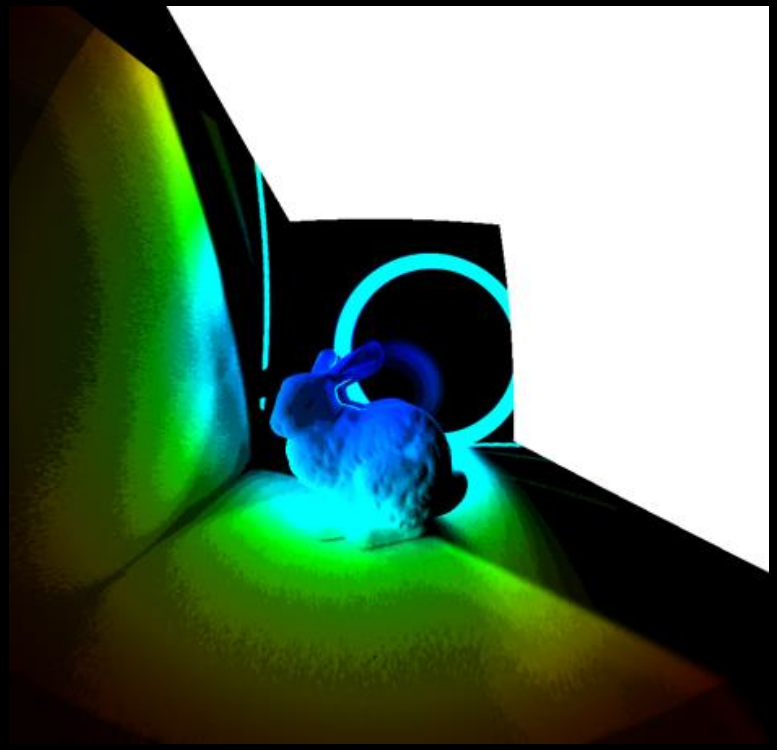
Relativistic Effects for Time-Resolved Light Transport



Adrian Jarabo[1] Belen Masia[1,2,3] Andreas Velten[4]
Christopher Barsi[2] Ramesh Raskar[2] Diego Gutierrez[1]

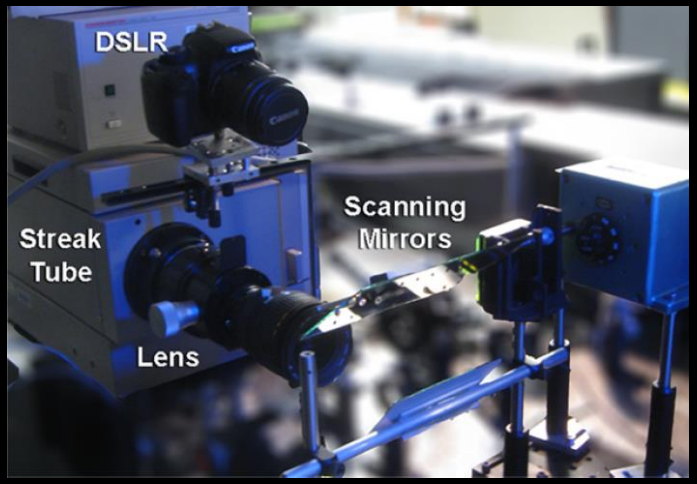
[1]Universidad de Zaragoza [2]MIT Media Lab [3]I3A [4]Morgridge Institute for Research

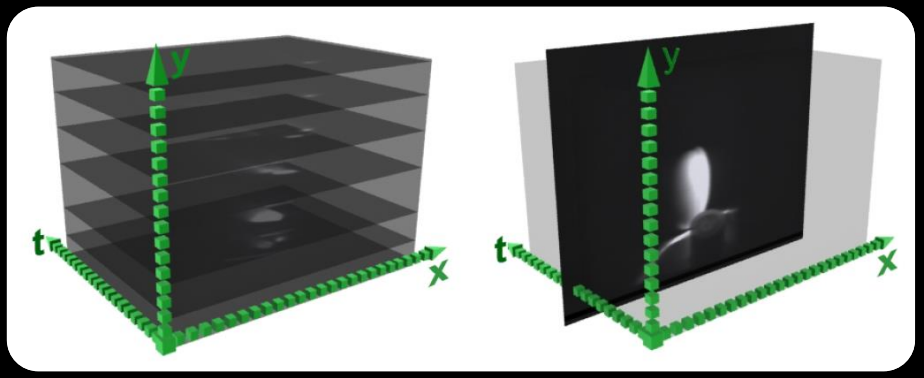
Motivation

Motivation – Time-resolved Imaging

[Velten et al. SIGGRAPH 2012; 2013]

Motivation – Time-resolved Imaging



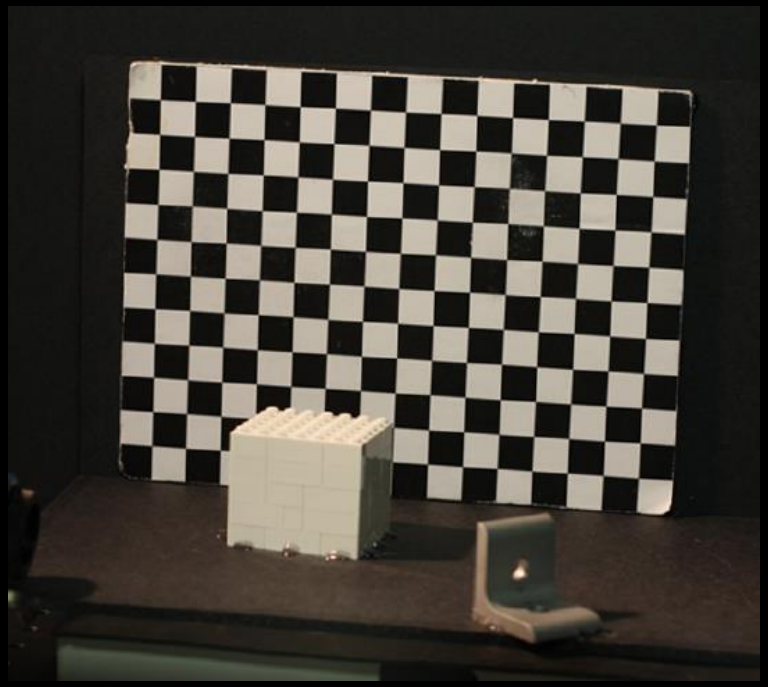


Time-Resolved Data

+ Obtained Geometry

Can we visualize the data from **different viewpoints**?

