



# Progressive Transient Photon Beams

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300,000 km/s LIGHT TRANSPORT

# TRANSIENT LIGHT TRANSPORT

Femto-photography [Velten et al. 2013]



# Femto-photography [Velten et al. 2013]



# Transient Light Transport- What for?

- Light in motion [*Velten13, Heide13, Peters15...*]
- Visible geometry [*Wu14, OToole14, Marco17...*]
- Transparent Objects [*Kadambi13*]
- Hidden geometry [*Velten12, Buttafava15, OToole18, Liu19,...*]
- Reflectance estimation [*Naik11, Naik13*]
- GI Components Separation [*Wu14, OToole14*]
- Vision through media [*Heide14, Wu18...*]
- ...

# SIMULATION

**Forward model  
for inverse  
problems**

**Benchmarking  
algorithms**

**Prototyping**

**Machine  
learning**

# Transient rendering

**Forward model  
for inverse  
problems**

**Benchmarking  
algorithms**

**Prototyping**

**Machine  
learning**



# OUR GOAL

**Robust time-resolved  
participating media**

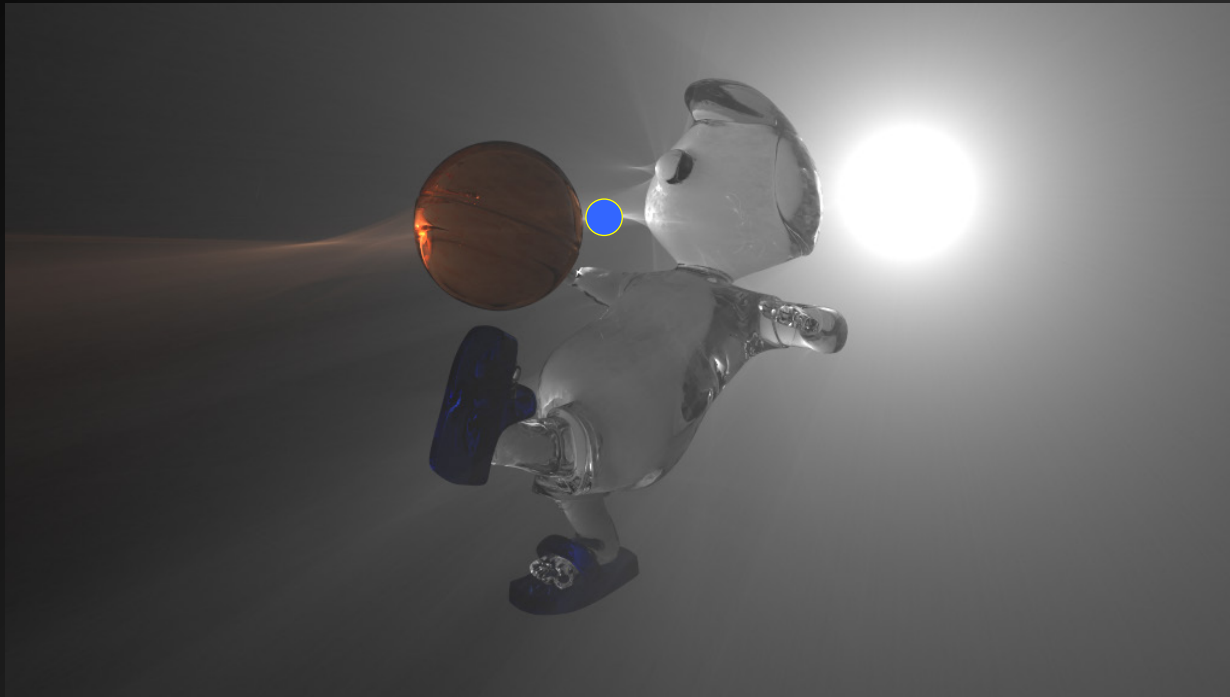
Forward model  
for inverse  
problems

Benchmarking  
algorithms

Prototyping

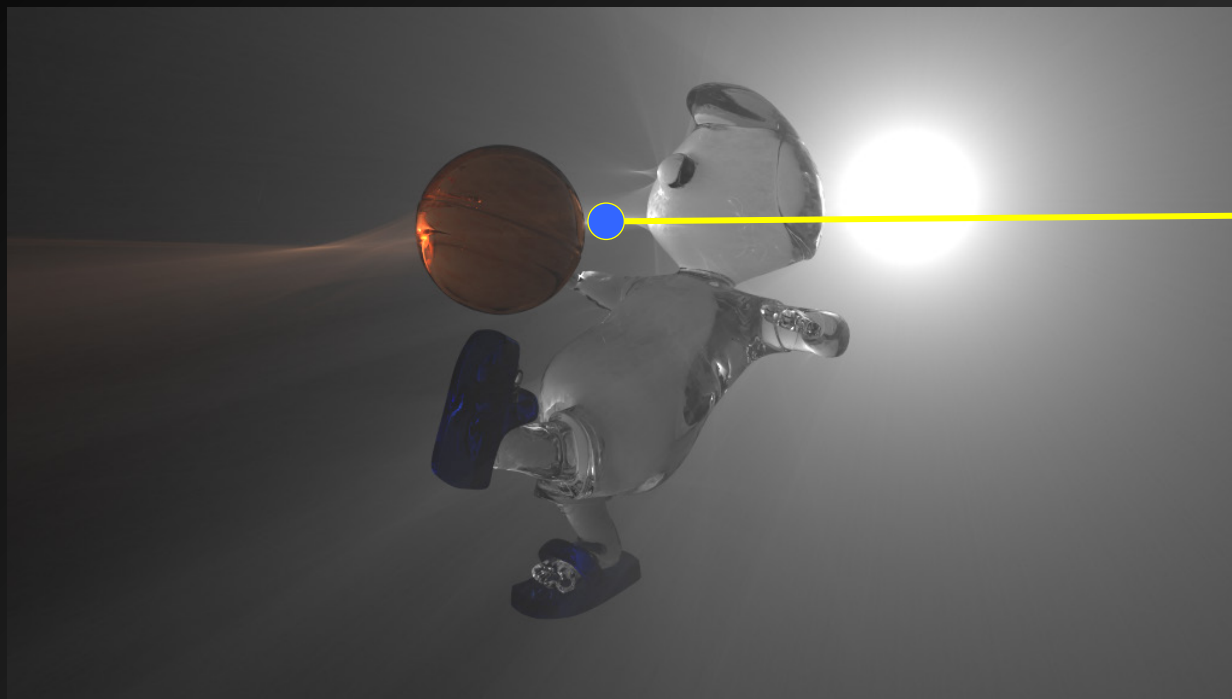
Machine  
learning

# Transient Rendering vs. Steady-state



*Steady state*

# Transient Rendering vs. Steady-state



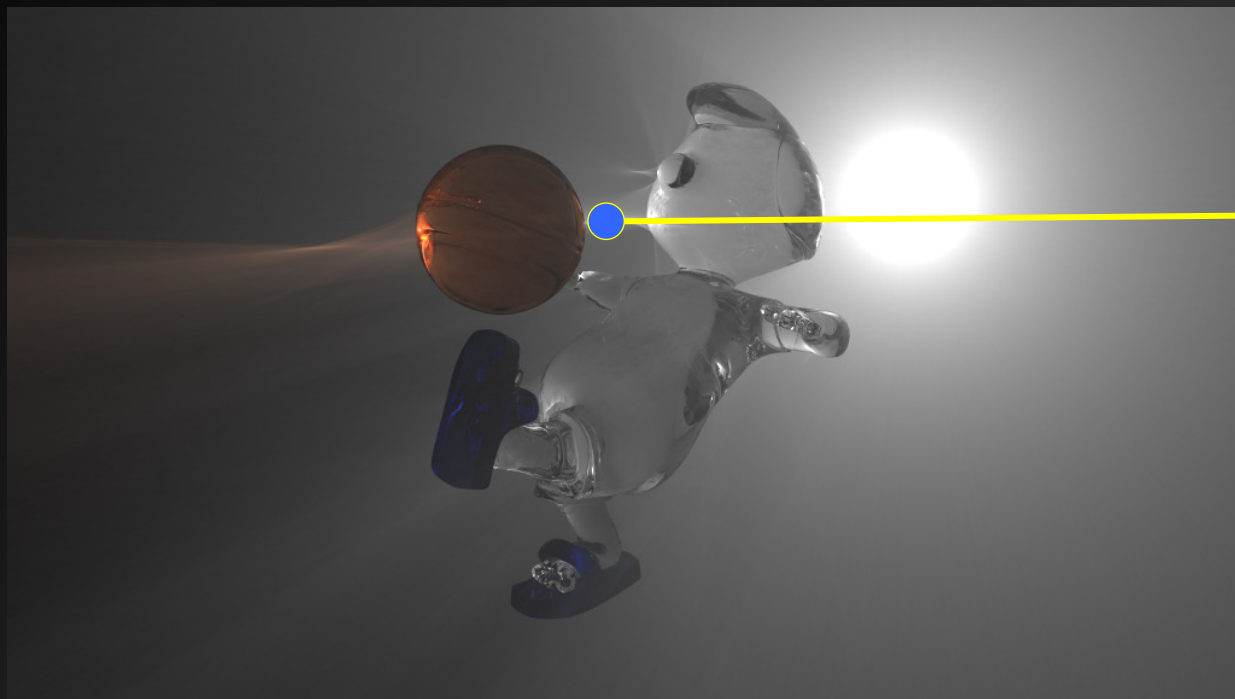
*Steady state*

$L$

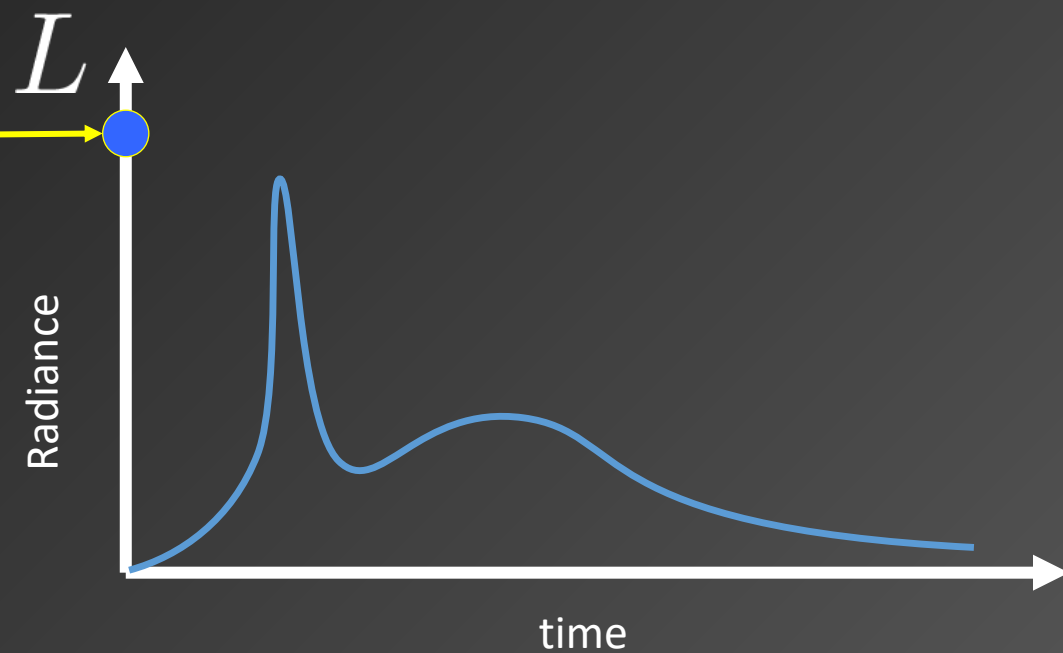
Radiance

# Transient Rendering

Finite speed of light  $\rightarrow$  Temporal dimension

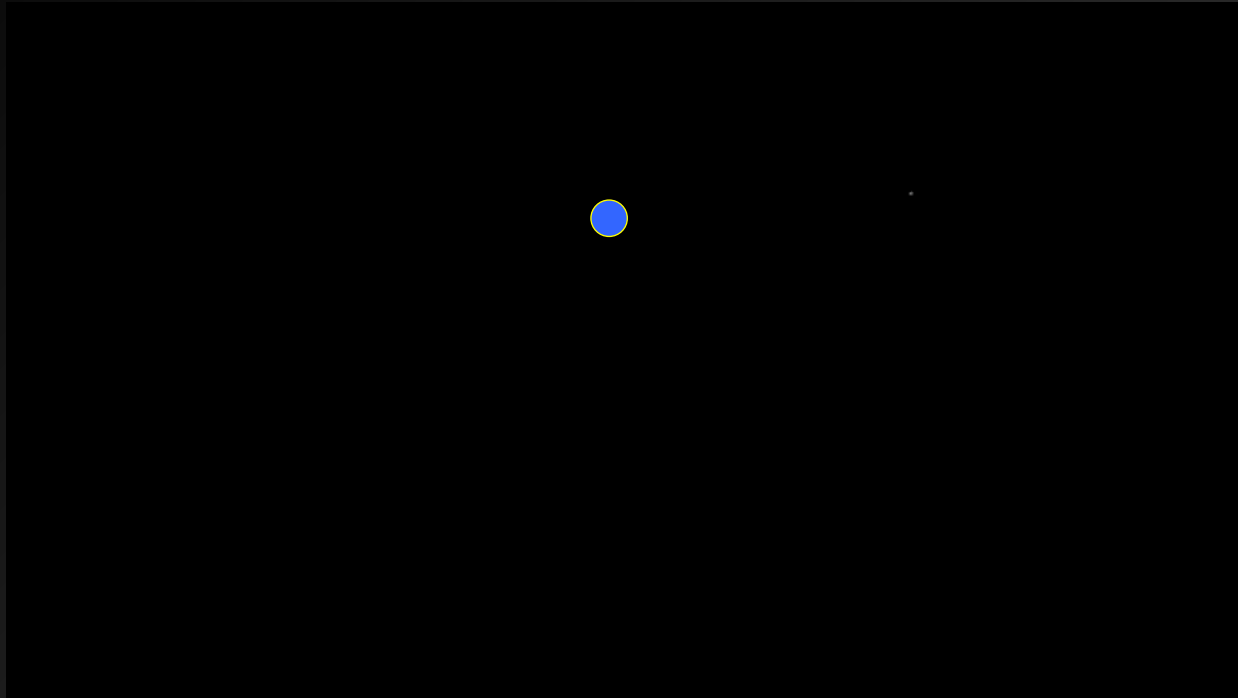


*Steady state*

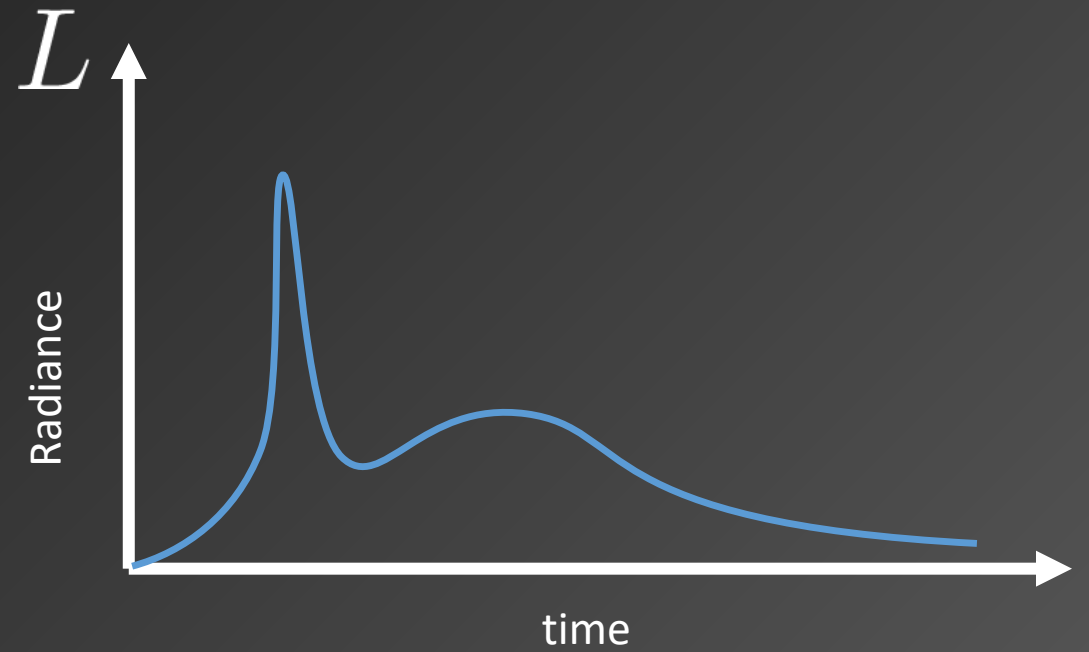


# Transient Rendering

Finite speed of light → Temporal dimension



*Steady state*



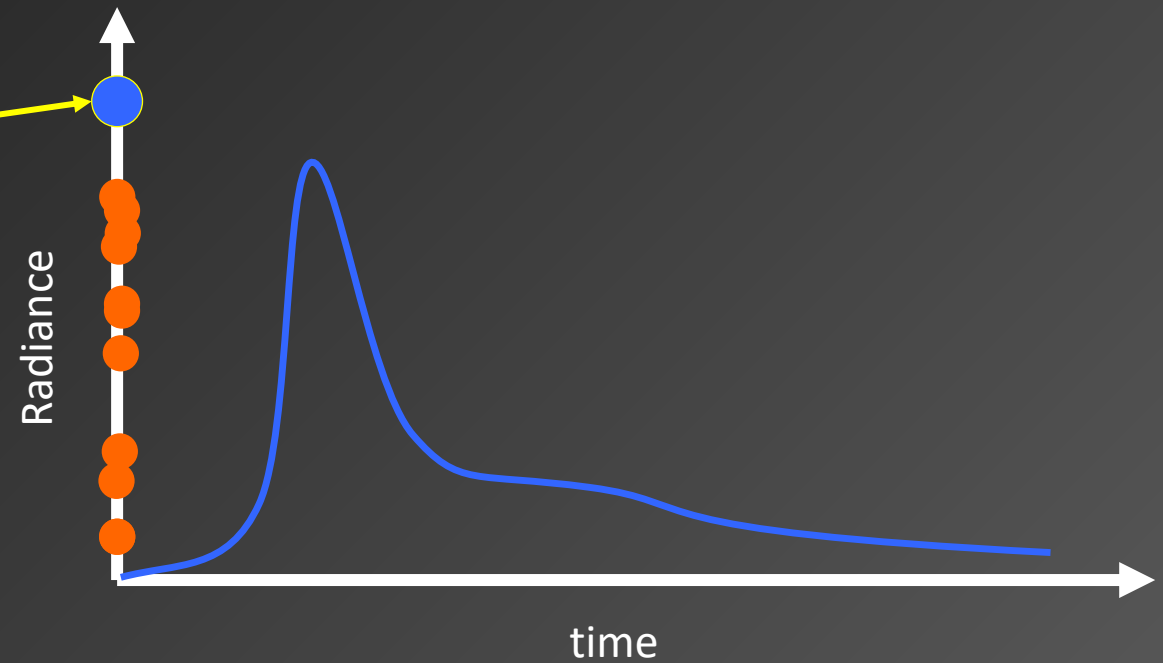
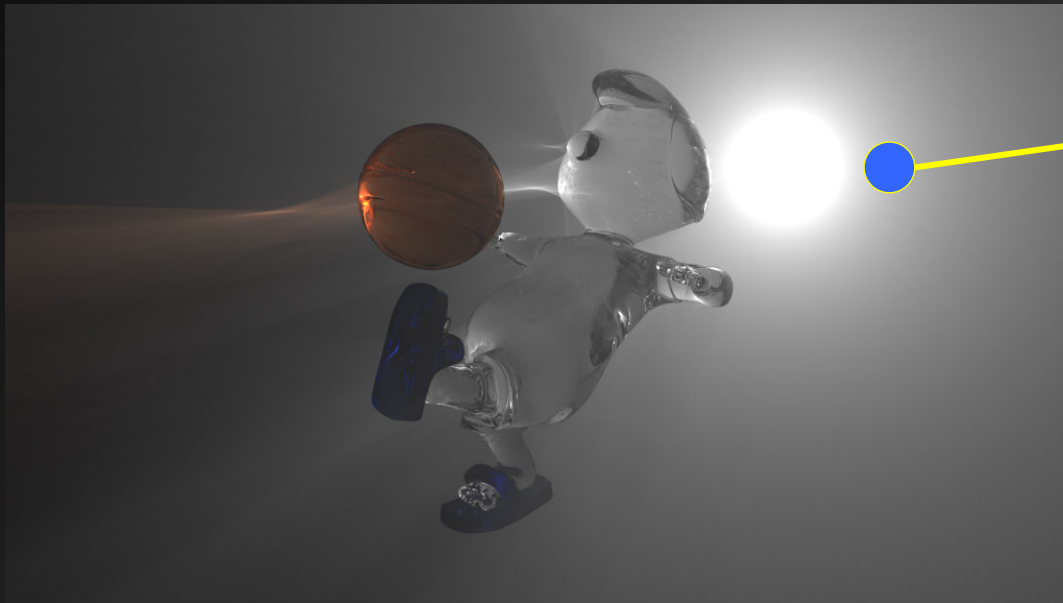
# Transient Rendering

- [Meister et al. 2013, Ament et al 2014, Hullin 2014]
