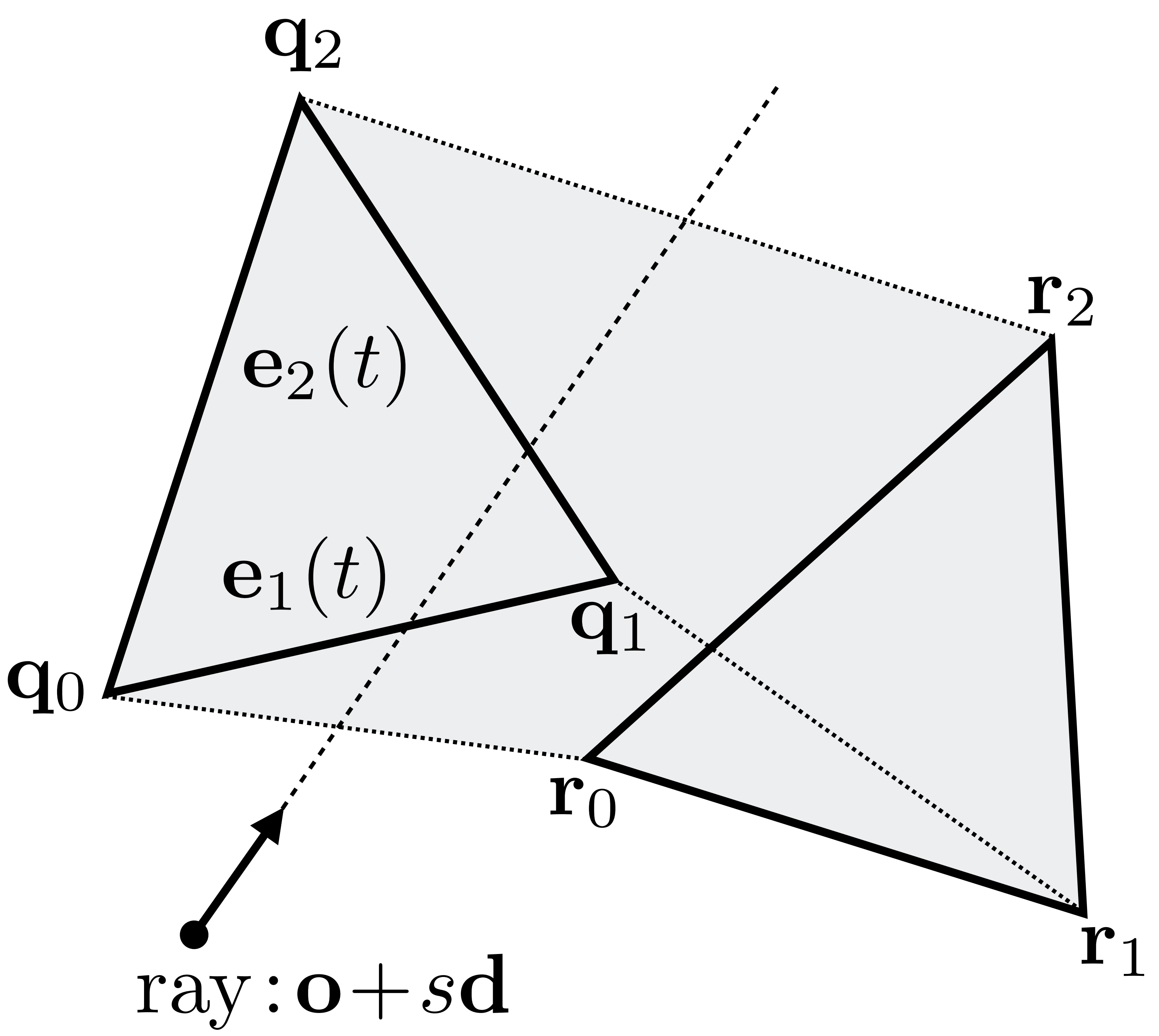
$$\begin{pmatrix} s(t) \\ u(t) \\ v(t) \end{pmatrix} = \begin{pmatrix} -\mathbf{d} \\ \mathbf{p}_1(t) - \mathbf{p}_0(t) \\ \mathbf{p}_2(t) - \mathbf{p}_0(t) \end{pmatrix}^{-\mathrm{T}} (\mathbf{o} - \mathbf{p}_0(t))$$

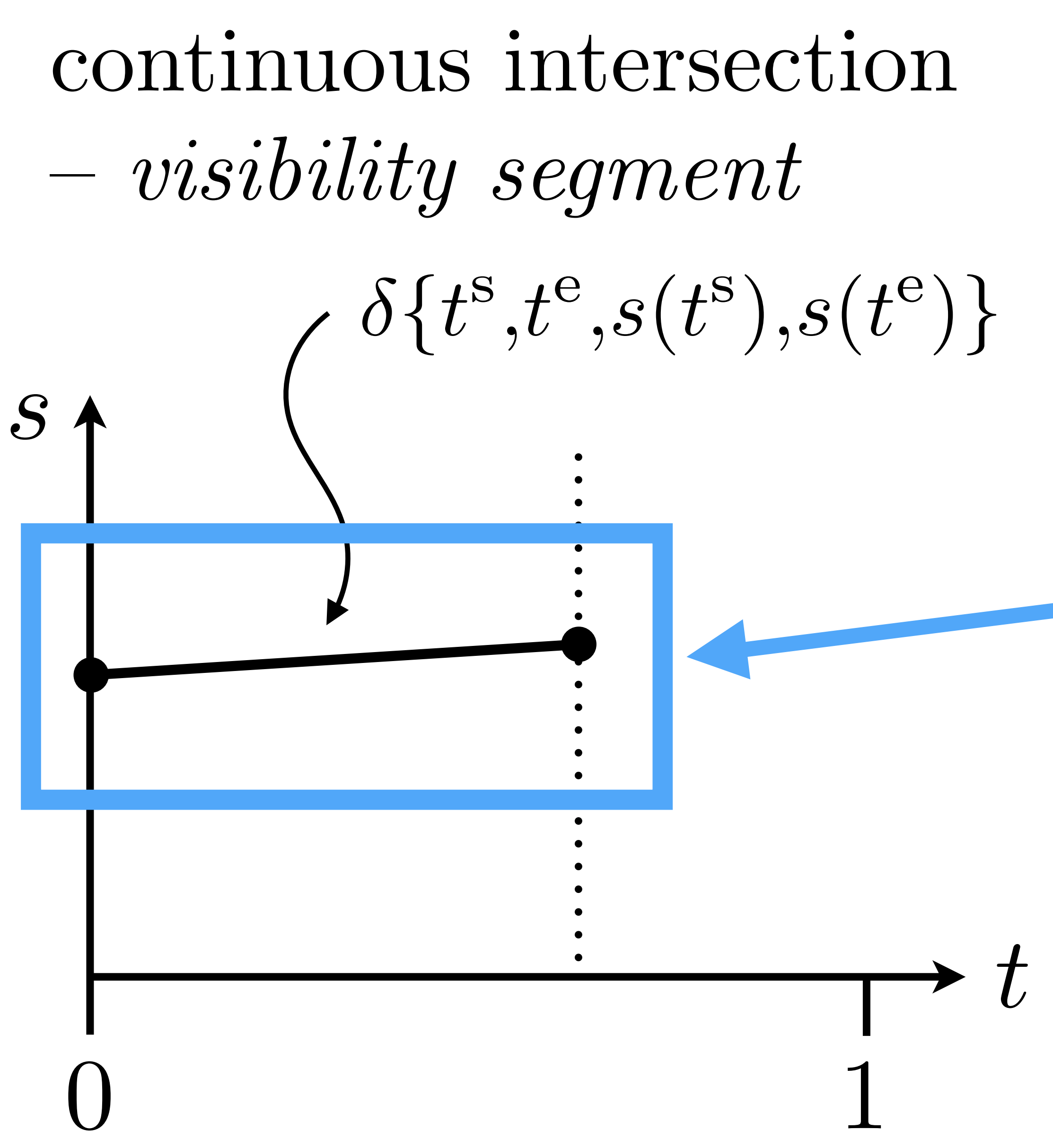
$$\left.\begin{matrix} u(t) \\ v(t) \\ 1 - u(t) - v(t) \end{matrix}\right\} \geq 0$$

u and v are 2nd degree polynomials (assuming per-vertex linear motion)

Ray vs. Moving Triangle

- Our approach: **reformulate & solve for *continuous* intersection**
- Interval of intersection – *visibility segment*





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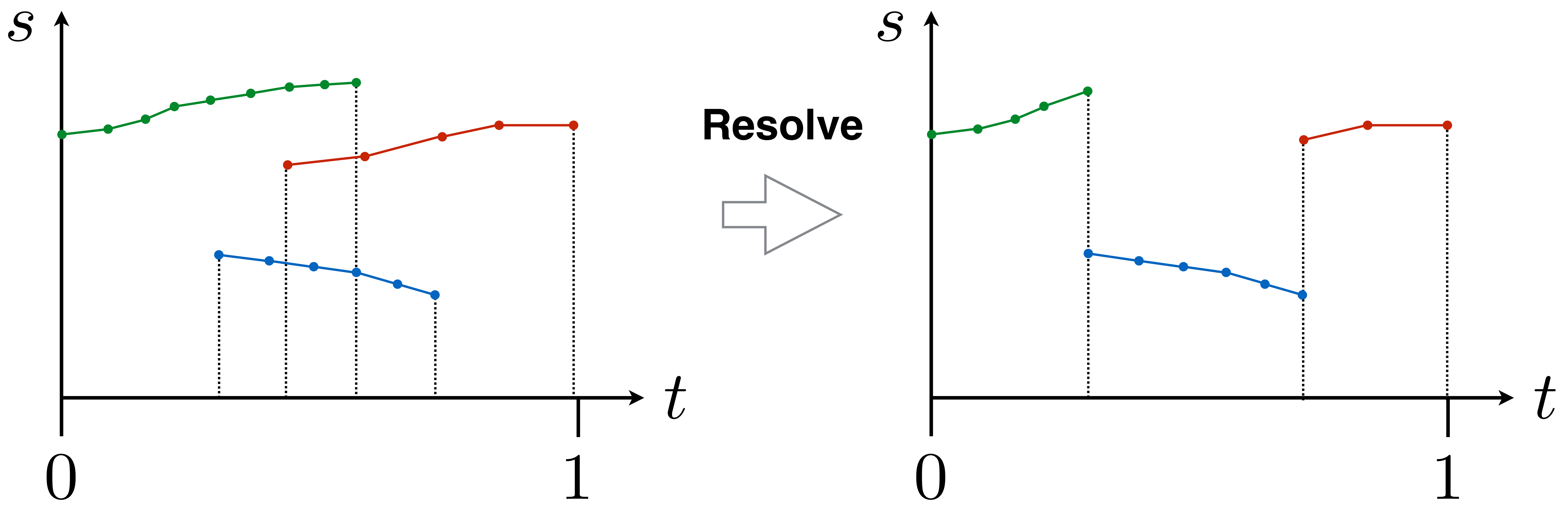
$$\left.\begin{matrix} u(t) \\ v(t) \\ 1 - u(t) - v(t) \end{matrix}\right\} \geq 0$$

Solve!

u and *v* are 2nd degree polynomials (assuming per-vertex linear motion)

Time-Continuous Ray – TC-Ray

- Collect visibility segments per ray during BVH traversal
- When traversal is done: **resolve** depth-wise (occlusion cull) to a sequence of non-overlapping segments [Barringer et al. 12]