Motivation – Time-resolved Imaging



Cube scene

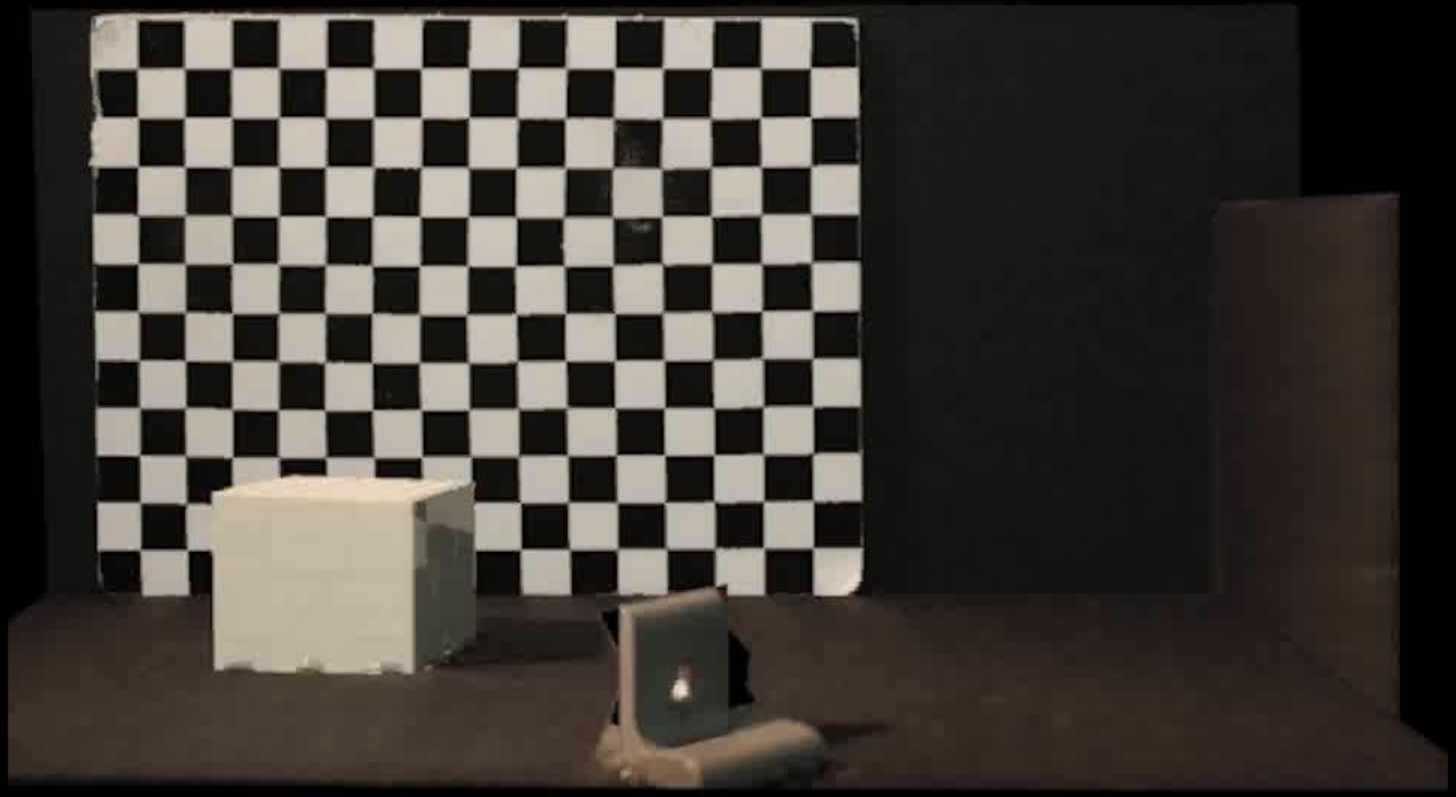
Can we visualize the data from **different viewpoints**?

Cube

Can we visualize the data
from **different viewpoints**?

Motivation – Time-resolved Imaging

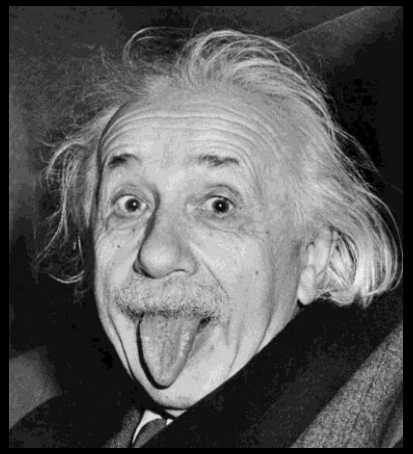
Cube



Can we visualize the data from **different viewpoints**?

Motivation – Time-resolved Imaging

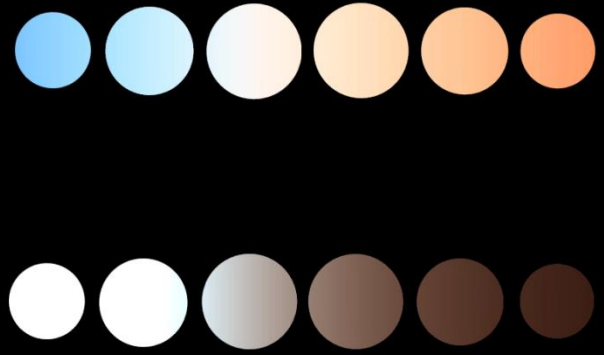
In the scene, the camera
is moving at relativistic speeds**.**



The need to model relativistic effects
naturally arises when visualizing time-resolved data**.**