  - ➔ Application-specific, approximations, point samples
- [Jarabo et al. 2014]
  - ➔ Time-resolved path integral formulation
  - ➔ Temporal progressive density estimations
  - ➔ Time-based importance sampling
  - ➔ Point samples: Bidirectional path tracing, photon mapping

# Transient Rendering

## Challenges

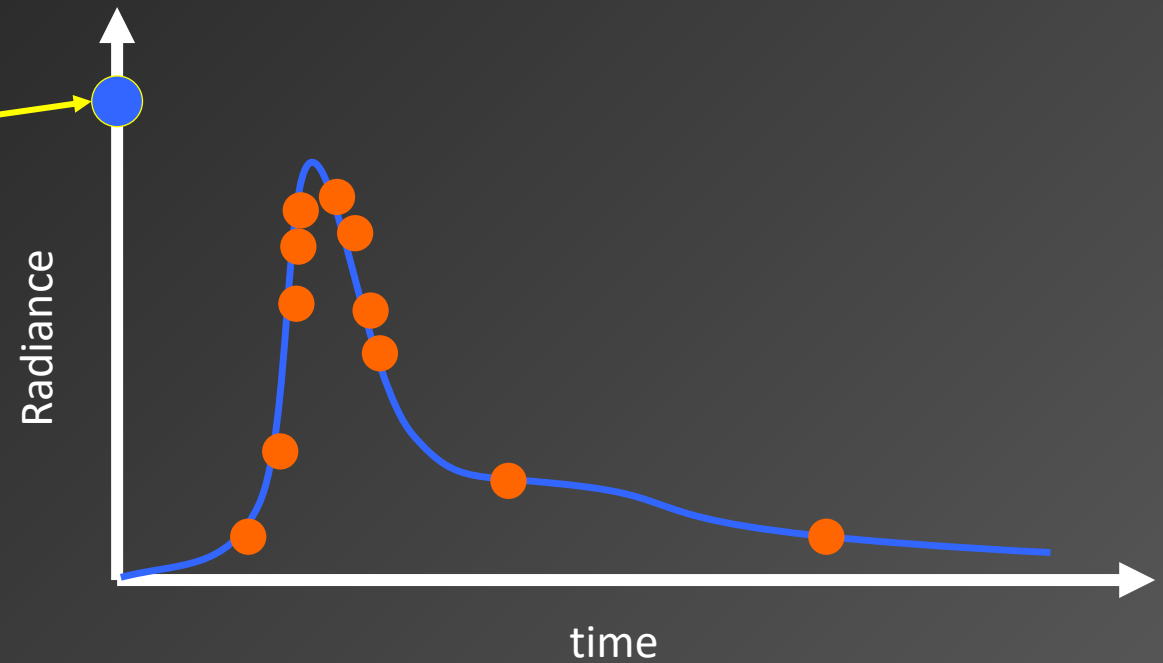
- Monte Carlo methods → Variance is aggravated in time



# Transient Rendering

## Challenges

- Monte Carlo methods → Variance is aggravated in time

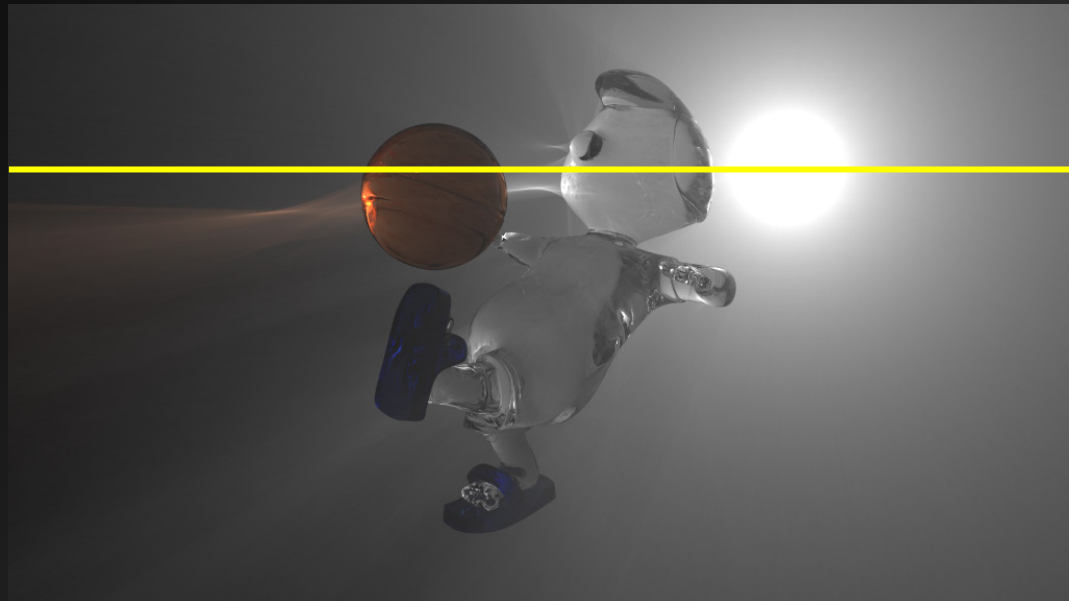




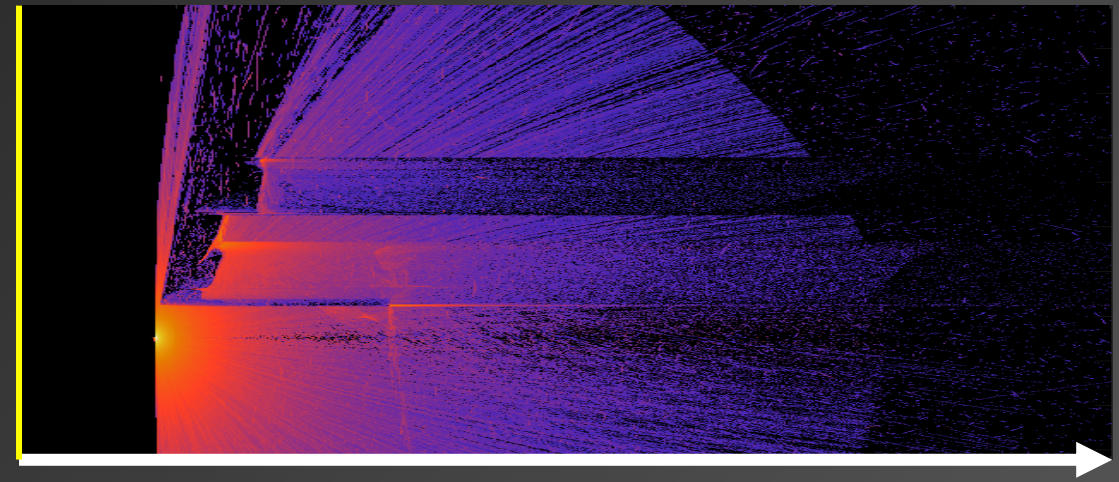
# Transient Rendering

## Challenges

- Monte Carlo methods → Variance is aggravated in time



Slow convergence



# Transient Rendering

## Participating media

Classic RTE in rendering

**TIME-INDEPENDENT**

$$L(\mathbf{x}, \vec{\omega}) = T_r(\mathbf{x}, \mathbf{x}_s) L_s(\mathbf{x}_s, \vec{\omega}) + \int_0^s \mu_s(\mathbf{x}_q) T_r(\mathbf{x}, \mathbf{x}_q) L_o(\mathbf{x}_q, \vec{\omega}) dq.$$

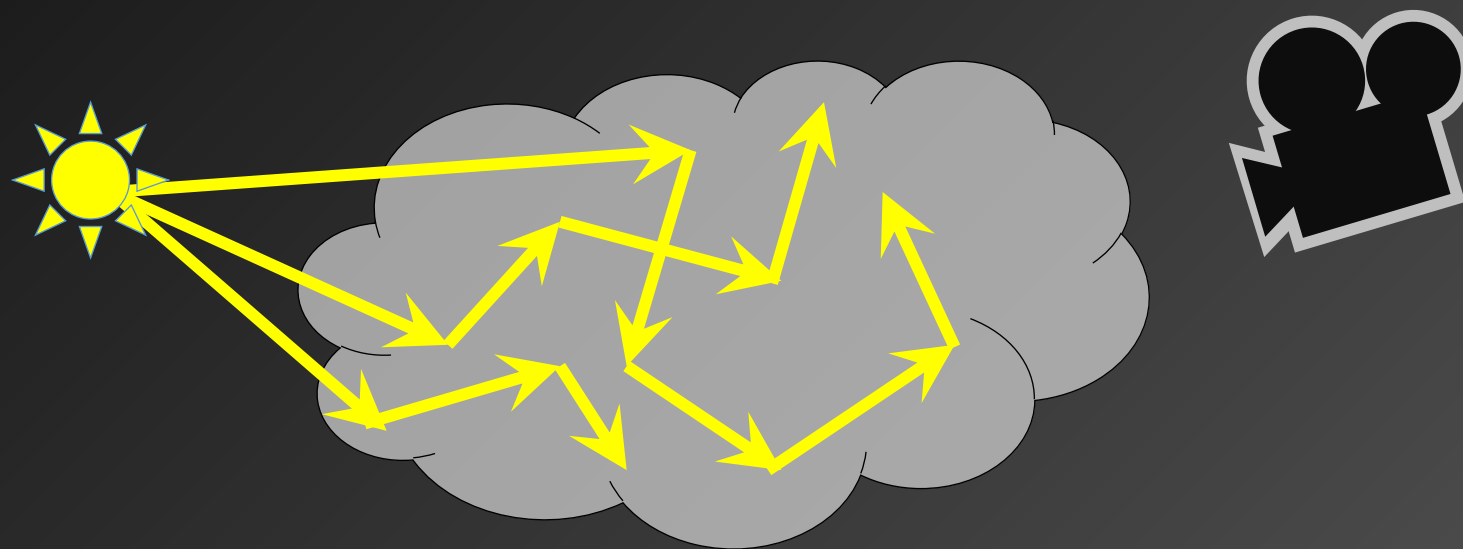
$$L_o(\mathbf{x}_q, \vec{\omega}) = L_e(\mathbf{x}_q, \vec{\omega}) + \int_{\mathcal{S}} f_s(\mathbf{x}_q, \vec{\omega}_i, \vec{\omega}) L(\mathbf{x}_q, \vec{\omega}_i) d\vec{\omega}_i$$

# Transient Rendering

Participating media

Classic RTE in rendering

**TIME-INDEPENDENT**

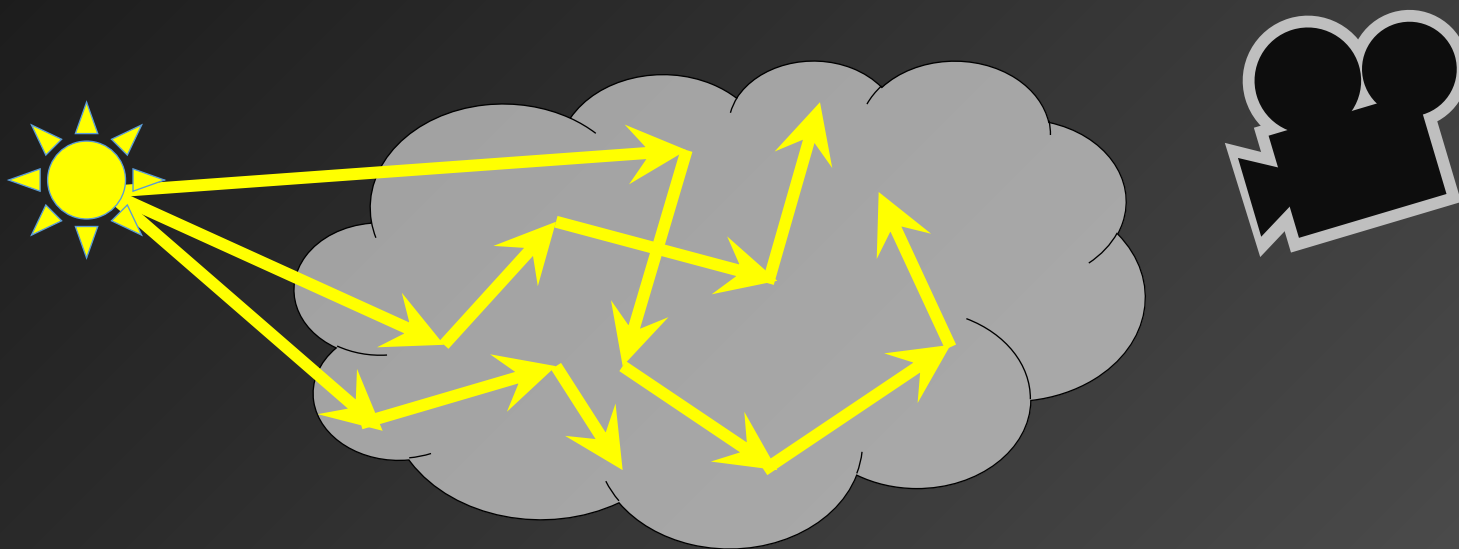


# Transient Rendering

## Participating media

Transient RTE

**NEED TO ACCOUNT FOR TIME**



# Transient Rendering

## Participating media

Transient RTE

**NEED TO ACCOUNT FOR TIME**

$$L(\mathbf{x}, \vec{\omega}, t) = T_r(\mathbf{x}, \mathbf{x}_p) L_s(\mathbf{x}_p, \vec{\omega}, t - \Delta t_p) + \int_0^p \mu_s(\mathbf{x}_q) T_r(\mathbf{x}, \mathbf{x}_q) L_o(\mathbf{x}_q, \vec{\omega}, t - \Delta t_q) dq,$$