Ray vs. Moving AABB

Levine's Moving Convex Polyhedra intersection test

(Algorithm published by Schneider and Eberly 02):

- Consider all candidate separating axes (Separating Axis Theorem)
- Compute temporal bounds of intersection per axis
- Terminate if bounds are disjoint, or – if union of all bounds are disjoint
- Assumes non-scaling AABB's

***Problem**:* AABB's in a BVH built for motion blur will usually scale

We extend this test to **support scaling AABB's**

- Formulation inspired by Ericson 04 (in the context of time-of-impact)

Ray vs. Moving AABB

- Candidate Separating axes for a ray $r = \mathbf{o} + s\mathbf{d}$ and an AABB:

$$\mathbf{n}_\mathrm{i} = \mathbf{u}_\mathrm{i} \times \mathbf{d} \qquad \text{where} \qquad \mathbf{u}_\mathrm{i} = \{(1,0,0),(0,1,1),(0,0,1)\}$$

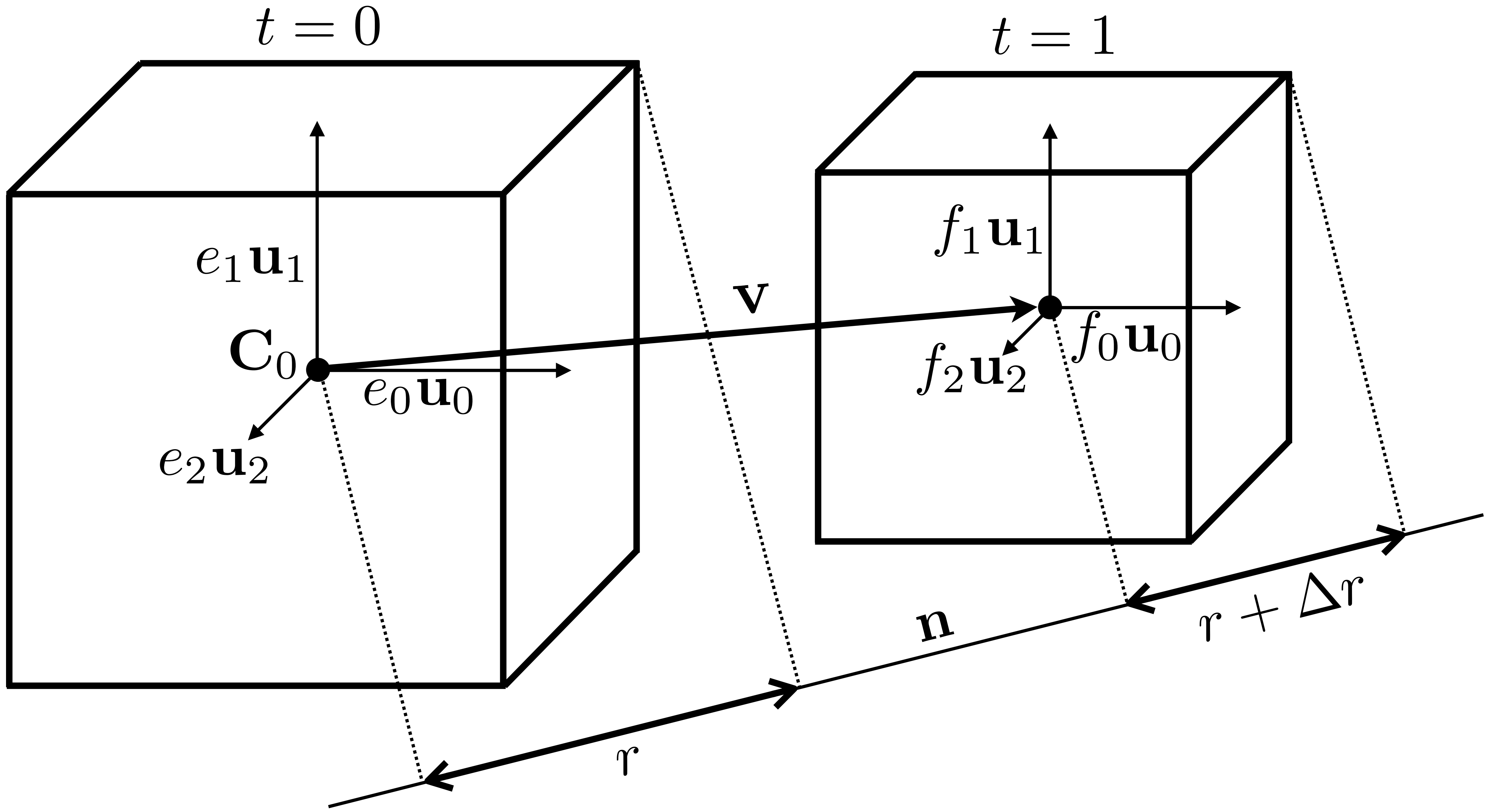
- These axes correspond to separating *planes*

$$\pi_\mathrm{i} : (\mathbf{u}_\mathrm{i} \times \mathbf{d}) \cdot (\mathbf{x} - \mathbf{o}) = 0$$

Ray vs. Moving AABB

Moving/scaling AABB vs. plane ($\mathbf{n}\cdot\mathbf{x} - d = 0$)
start/end times of intersection

$$t^{\pm} = \frac{\pm r_0 + d - \mathbf{n}\cdot\mathbf{C}_0}{\mathbf{n}\cdot\mathbf{v} - \pm\Delta r}$$



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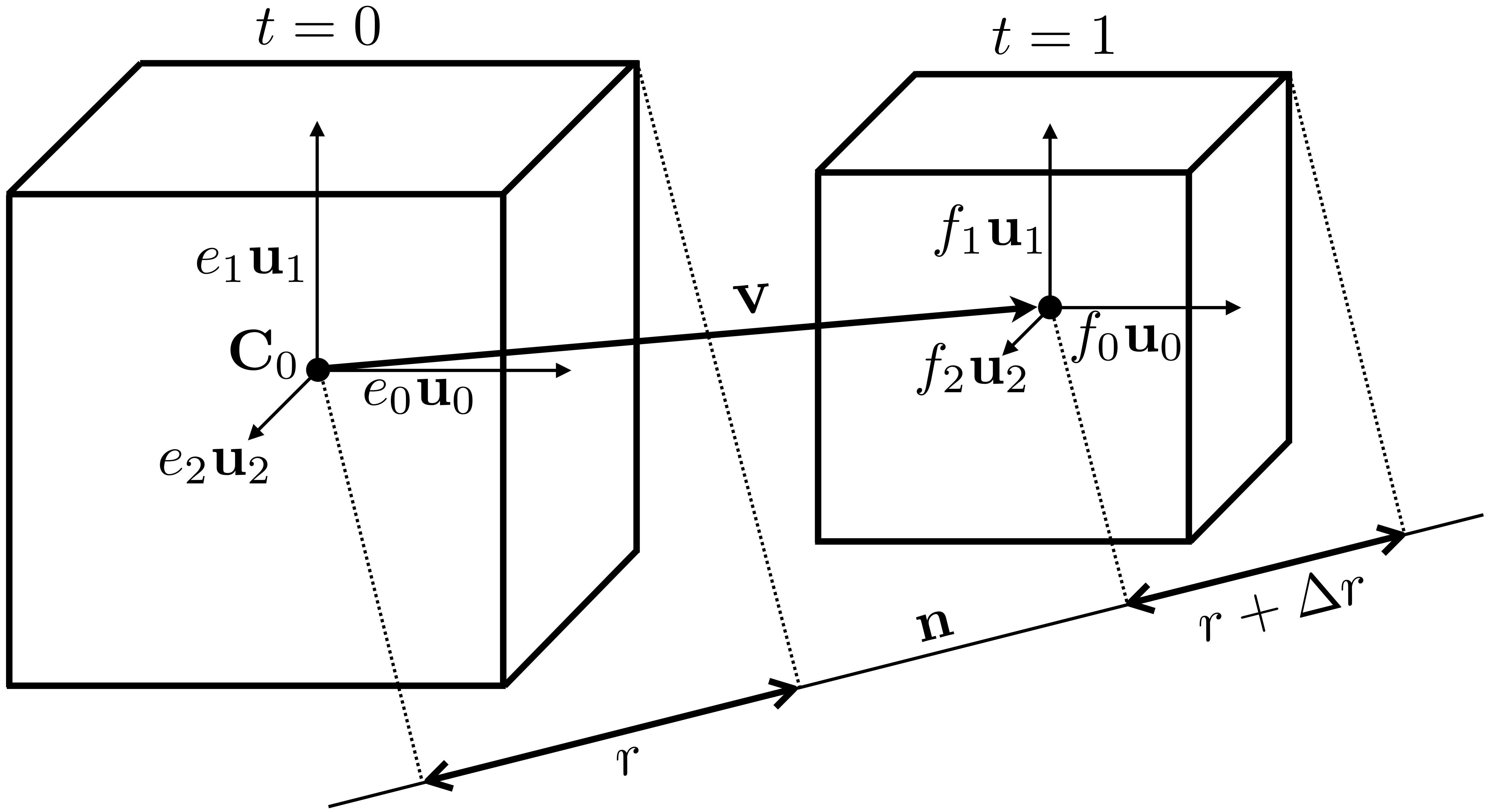

- Which is start/end?
- May be outside of $t = [0, 1]$
  – We need this form for our test:

$$[t^{\text{start}}, t^{\text{end}}] \in [0, 1]$$

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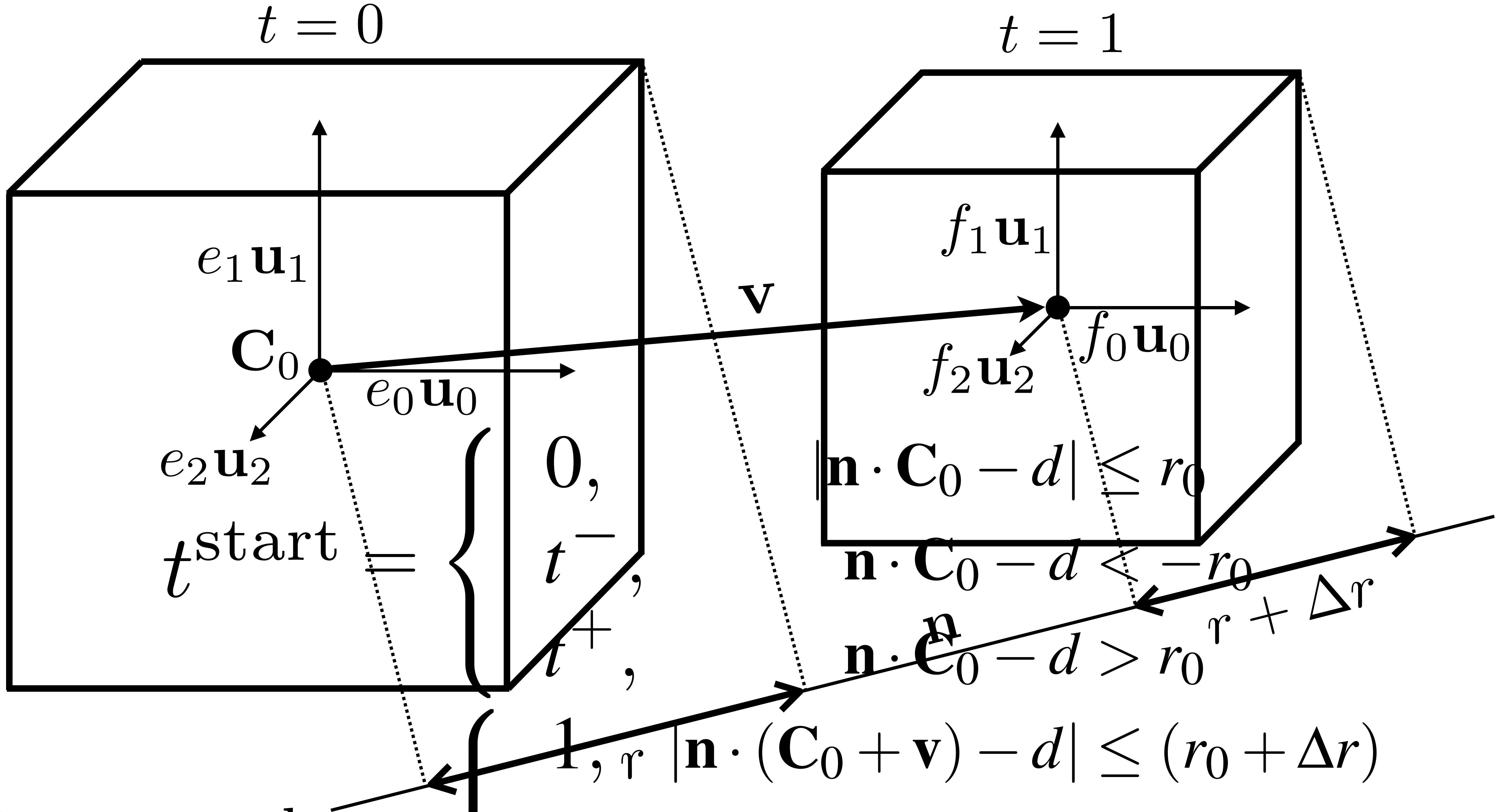
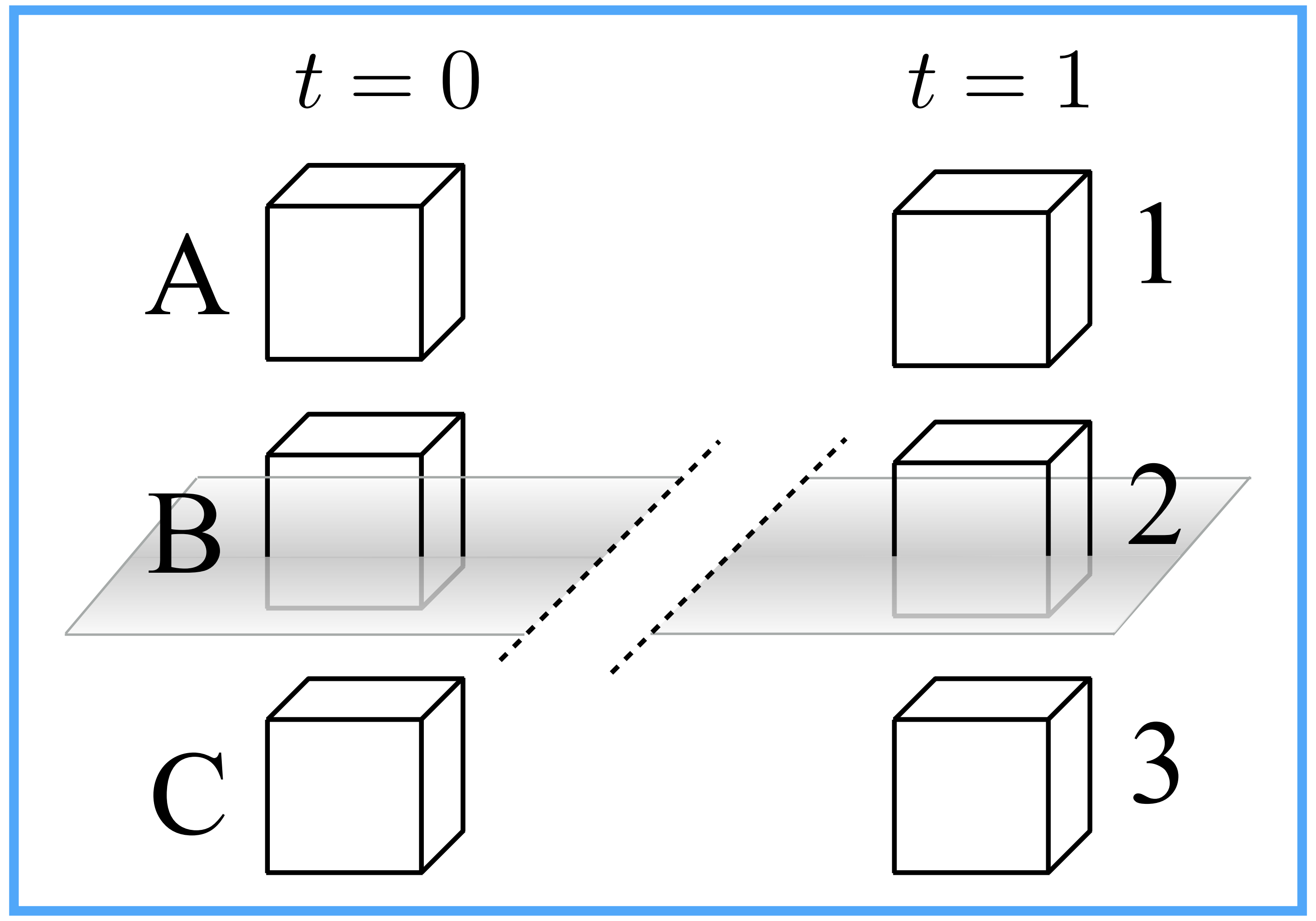


$$t^{\text{start}} = \begin{cases} 0, & |\mathbf{n}\cdot\mathbf{C}_0 - d| \le r_0 \\ t^{-}, & \mathbf{n}\cdot\mathbf{C}_0 - d < -r_0 \\ t^{+}, & \mathbf{n}\cdot\mathbf{C}_0 - d > r_0 \end{cases}$$

$$t^{\text{end}} = \begin{cases} 1, & |\mathbf{n}\cdot(\mathbf{C}_0 + \mathbf{v}) - d| \le (r_0 + \Delta r) \\ t^{-}, & \mathbf{n}\cdot(\mathbf{C}_0 + \mathbf{v}) - d < -(r_0 + \Delta r) \\ t^{+}, & \mathbf{n}\cdot(\mathbf{C}_0 + \mathbf{v}) - d > (r_0 + \Delta r) \end{cases}$$

Ray vs. Moving AABB



Moving/scaling AABB vs. plane ($\mathbf{n}\cdot\mathbf{x} - d = 0$)
start/end times of intersection

$$t^{\pm} = \frac{\pm r_0 + d - \mathbf{n}\cdot\mathbf{C}_0}{\mathbf{n}\cdot\mathbf{v} - \pm\Delta r}$$

- Which is start/end?
- May be outside of $t = [0, 1]$
  – We need this form for our test:

$$[t^{\text{start}}, t^{\text{end}}] \in [0, 1] \longrightarrow$$

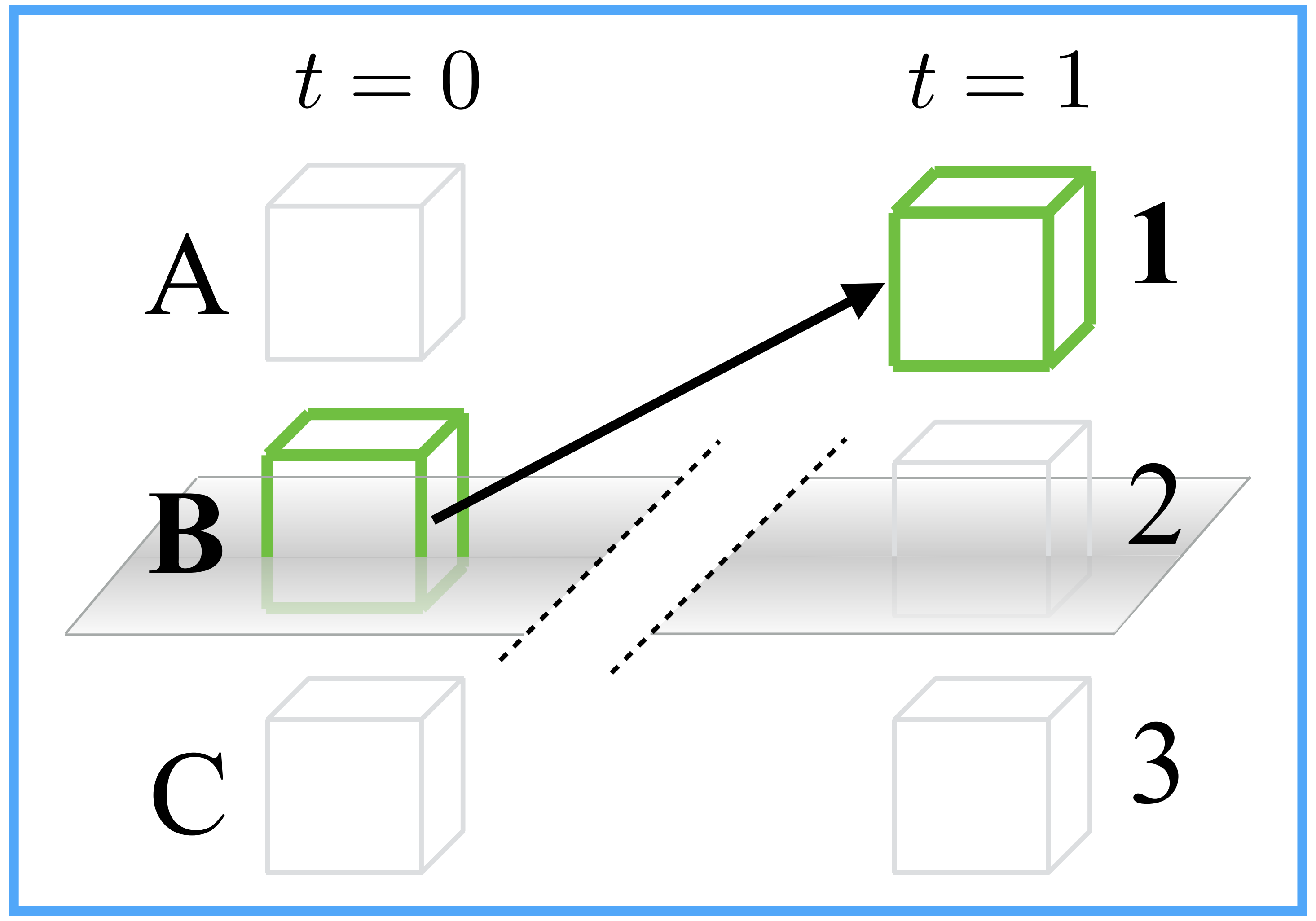
$$t^{\text{start}} = \begin{cases} 0, & \text{B} \\ t^{-}, & \text{C2 or C1} \\ t^{+}, & \text{A2 or A3} \end{cases}$$

$$t^{\text{end}} = \begin{cases} 1, & \text{2} \\ t^{-}, & \text{A3 or B3} \\ t^{+}, & \text{B1 or C1} \end{cases}$$