Time-Resolved Imaging & Relativistic Rendering

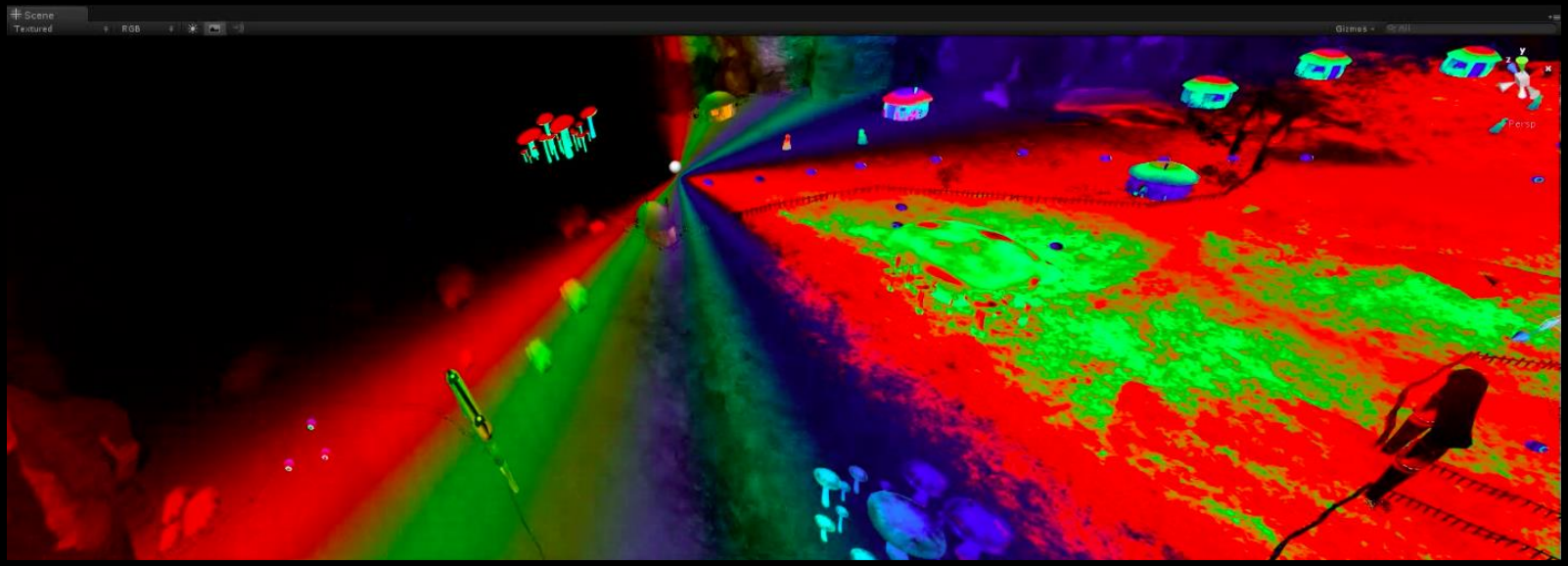
We are not the first to do relativistic rendering…



[Hsiung et al. 1990; Chang et al. 1996;
Weiskopf et al. 1999; 2000]
[Weiskopf et al. 2006]

Time-Resolved Imaging & Relativistic Rendering

We are not the first to do relativistic rendering…



OpenRelativity [Kortemeyer et al. 2013]
A Slower Speed of Light

Time-Resolved Imaging & Relativistic Rendering

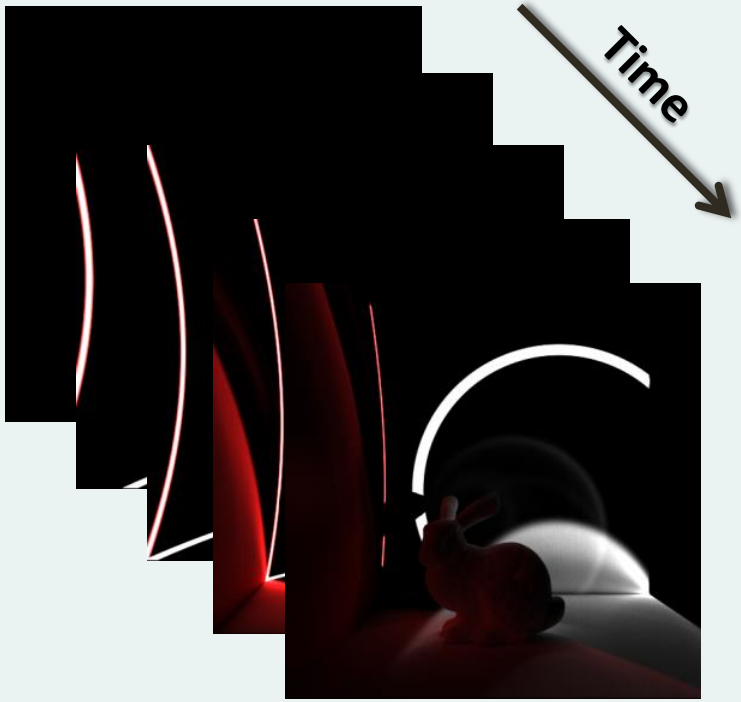
We are not the first to do relativistic rendering**…**

Limitations of previous methods:

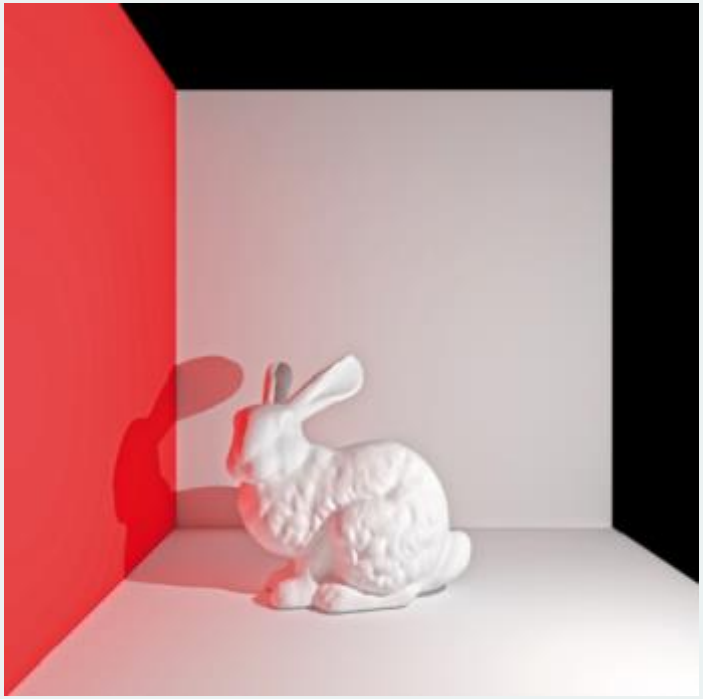
(1) do not deal with non-constant irradiance

Time-Resolved Imaging & Relativistic Rendering

Us (Time-resolved)