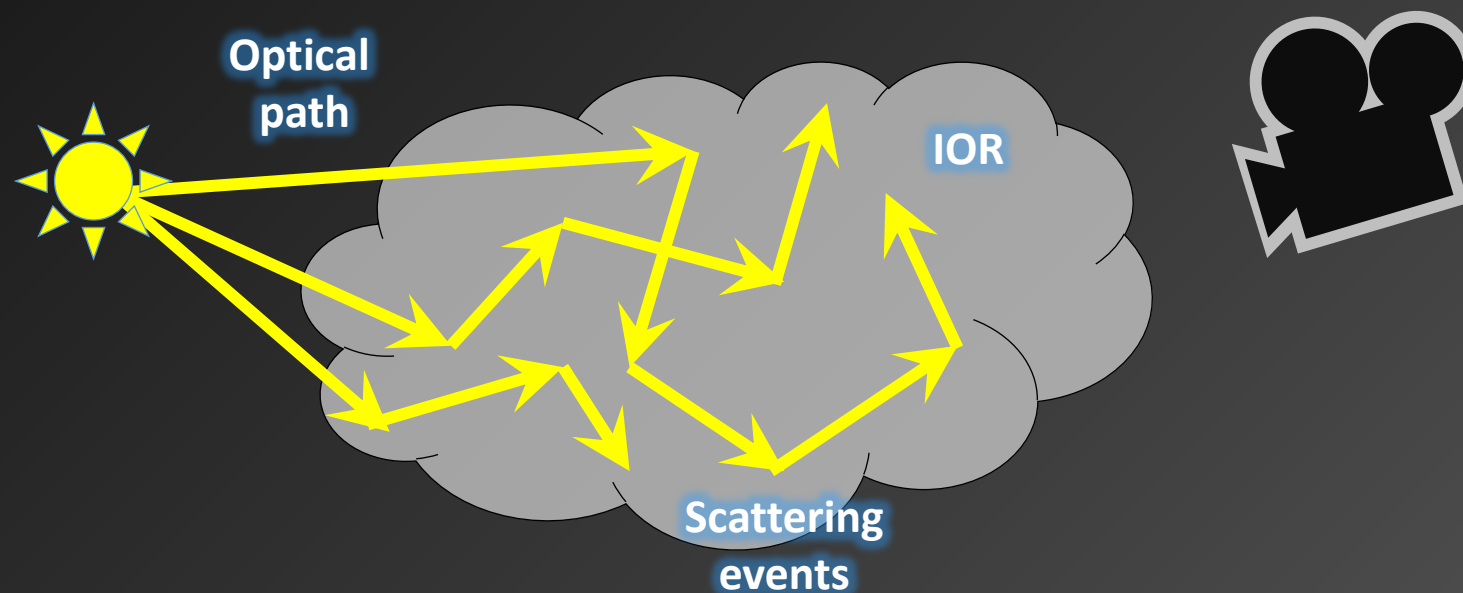
$$L_o(\mathbf{x}_q, \vec{\omega}, t) = \int_{-\infty}^t L_e(\mathbf{x}_q, \vec{\omega}, t') dt' + \int_{\mathcal{S}} \int_{-\infty}^t f_s(\mathbf{x}_q, \vec{\omega}_i, \vec{\omega}, t - t') L(\mathbf{x}_q, \vec{\omega}_i, t') dt' d\vec{\omega}_i$$

# Transient Rendering

## Participating media

Transient RTE

**NEED TO ACCOUNT FOR TIME**

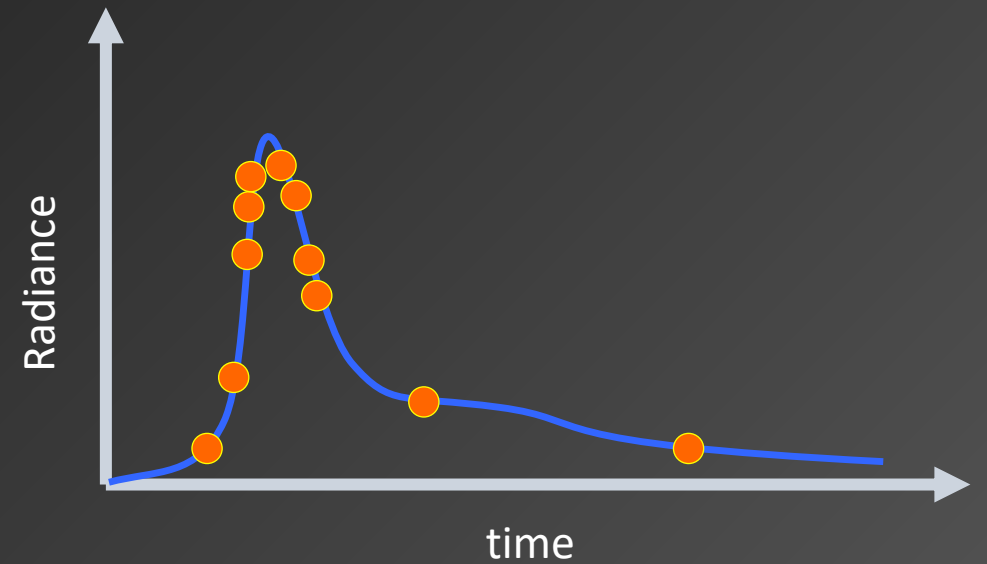
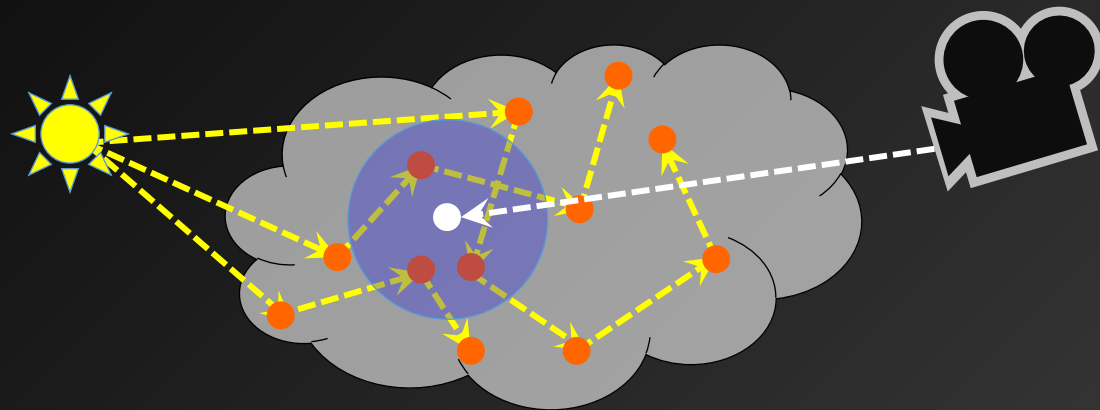


# Transient Rendering

## Participating media

[Jarabo 2014] → Point samples (BDPT, photon mapping)

→ SPARSE SAMPLES IN TIME

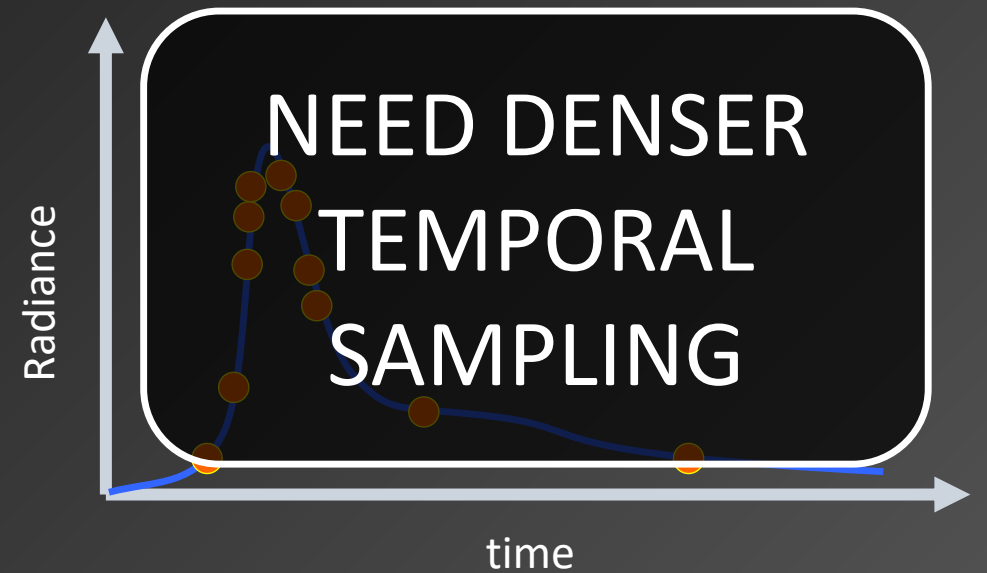
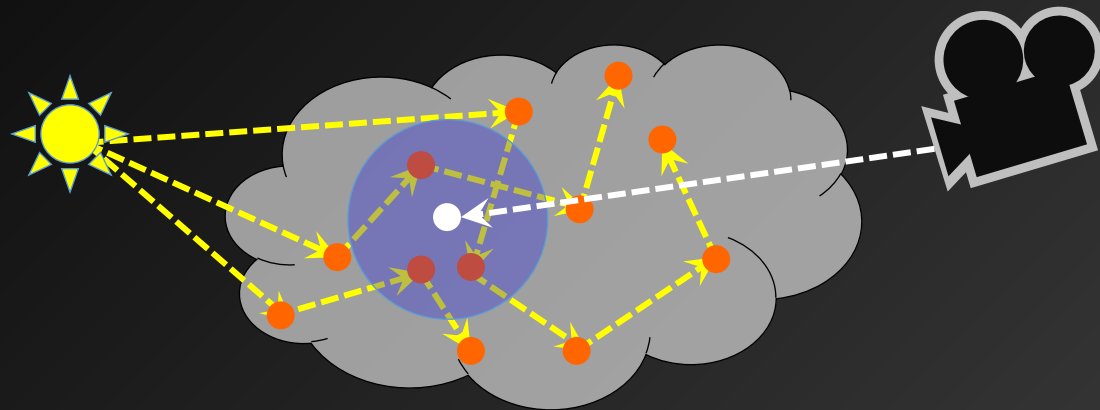


# Transient Rendering

## Participating media

[Jarabo 2014] → Point samples (BDPT, photon mapping)

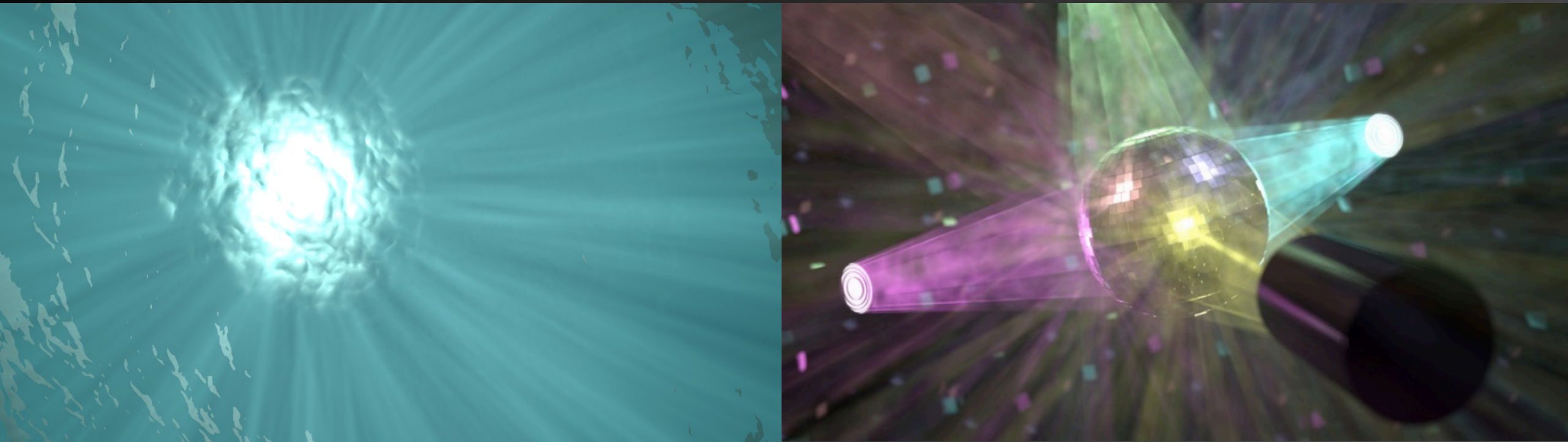
→ SPARSE SAMPLES IN TIME





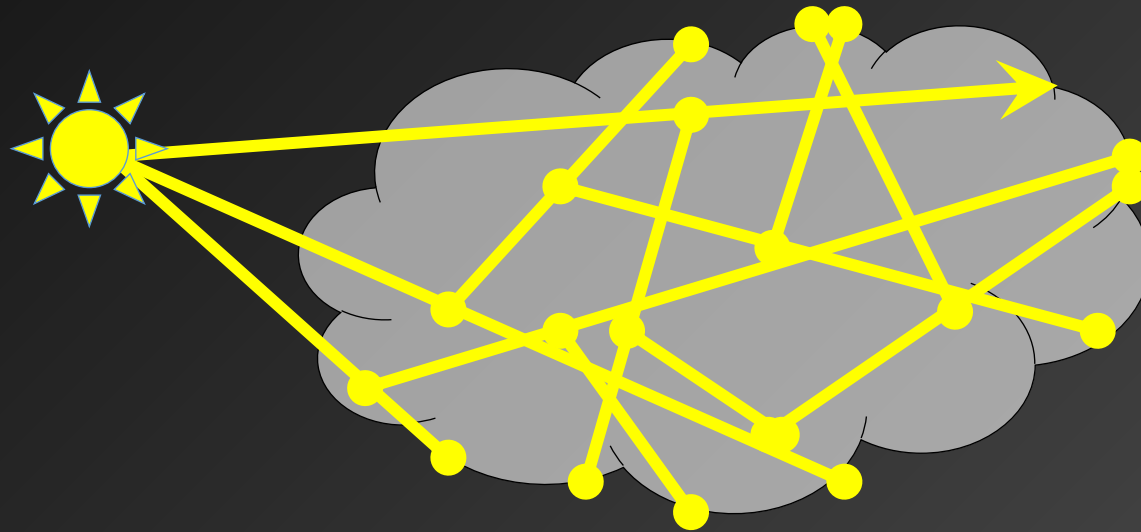
# Steady-state - Photon Beams

[Jarosz et al. 2011a, 2011b]: **Steady-state media rendering**



# Steady-state - Photon Beams

1. Stores photon trajectories on a BEAMS MAP

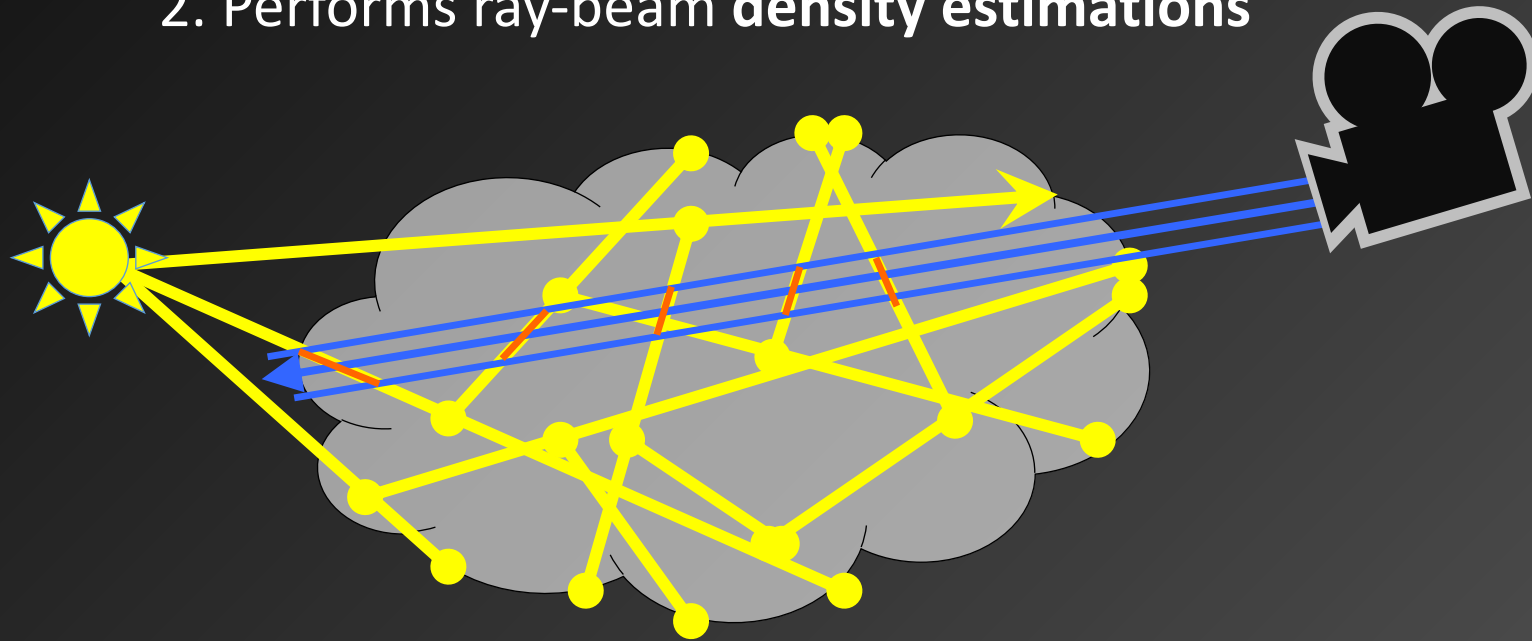


# Steady-state - Photon Beams

1. Stores photon trajectories on a BEAMS MAP



2. Performs ray-beam density estimations

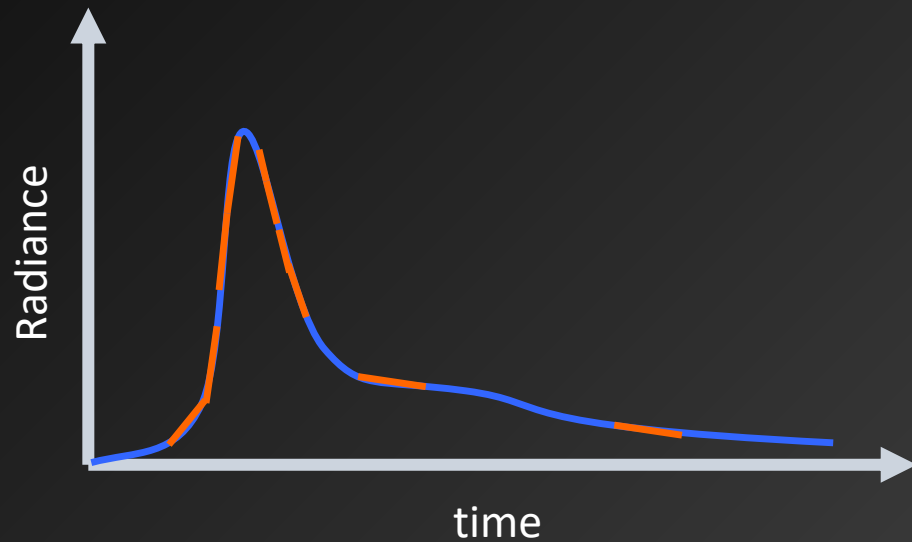


# Transient Photon Beams

Why photon beams for transient rendering?

