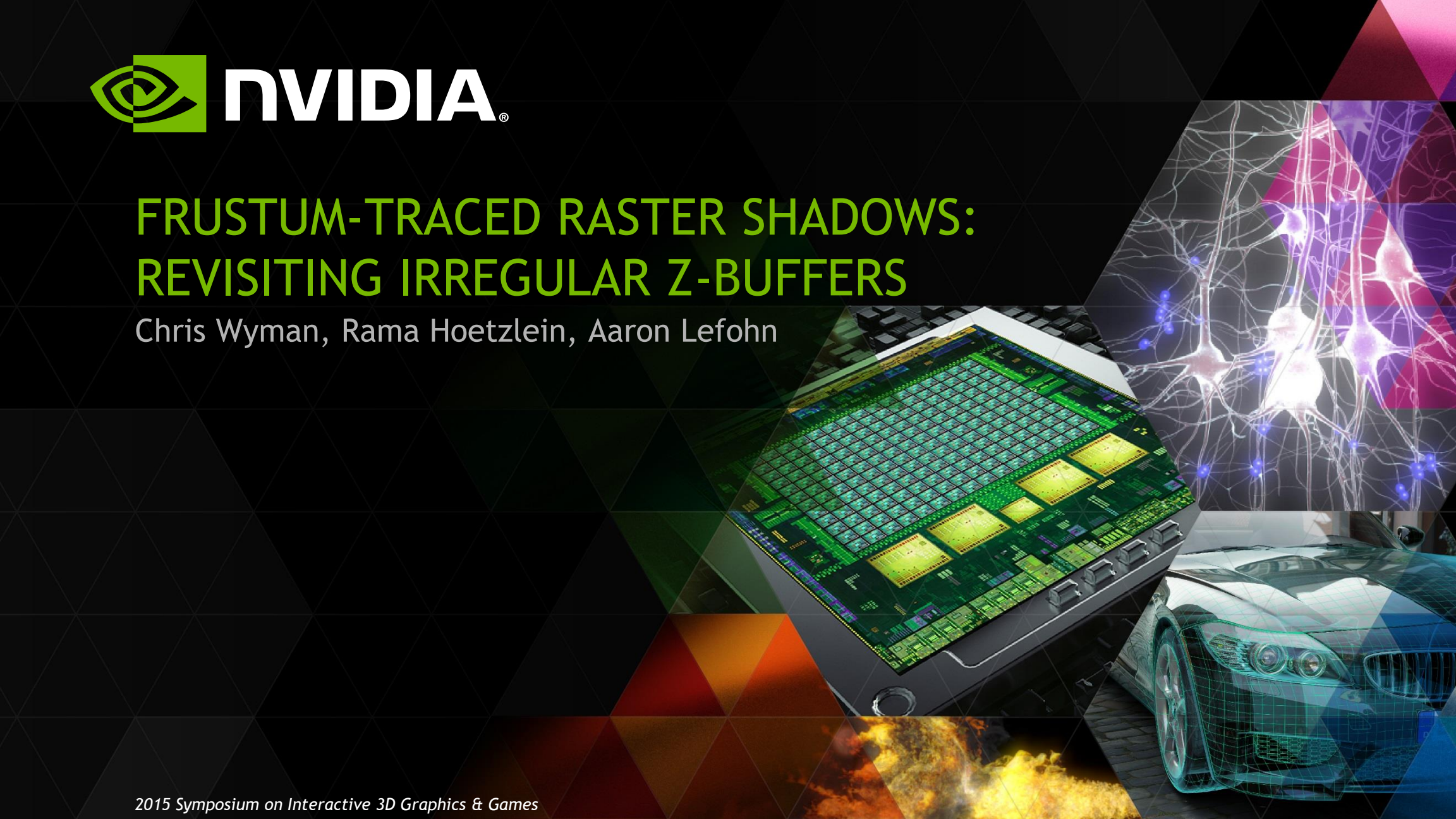


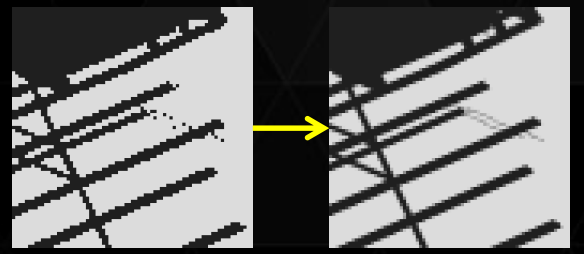
FRUSTUM-TRACED RASTER SHADOWS: REVISITING IRREGULAR Z-BUFFERS

Chris Wyman, Rama Hoetzlein, Aaron Lefohn

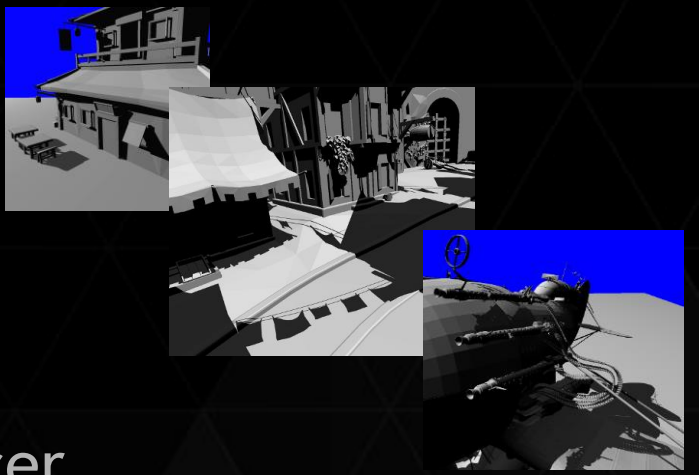
2015 Symposium on Interactive 3D Graphics & Games

CONTRIBUTIONS

- Full scene, fully dynamic alias-free hard shadows
  - Show 32 spp shadows are under 2x cost of 1 spp shadows



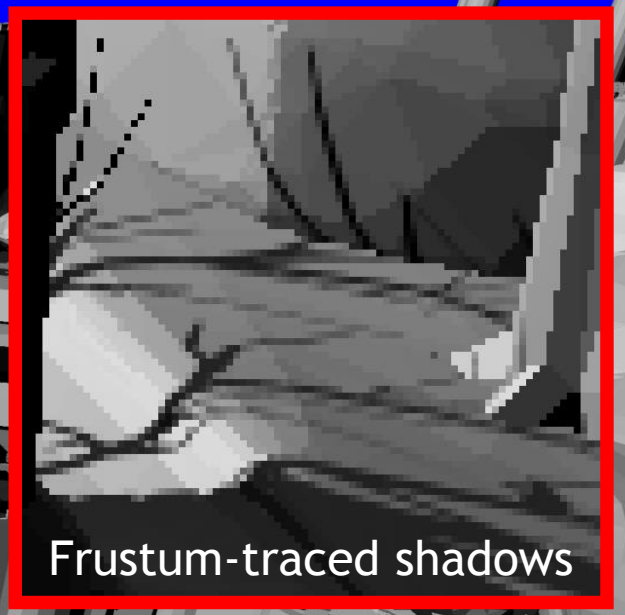
- Evolution of irregular z-buffering
  - For modern game-quality and CAD-quality assets
  - Builds on existing graphics hardware & pipeline
  - Demonstrate efficient frustum intersection for 32 spp



- # frustum-triangle tests competitive with ray tracer
  - We build our data structure in ~2 ms per frame

WHY?

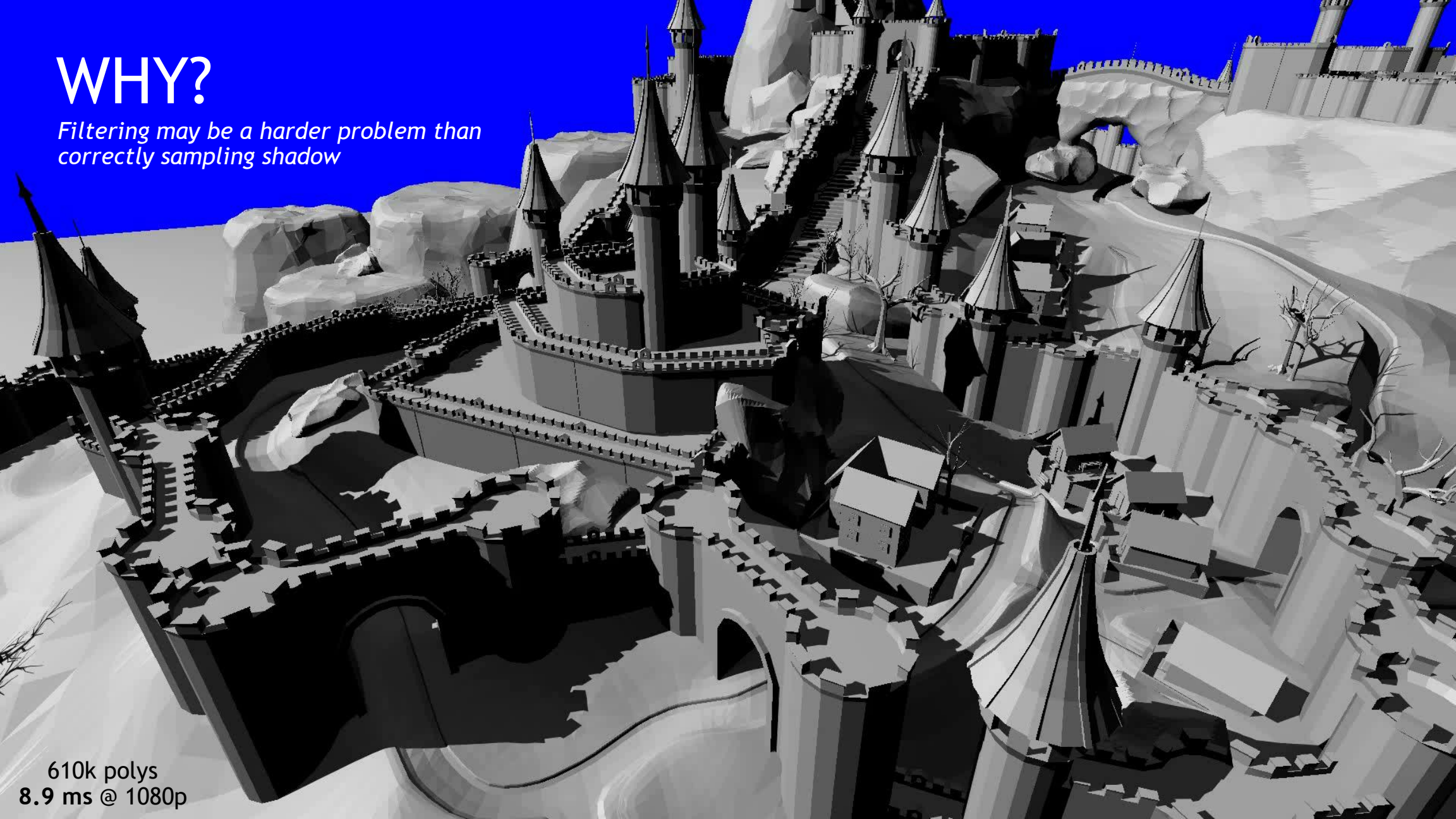
Still don't have robust, high quality interactive hard shadow algorithm



610k polys
8.9 ms @ 1080p

WHY?

Filtering may be a harder problem than correctly sampling shadow



610k polys
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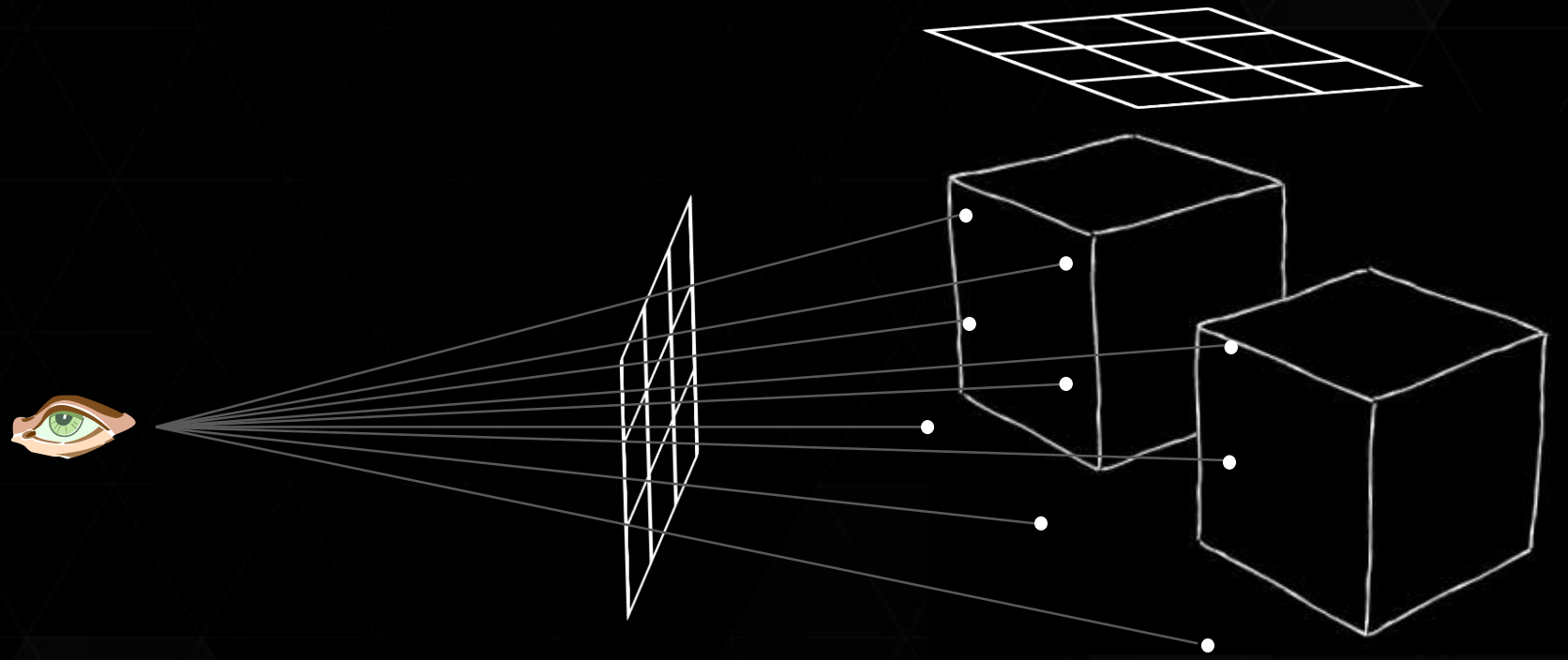
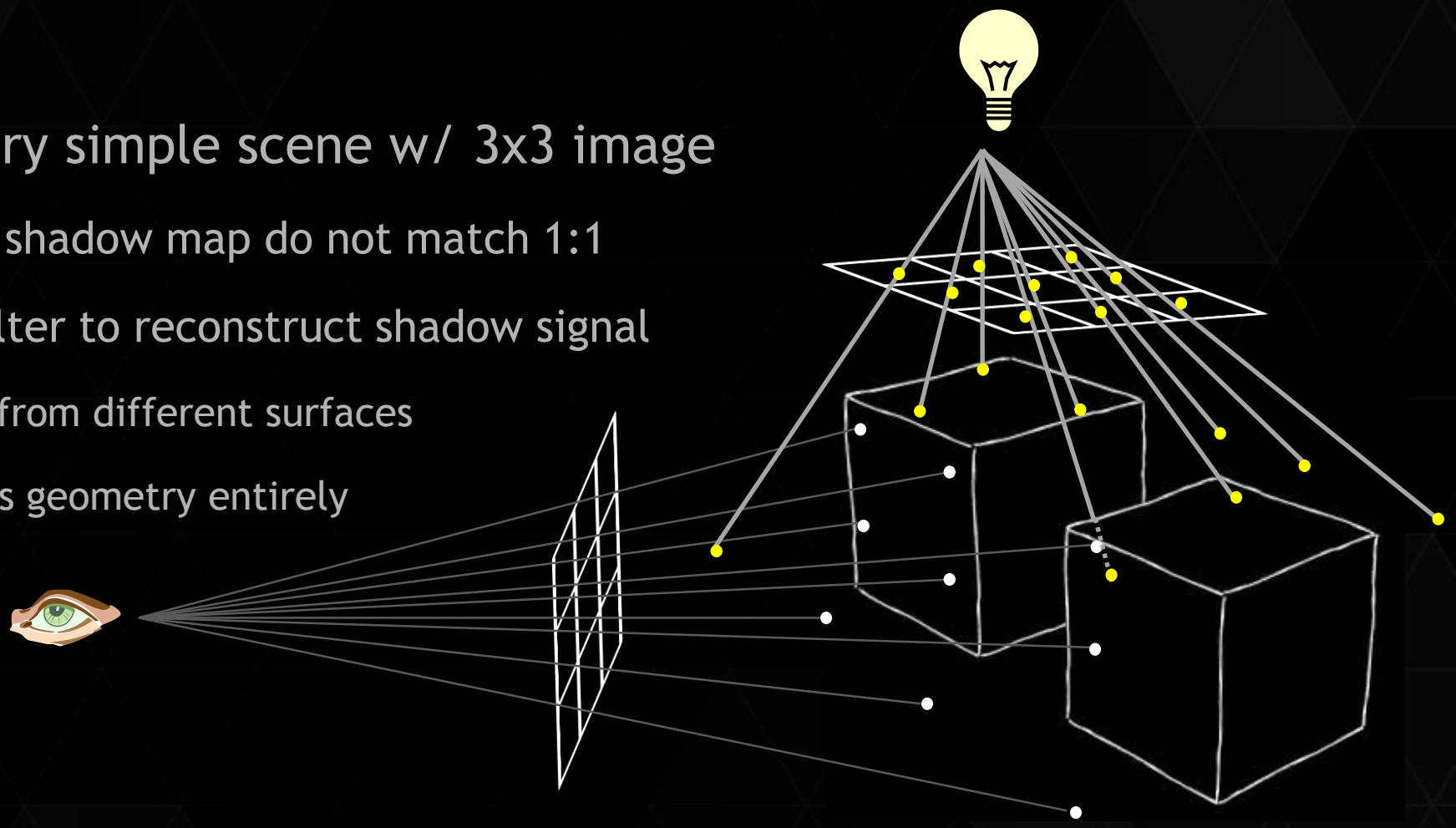
WHAT'S WRONG WITH EXISTING SHADOWS?