Ray vs. Moving AABB

Moving/scaling AABB vs. plane ($\mathbf{n}\cdot\mathbf{x} - d = 0$)
start/end times of intersection

$$t^{\pm} = \frac{\pm r_0 + d - \mathbf{n}\cdot\mathbf{C}_0}{\mathbf{n}\cdot\mathbf{v} - \pm\Delta r}$$



- Which is start/end?
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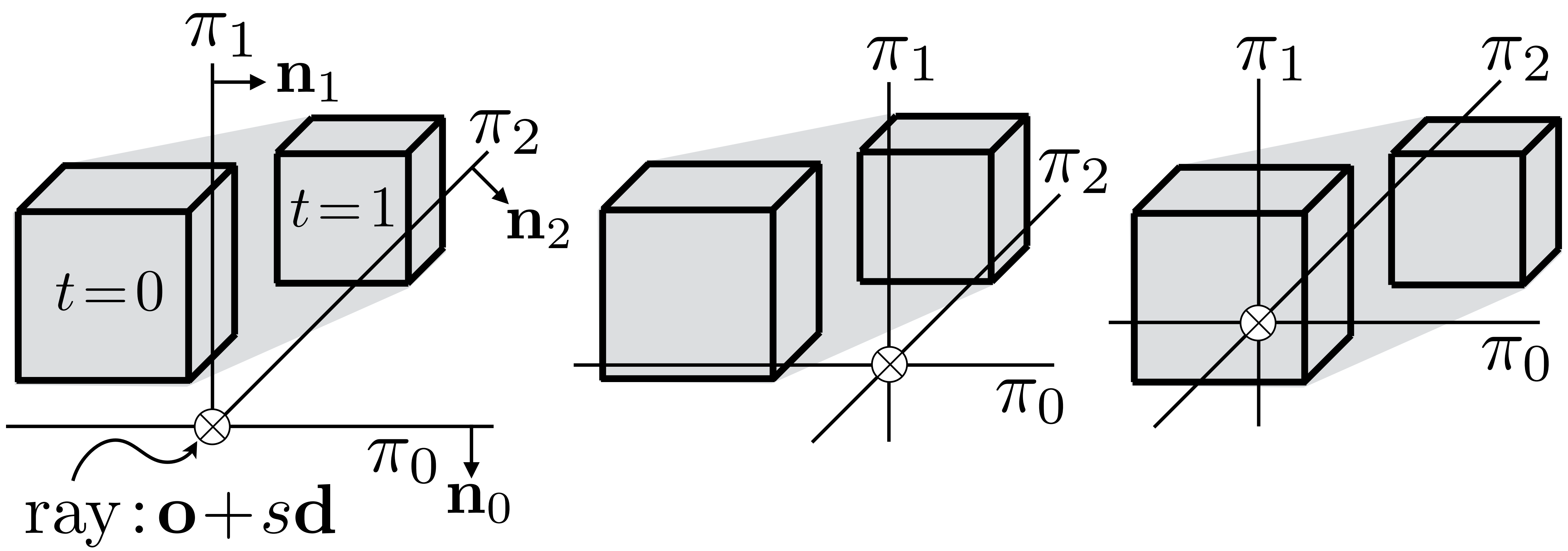
  – We need this form for our test:

$$[t^{\text{start}}, t^{\text{end}}] \in [0, 1] \longrightarrow$$

$$t^{\text{start}} = \begin{cases} 0, \\ t^{-}, \\ t^{+}, \end{cases} \qquad t^{\text{end}} = \begin{cases} 1, \\ t^{-}, \\ t^{+}, \end{cases}$$

B
C2 or C1
A2 or A3
2
A3 or B3
B1 or C1

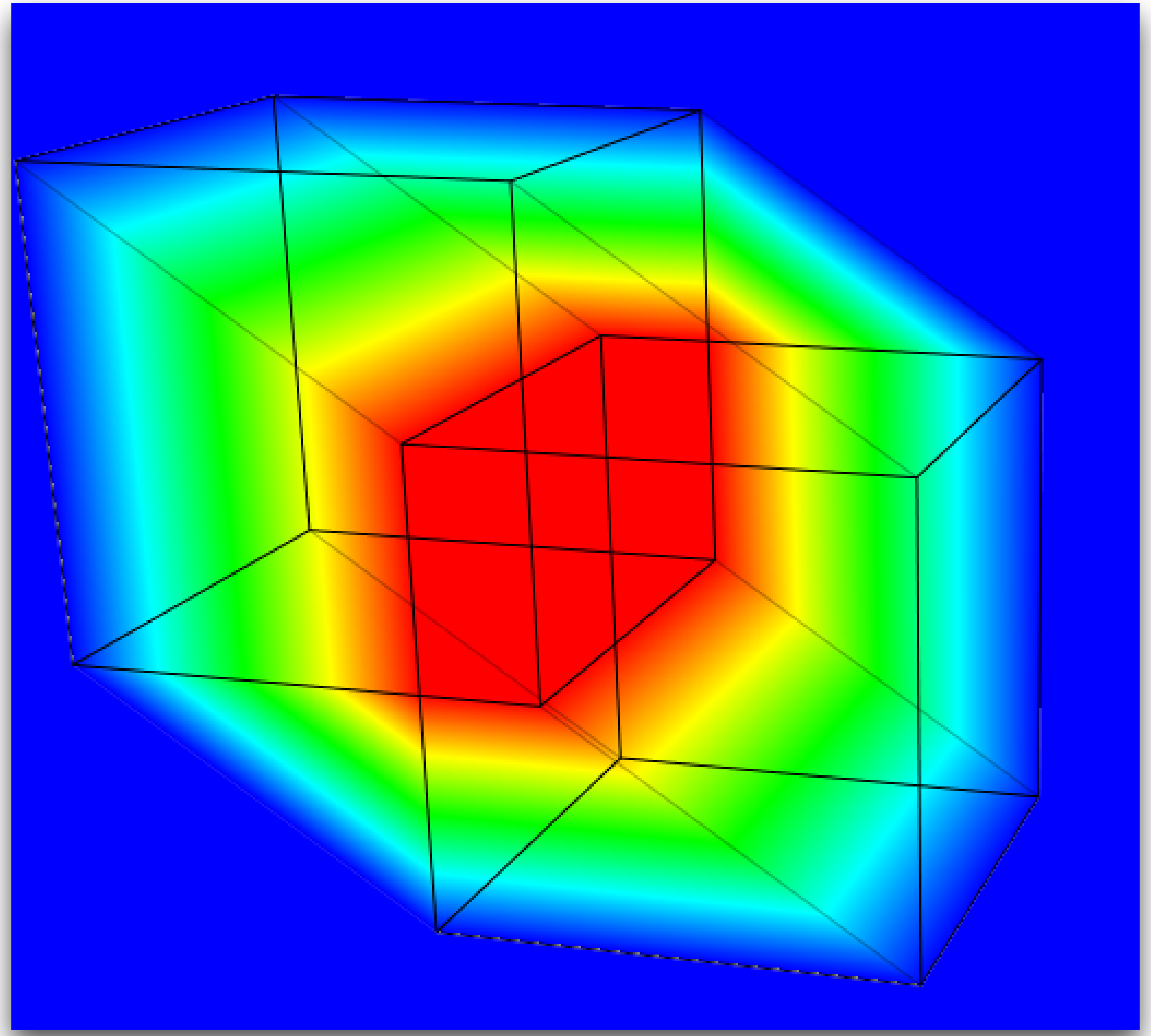
Ray vs. Moving AABB



$t_0^{s,e}$	$\varnothing$	$[0.0, 0.1]$	$[0.0, 0.6]$
$t_1^{s,e}$	ABORT	$[0.3, 1.0]$	$[0.0, 0.5]$
$t_2^{s,e}$		ABORT	$[0.0, 1.0]$
$\bigcap_{i=0}^{2}$	$\varnothing$	$\varnothing$	$[0.0, 0.5]$

Ray vs. Moving AABB

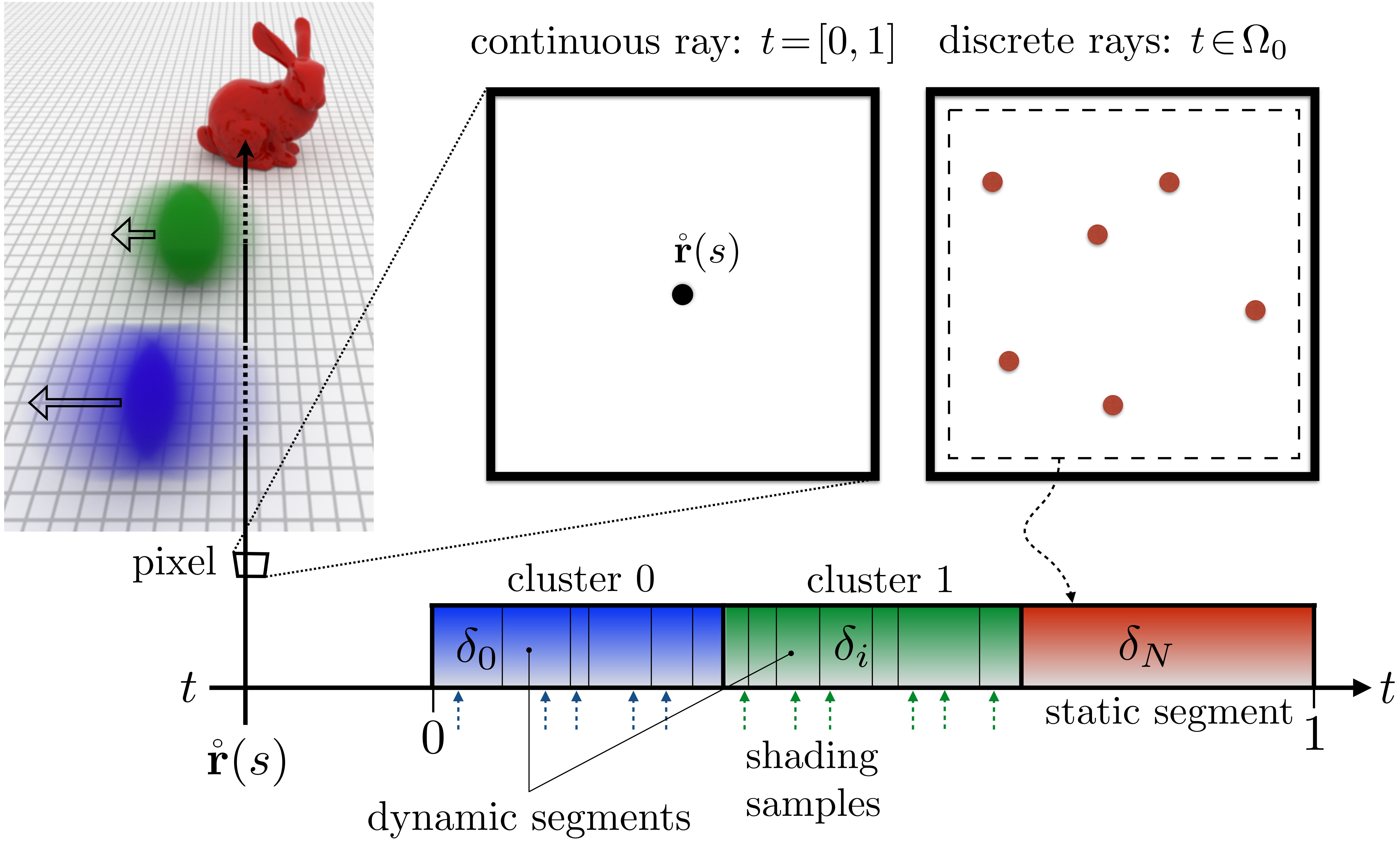
- Bound accuracy
  - Blue: empty bounds
  - Red: [0,1]