## Full photon trajectories

Denser sampling  
the temporal domain



# Transient Photon Beams

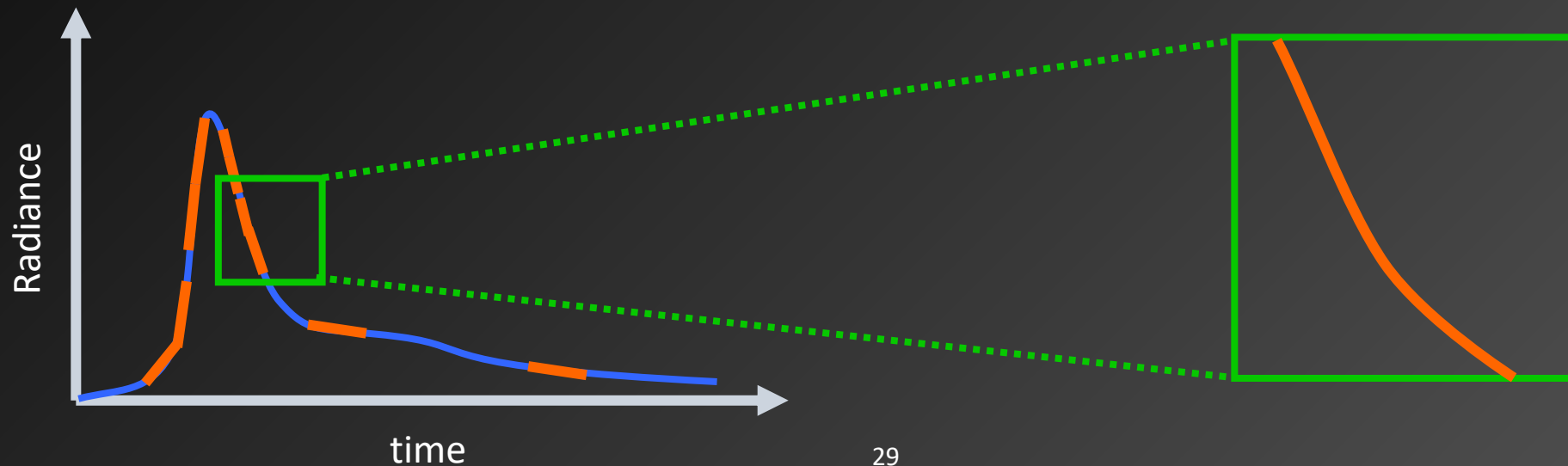
Why photon beams for transient rendering?

Full photon trajectories

Closed form density estimations

Denser sampling  
the temporal domain

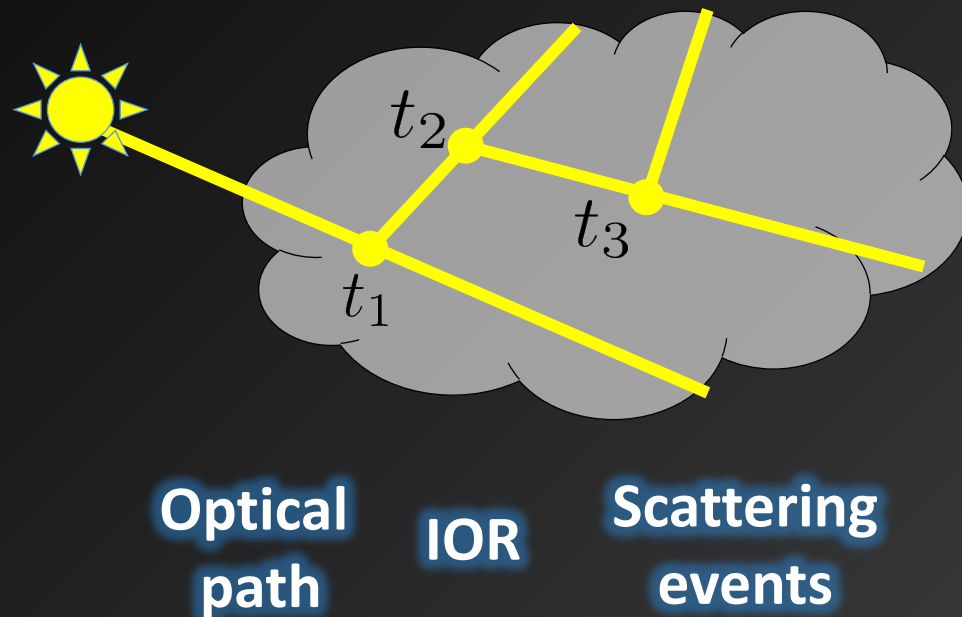
Arbitrary temporal  
resolution



# Transient Photon Beams

## 1. Tracing: Sample Transient RTE

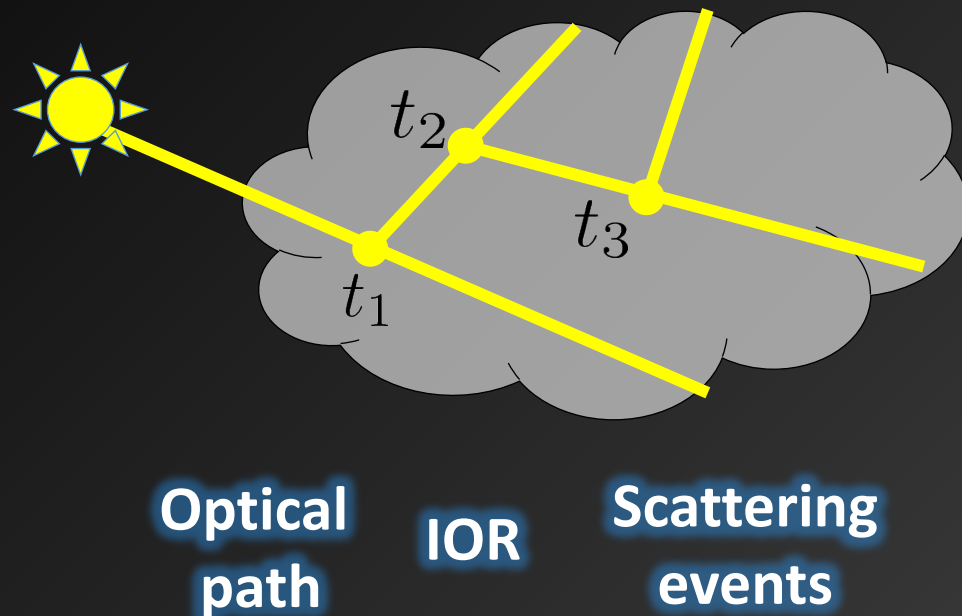
→ Store **beam starting time**



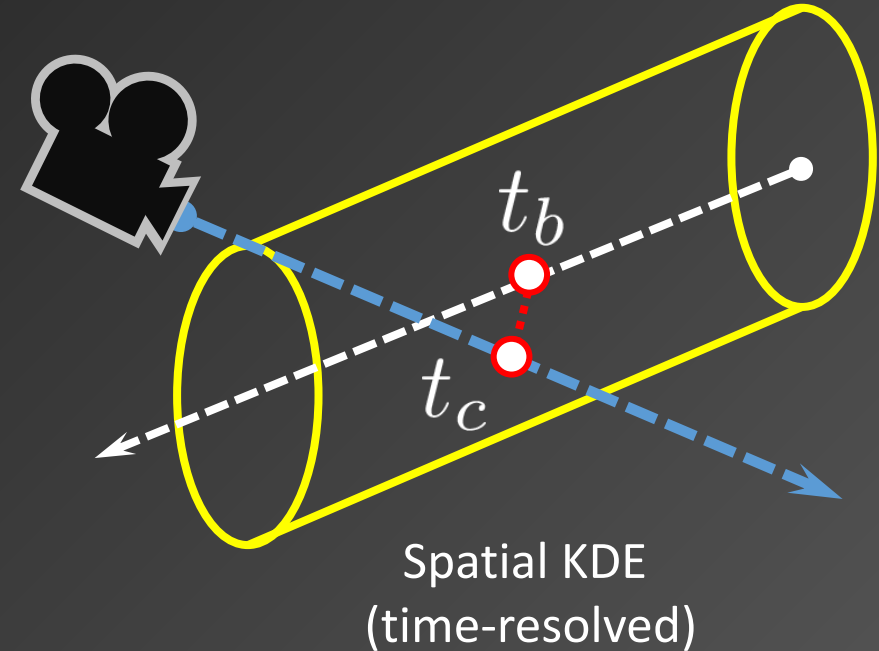
# Transient Photon Beams

1. Tracing: Sample Transient RTE

→ Store **beam starting time**



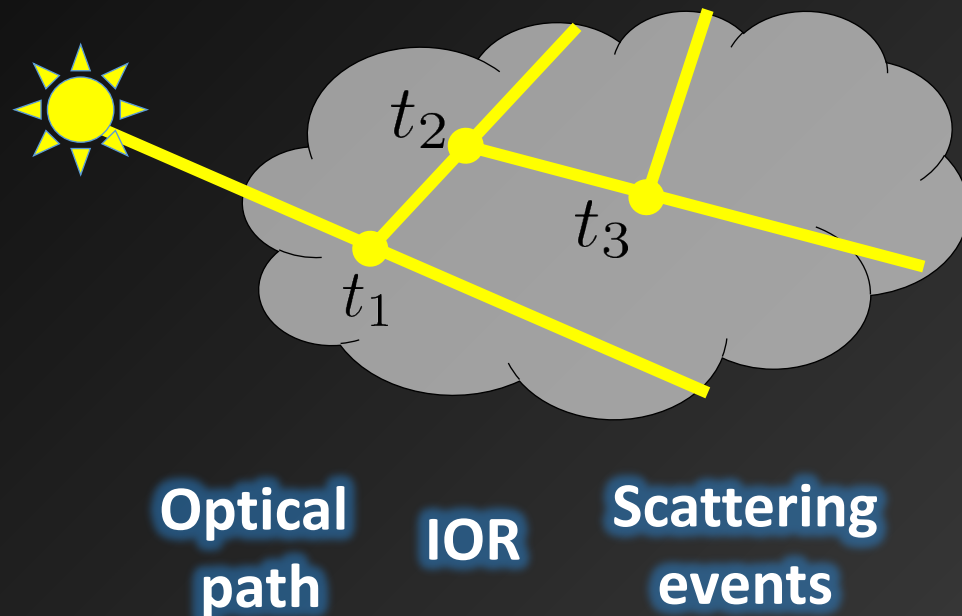
2. Rendering: Spatio-temporal density estimations



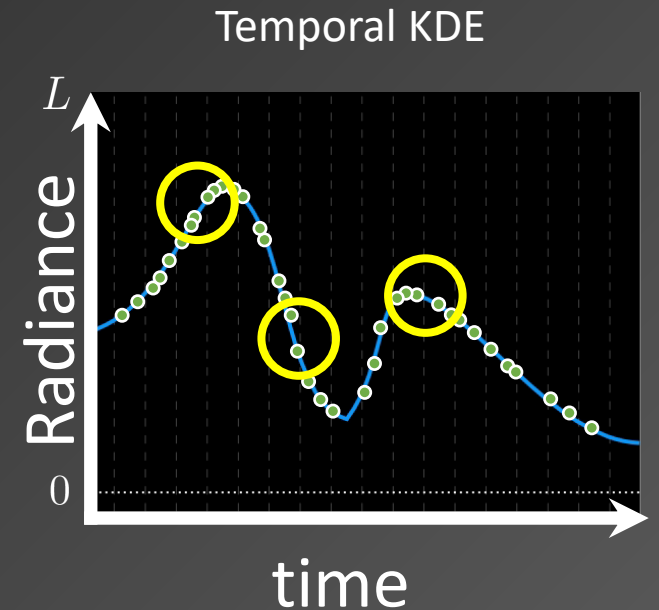
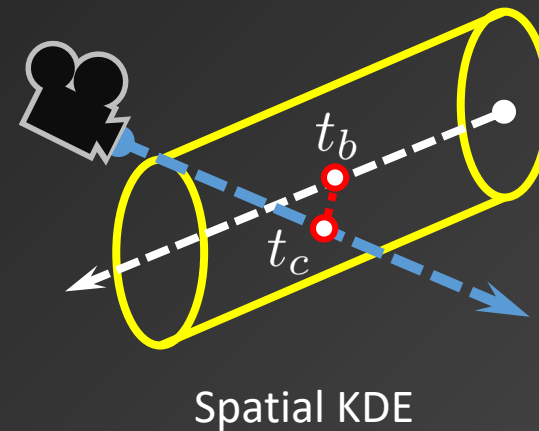
# Transient Photon Beams

1. Tracing: Sample Transient RTE

→ Store beam starting time

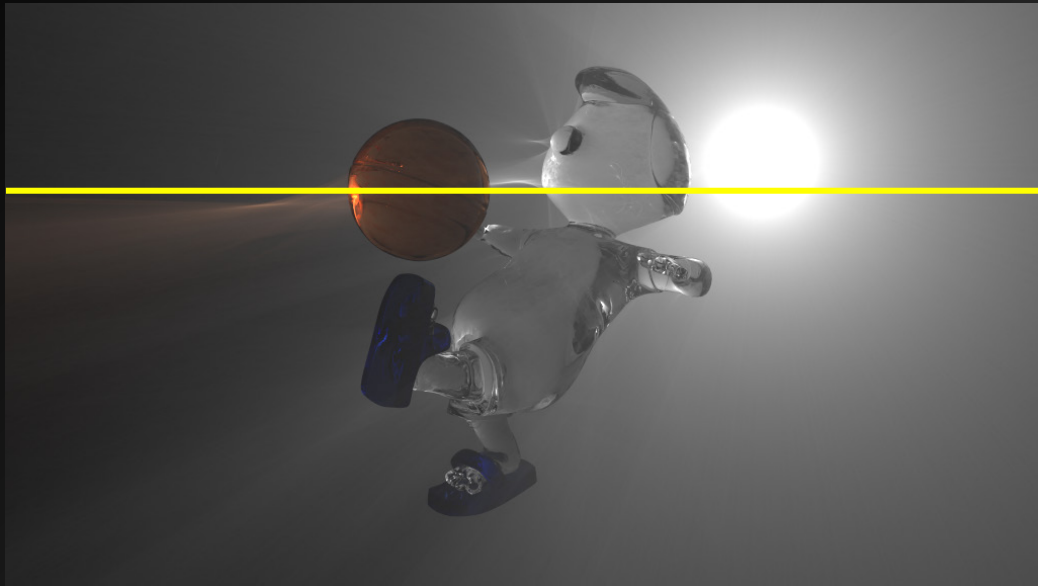


2. Rendering: Spatio-temporal density estimations



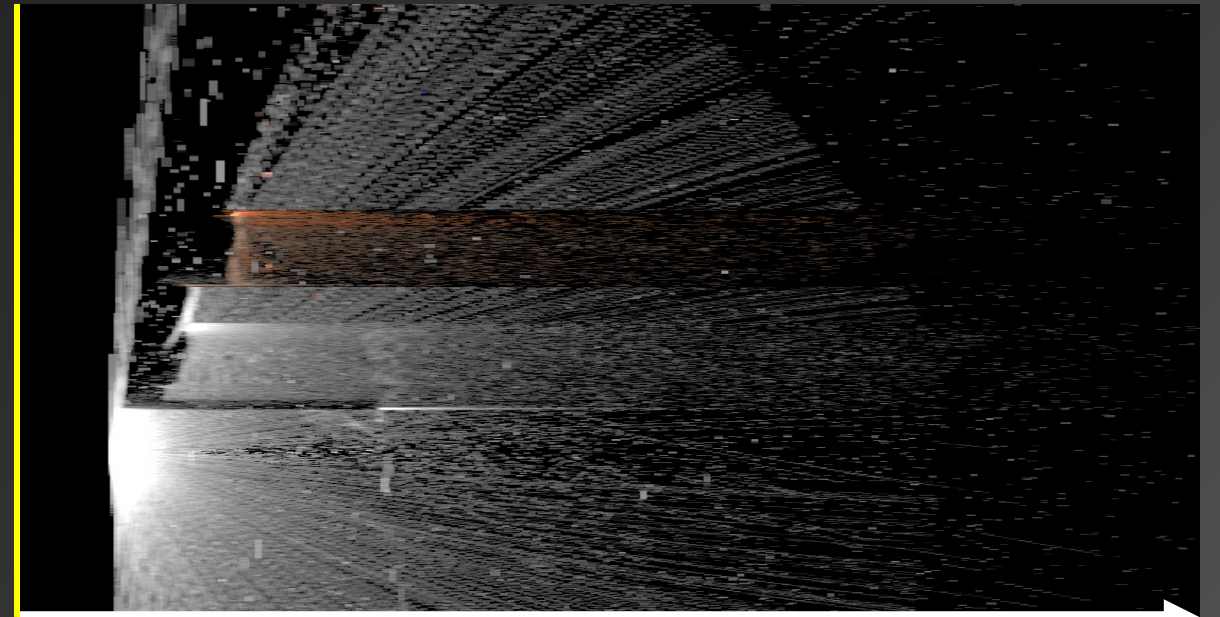
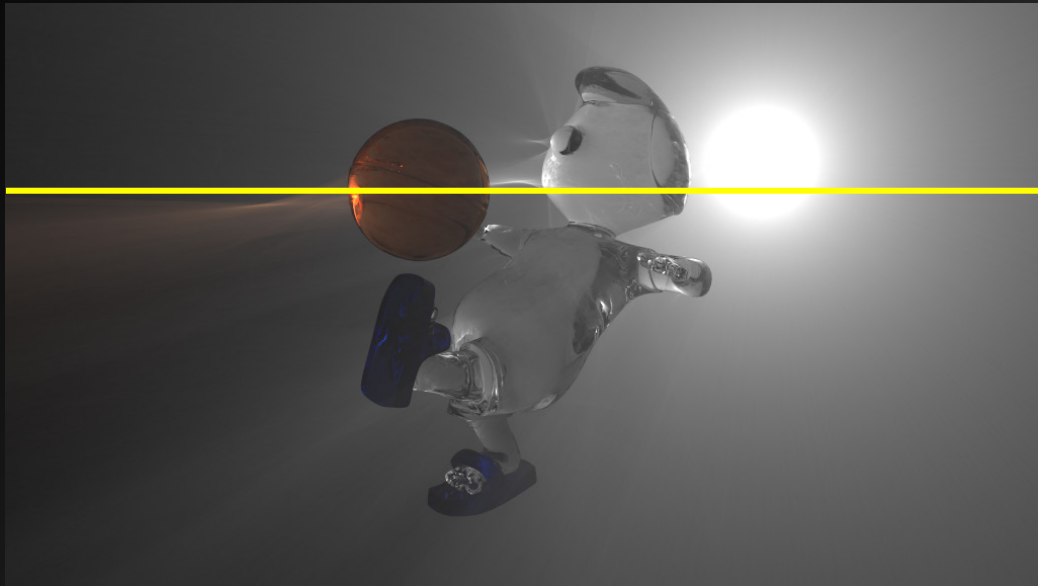