- Consider a very simple scene w/ 3x3 image



WHAT'S WRONG WITH EXISTING SHADOWS?

- Consider a very simple scene w/ 3x3 image
  - Samples in shadow map do not match 1:1
  - Requires filter to reconstruct shadow signal
    - May be from different surfaces
    - Can miss geometry entirely



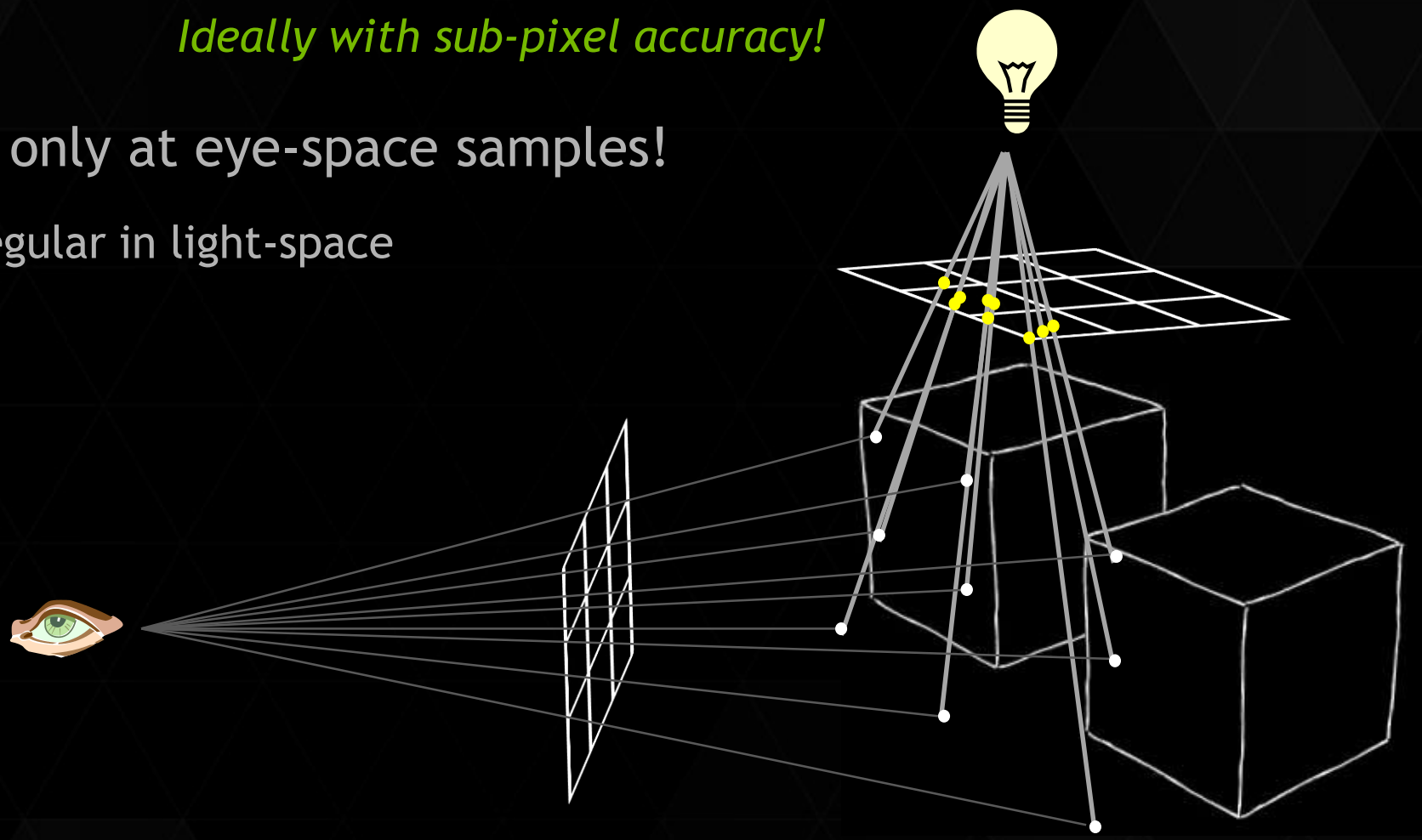
PRIOR WORK ON SHADOW MAPS

- Does one of two things:
  - Filter better *(e.g., [Peters15], [Donnelly06], [Fernando05])*
    - Filtering is very hard; we still have problem antialiasing other signals
  - Better match eye & light-space samples *(e.g., [Fernando01], [Stamminger02], [Lloyd08])*
    - Perfect match impossible if requiring regular sampling in both eye & light space

OUR GOAL: ALIAS-FREE SHADOWS

Ideally with sub-pixel accuracy!

- Want to light only at eye-space samples!
  - Will be irregular in light-space



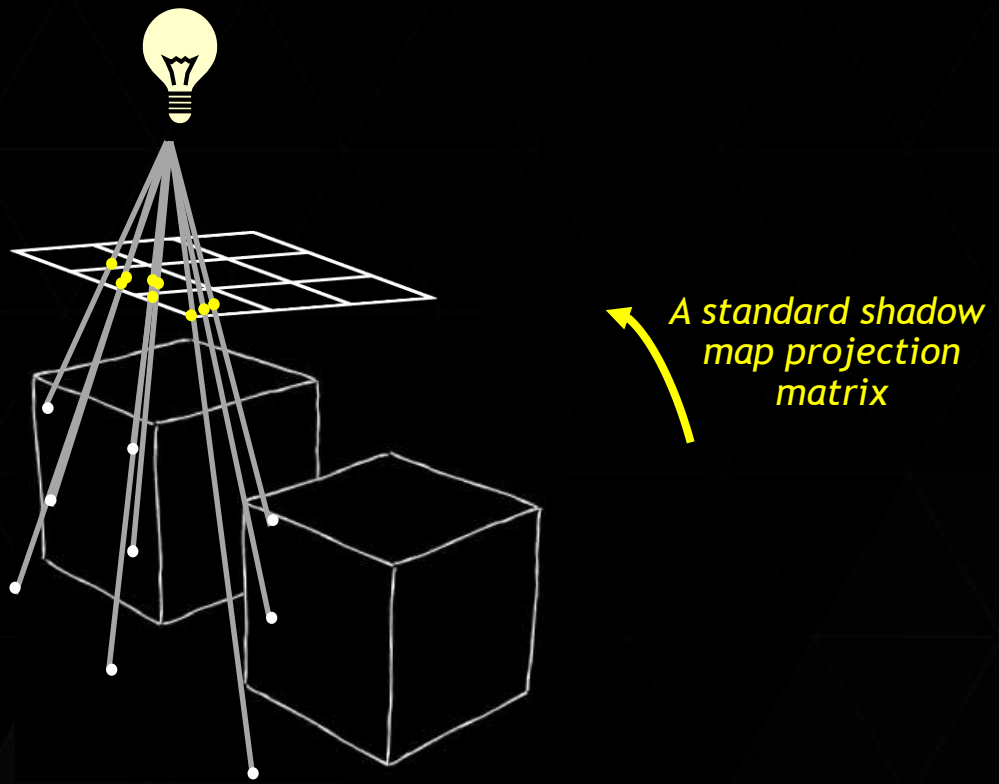
HOW TO DO THIS?

- Test triangle occlusion at these irregular sample points
  - Ray trace *(e.g., [Whitted80], [Parker10], [Mittring14])*
    - Query visibility at each ray, march through acceleration structure
  - Shadow volumes *(e.g., [Crow77], [Sintorn14], [Gerhards15])*
    - Test shadow quads to query if samples are in shadow
  - Irregular z-buffer *(e.g., [Johnson05], [Sintorn08], [Pan09])*
    - Rasterize over irregular sample points

- We converged on irregular z-buffering
  - Why? Allows us to leverage aspects of graphics pipe (e.g., culling)

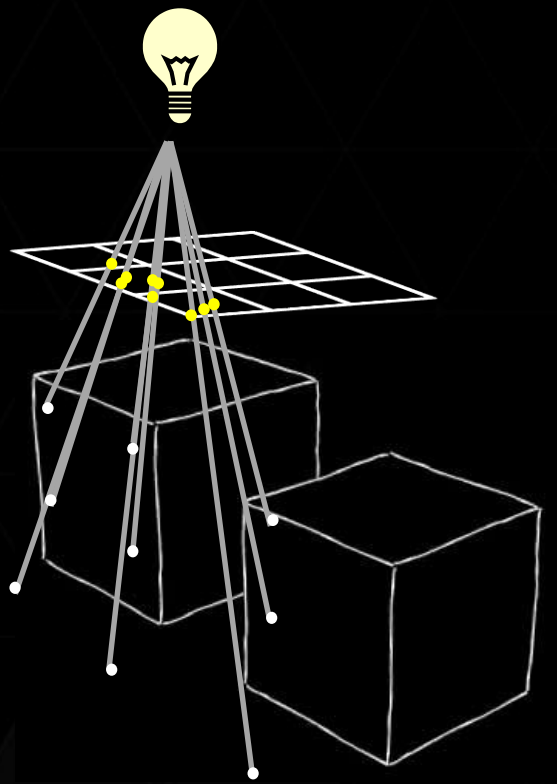
WHAT IS AN IRREGULAR Z-BUFFER?

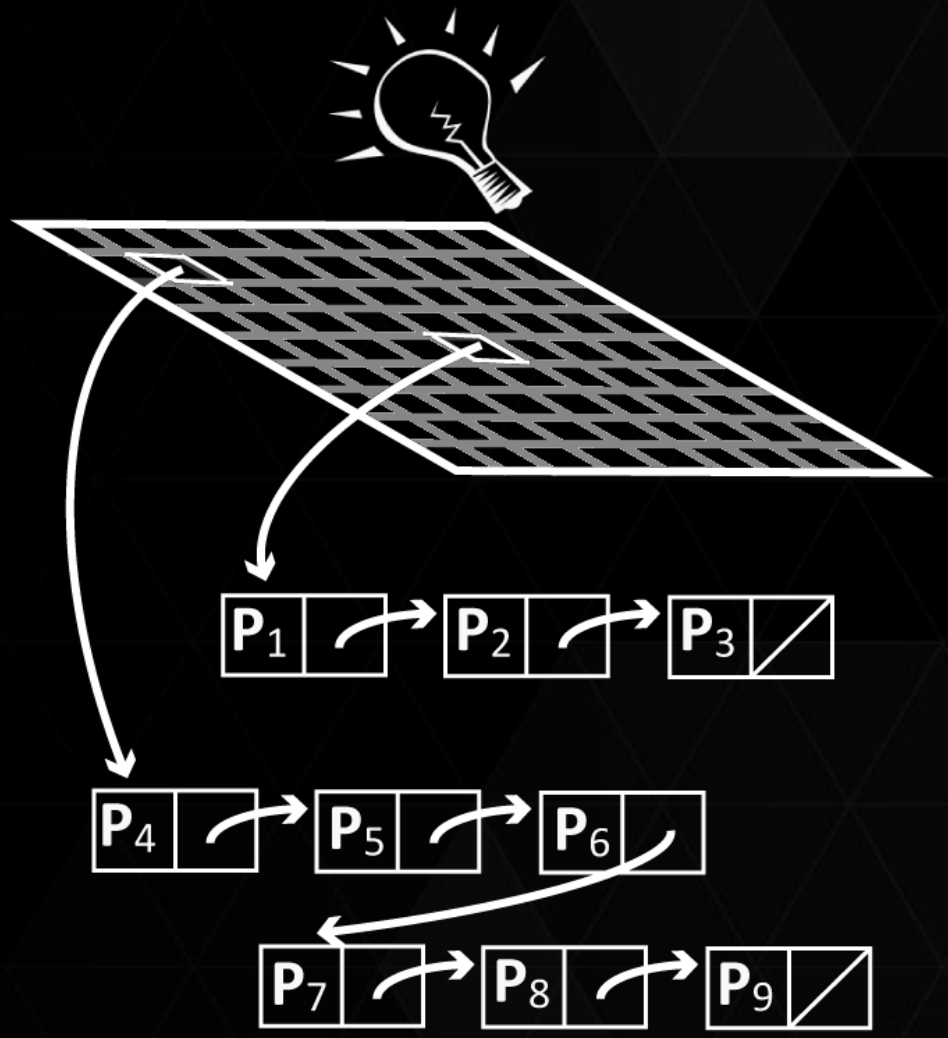
- Insert pixel samples (white dots) into light space grid at yellow samples



WHAT IS AN IRREGULAR Z-BUFFER?