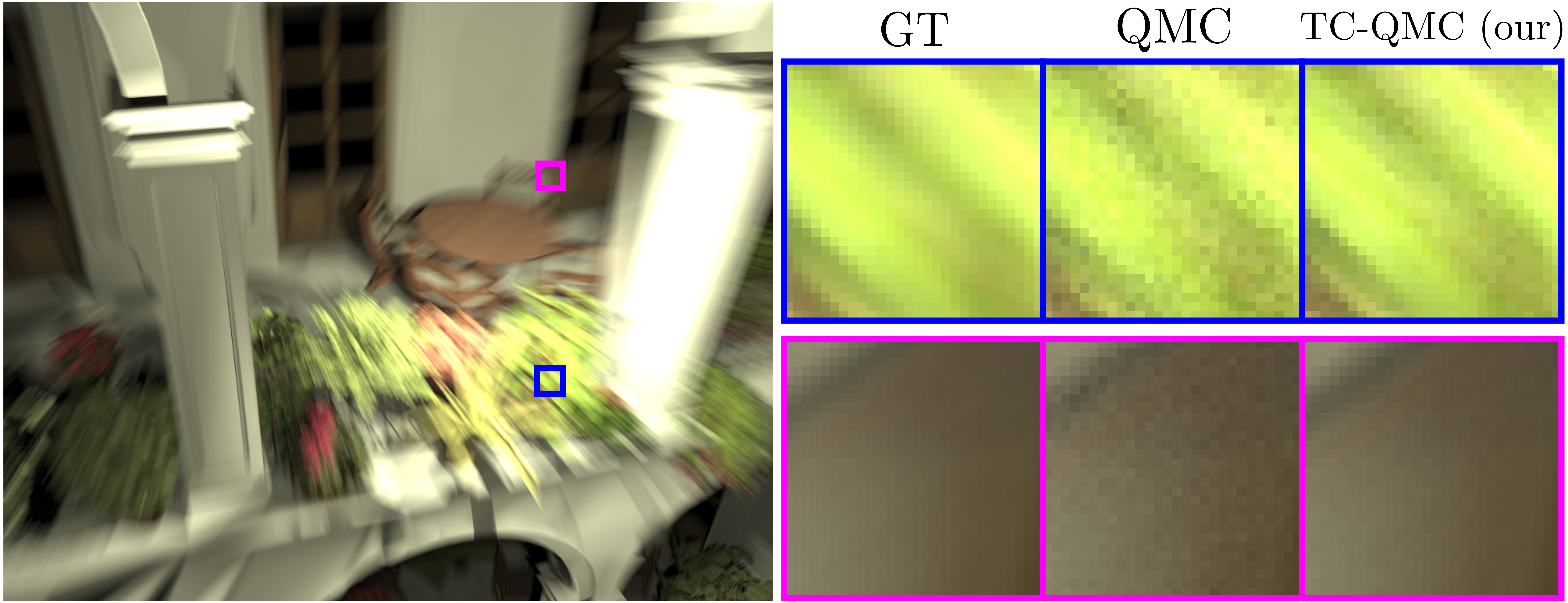
Prototype Ray Tracer

- Based on Intel's *Embree* [Wald et al. 14]
- **Shading**: *N* shading samples over the set of visibility segments
  - C^1-clustering: Group geometrically similar segments and blend shading with a common weight (temporal length of group)
- **Dual traversal kernels**: time-discrete & time-continuous
  - Mixed Sampling: Detect static geometry and fall back to regular point sampling

Mixed Sampling and Clustering



Equal Time

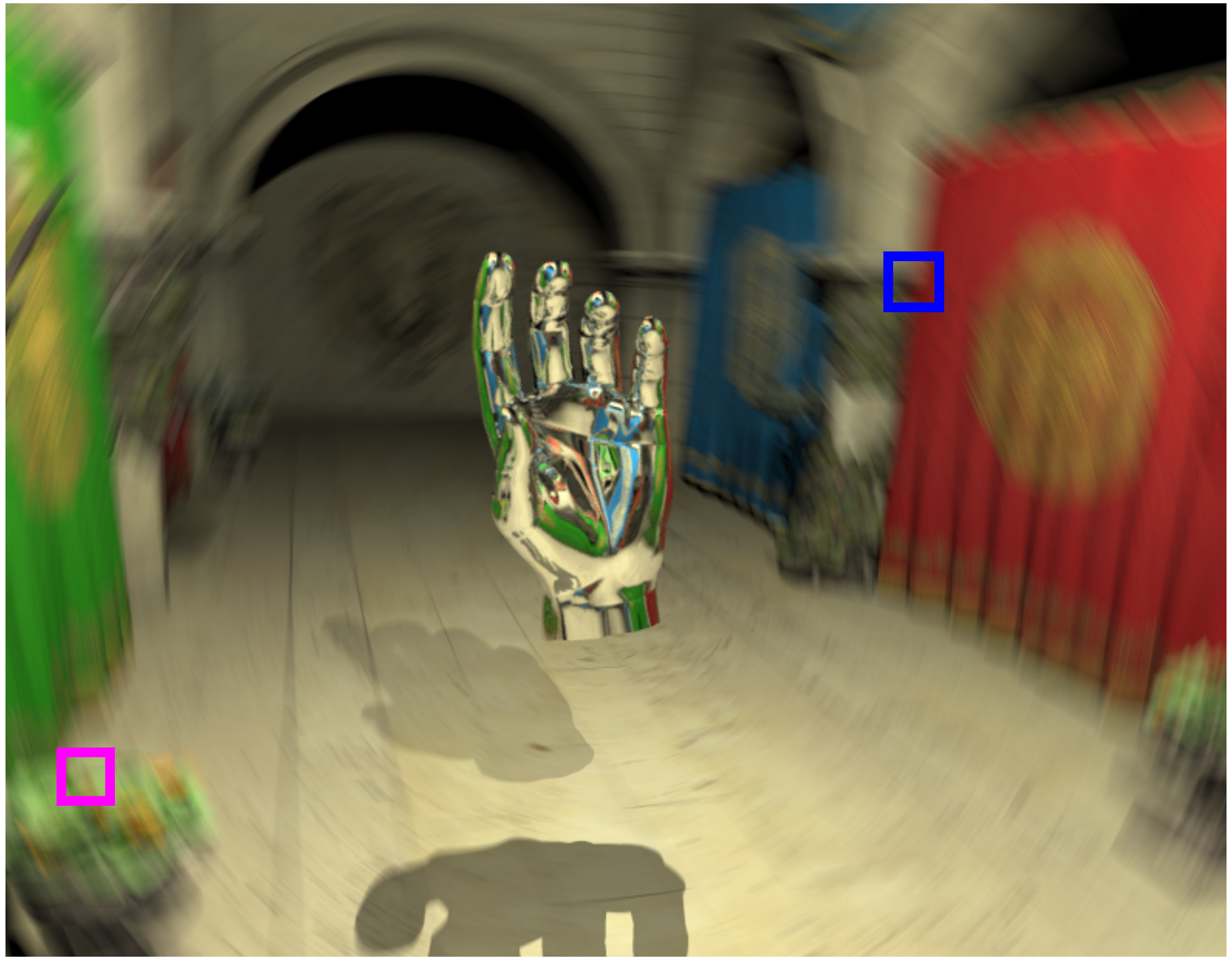


SAN MIGUEL: 7.8M triangles

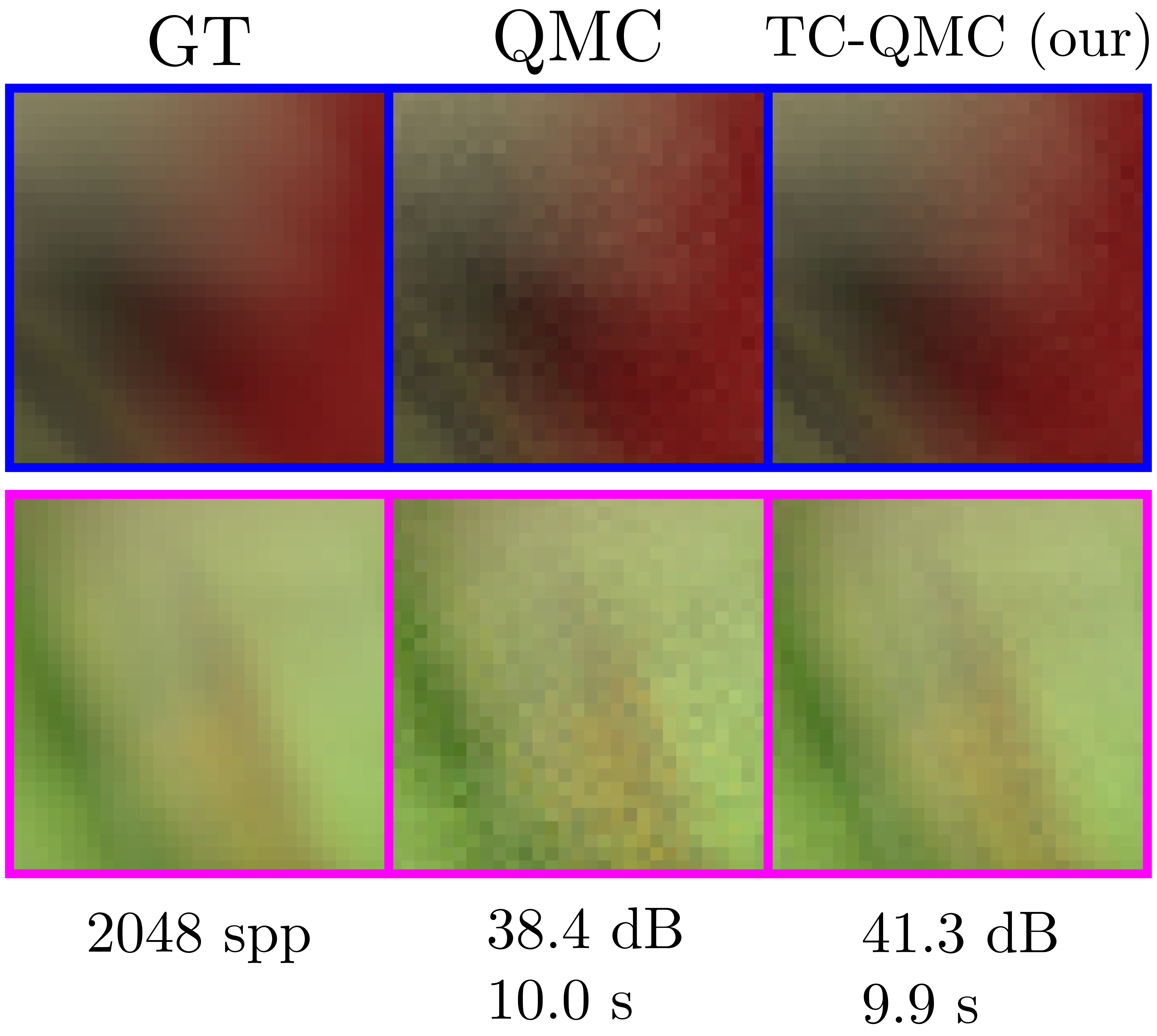
GT	QMC	TC-QMC (our)
2048 spp	38.1 dB 22.7 s	40.8 dB 22.1 s