# Transient Photon Beams



# Transient Photon Beams

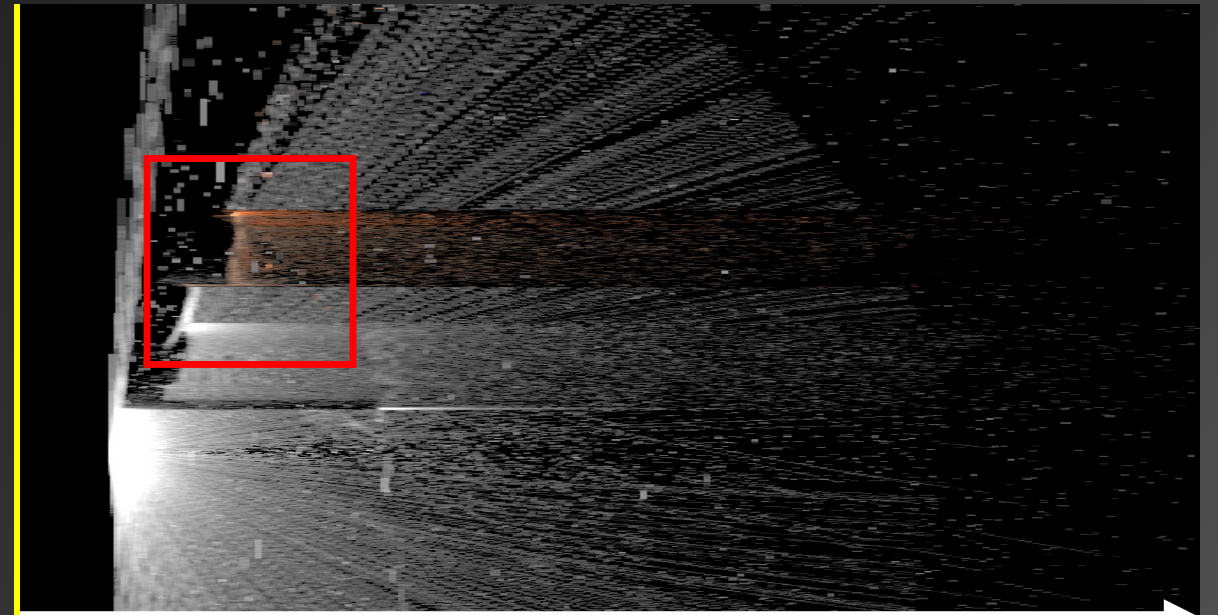
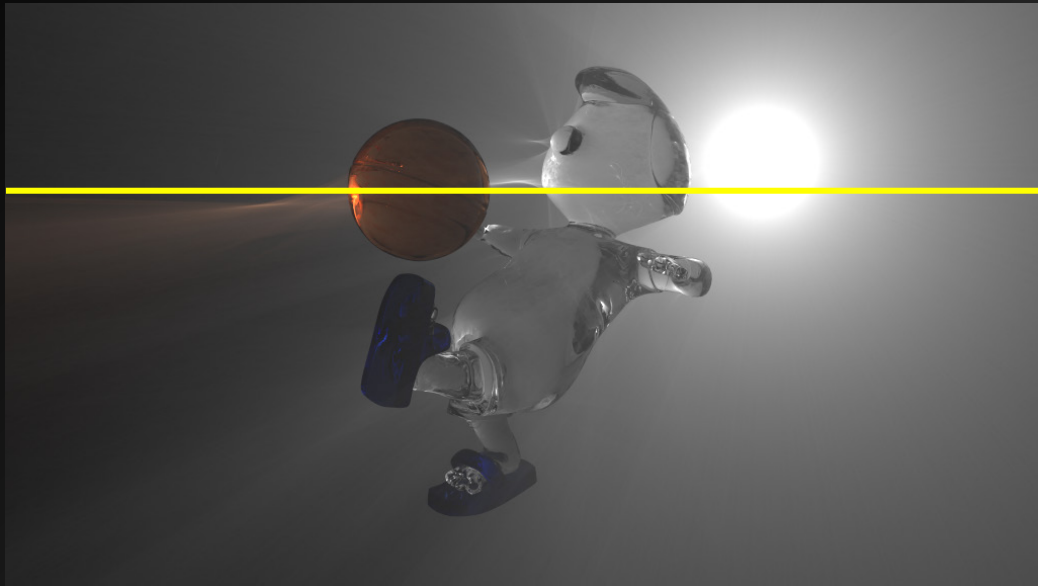
Spatio-temporal slice



time

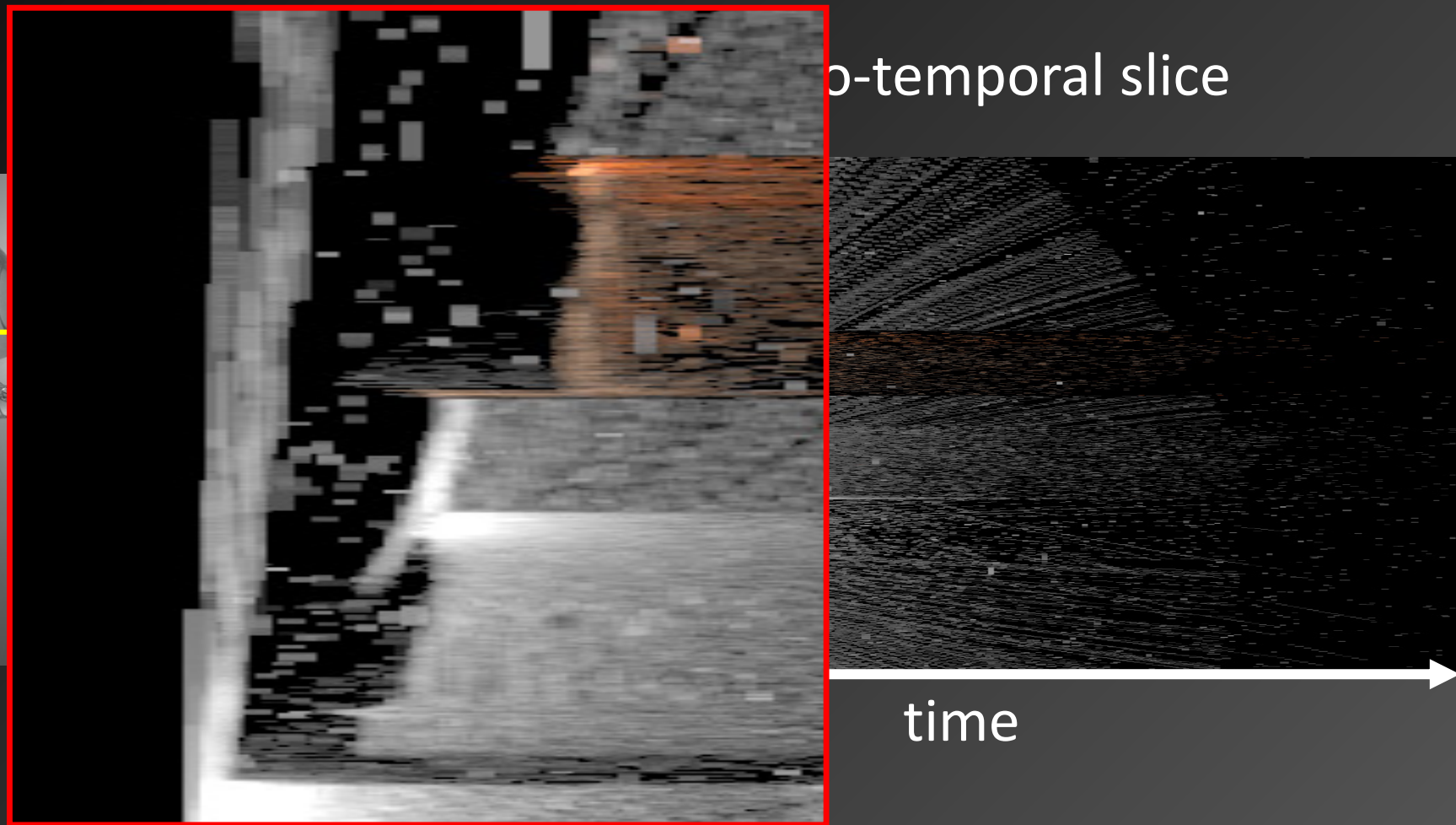
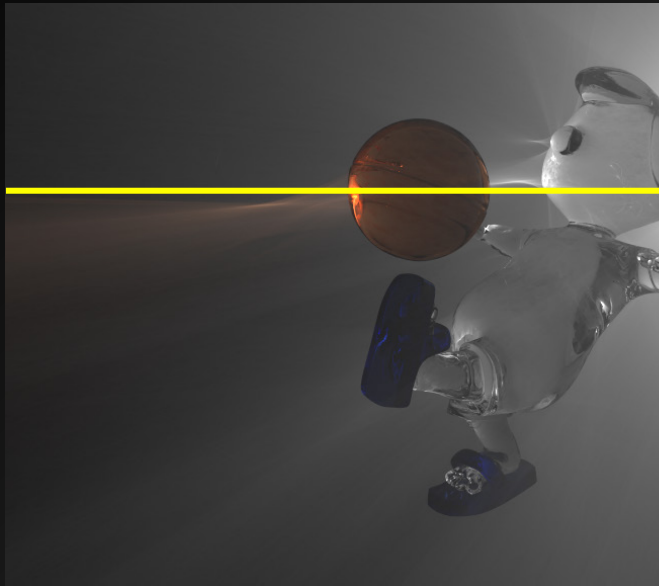
# Transient Photon Beams

Spatio-temporal slice

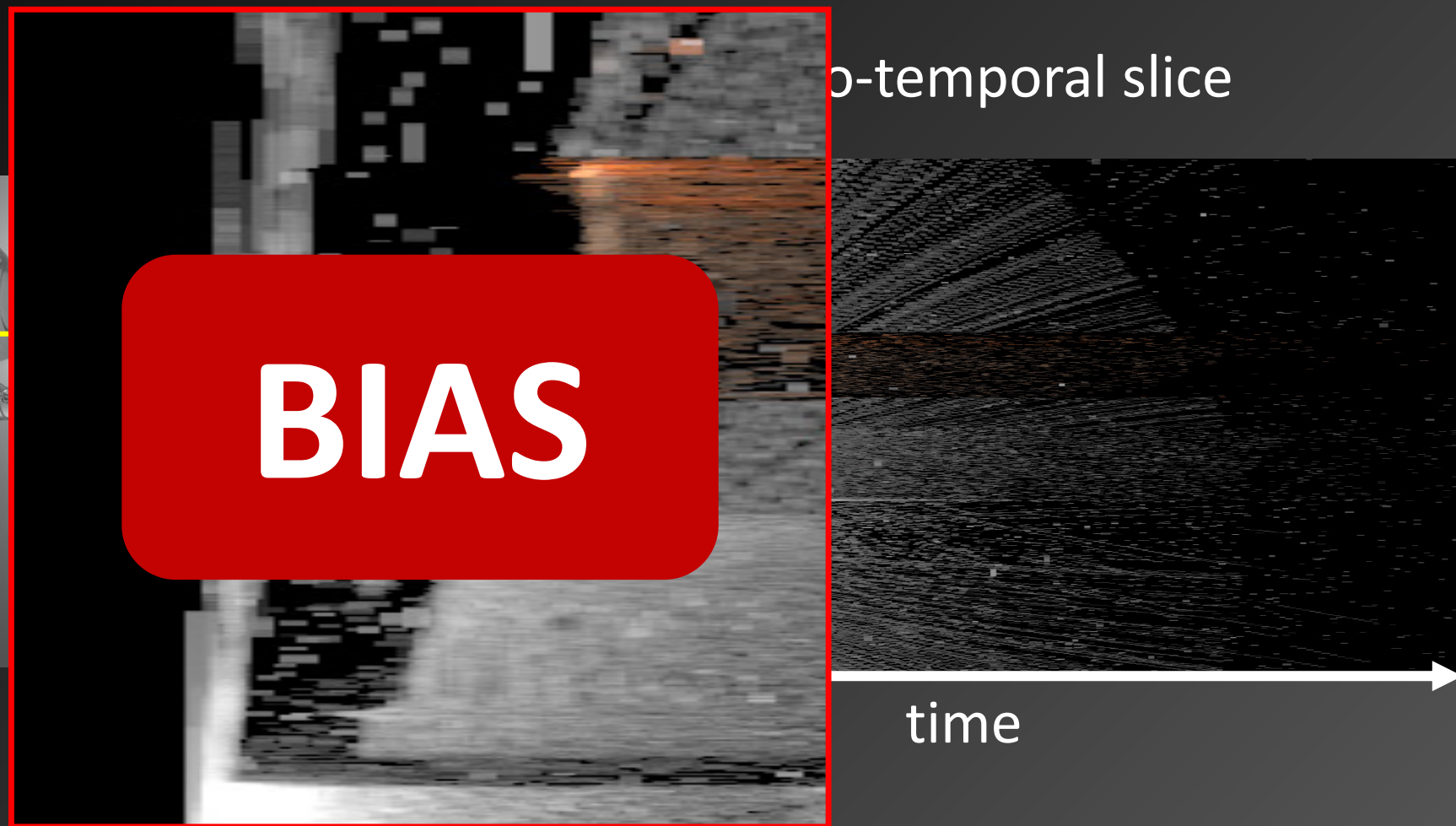
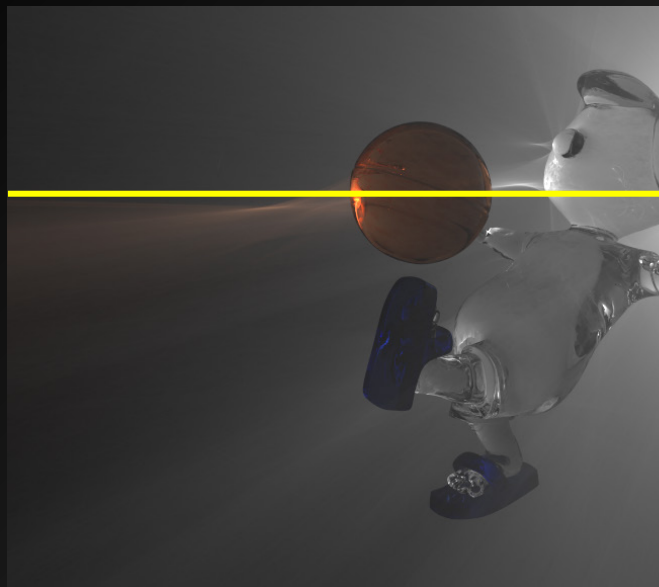