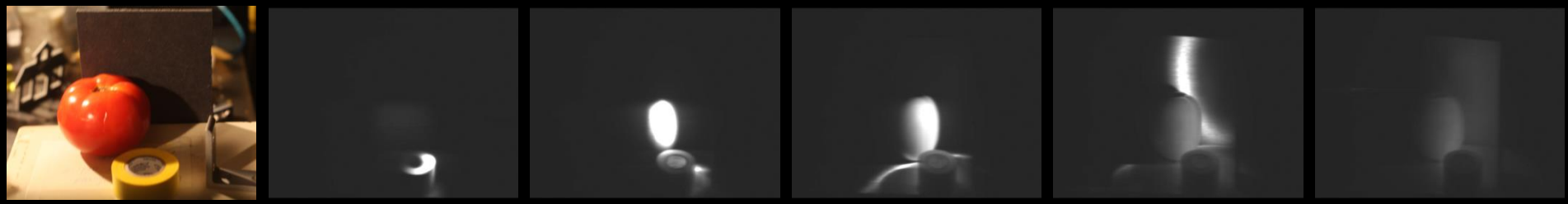


Previous Work

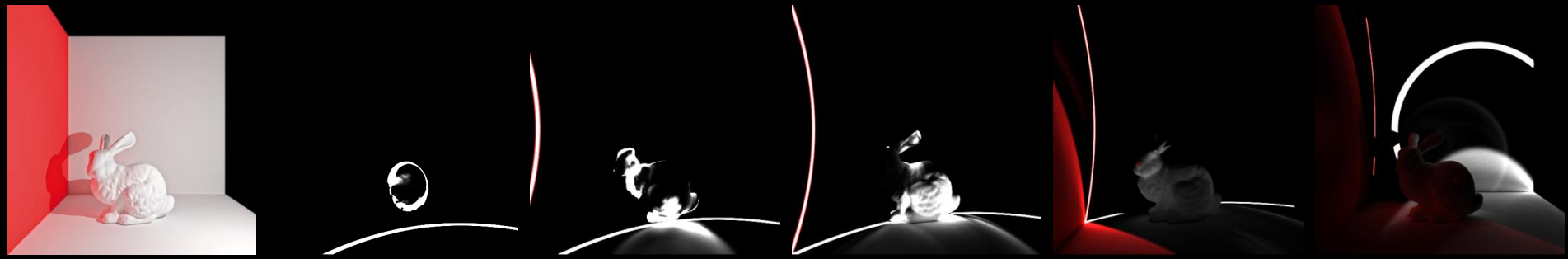


Time-Resolved Imaging & Relativistic Rendering

Real Captured Data [Velten et al. SIGGRAPH 2013]



Synthetic Data [Jarabo et al. SIGGRAPH ASIA 2014]



Time-Resolved Imaging & Relativistic Rendering

We are not the first to do relativistic rendering**…**

Limitations of previous methods:

(1) do not deal with non-constant irradiance

Time-Resolved Imaging & Relativistic Rendering

We are not the first to do relativistic rendering**…**

Limitations of previous methods:

(1) do not deal with non-constant irradiance
(2) do not consider camera transformations

Time-Resolved Imaging & Relativistic Rendering

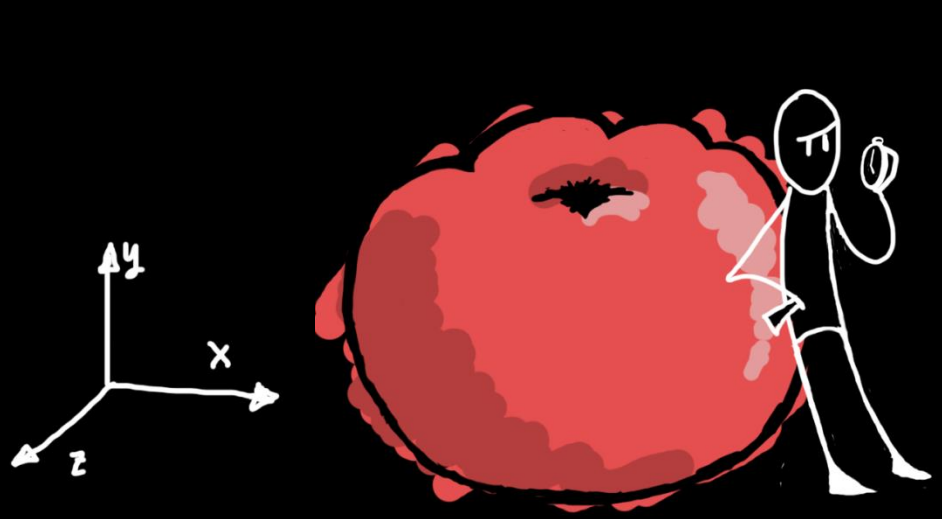
We are not the first to do relativistic rendering**…**

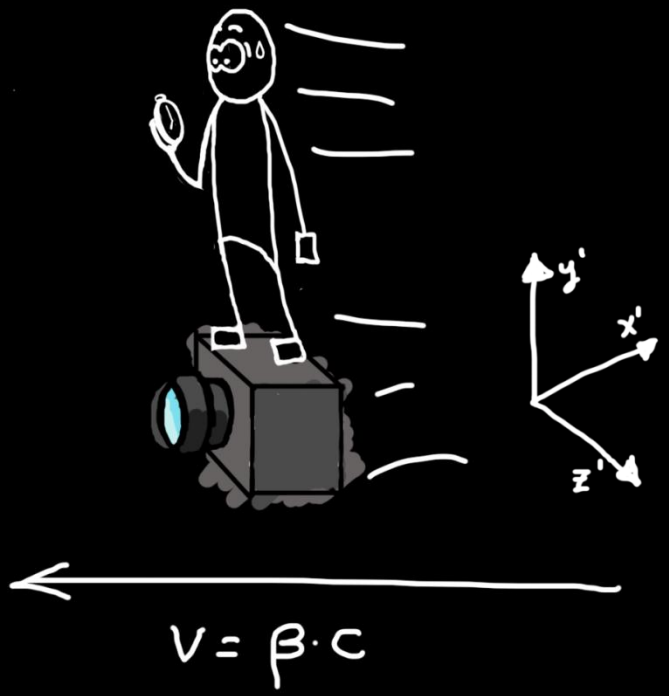
Limitations of previous methods:

(1) do not deal with non-constant irradiance
(2) do not consider camera transformations
(3) do not handle relativistic rotation

Rendering Relativistic Effects

$$\underbrace{L_\lambda(\theta, \phi, \lambda, t)}_{\text{Radiance in world frame}} \Longleftrightarrow \underbrace{L'_\lambda(\theta', \phi', \lambda', t')}_{\text{Radiance in camera frame}}$$





Rendering Relativistic Effects

Five main phenomena:

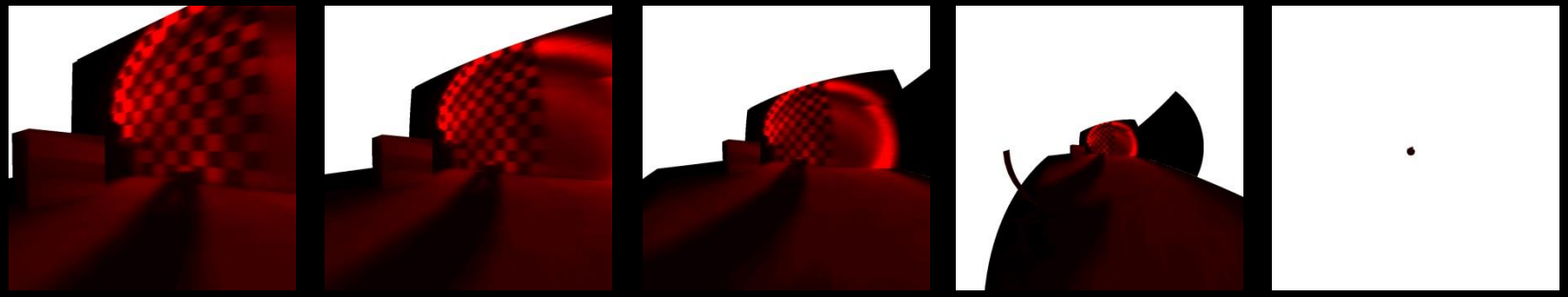
Previous Work

- Light aberration → Geometry deformation
- Doppler effect
- Searchlight effect
- Time dilation
- Camera deformation