(values for frame as a whole)

Equal Time

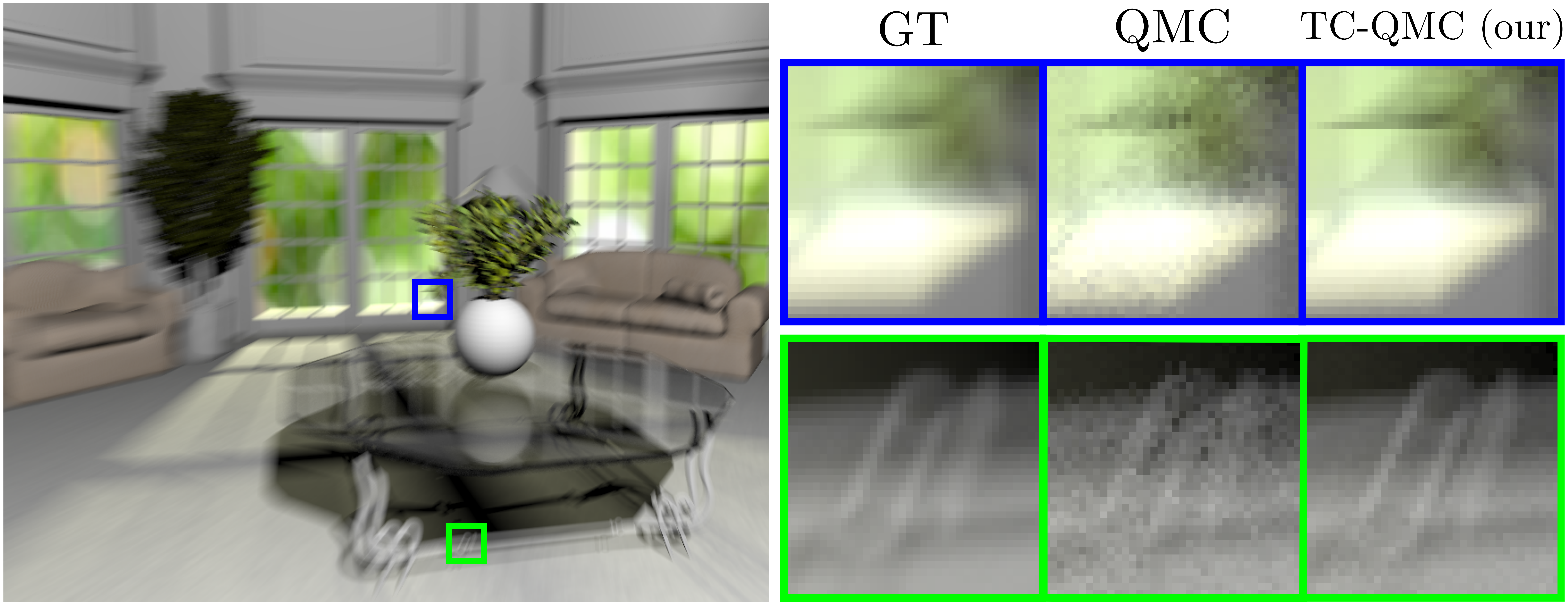


SPONZA+HAND: 262k + 16k triangles



(values for frame as a whole)

Equal Time



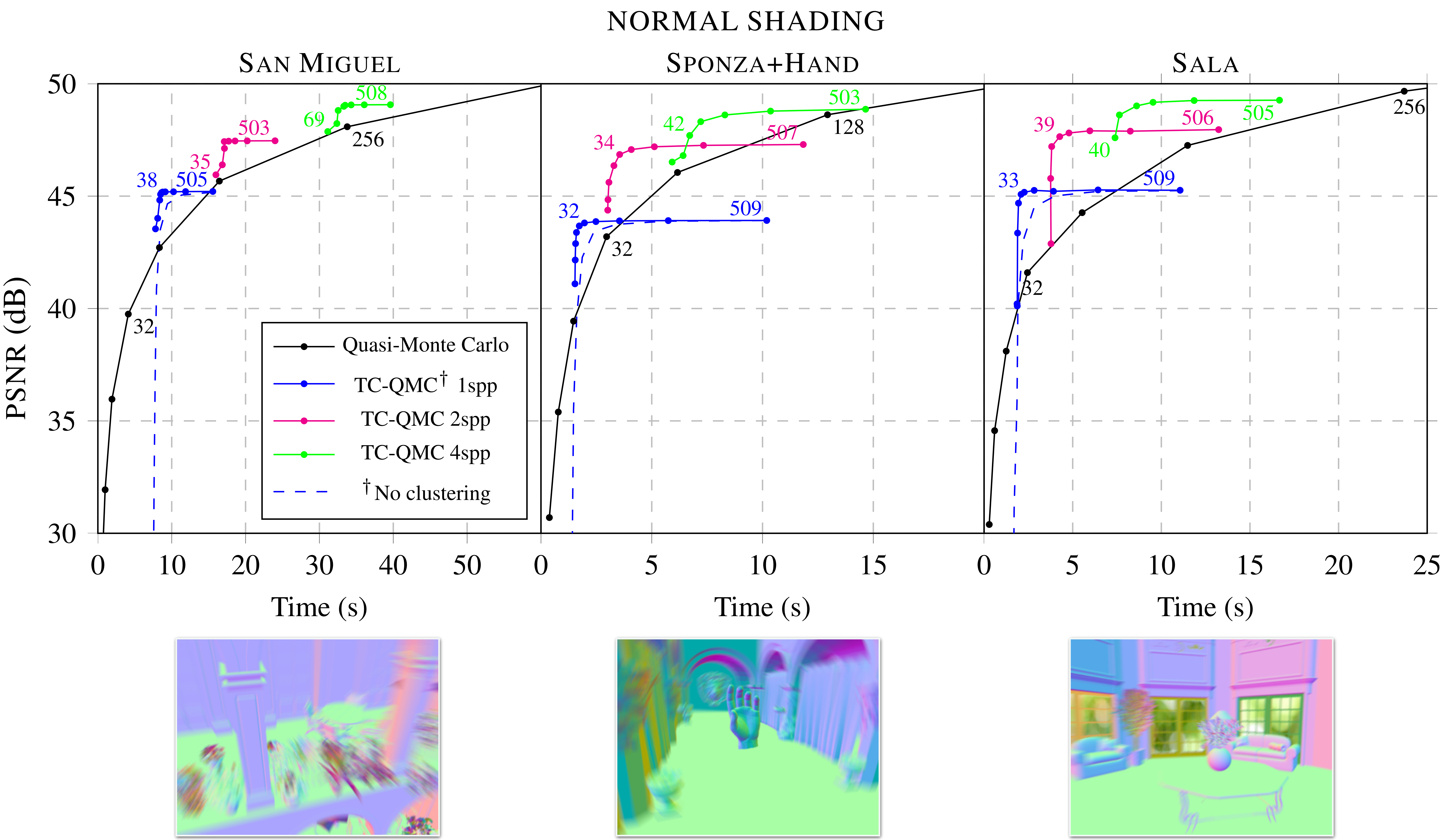
SALA: 400k triangles

2048 spp

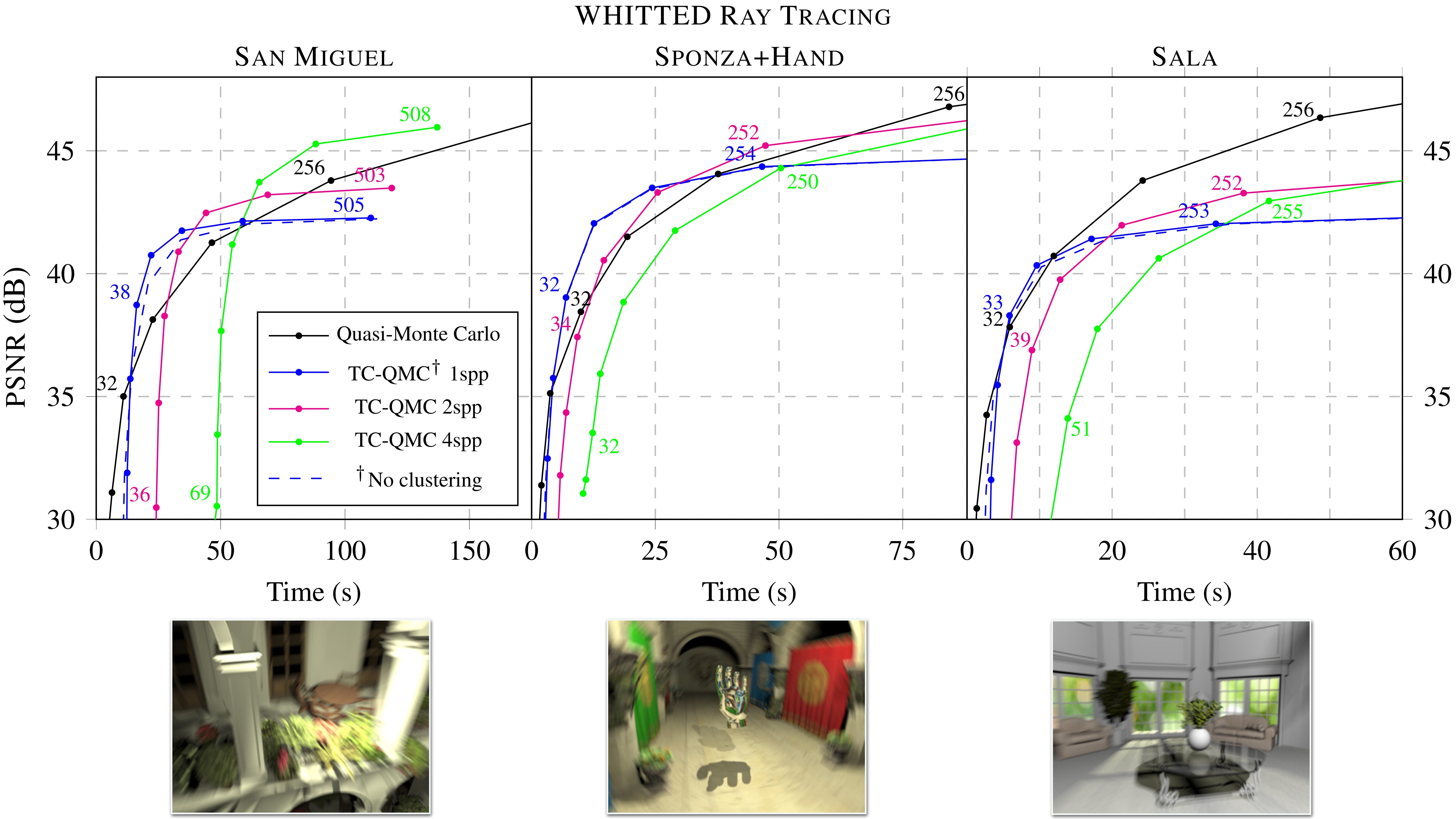
37.8 dB
5.87 s

38.3 dB
5.86 s

(values for frame as a whole)



NORMAL SHADING
SAN MIGUEL
SPONZA+HAND
SALA
PSNR (dB)
Time (s)
Quasi-Monte Carlo
TC-QMC† 1spp
TC-QMC 2spp
TC-QMC 4spp
† No clustering



WHITTED RAY TRACING
SAN MIGUEL
SPONZA+HAND
SALA
PSNR (dB)
Time (s)
Quasi-Monte Carlo
TC-QMC† 1spp
TC-QMC 2spp
TC-QMC 4spp
†No clustering

Thanks!