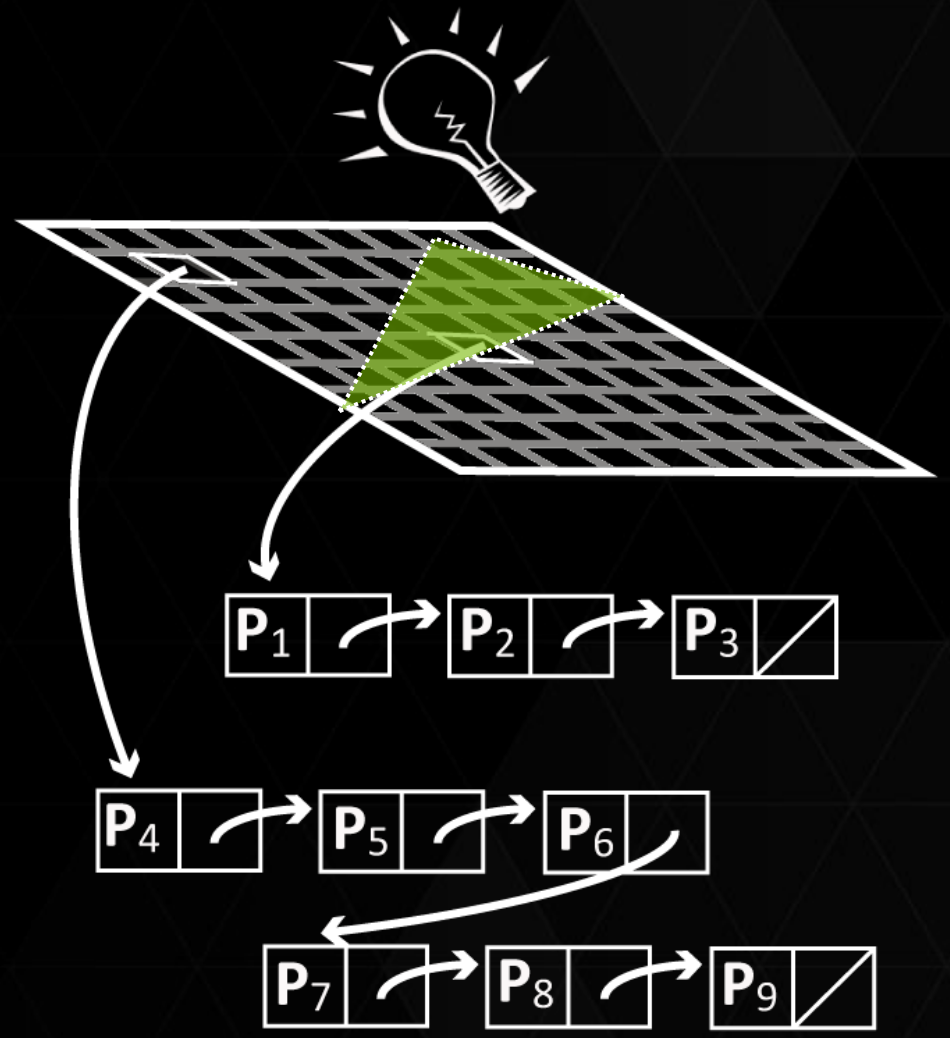
- Insert pixel samples (white dots) into light space grid at yellow samples
  - Creates grid-of-lists data structure





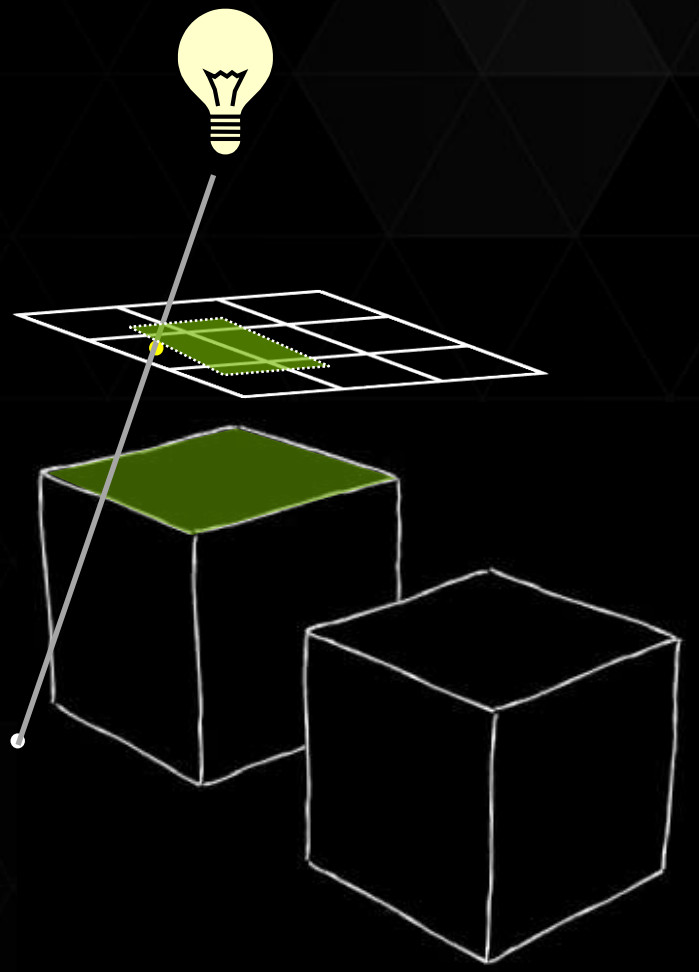
HOW DO YOU USE AN IZB?

- Rasterize from light view
  - For each texel (partially) covered
    - Walk through list of eye-space pixels P_i
    - Test ray from P_i to the light
    - Update visibility at P_i
- We use eye-space buffer to store visibility for all pixels P_i



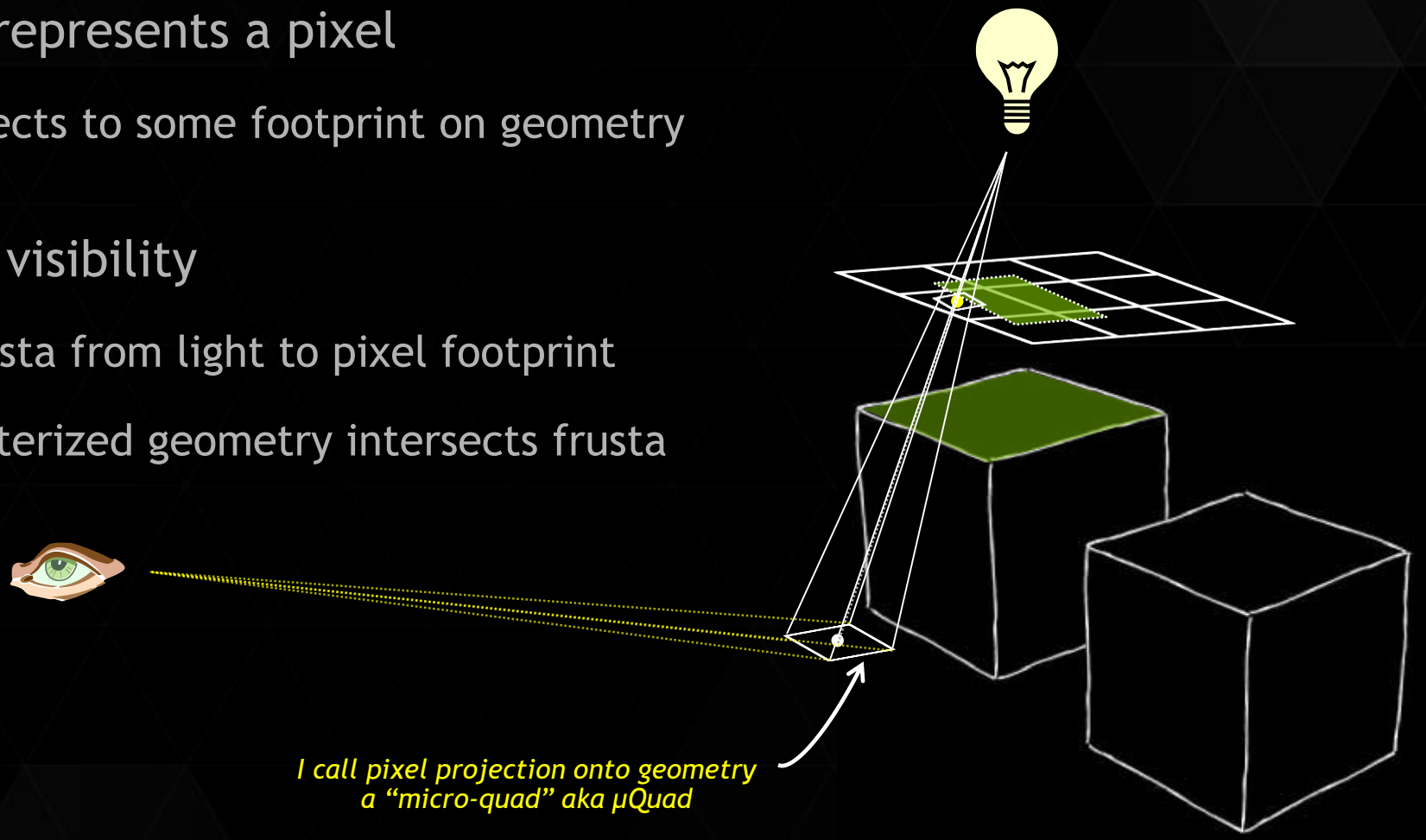
HOW DO YOU USE AN IZB?

- In my simple example
  - When rendering top of box to light space
  - Partially covers texel containing a sample
  - Analytically test visibility for list of samples
  - Our sample ends up unshadowed



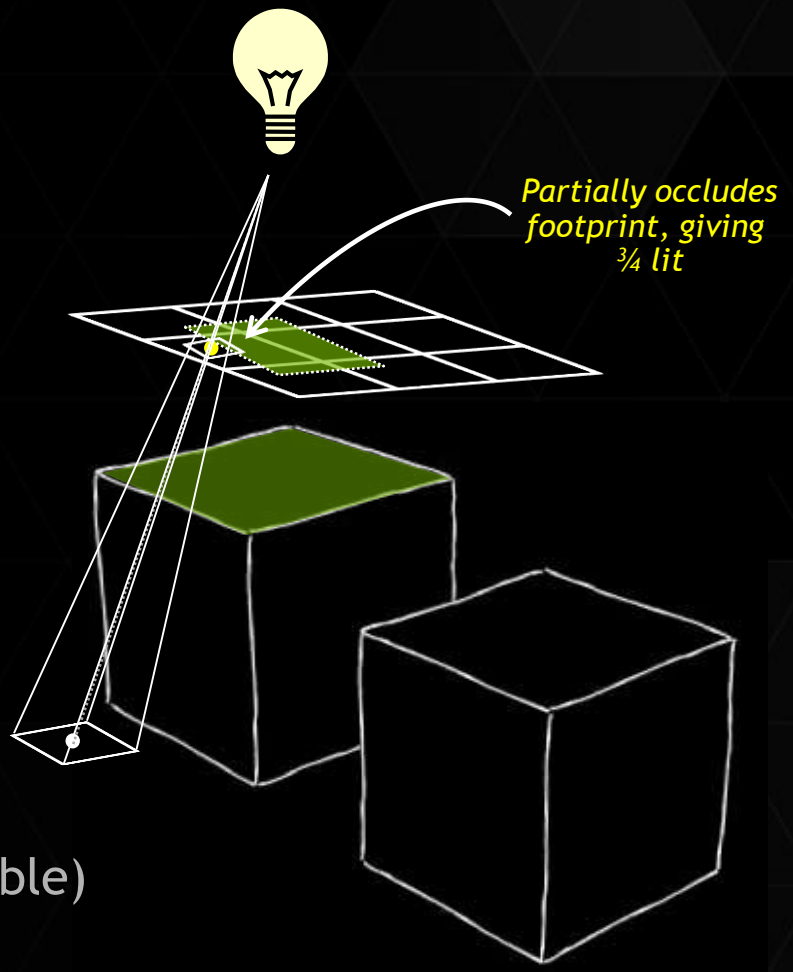
ADDING MULTIPLE SAMPLES PER PIXEL

- Each sample represents a pixel
  - Pixel projects to some footprint on geometry
- When testing visibility
  - Create frusta from light to pixel footprint
  - Test if rasterized geometry intersects frusta



ADDING MULTIPLE SAMPLES PER PIXEL

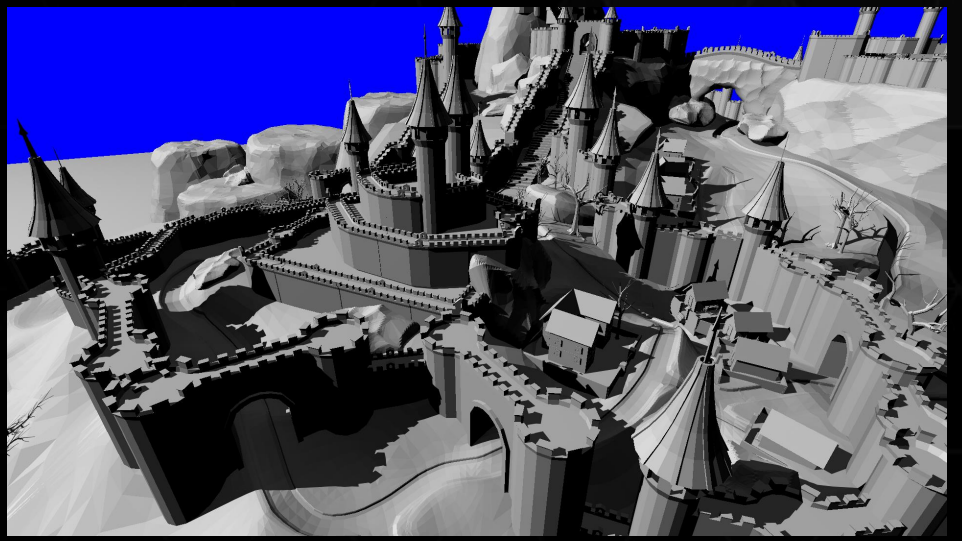
- Each sample represents a pixel
  - Pixel projects to some footprint on geometry
- When testing visibility
  - Create frusta from light to pixel footprint
  - Test if rasterized geometry intersects frusta
- Discretize visibility sampling on µQuad
  - We use pattern with 32 samples
  - Can be developer specified (currently a lookup table)
  - Each sample stores binary visibility

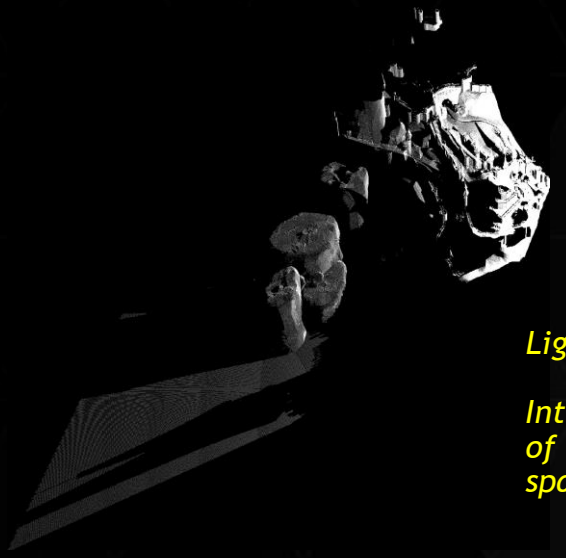


Problem with Irregular Z-Buffering

IRREGULARITY: BAD FOR GPU UTILIZATION

- By construction:
  - Introduce irregular workloads
  - As variable-length light-space lists
- When rasterizing in light space
  - Some frags test visibility of no pixels
  - Some frags test at 1000's of pixels
- Naïve implementation
  - Leads to 100:1 variation in frame time





Light-space visualization

Intensity represents number of list elements per light space texel

IZB Complexity Considerations

WHAT WORK ARE WE DOING?

- Complexity is simple: $O(N)$
  - N = # of frusta-triangle visibility tests
- More usefully, complexity is: $O(f_{ls} * L_{avg})$
  - f_{ls} = # of light-space fragments from rasterizer
  - L_{avg} = average list length (i.e., # of pixels tested)
- For poorly utilized GPU, complexity is roughly: $O(f_{ls} * L_{max})$
  - L_{max} = # of pixels tested by slowest thread

HOW DO WE REDUCE COST?

- Either:
  - Reduce the number of fragments, f_{ls}.
  - Reduce the list length, L_{avg}.
  - Reduce the variance, to reduce gap between L_{max} and L_{avg}.