time

# Transient Photon Beams



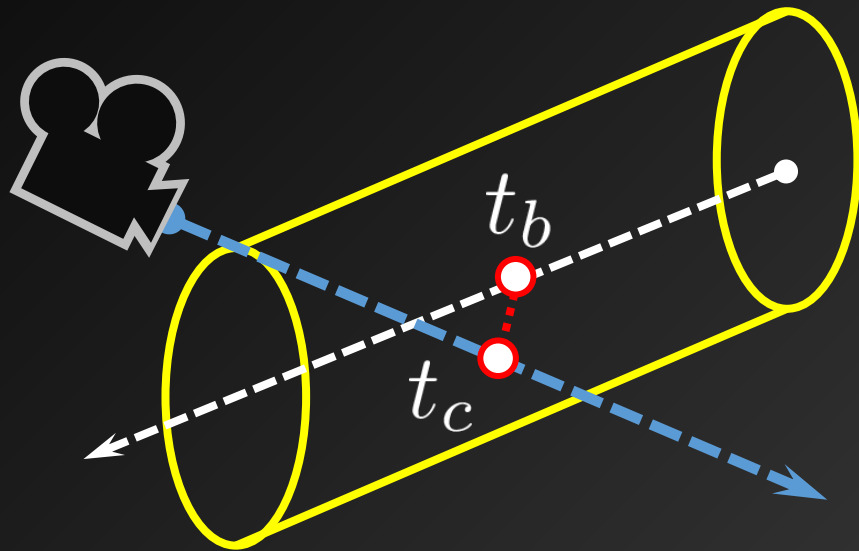
# Transient Photon Beams



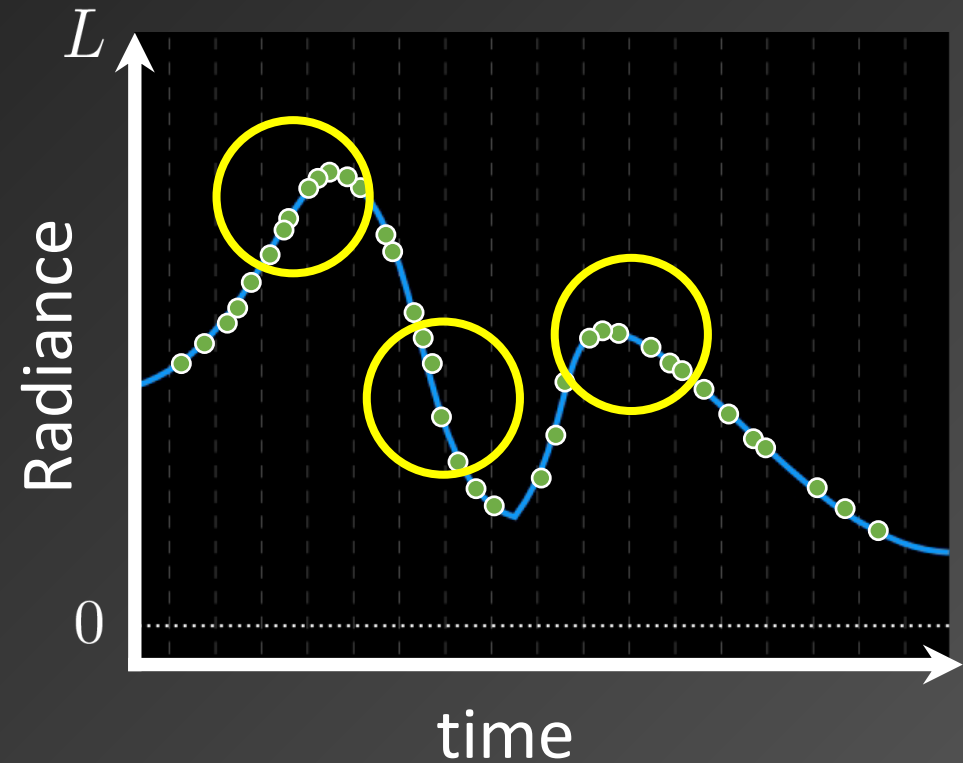
# PROGRESSIVE APPROACH

# Progressive Transient Photon Beams

Spatial density estimations

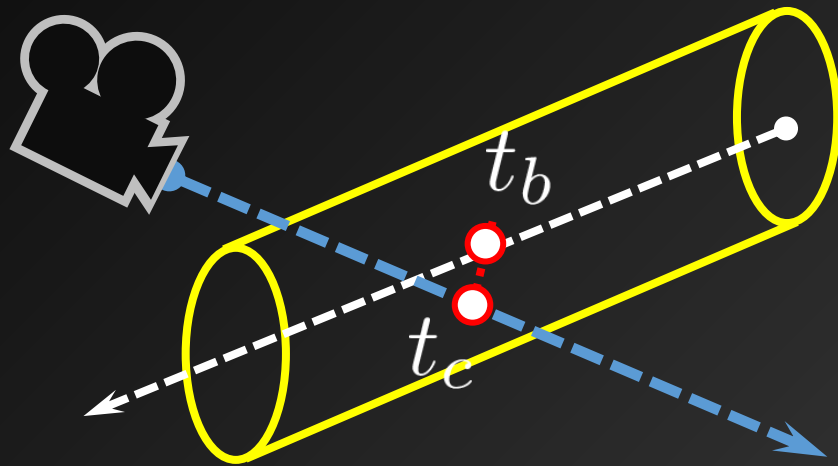


Temporal density estimations

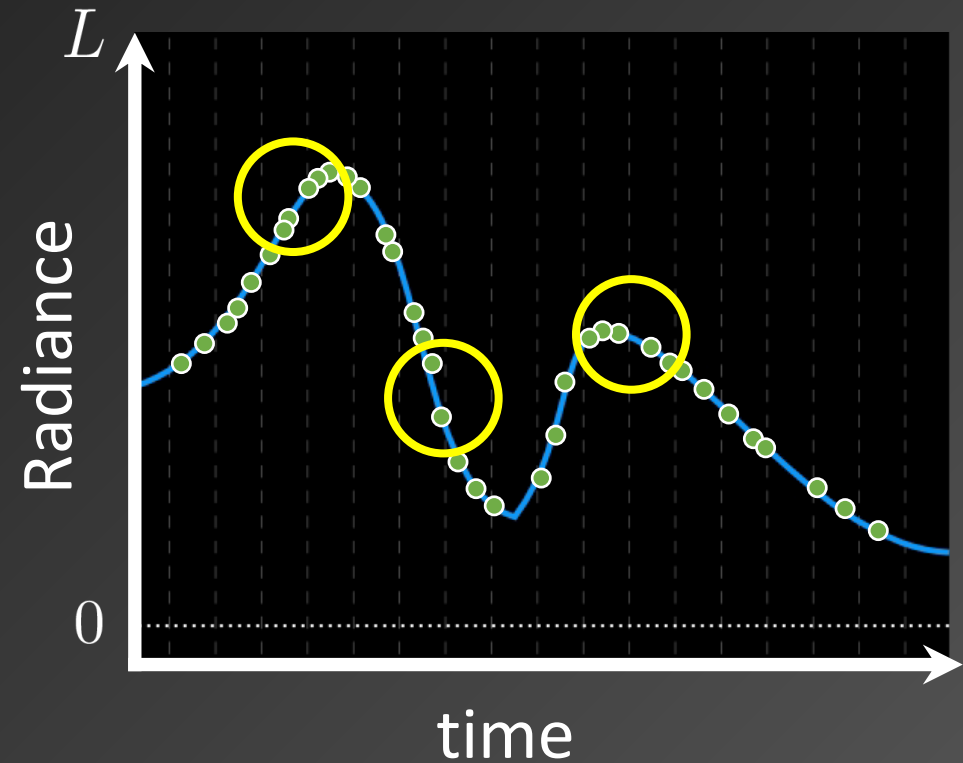


# Progressive Transient Photon Beams

Spatial density estimations



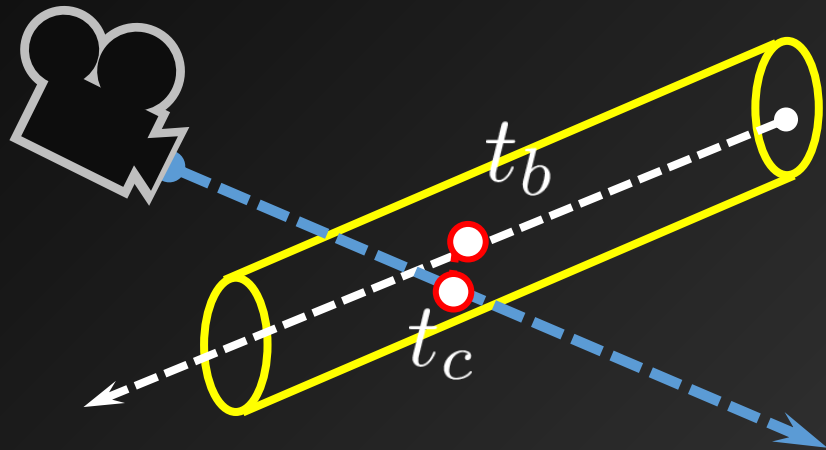
Temporal density estimations



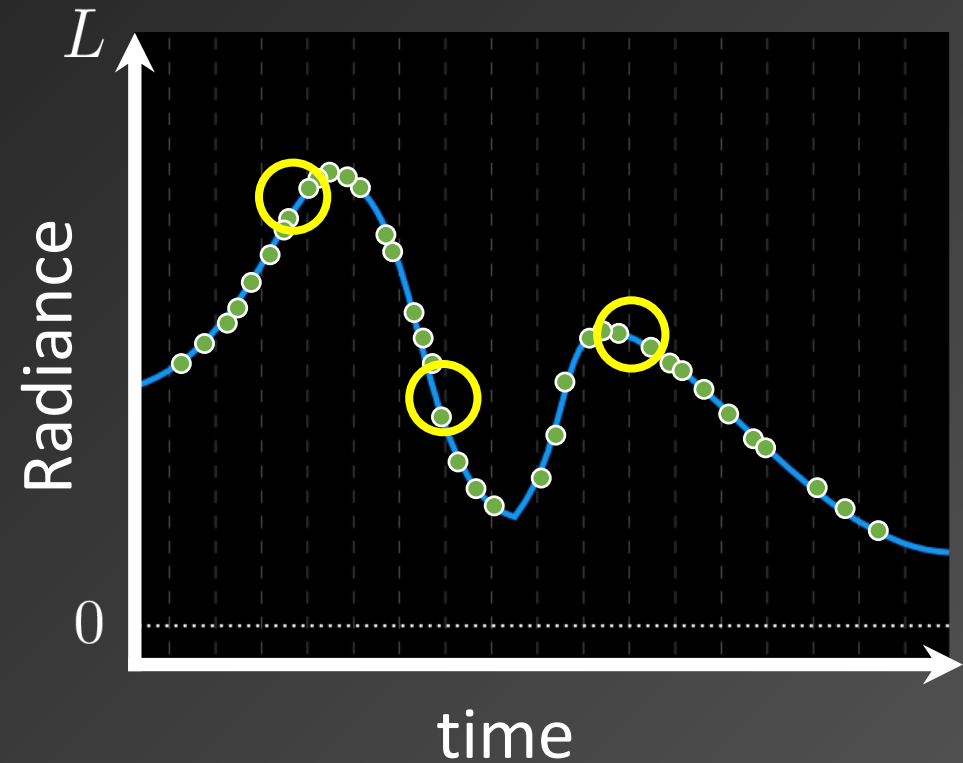


# Progressive Transient Photon Beams

Spatial density estimations

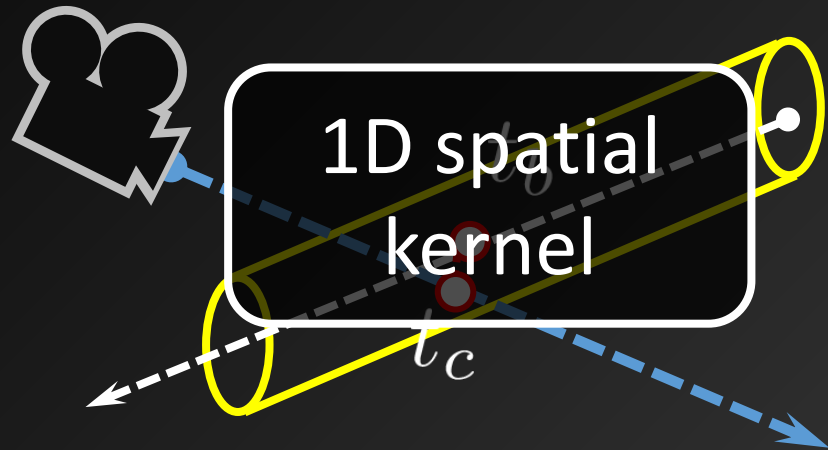


Temporal density estimations

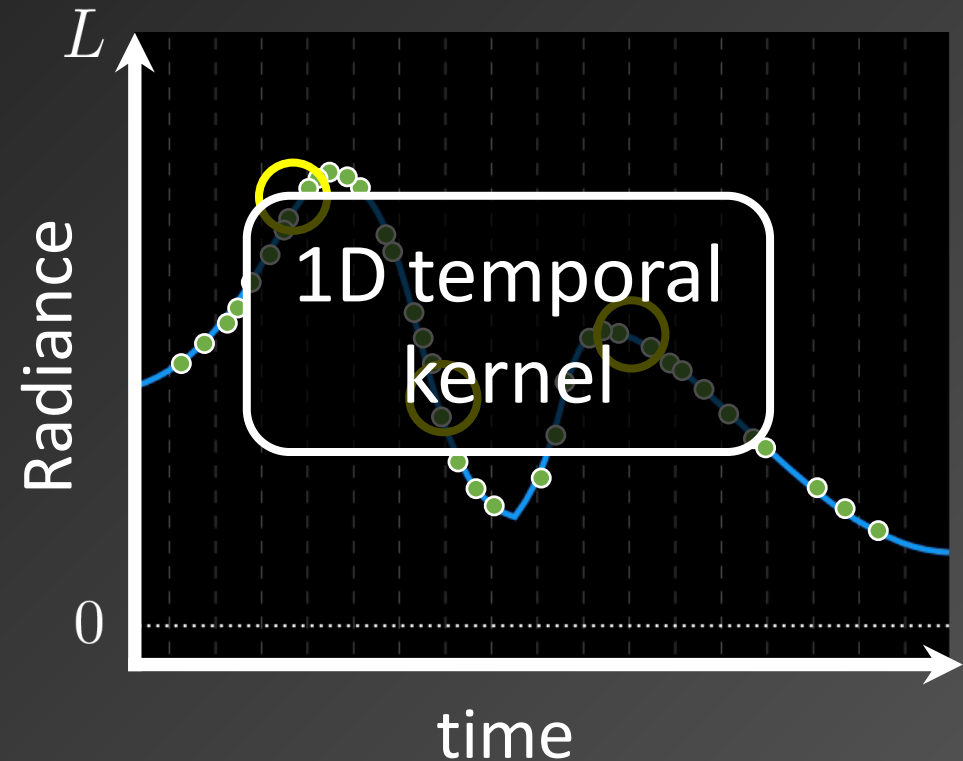


# Progressive Transient Photon Beams

Spatial density estimations



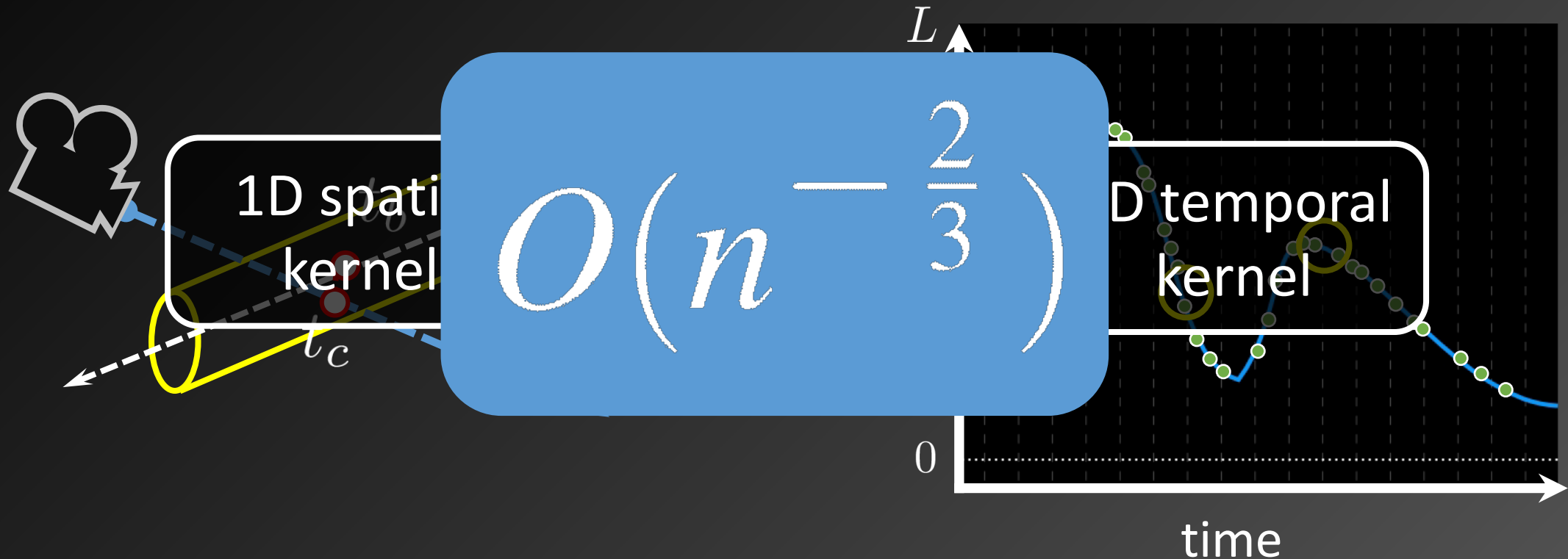