Thanks to

Dept. of Computer Science, Malmö University

Intel's Advanced Rendering Technology team

Rasmus Barringer for SIMD–fu

CGF Reviewers for valuable feedback

…and to my family …and to You!

😃🇯🇵

Scenes

Hand: Utah 3D Animation Repository

Crytek Sponza: Marko Dabrovic/Frank Meinl

San Miguel: Guillermo M. Leal Llaguno

MALMÖ UNIVERSITY

LUND UNIVERSITY

intel

Backup

Time-Continuous Quasi-Monte Carlo Ray Tracing

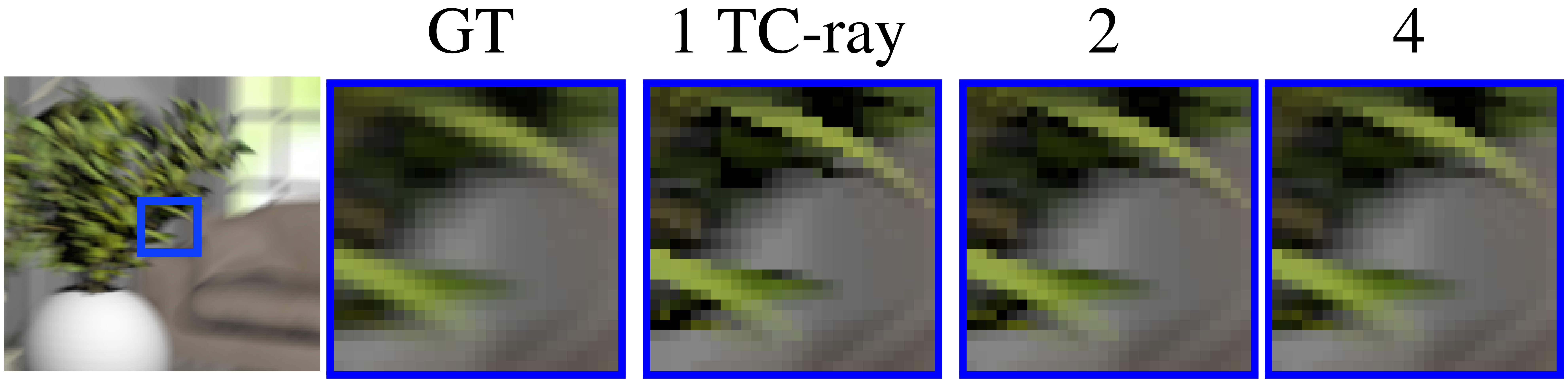
Carl Johan Gribel and Tomas Akenine-Möller

Submission CGF-15-OA-073

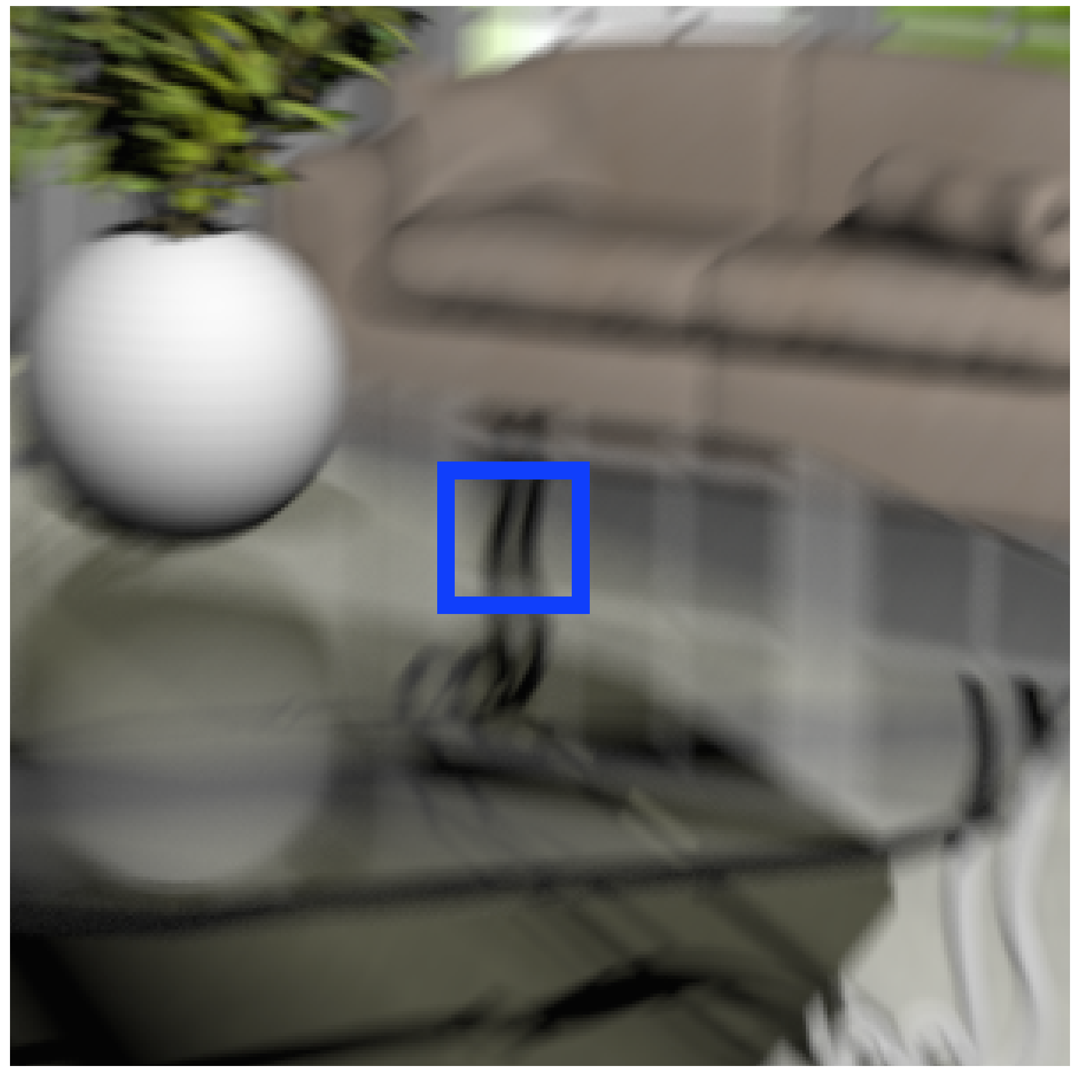
Highlights:

– Temporal coherency of the algorithm
Side-by-side comparison with time-discrete Quasi-Monte Carlo:
– Improved temporal anti-aliasing
– Slight spatial alias in low-velocity regions