REDUCING WORK

- How to reduce # fragments f_{ls}?
  - Reduce *number* of occluder triangles
    - Front/back face culling (we do this)
    - Z-culling (we do this, partially)
    - Frustum culling (we do not do this)
    - Artistic direction (we do not do this)

REDUCING WORK

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    - Front/back face culling (we do this)
    - Z-culling (we do this, partially)
    - Frustum culling (we do not do this)
    - Artistic direction (we do not do this)
  - Reduce rasterized *size* of occluder triangles (i.e., change grid size)
    - But this increases L_{avg}, L_{max}, and other overheads
    - A broad resolution “sweet spot” per scene for optimal performance

REDUCING WORK

- How to reduce L_{avg} and L_{max}?
  - Reduce # of pixels *inserted* into IZB
    - Use z-prepass to insert only visible pixels (we do this)
    - Skip known shadowed pixels (N•L < 0) (we do this)
    - Skip known lit pixels (e.g., artistic direction) (we do not do this)
    - Avoid duplicates nodes (e.g., when using 32spp) (we do this)
    - For 32spp, use approximate insertion (we do this; see paper)

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    - Avoid duplicates nodes (e.g., when using 32spp) (we do this)
    - For 32spp, use approximate insertion (we do this; see paper)
  - *Remove* fully shadowed pixels from IZB
    - Gradually reduces L_{avg} and L_{max} over the frame (we do this)

REDUCING WORK

- Reducing *variance* in L? (i.e., cause $L_{max} \rightarrow L_{avg}$)
  - Match sampling rate between eye- & light-space (ideally 1:1)
    - Same goal as perspective, logarithm, adaptive, and cascaded shadow maps
  - The *key goal* for fast GPU implementation

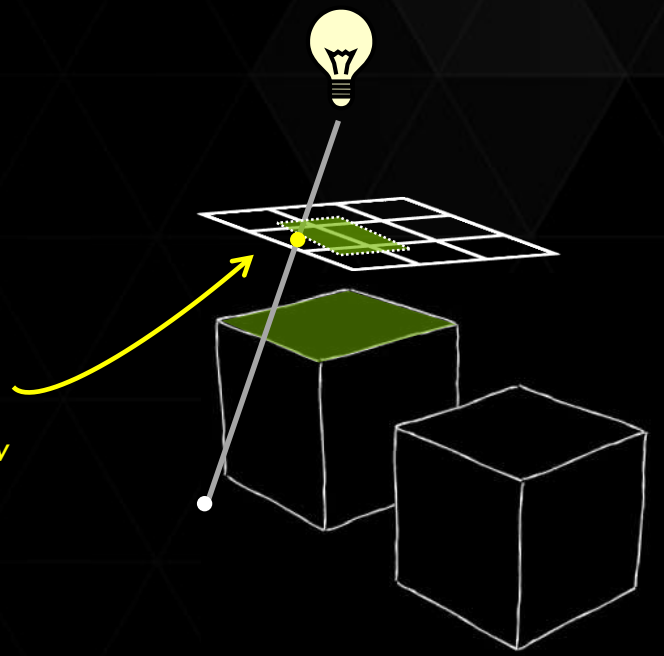
REDUCING WORK

- Reducing *variance* in L? (i.e., cause $L_{max} \rightarrow L_{avg}$)
  - Match sampling rate between eye- & light-space (ideally 1:1)
    - Same goal as perspective, logarithm, adaptive, and cascaded shadow maps
  - The *key goal* for fast GPU implementation
    - Use these shadow map techniques (we use cascades)
    - Tightly bound light frustum to visible scene (we do this)


Miscellaneous
Optimizations

GENERAL GPU OPTIMIZATIONS

- IZBs require conservative rasterization
  - Hardware conservative raster: up to *3x faster*



GENERAL GPU OPTIMIZATIONS

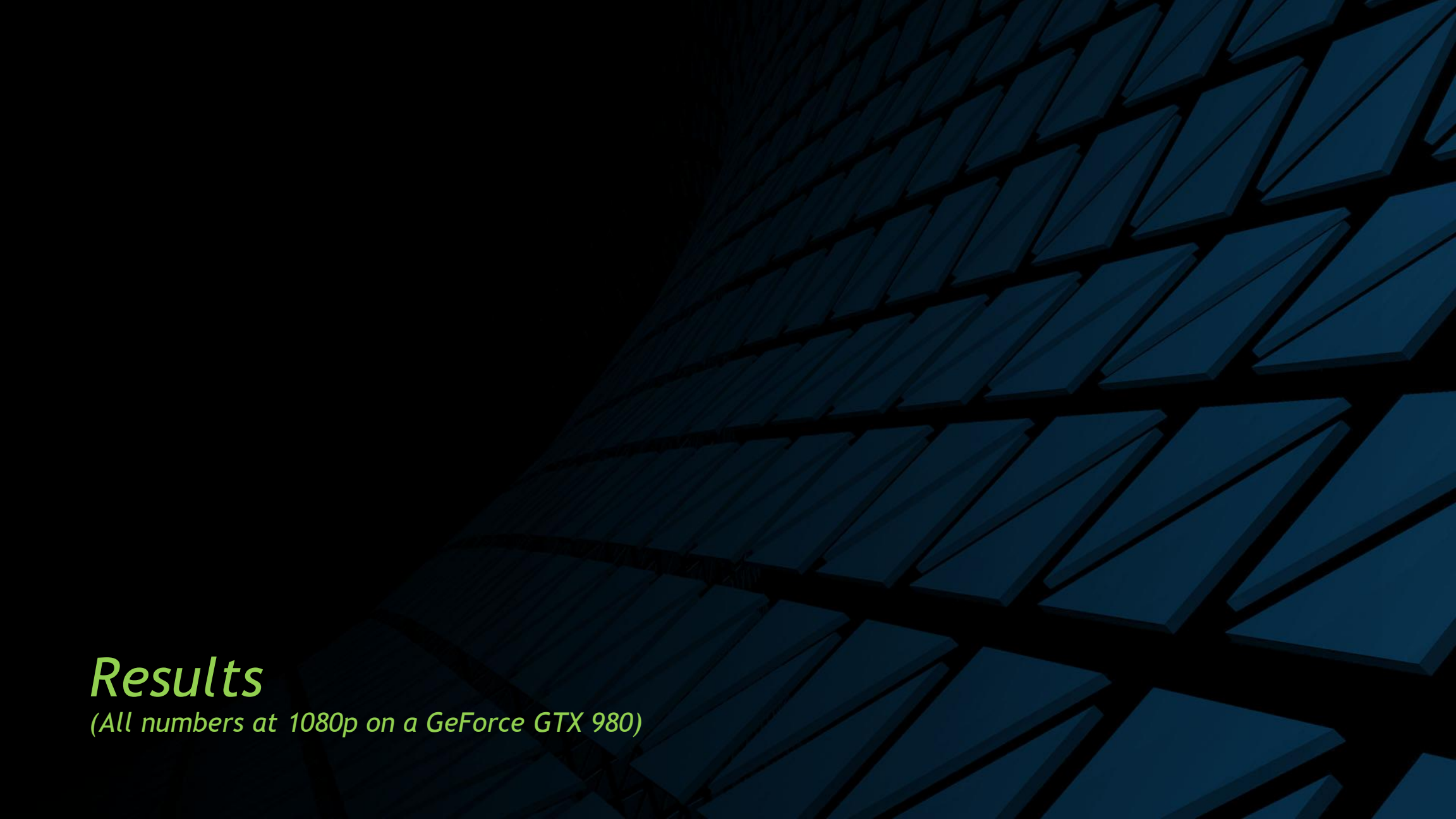
- IZBs require conservative rasterization
  - Hardware conservative raster: *up to 3x faster*
- Memory contention / atomics are slower
  - Only update visibility mask *if change occurs*
  - Use *implicit indices*; skip global memory pools
  - Structure traversal to *avoid atomics*

GENERAL GPU OPTIMIZATIONS

- List traversal induces long dependency chains
  - Hide latency via *software pipelining*
  - *Avoid long latency* operations (e.g., int divide, modulo)

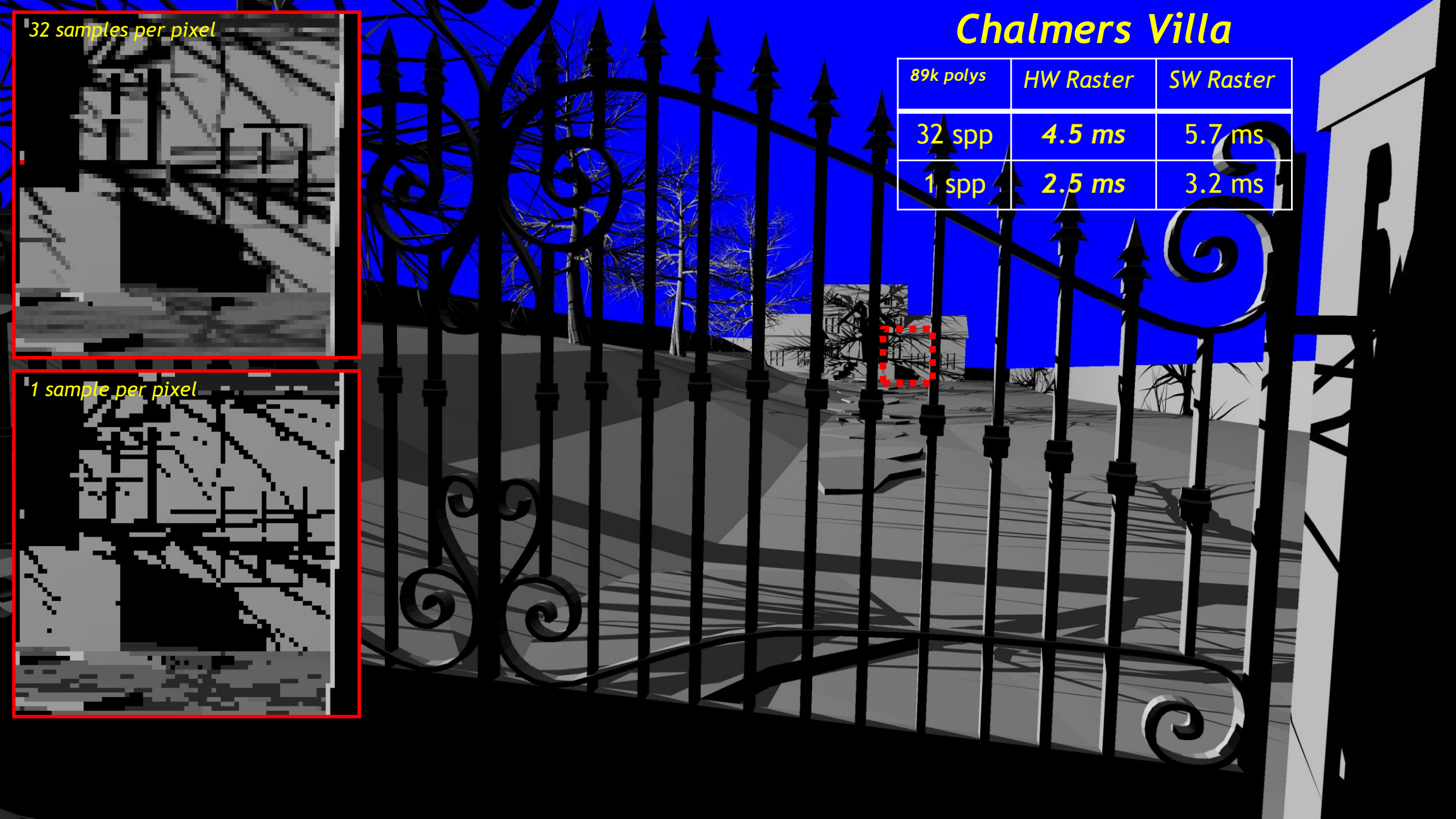
GENERAL GPU OPTIMIZATIONS

- List traversal induces long dependency chains
  - Hide latency via *software pipelining*
  - *Avoid long latency* operations (e.g., int divide, modulo)
- Reduce SIMD divergence
  - *Flatten control flow* as much as possible



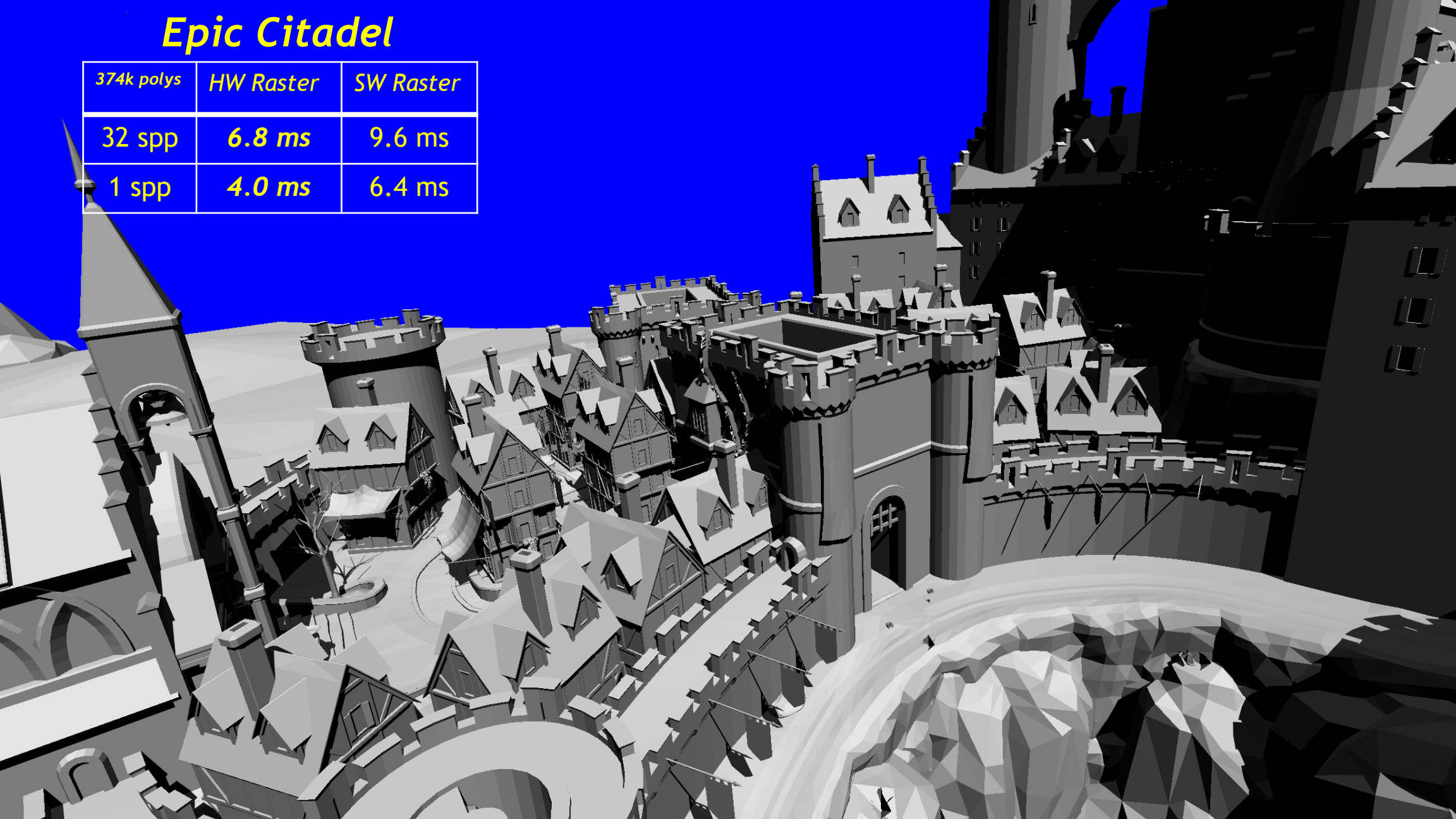
Results

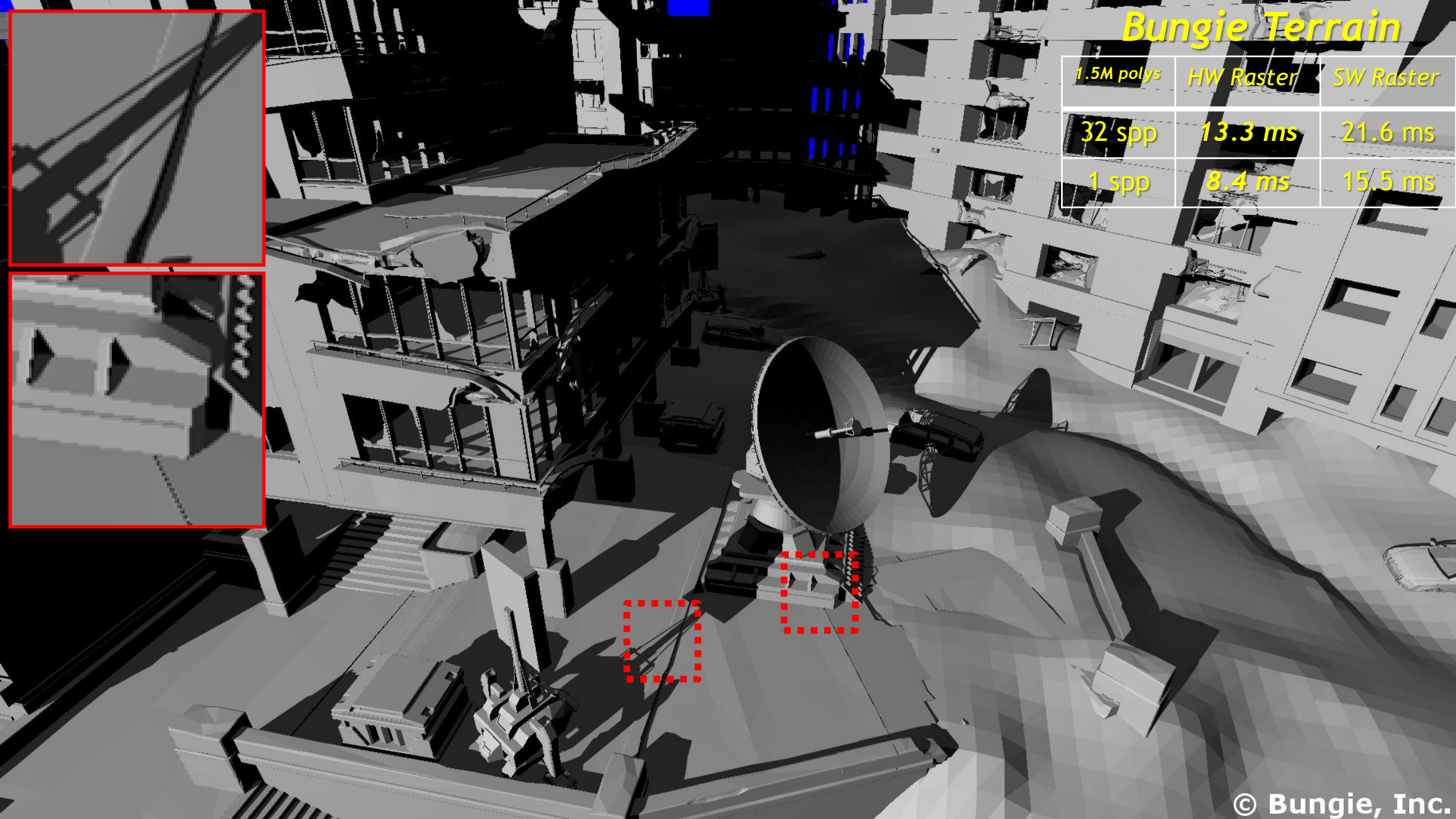
(All numbers at 1080p on a GeForce GTX 980)