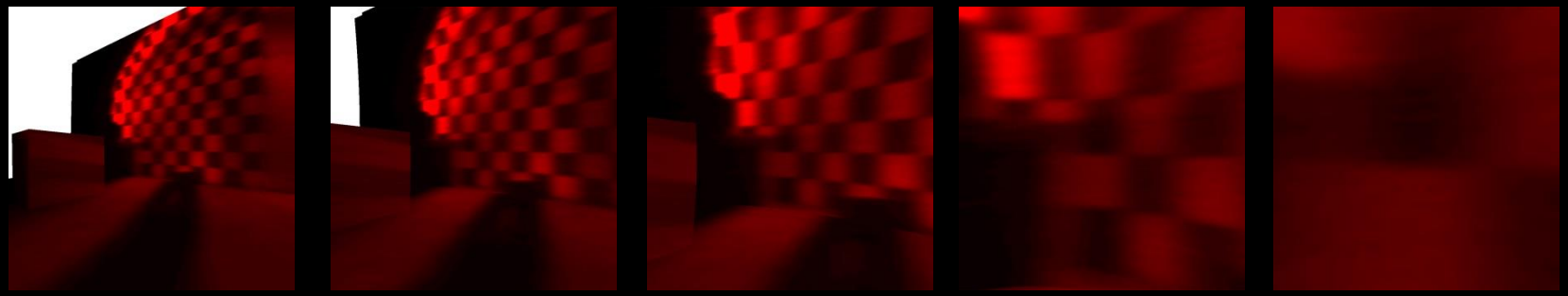
Relativistic Effects – **Light Aberration**

Static

$\beta = 0$ $\beta = 0.3$ $\beta = 0.6$ $\beta = 0.9$ $\beta = 0.99$



Camera approaching the scene



Camera moving away from the scene

Rendering Relativistic Effects

Five main phenomena:

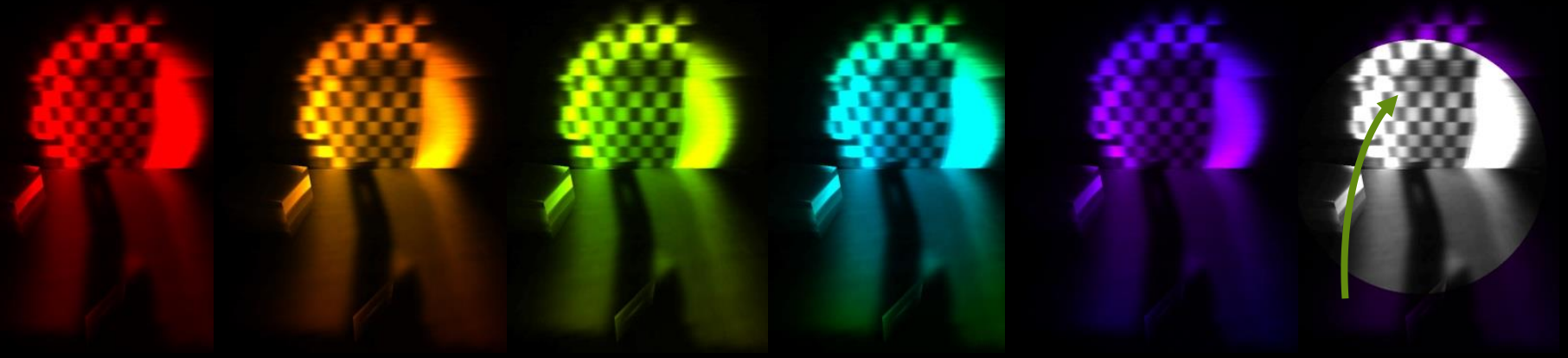
Previous Work

- **Light aberration** → Geometry deformation
- **Doppler effect** → Color shift
- **Searchlight effect**
- **Time dilation**
- **Camera deformation**

Relativistic Effects – **Doppler Effect**

Static

$\beta = 0$ $\beta = 0.15$ $\beta = 0.25$ $\beta = 0.35$ $\beta = 0.50$ $\beta = 0.55$



Camera approaching the scene

UV

Rendering Relativistic Effects

Five main phenomena:

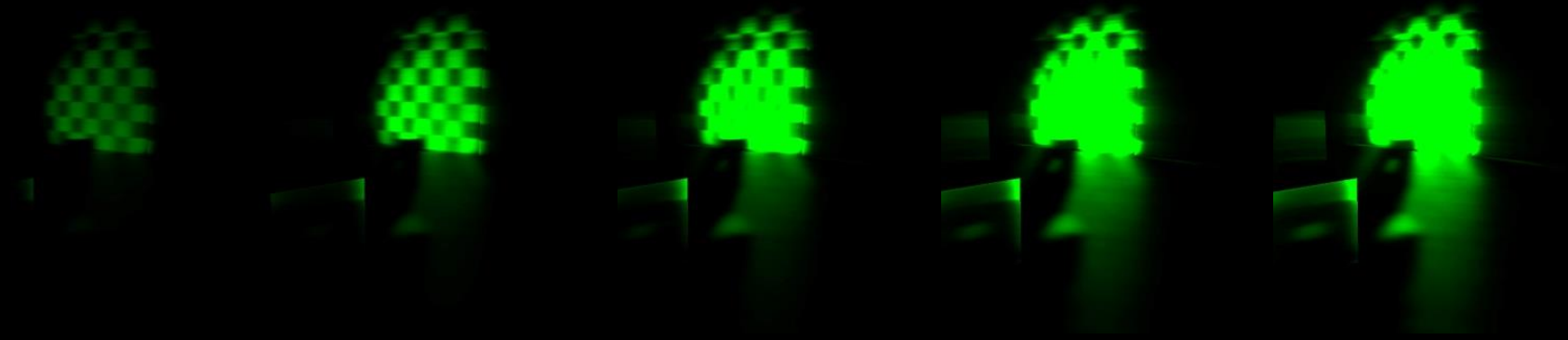
Previous Work

- **Light aberration** → Geometry deformation
- **Doppler effect** → Color shift
- **Searchlight effect** → Change in brightness
- **Time dilation**
- **Camera deformation**