Temporal density estimations



# Progressive Transient Photon Beams

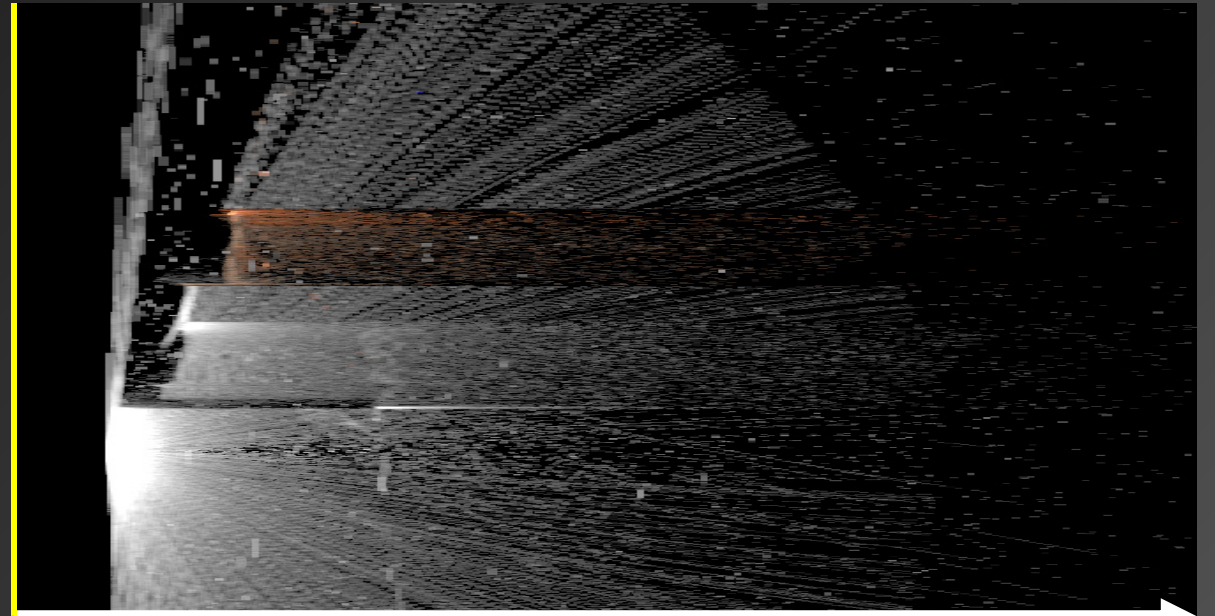
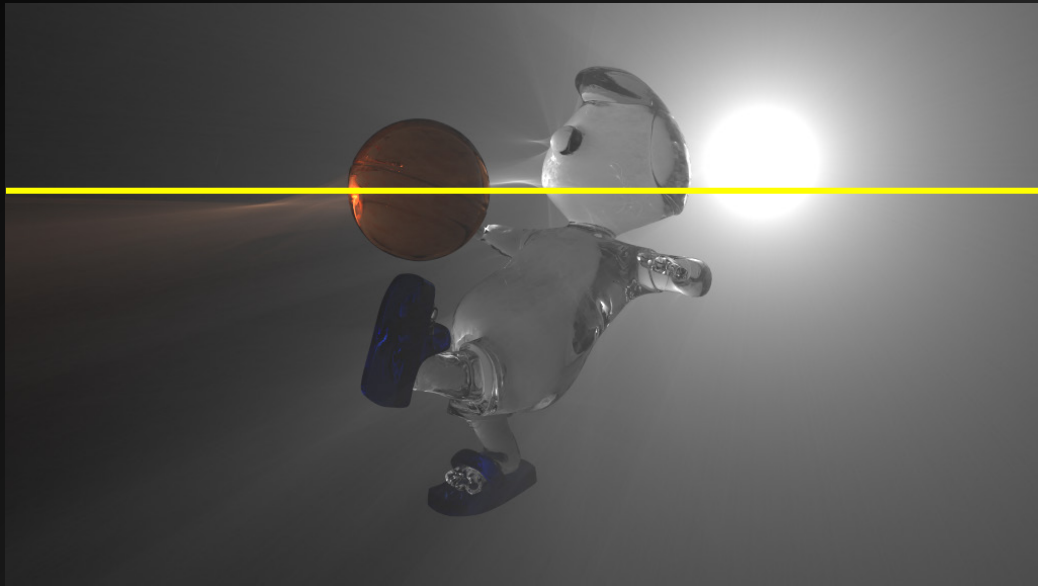
Spatial density estimations

Temporal density estimations



# Progressive Transient Photon Beams

Spatio-temporal slice

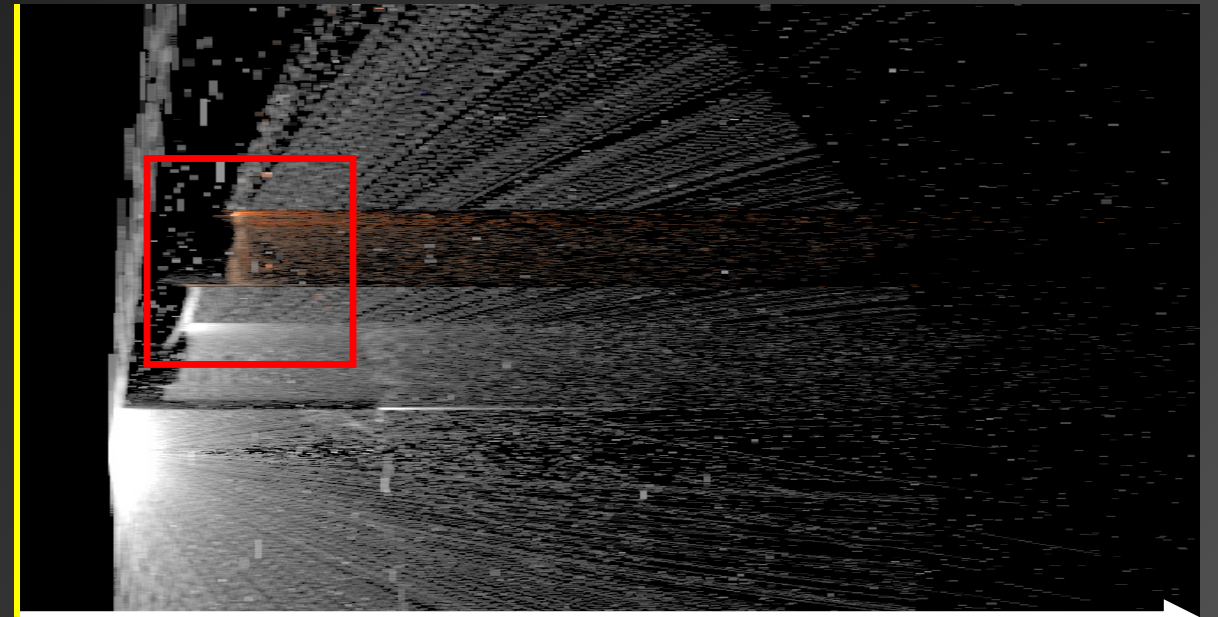
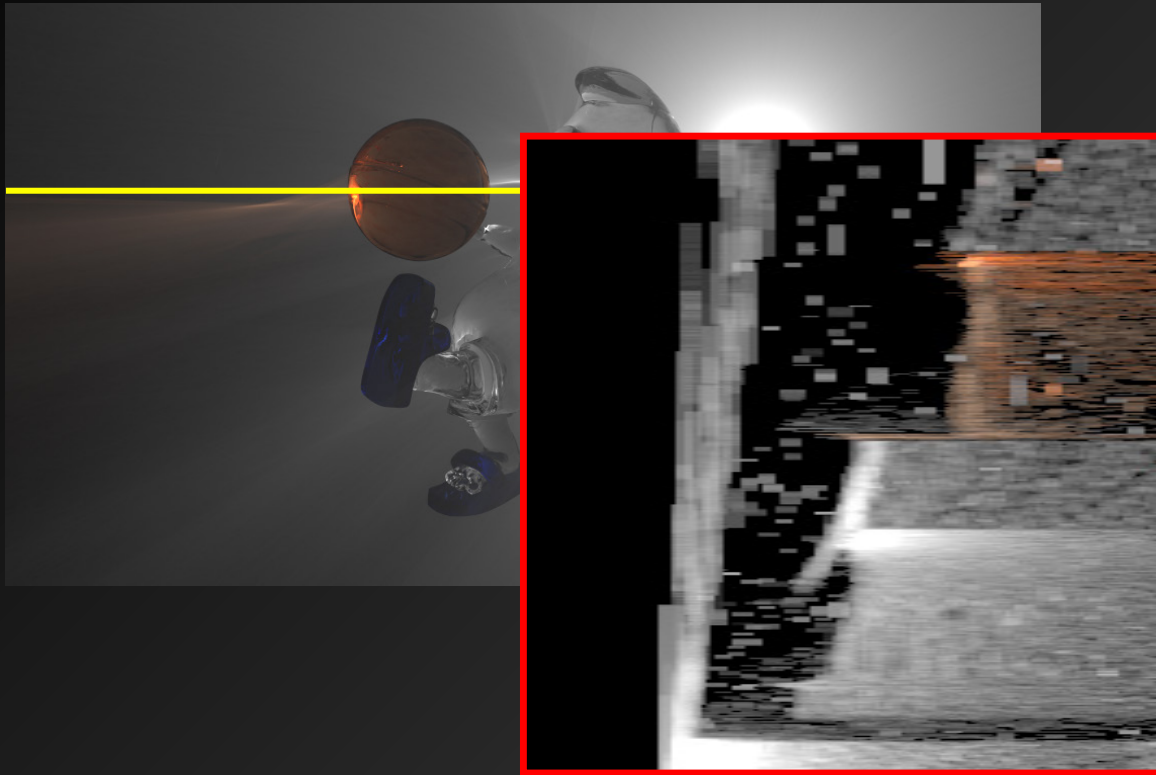


time

24 iterations

# Progressive Transient Photon Beams

Spatio-temporal slice

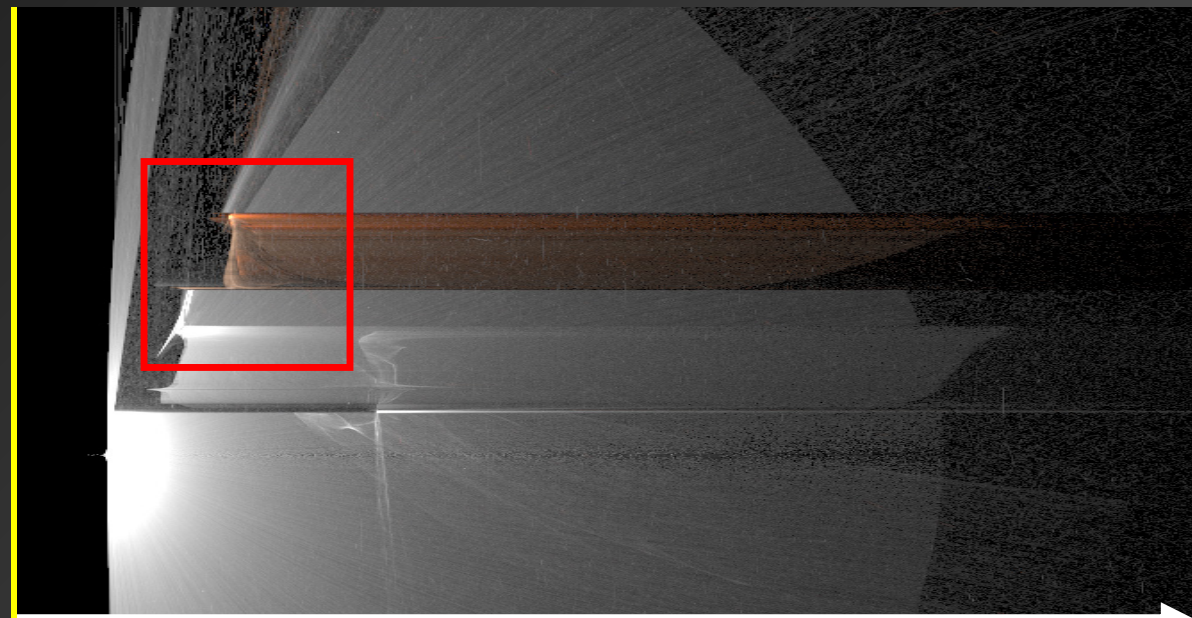
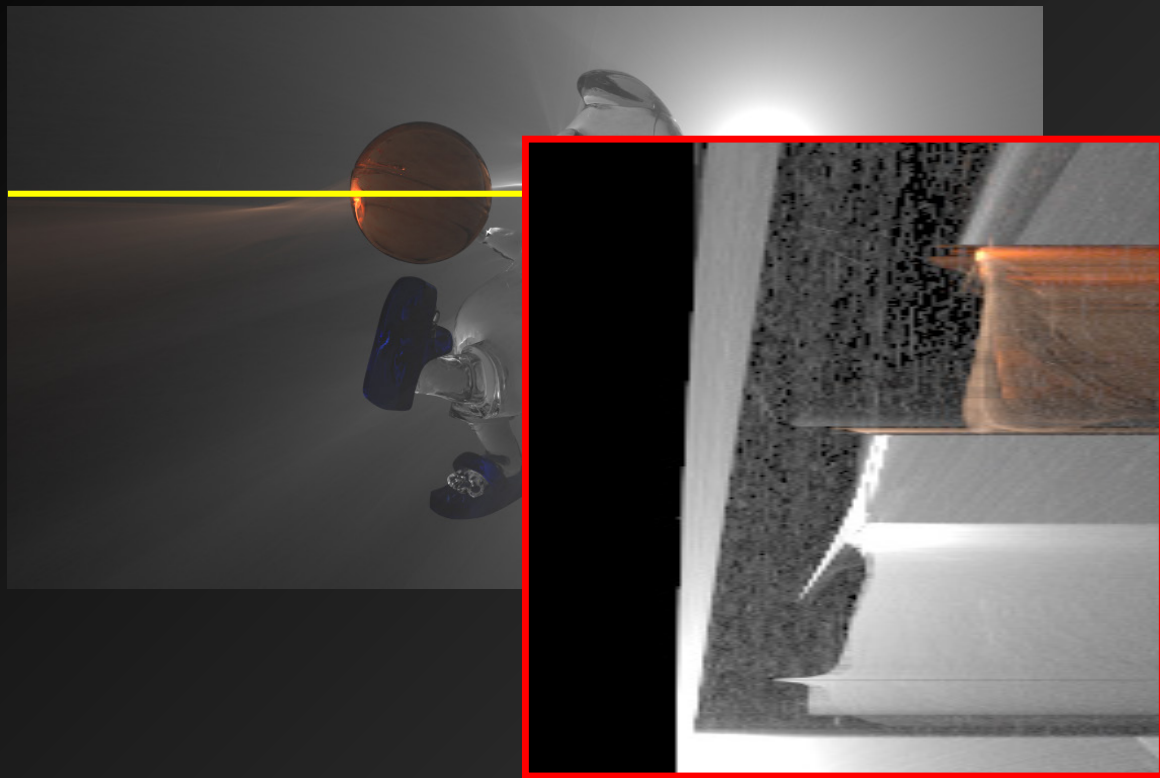


time

24 iterations

# Progressive Transient Photon Beams

Spatio-temporal slice



time

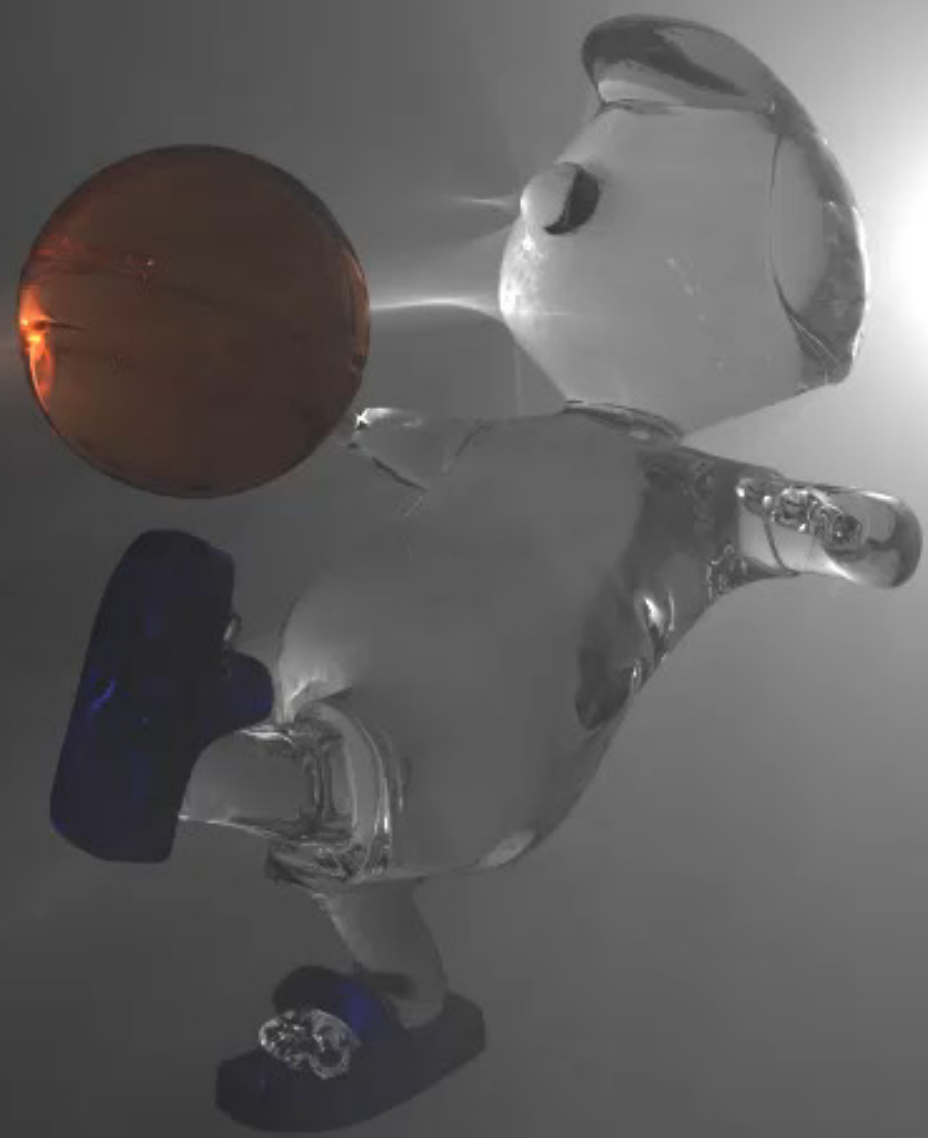
2000 iterations

# RESULTS

# Soccer

40M beams  
(2000 iterations x 20k beams/iteration)





# Pumpkin

Progressive transient PT [Jarabo 2014]

vs.