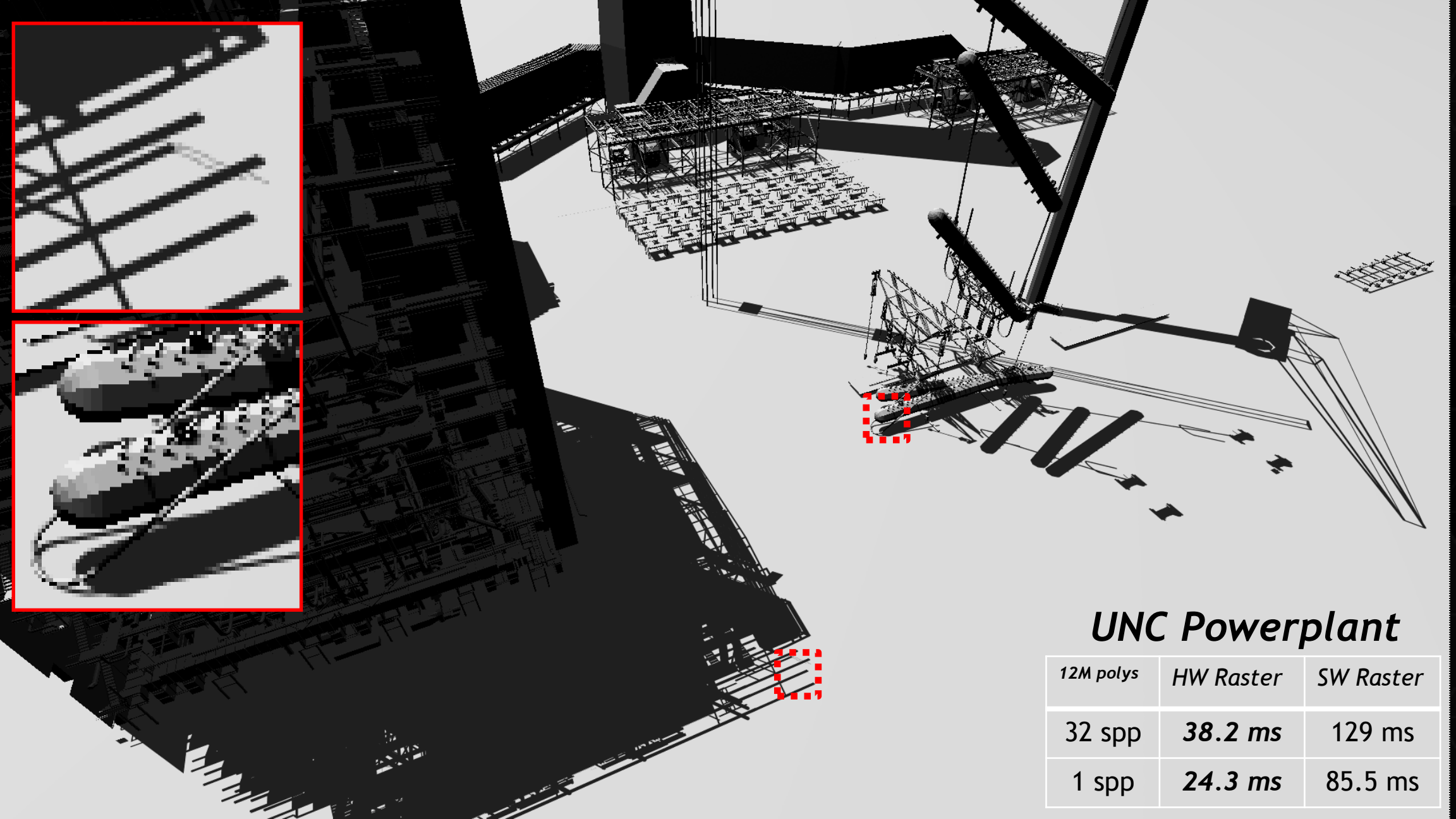

32 samples per pixel
1 sample per pixel
Chalmers Villa
89k polys
HW Raster
SW Raster
32 spp
4.5 ms
5.7 ms
1 spp
2.5 ms
3.2 ms

Epic Citadel

374k polys	HW Raster	SW Raster
32 spp	***6.8 ms***	9.6 ms
1 spp	***4.0 ms***	6.4 ms




Bungie Terrain
1.5M polys
HW Raster
SW Raster
32 spp
13.3 ms
21.6 ms
1 spp
8.4 ms
15.5 ms
© Bungie, Inc.



UNC Powerplant

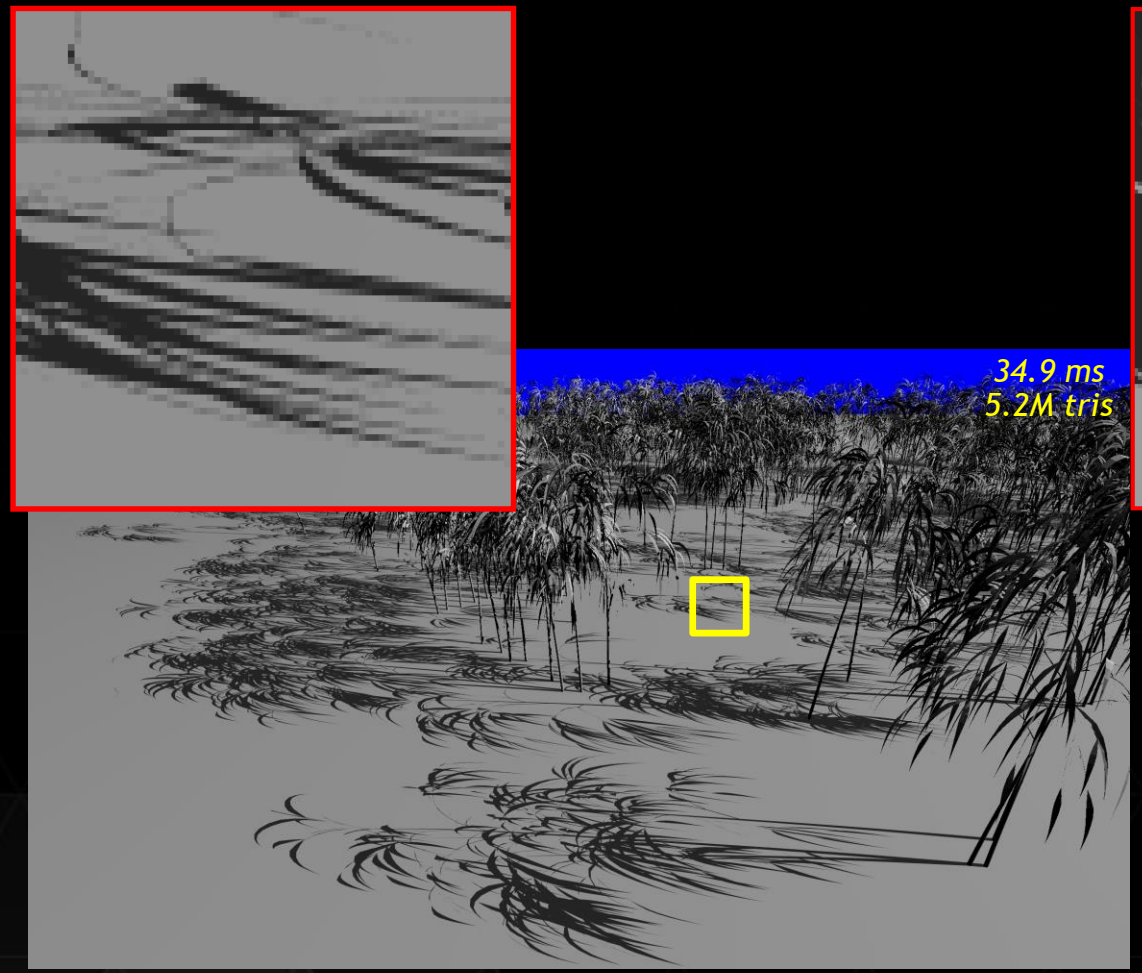
12M polys	HW Raster	SW Raster
32 spp	***38.2 ms***	129 ms
1 spp	***24.3 ms***	85.5 ms

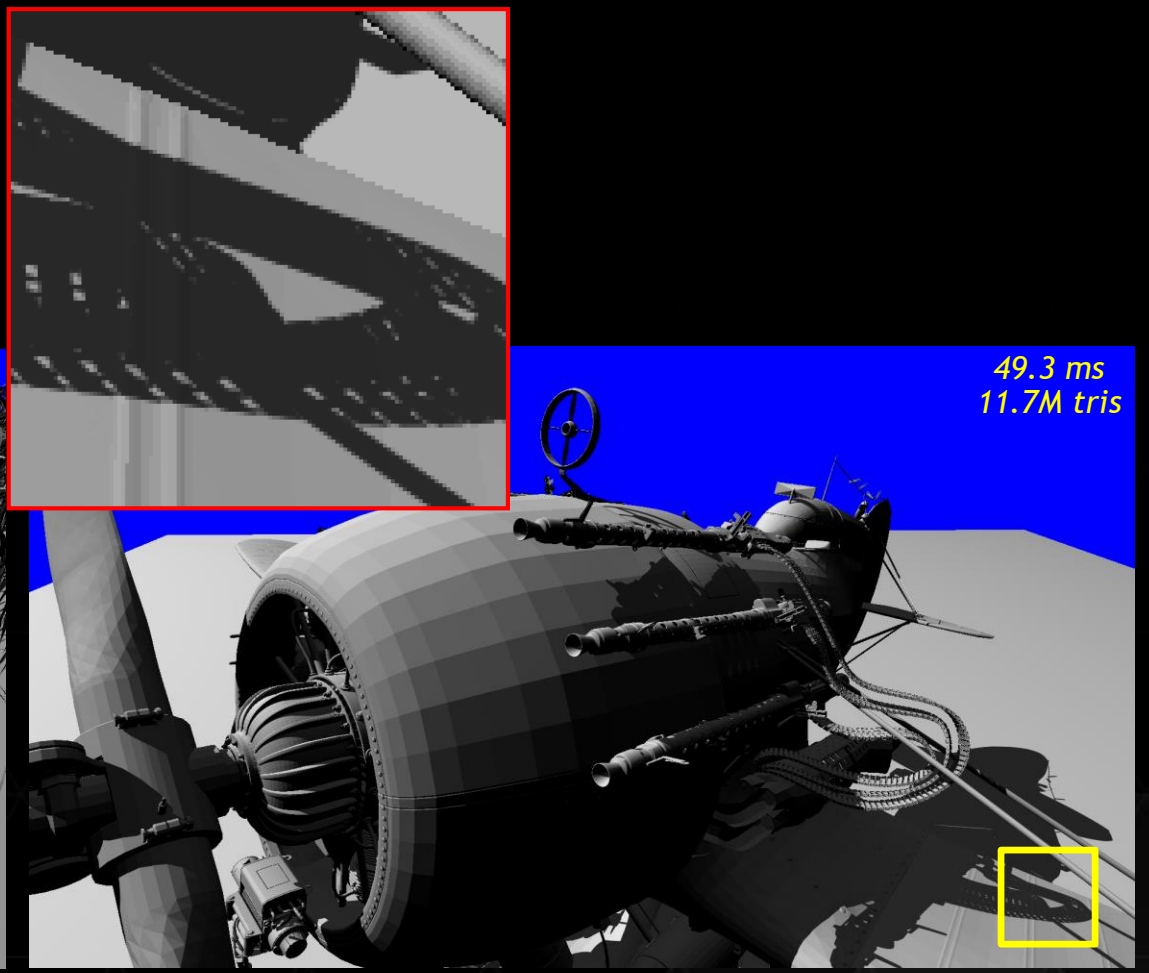
UNC Powerplant

12M polys	*HW Raster*	*SW Raster*
32 spp	***38.2 ms***	129 ms
1 spp	***24.3 ms***	85.5 ms

LIMITATIONS

- Requires an epsilon
  - In world space, to avoid self shadows; roughly same as ray tracing
- Performance still variable (around 2x)
  - We’re still working on this
- Approximate 32 spp IZB insertion can break
  - Causes slight light leaking, esp. for finely tessellated models in distance
- Some sub-pixel robustness tricks needed for 32 spp
  - To avoid shadow leaks at interpenetrating triangle boundaries





QUESTIONS?

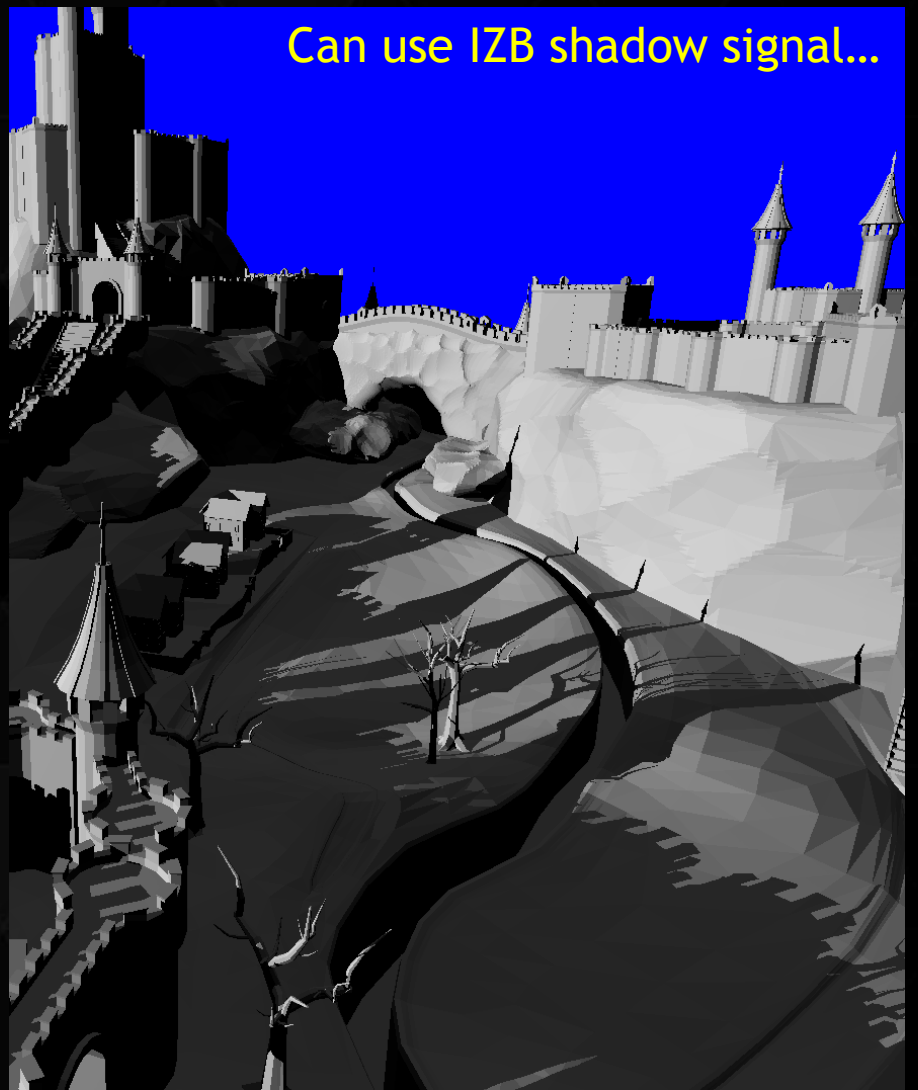
cwyman@nvidia.com http://chriswyman.org @_cwyman_