Relativistic Effects – **Searchlight Effect**

Static

$\beta = 0$ *$\beta = 0.2$* *$\beta = 0.3$* *$\beta = 0.4$* *$\beta = 0.5$*



Camera approaching the scene

Rendering Relativistic Effects

Five main phenomena:

Previous Work

- **Light aberration** → Geometry deformation
- **Doppler effect** → Color shift
- **Searchlight effect** → Change in brightness
- **Time dilation**
- **Camera deformation**

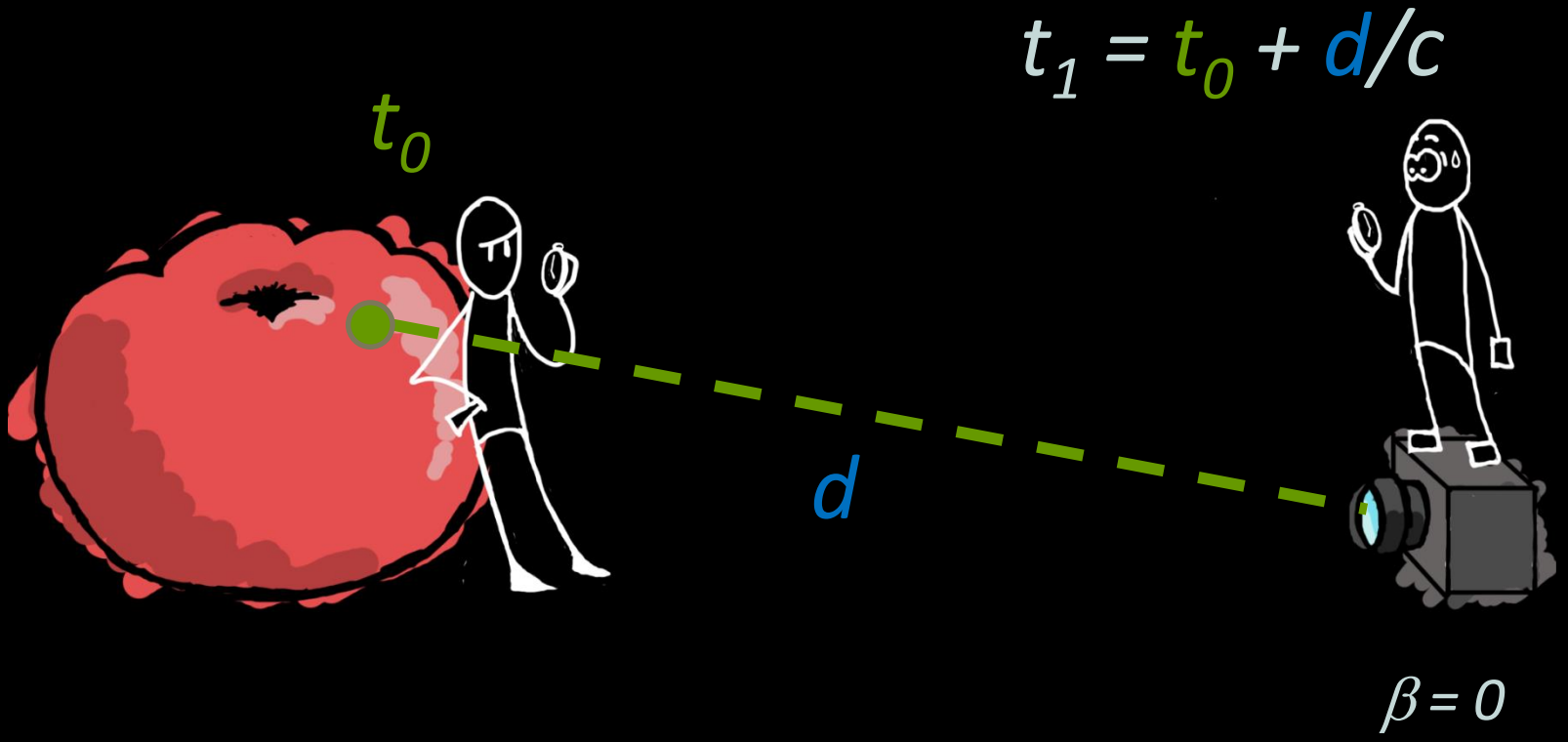
Rendering Relativistic Effects

Five main phenomena:

- Light aberration
- Time-Resolved
  - Doppler effect
  - Searchlight effect
  - Time dilation
- Camera deformation