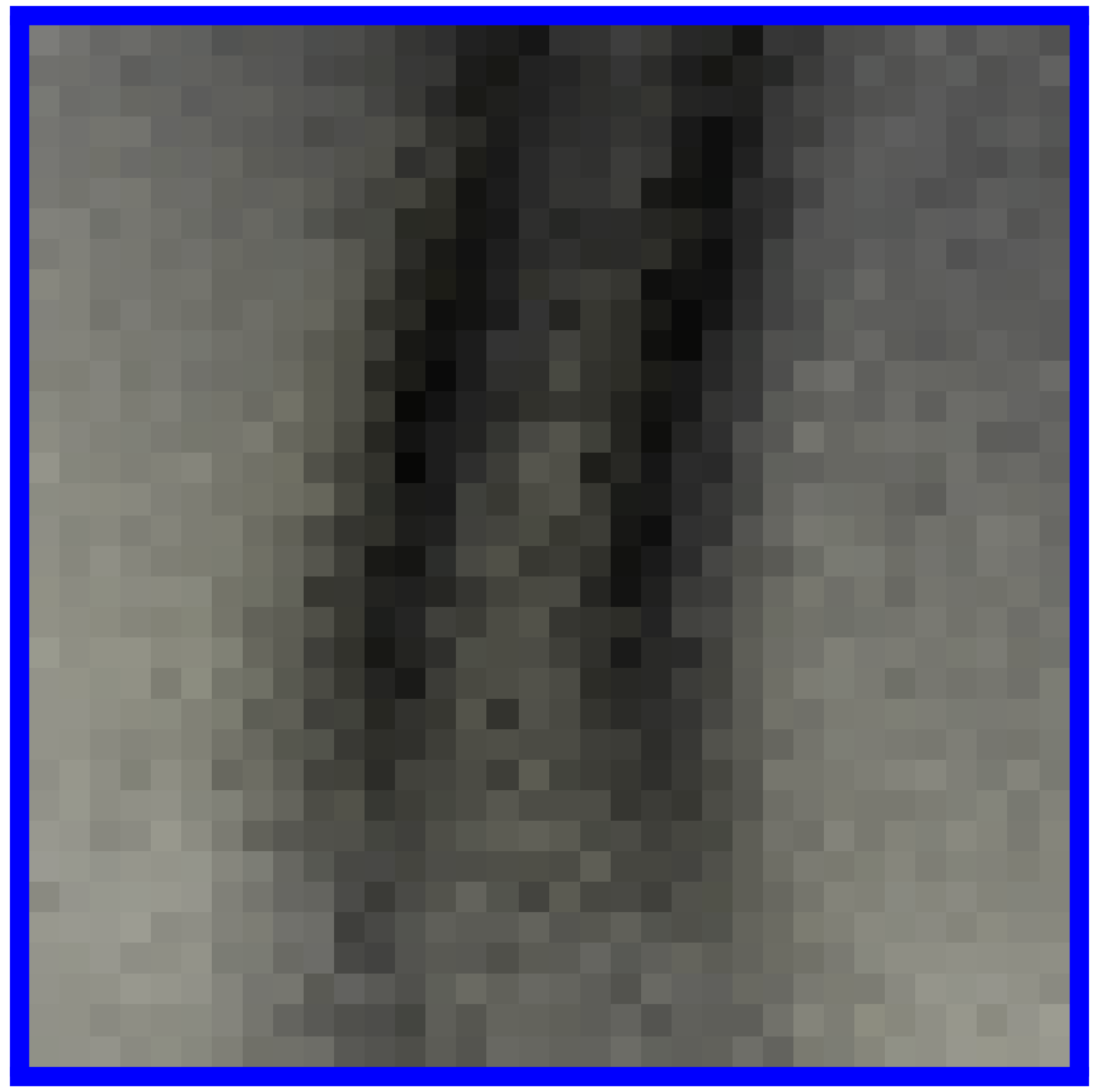
Spatial alias



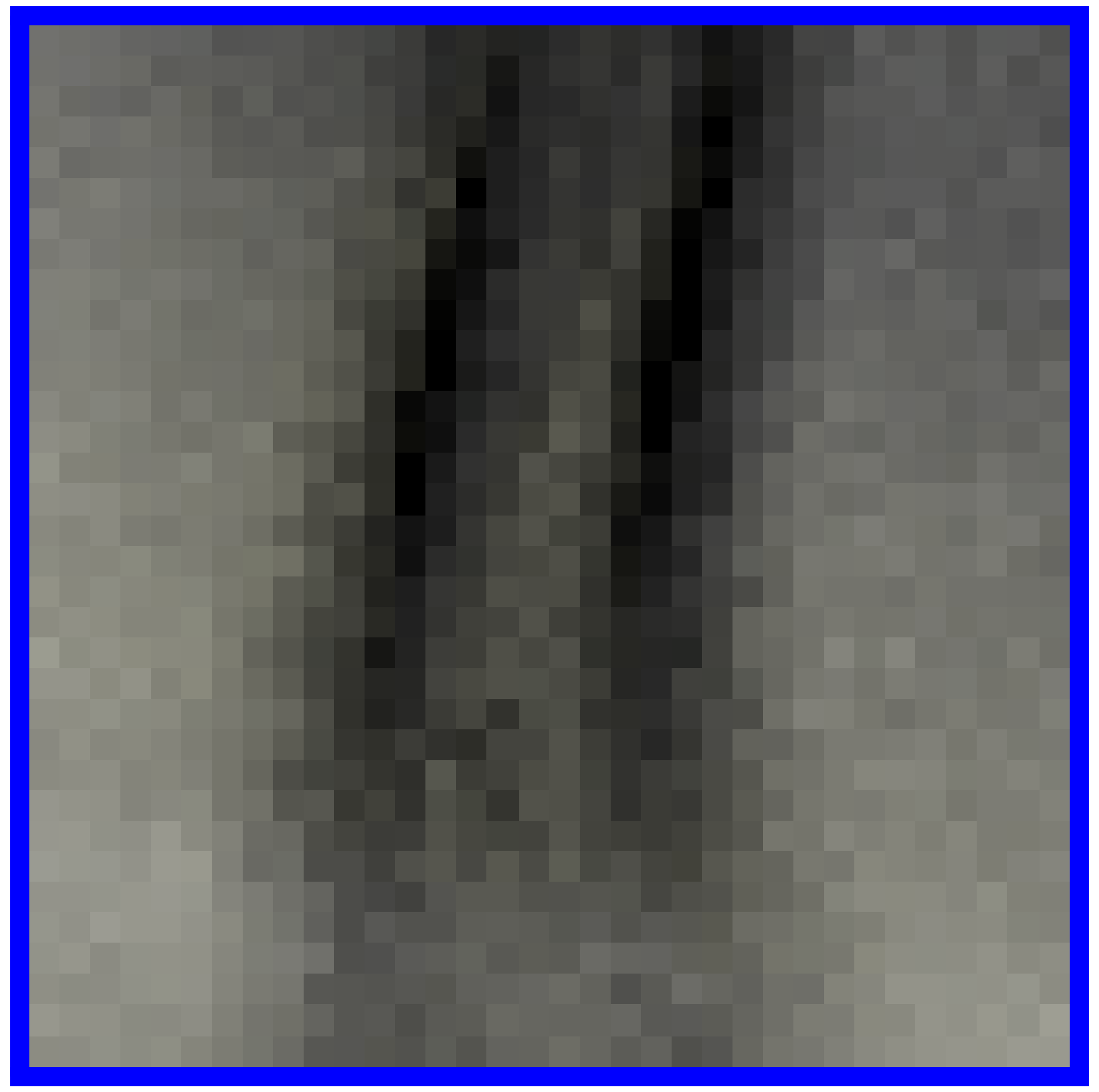
Secondary visibility

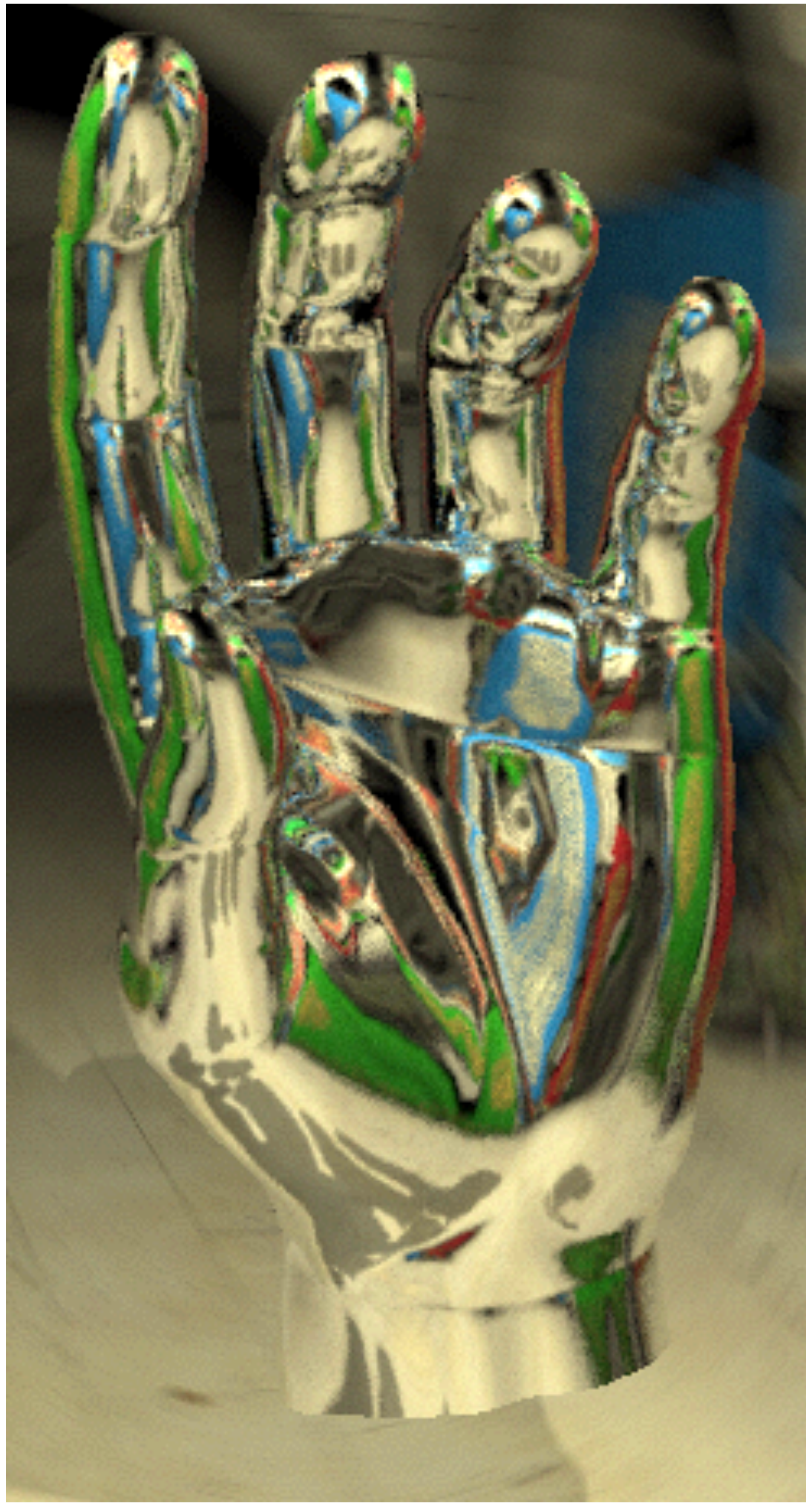


QMC

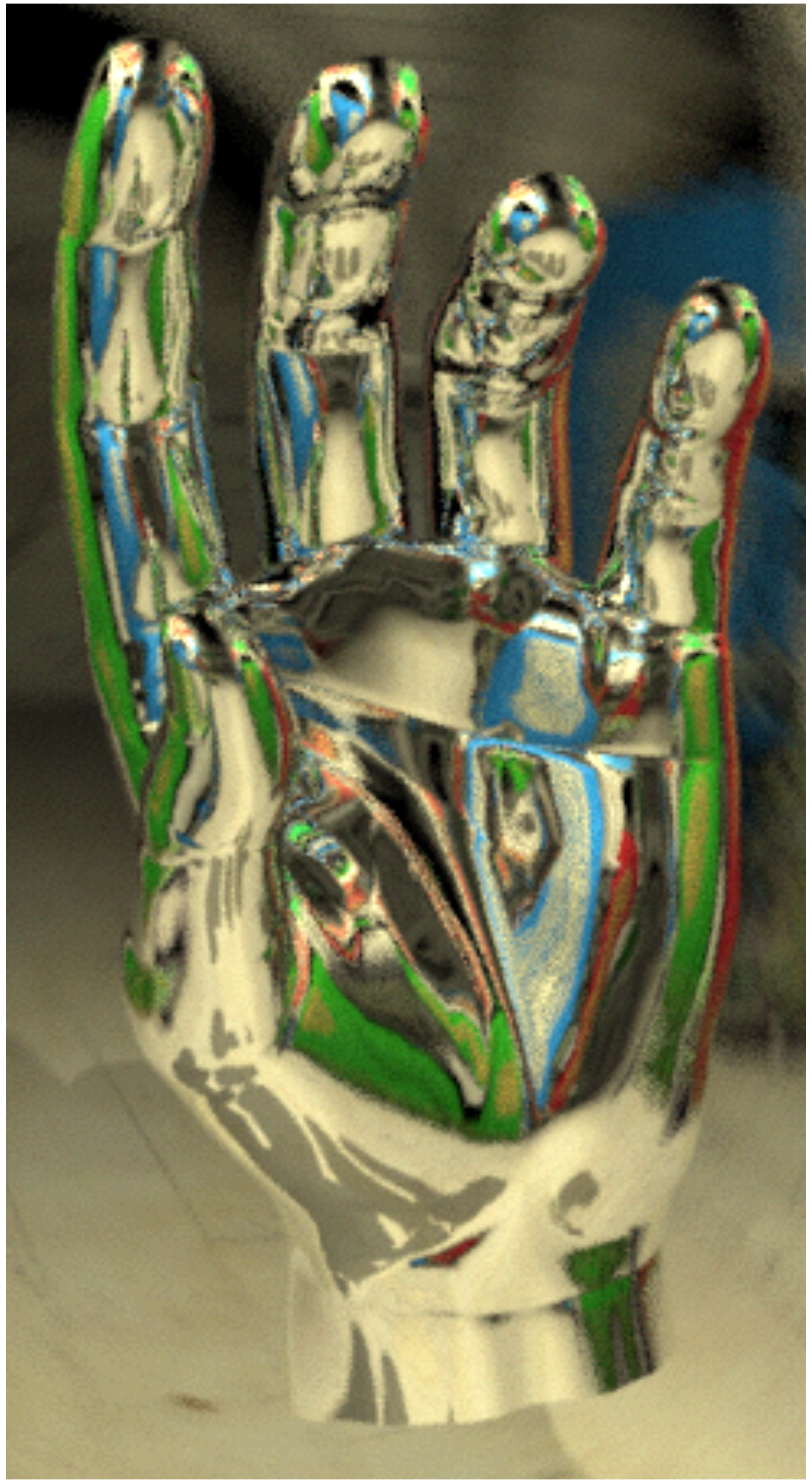


TC-QMC





Our, N=32



QMC, N = 32

Comparison setup: at a glance

- Our: **Time-Continuous Quasi-Monte Carlo (TC-QMC)**
  - 1, 2 or 4 TC-rays per pixel, *N* shading samples
  - TC-rays only at the primary level
- Reference: **Quasi-Monte Carlo (QMC)**
  - Stochastic sampling with *N* multi-jittered samples

- Shading Models: **Normal Shading, Whitted Ray Tracing**

- Presentation: **Quality as a function of rendering time** (growing *N*)
  - Quality metric: PSNR – Peak-Signal to Noise Ratio (dB)
  - Ground Truth: 1024-2048 spp Quasi-Monte Carlo

Future Work

- Improved shading reconstruction
- Smarter heuristics for mixed sampling (static & dynamic geometry)
- Secondary rays
    - Probably not worth the effort…
- Shadow Rays
    - Very high-frequent for point lights, so this is an interesting avenue