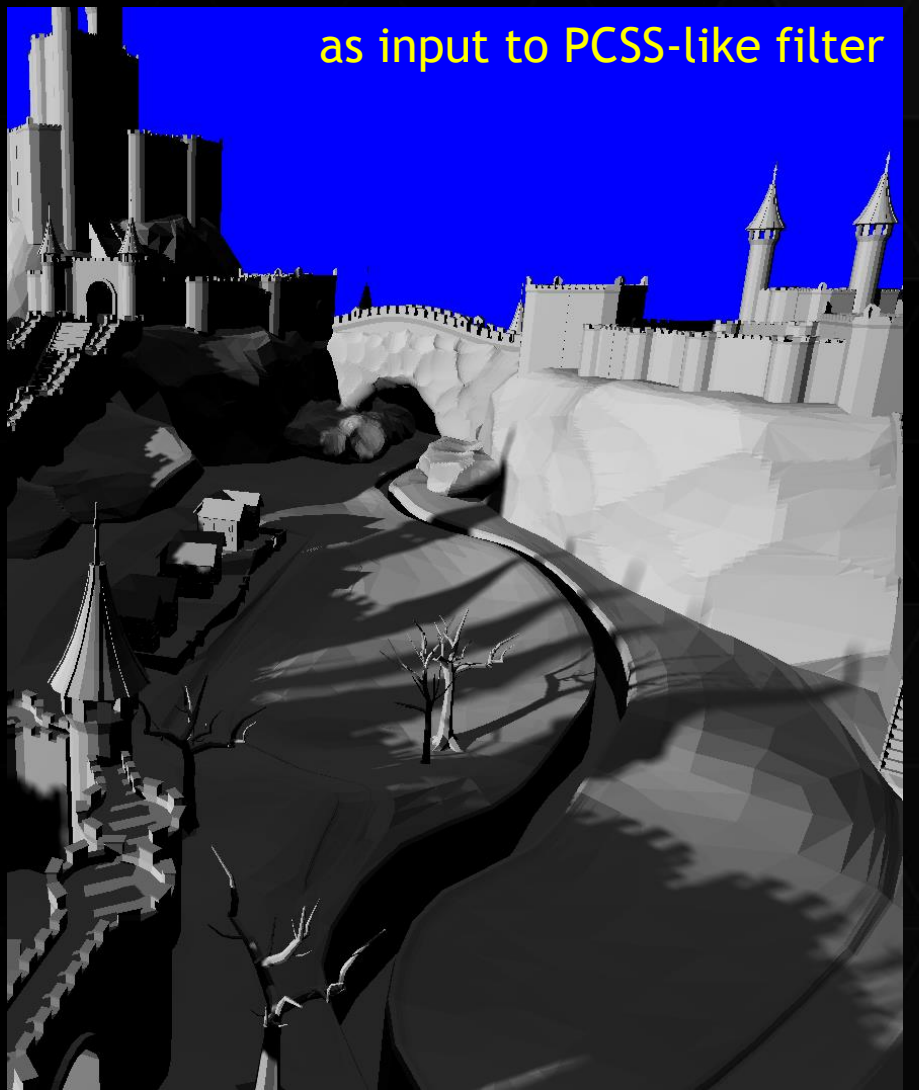
Demo? Find me during poster / demo session!

BACKUP SLIDES

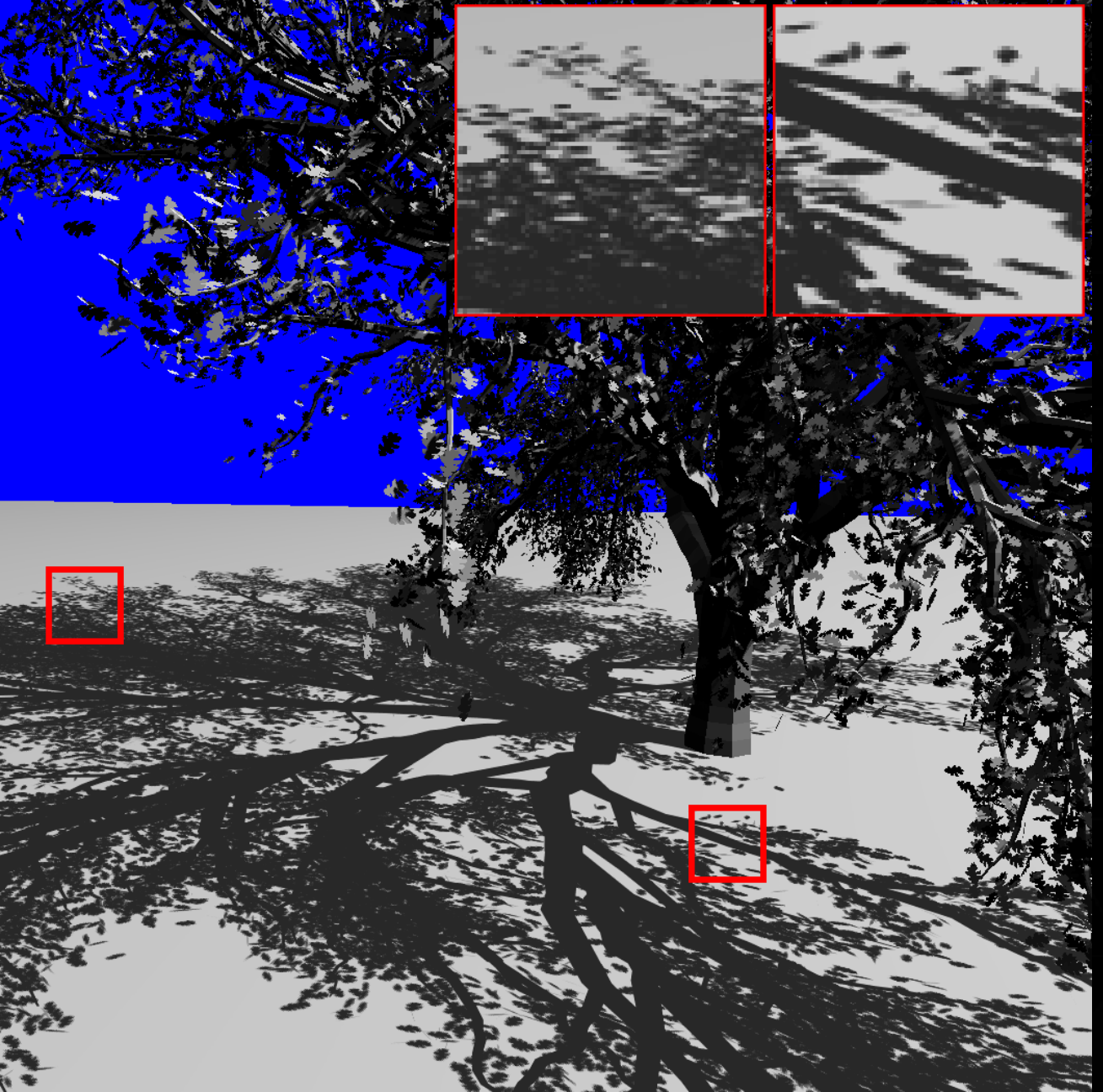
Soft Shadows?

WHAT ABOUT SOFT SHADOWS?





Alpha Mapped Triangles?



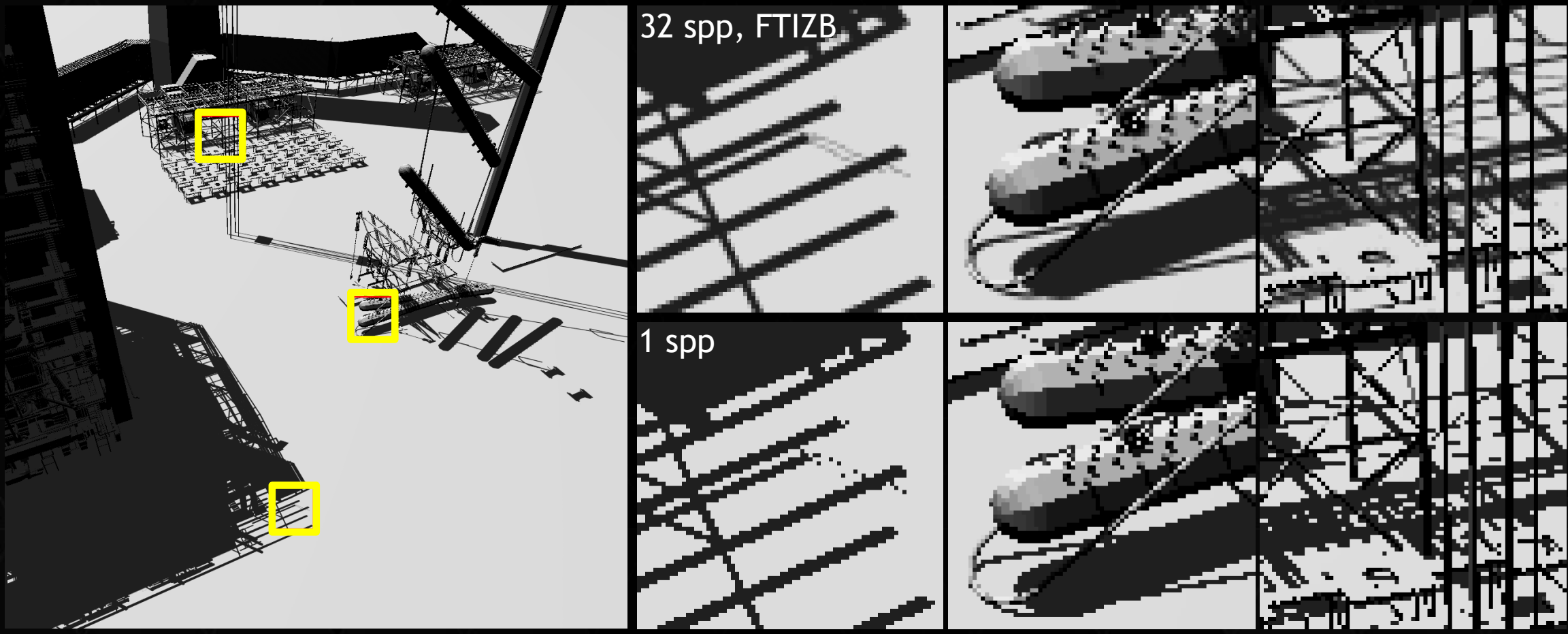
- 2.4 M polygons, most w/alpha
  - ~20 ms, unoptimized
- Use alpha-to-coverage
  - Here with 32 coverage samples
  - Even our first, naïve coverage selection works well
- Has more aliasing
  - Can’t get analytic answer with sampled input
  - Essentially resampling alpha textures in light space

Quality Comparison

32 spp v.s. 1 spp v.s. shadow map

QUALITY COMPARISONS

UNC Powerplant, 12.3 million triangles



QUALITY COMPARISONS

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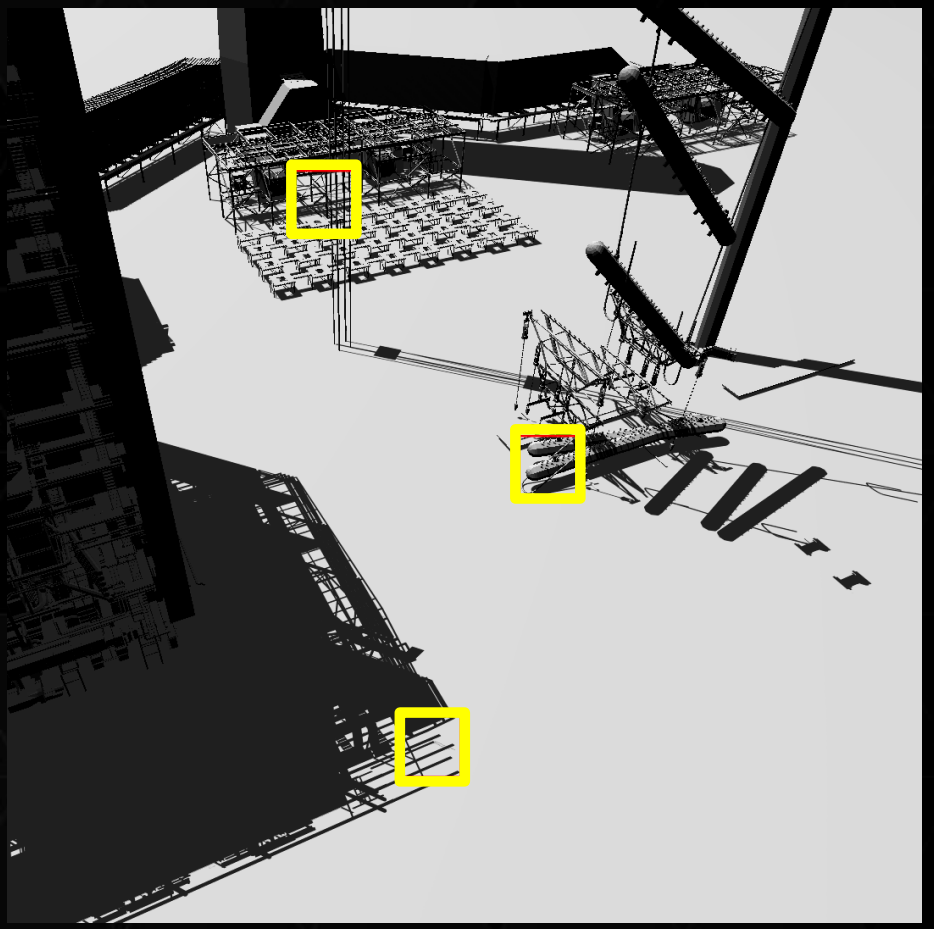