Relativistic Effects – **Time Dilation**

Relativistic Effects – **Time Dilation**

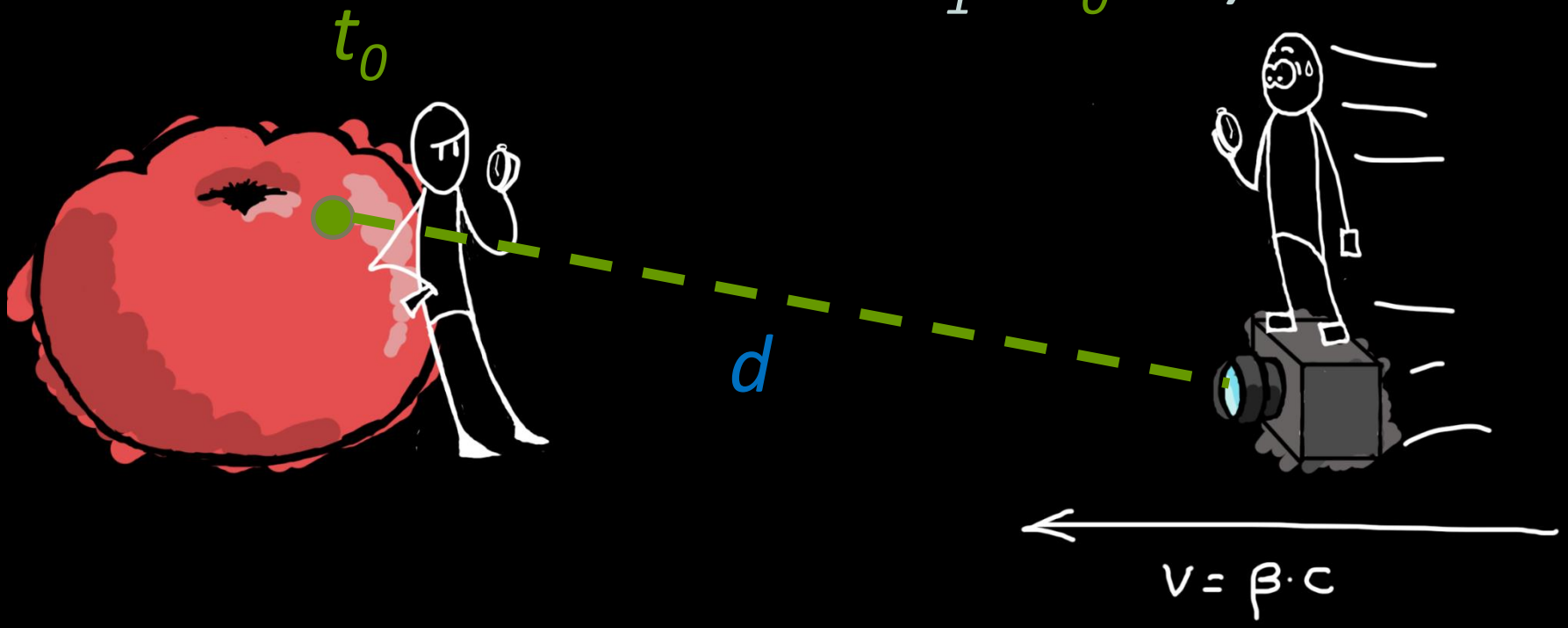


Relativistic Effects – **Time Dilation**

Lorentz contraction

$$l' = \frac{l}{\gamma} \qquad \Delta t' = \gamma \Delta t \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$t_1 = t_0 + d/c$

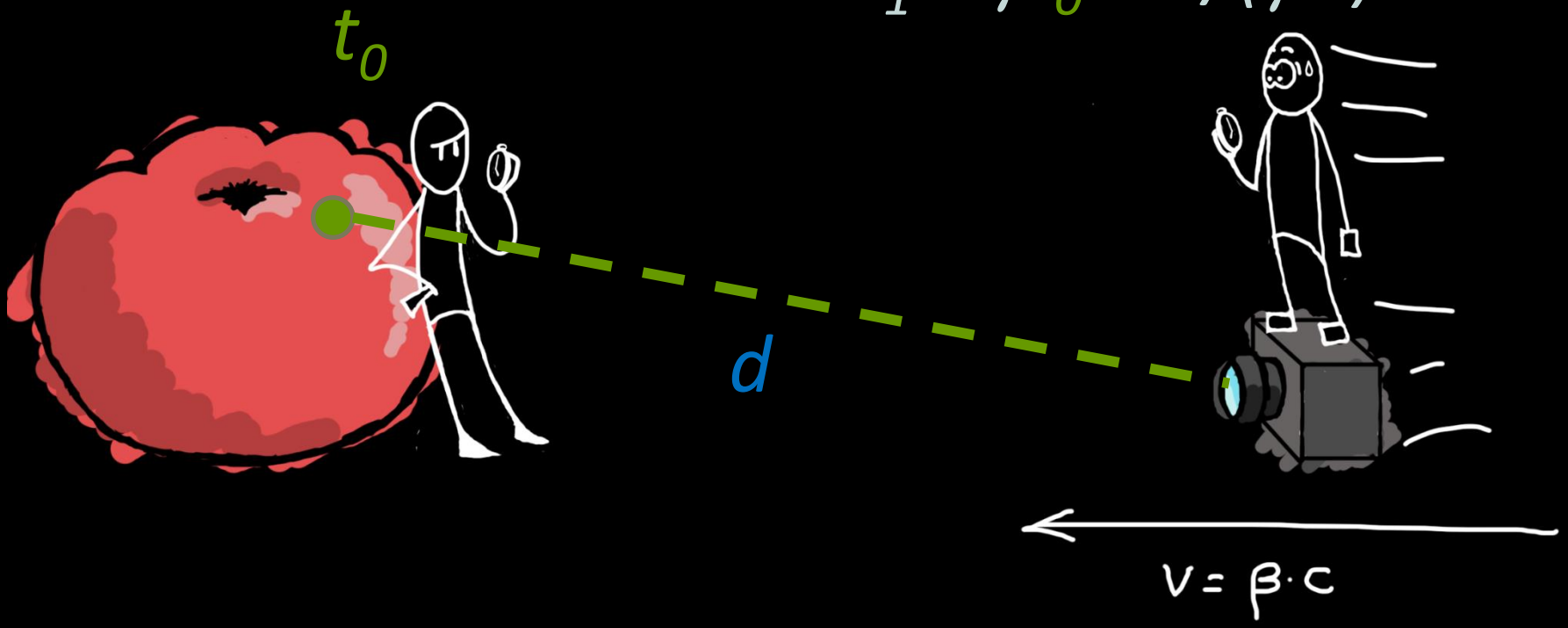


Relativistic Effects – **Time Dilation**

Lorentz contraction

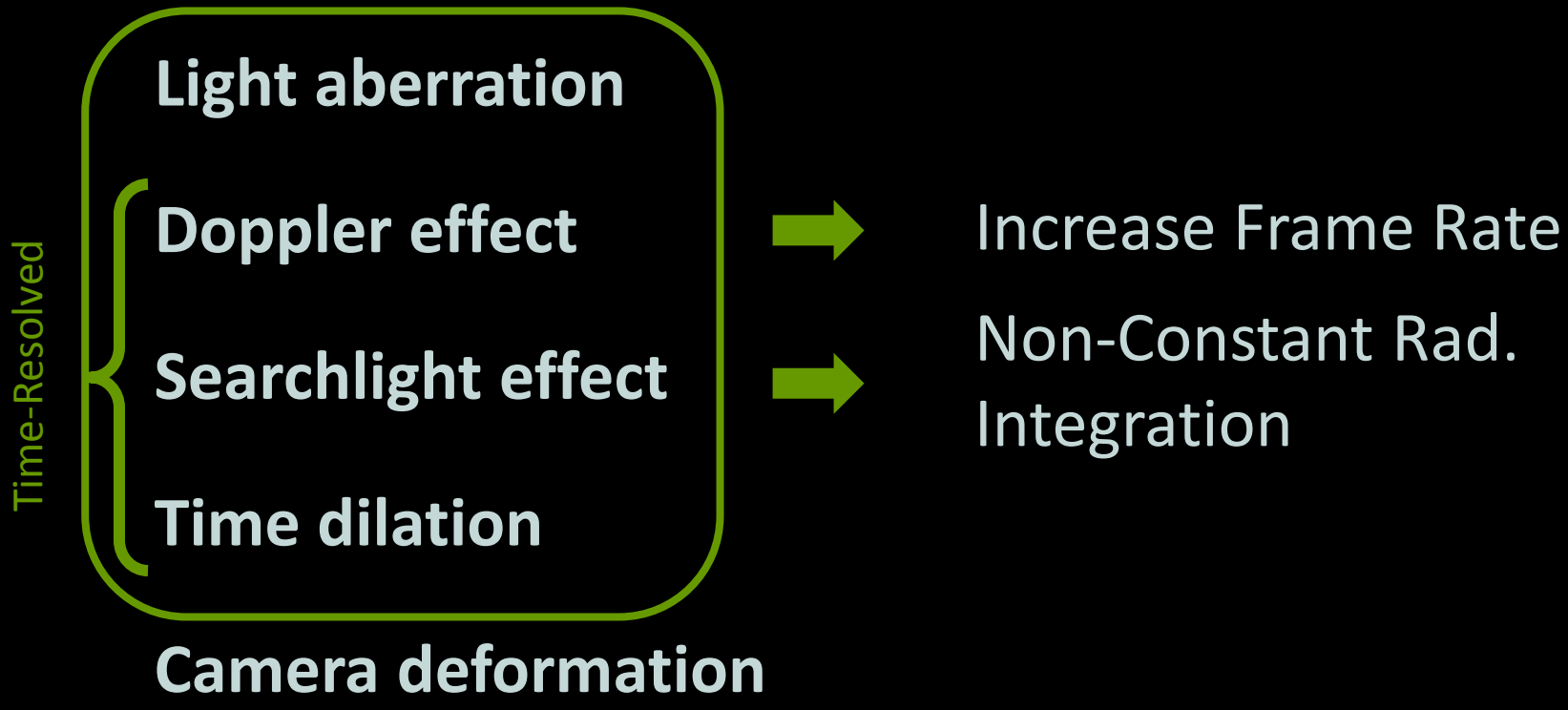
$$l' = \frac{l}{\gamma} \qquad \Delta t' = \gamma \Delta t \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$t'_1 = \gamma t_0 + d/(\gamma c)$