Our method

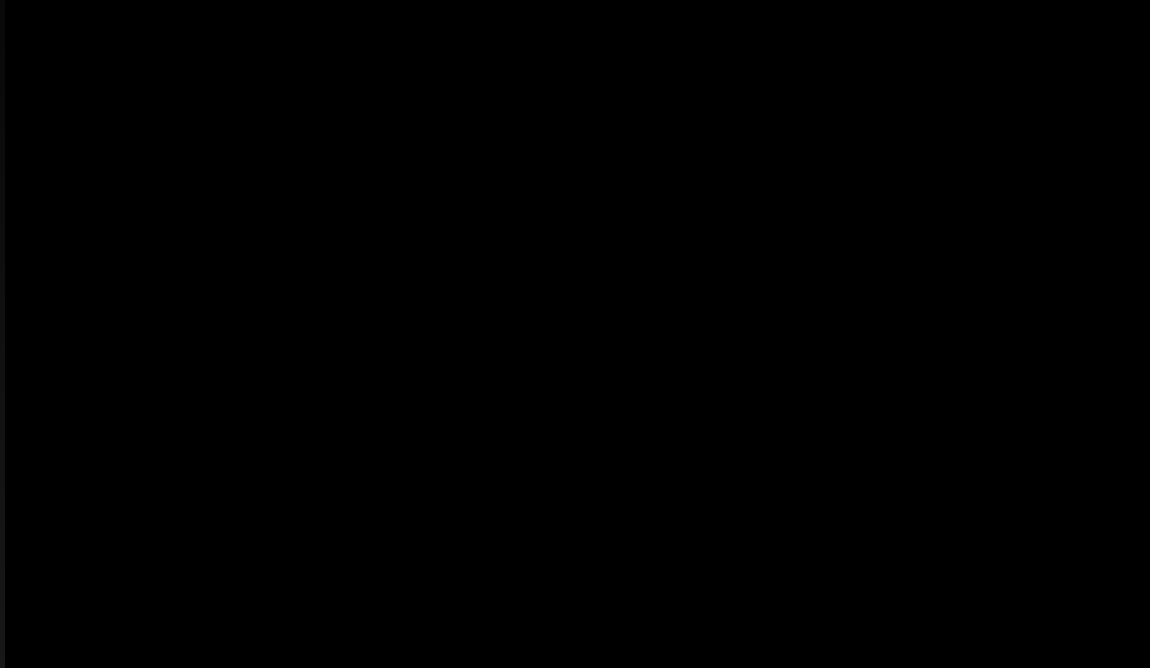
(equal-time comparison)

# Pumpkin – Equal-time comparison

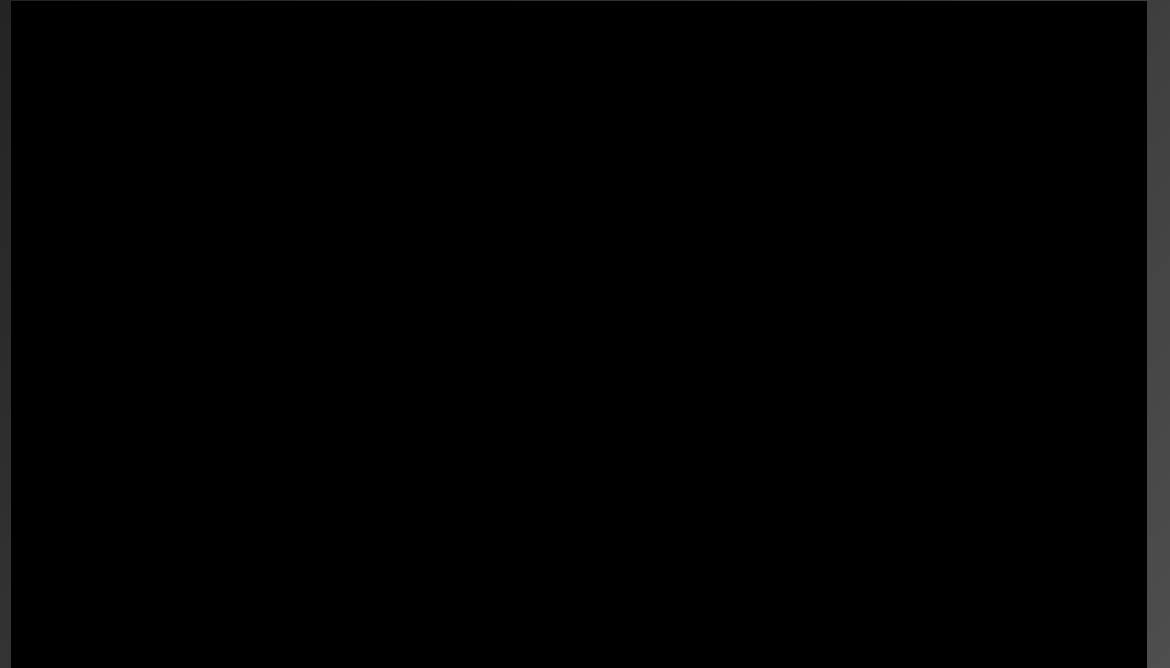


Steady state

# Pumpkin – Equal-time comparison



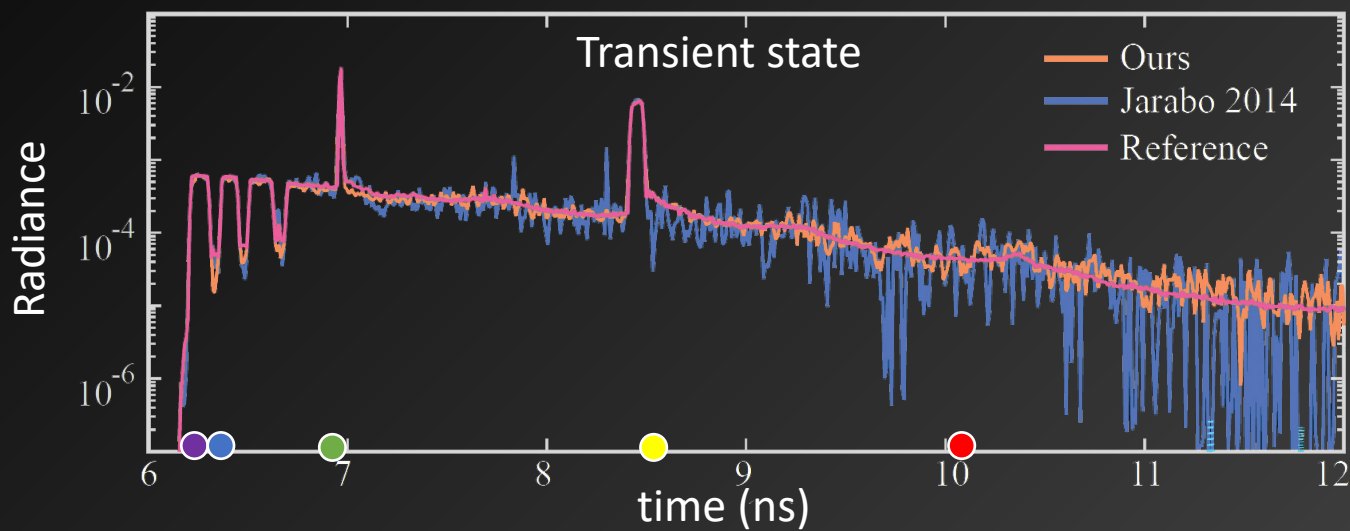
[Jarabo et al. 2014]



Our method

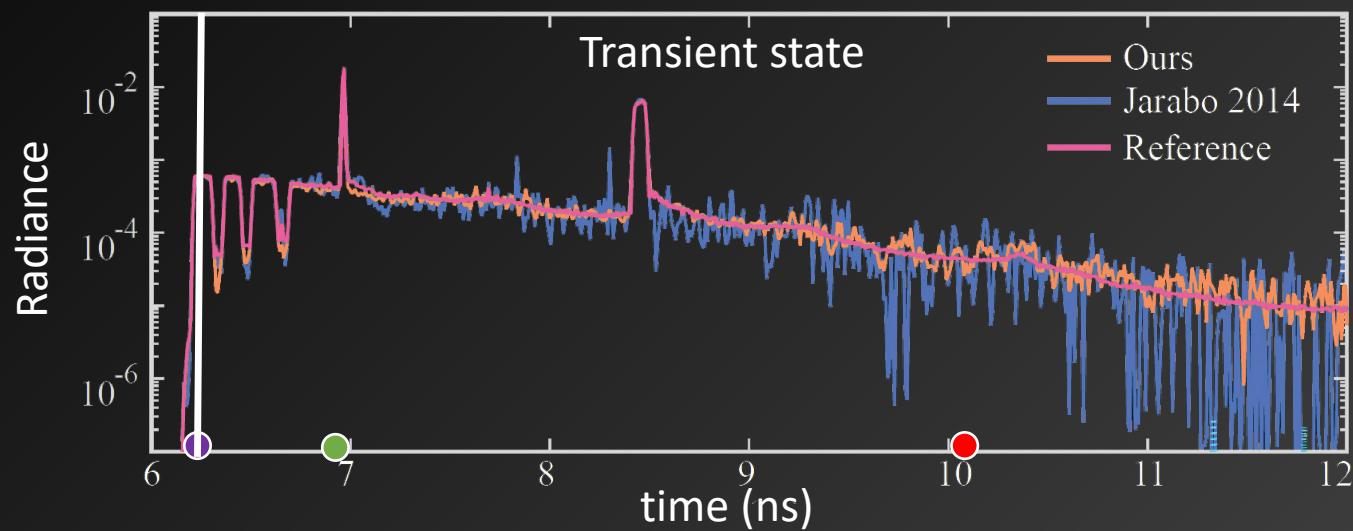
# Pumpkin – Equal-time comparison

Steady state



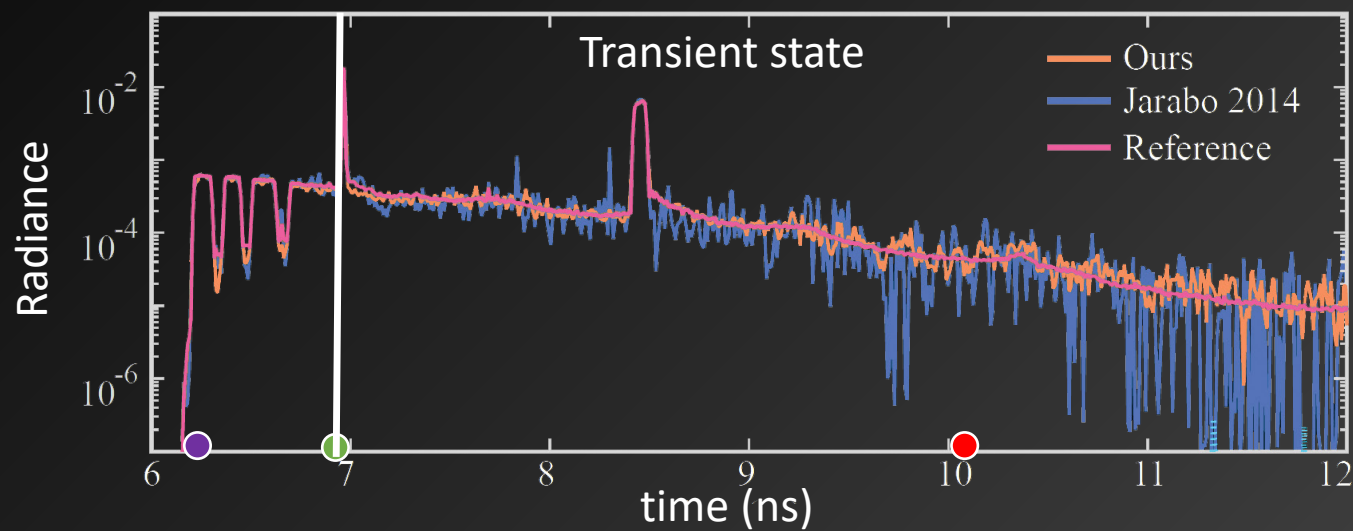
# Pumpkin – Equal-time comparison

Steady state



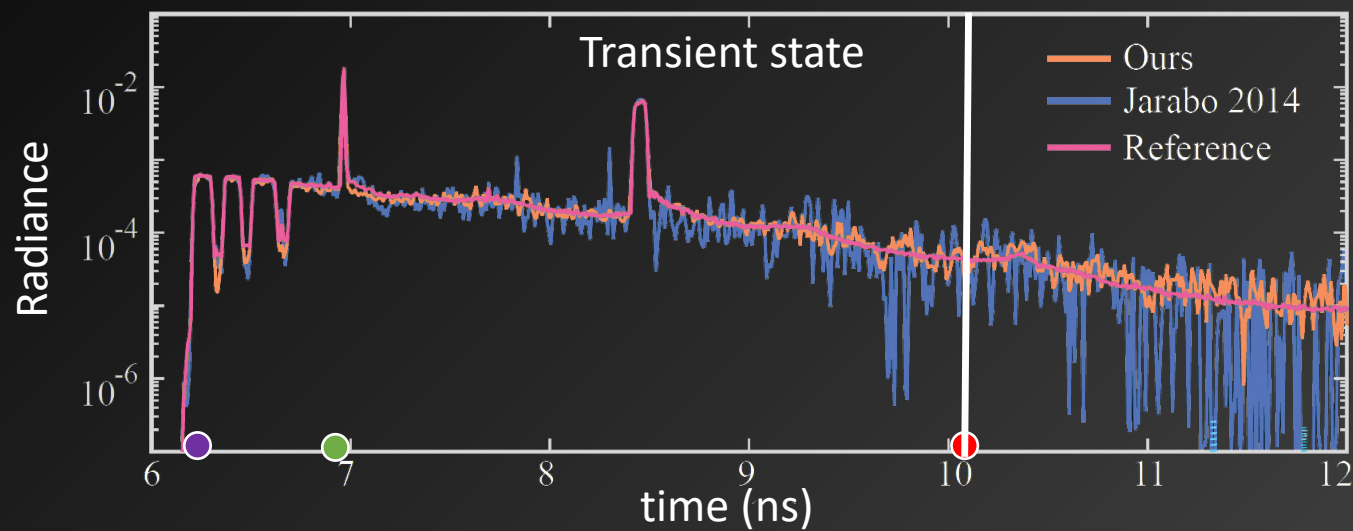
# Pumpkin – Equal-time comparison

Steady state



# Pumpkin – Equal-time comparison

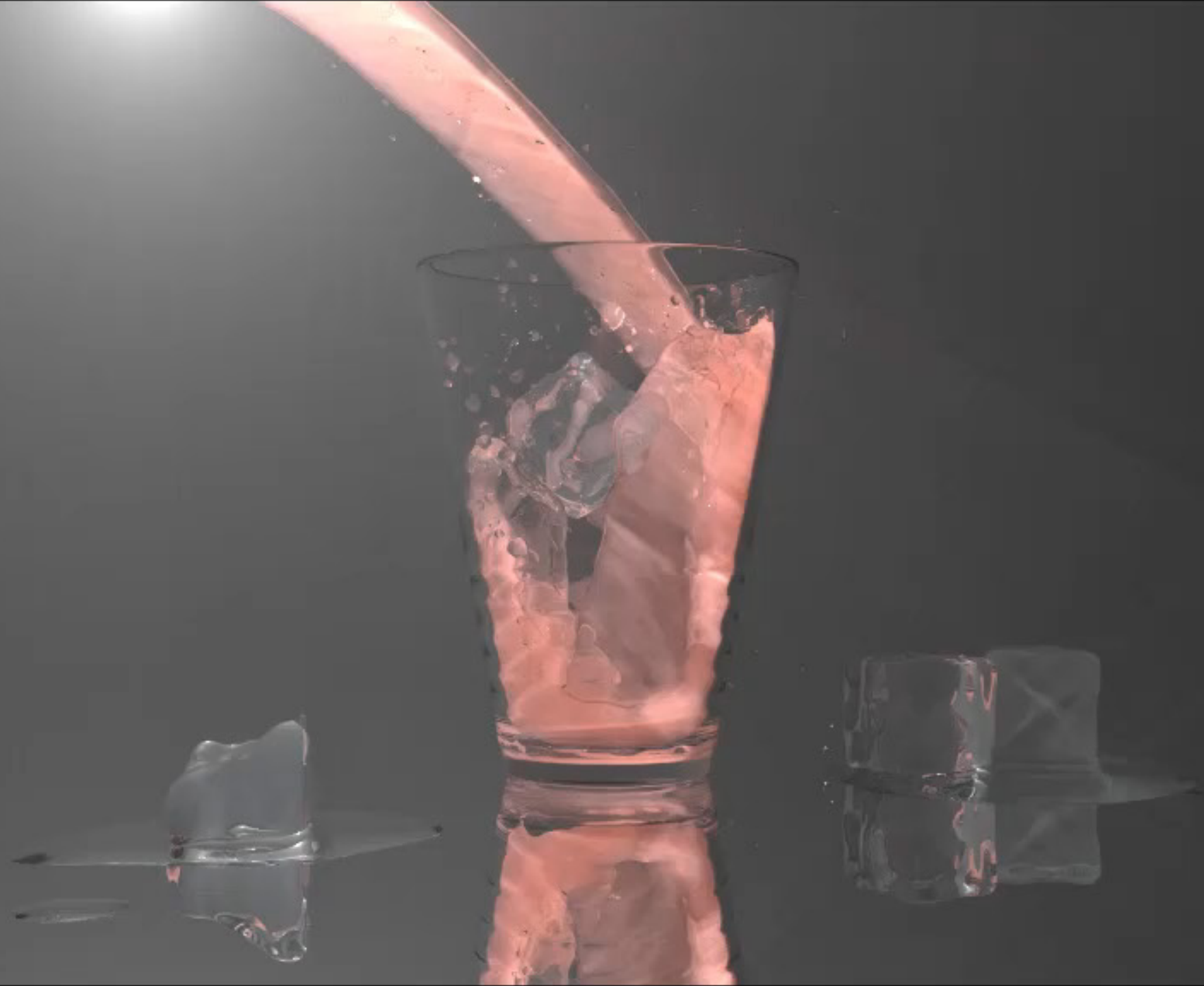
Steady state





# Juice

24M beams  
(1200 iterations x 20k beams/iteration)



# Conclusion

- Robust method for low-variance time-resolved participating media
- Render complex time-resolved effects
- Consistent approach
- Optimal 1D x 1D spatio-temporal kernel reduction ratios

# What next?

- Introduce time-based importance sampling [Jarabo et al. 2014]
- Extend to hybrid methods, all volumetric estimators
- Improve temporal reconstruction

Thanks!