32 spp, FTIZB

8k shadow map

QUALITY COMPARISONS

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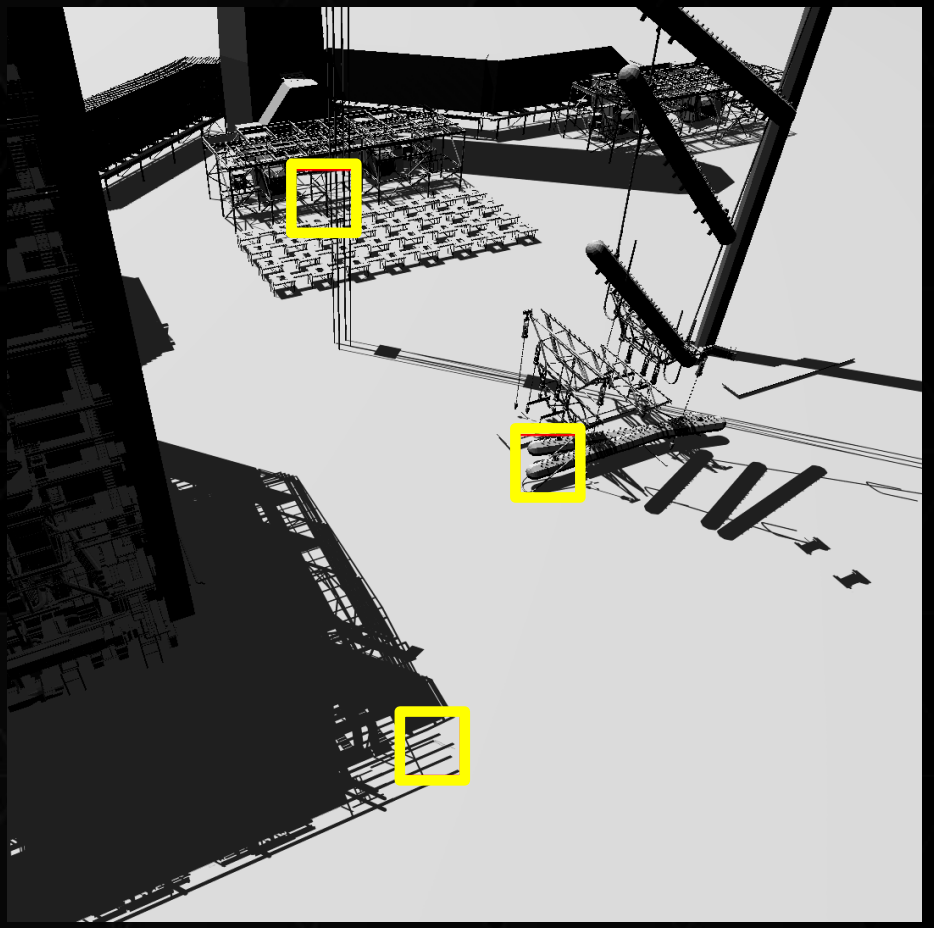
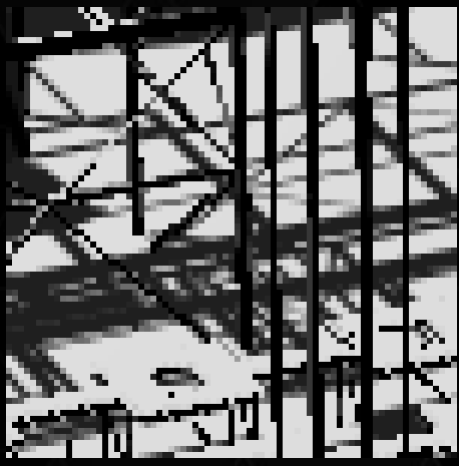
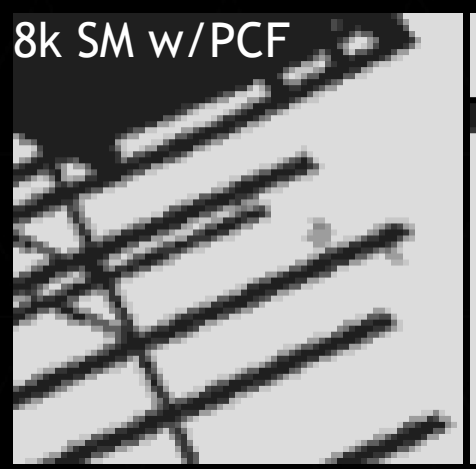
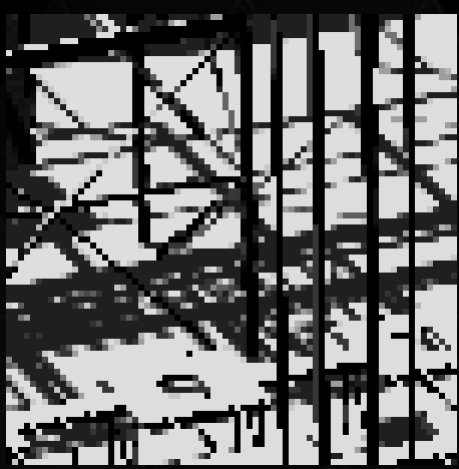
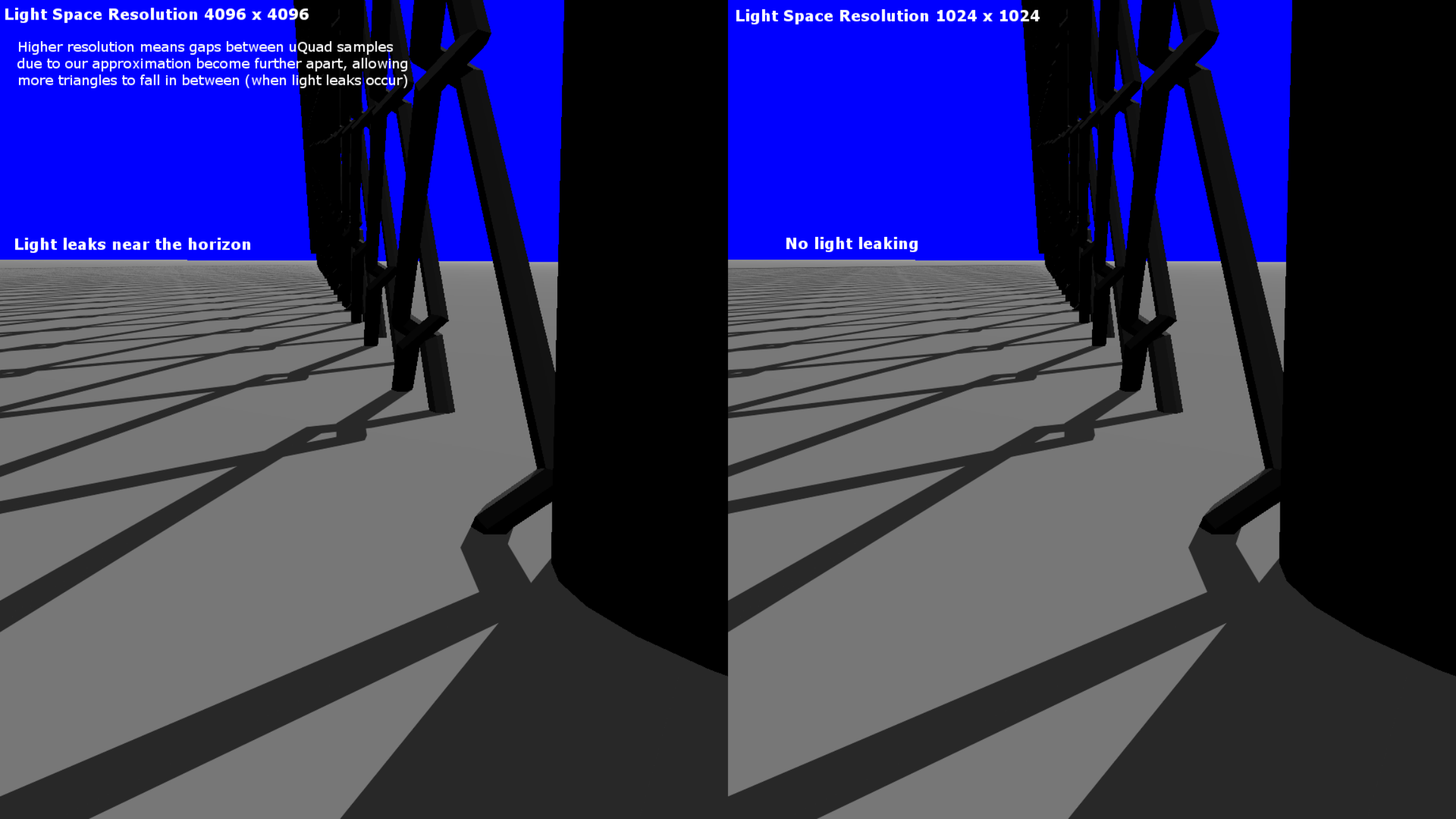


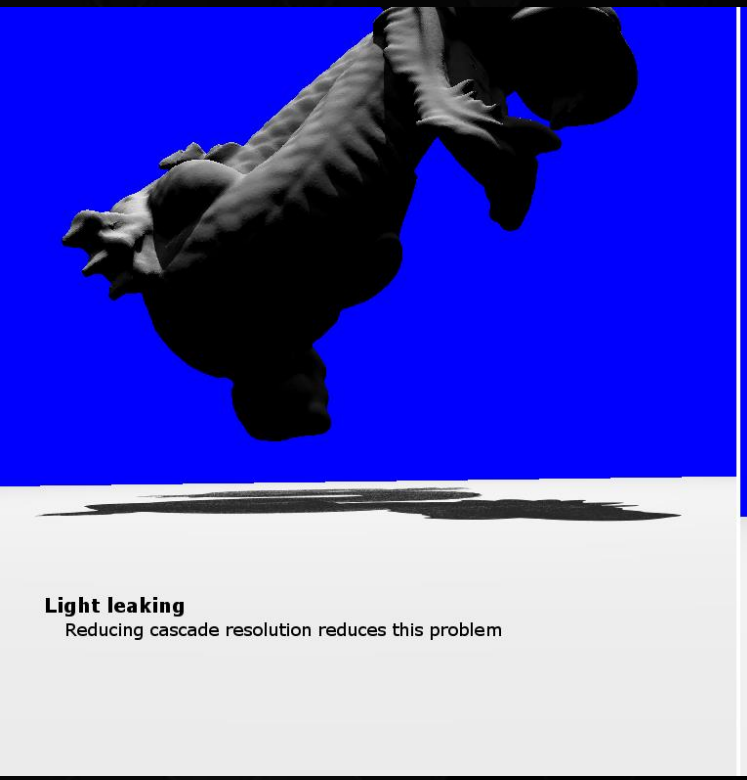






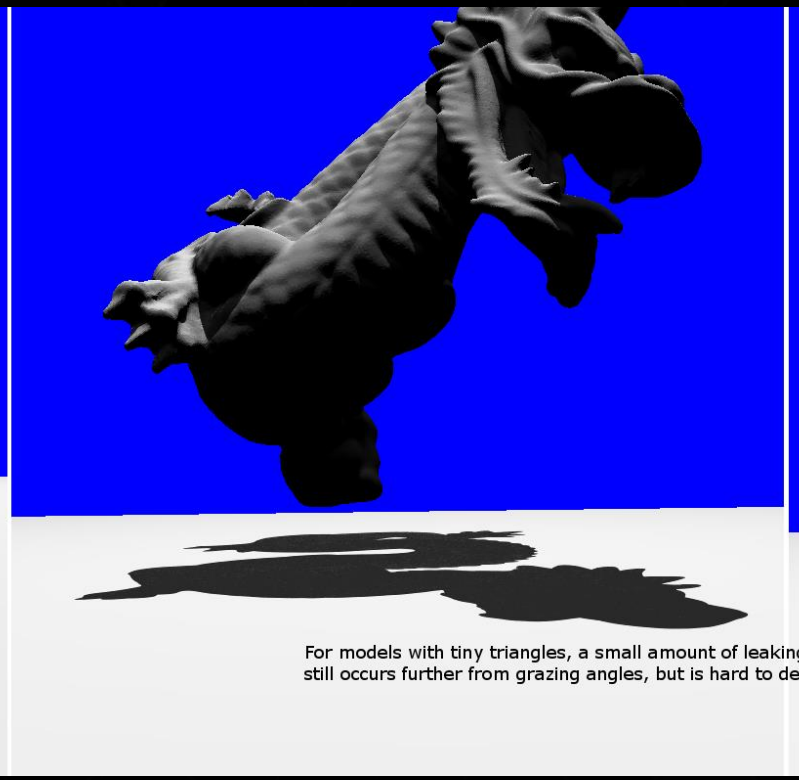
Light Leaking


Light Space Resolution 4096 x 4096
Higher resolution means gaps between uQuad samples due to our approximation become further apart, allowing more triangles to fall in between (when light leaks occur)
Light leaks near the horizon
Light Space Resolution 1024 x 1024
No light leaking

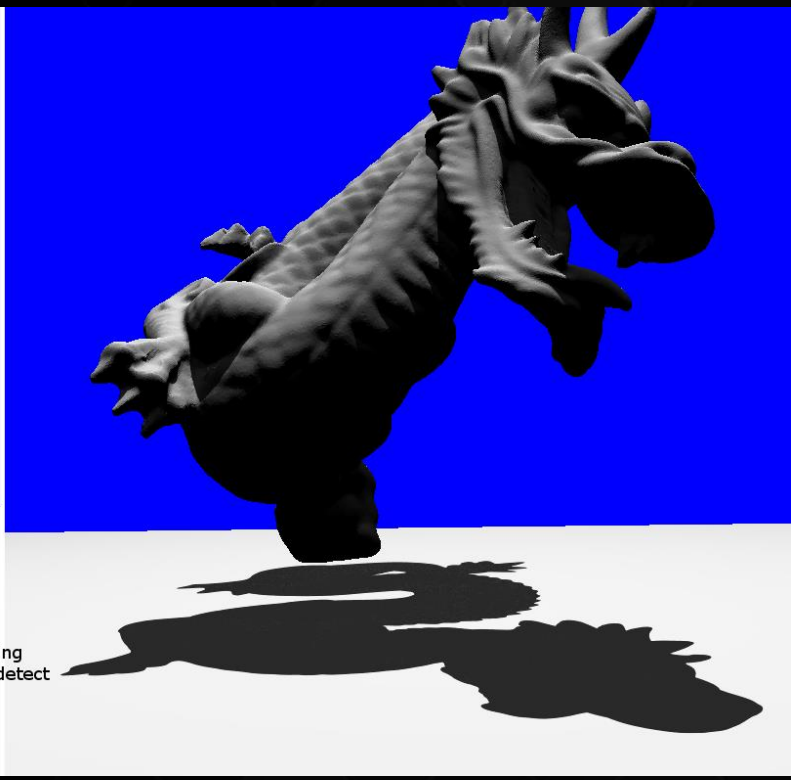


Light leaking

Reducing cascade resolution reduces this problem



For models with tiny triangles, a small amount of leaking still occurs further from grazing angles, but is hard to detect



Comparison With Ray Tracing

PERFORMANCE

Data using frustum traced IZB

	Frustum tests (millions)	Avg. tests per tri fragment	Avg. tests per pixel
Terrain	32.5	1.3	22.1
Trees	9.3	1.0	9.0
Old City	18.9	1.2	9.8
Ruined Building	19.1	1.0	11.5
Rungholt	32.1	1.4	26.8

Ray tracing with state of art BVH

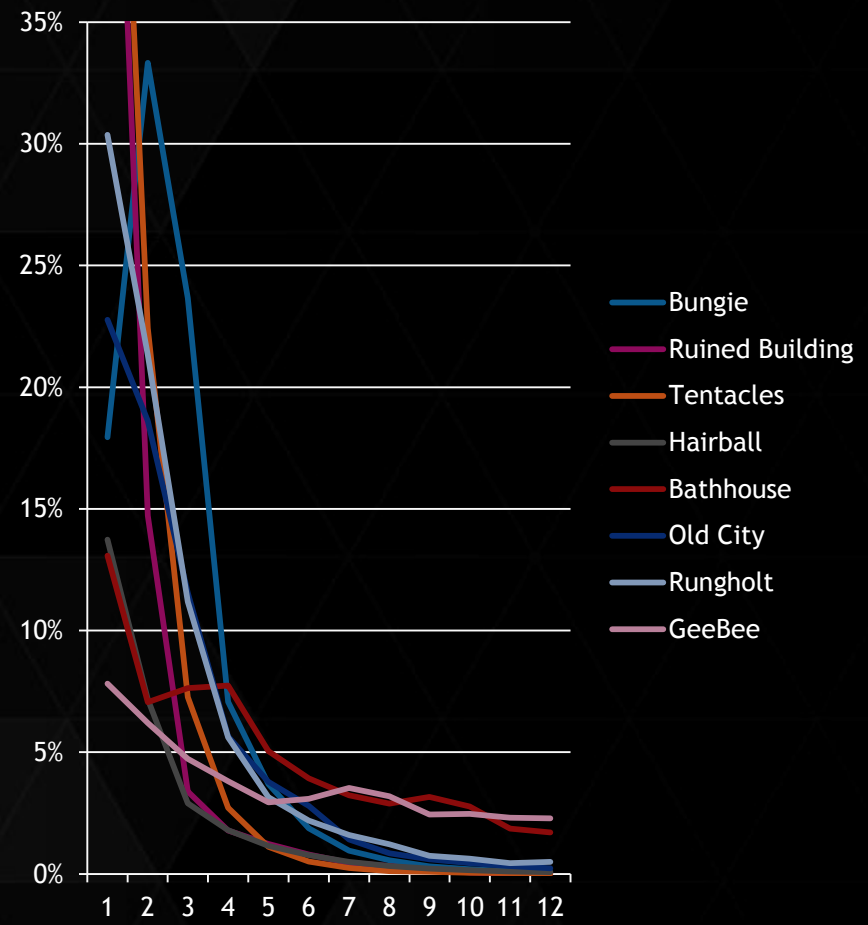
Frustum tests (millions)	Avg. tests per pixel
12.4	7.1
6.0	5.9
25.4	13.3
14.6	8.8
6.9	5.9

- Performance metrics really good
  - Tests per pixel *within factor of 1-3x* of state-of-art BVH for ray tracing
    - Building our acceleration structure costs, a roughly constant, ~2 ms per frame

Divergence / Irregularity

IRREGULARITY

Our irregularity (and perf problem) occurs where shadow maps have aliasing

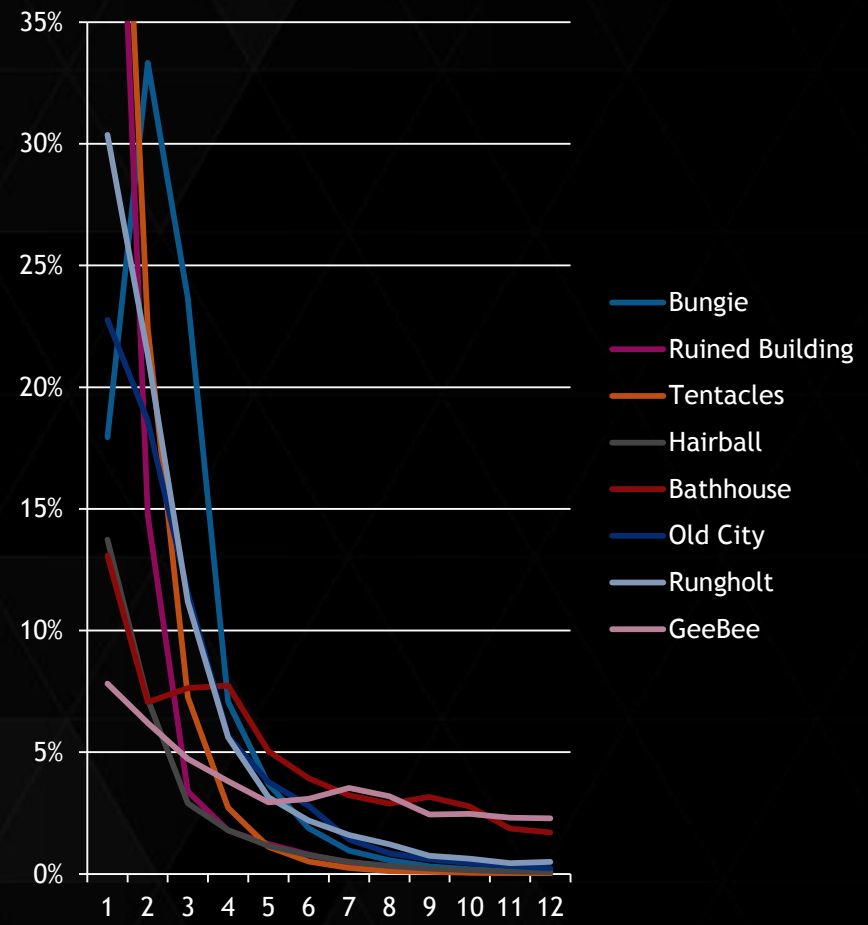


% of pixels with triangle count (no cascades)

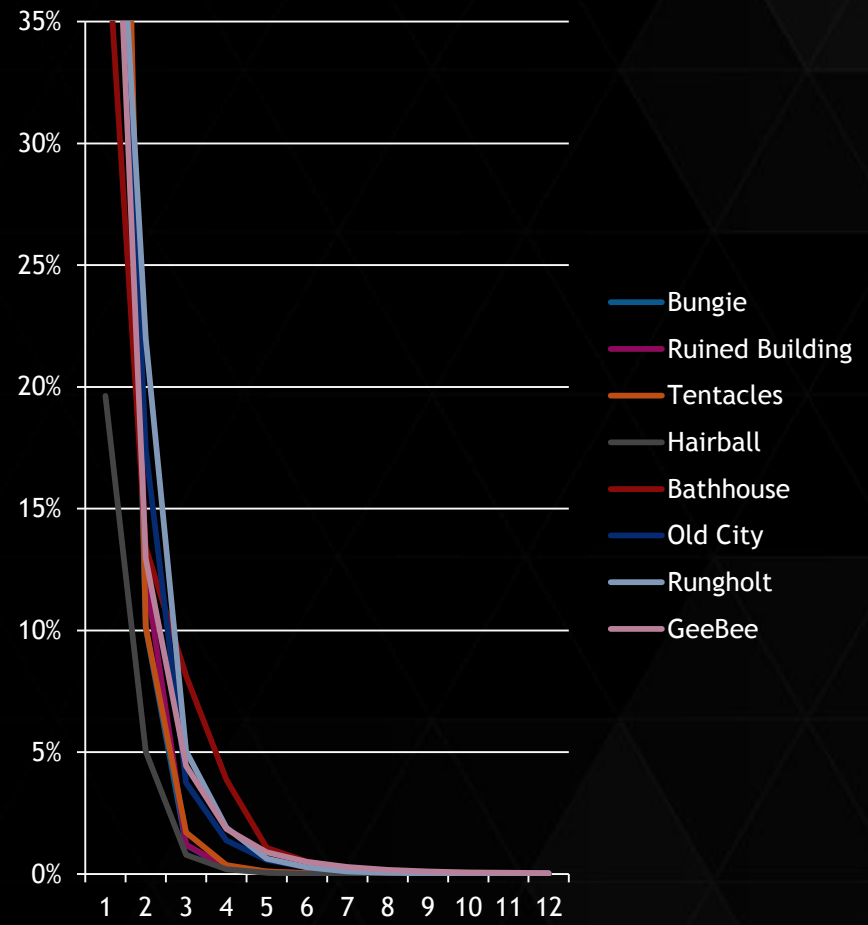
- Ideal world:
  - Each pixel tests exactly one triangle to determine shadow
- Threads stall waiting for warp
  - Desire uniform list length in warp
  - No cascades, high irregularity

IRREGULARITY

Our irregularity (and perf problem) occurs where shadow maps have aliasing



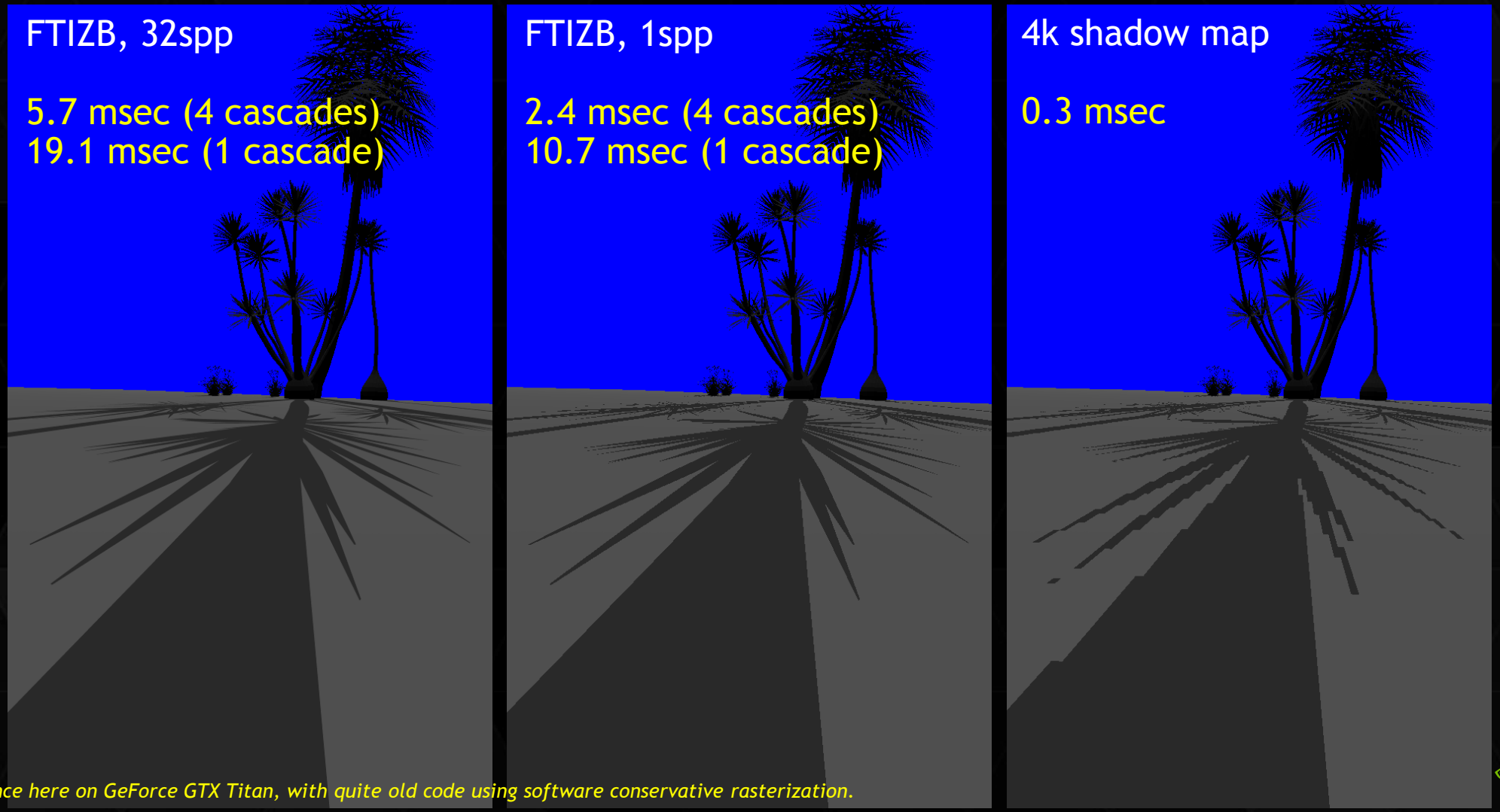
% of pixels with triangle count (no cascades)



% of pixels with triangle count (with cascades)

Dueling Frusta

HARD CASE: DUELING FRUSTA

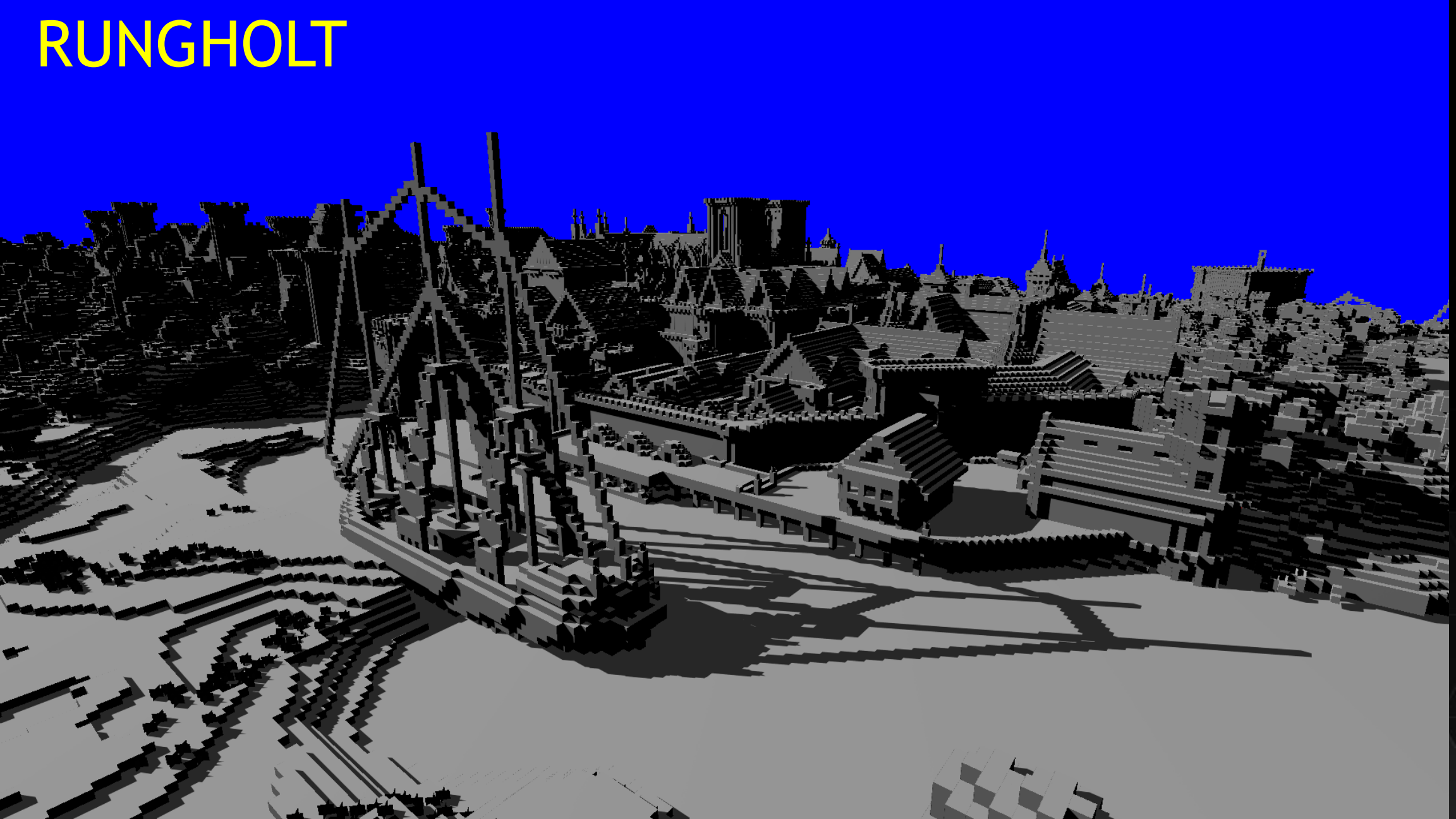


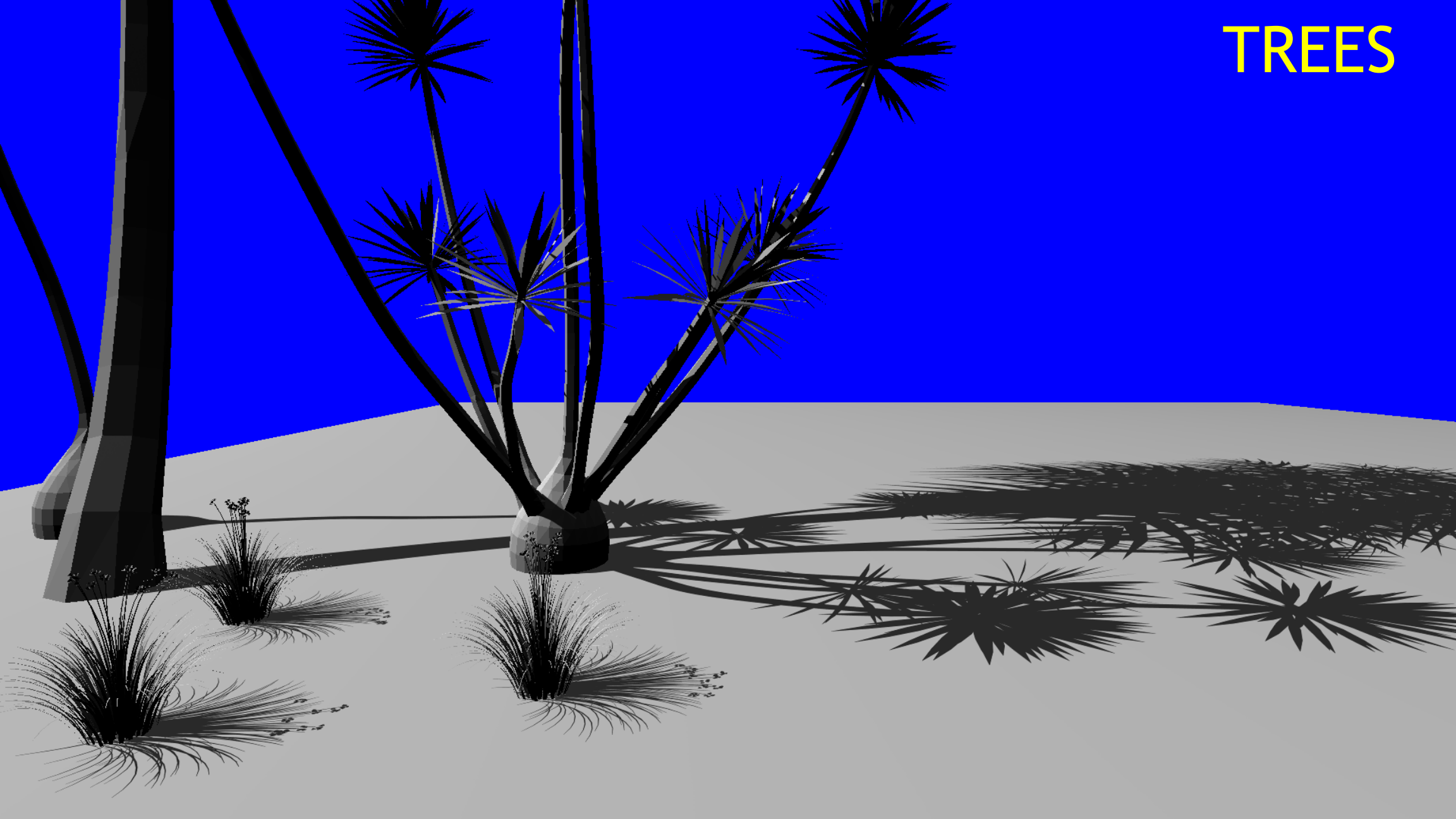
Performance here on GeForce GTX Titan, with quite old code using software conservative rasterization.

NVIDIA

Other scenes…


OLD CITY


RUNGHOLT


TREES