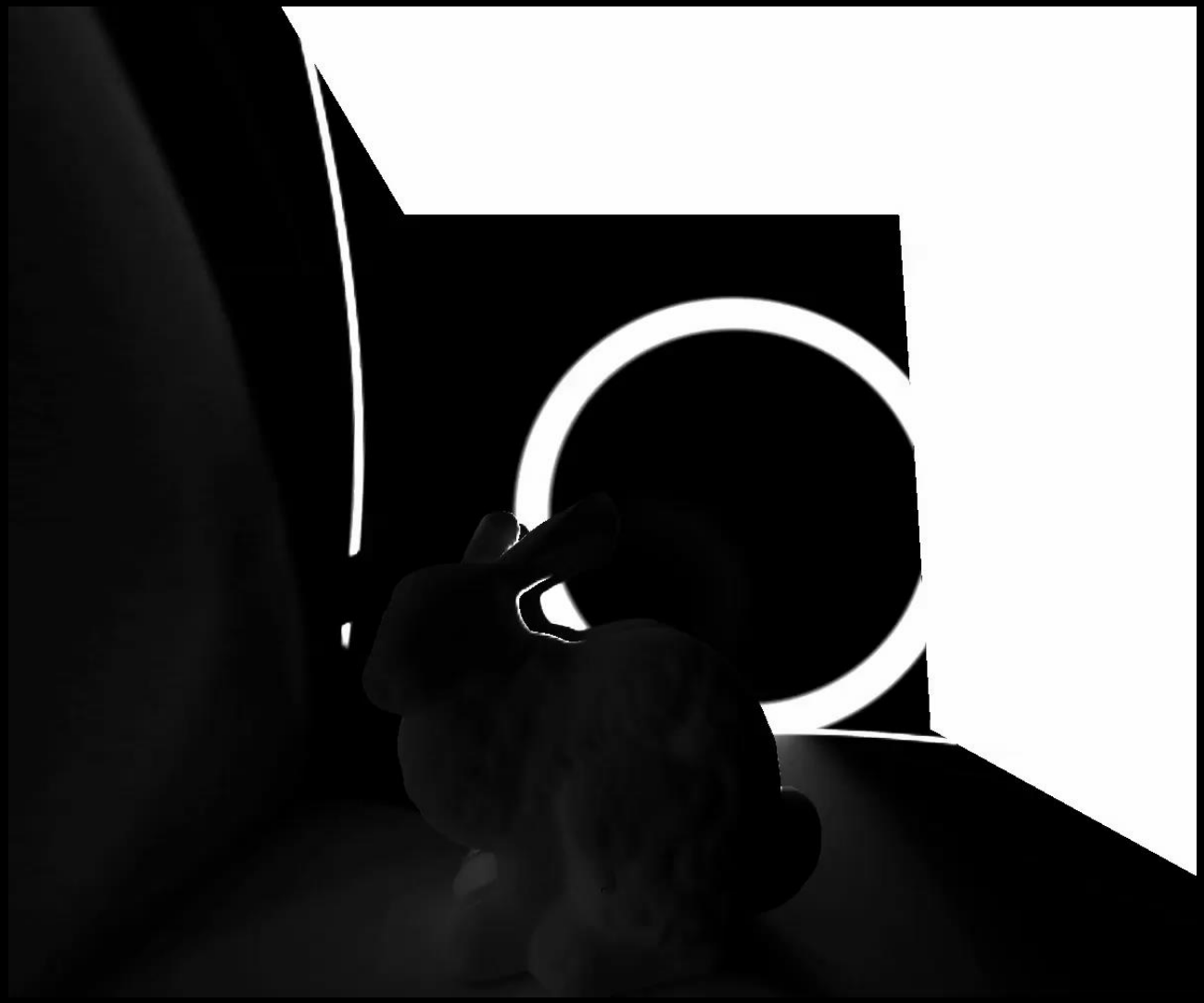
Rendering Relativistic Effects

Five main phenomena:



Rendering Relativistic Effects

Rendering Relativistic Effects



Rendering Relativistic Effects

Five main phenomena:

- Light aberration
- Doppler effect
- Searchlight effect
- Time dilation
- Camera deformation

Previous Work

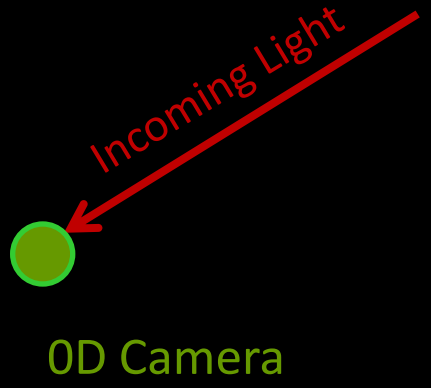
Time-Resolved

Relativistic Effects – **Camera deformation**

Old camera model:

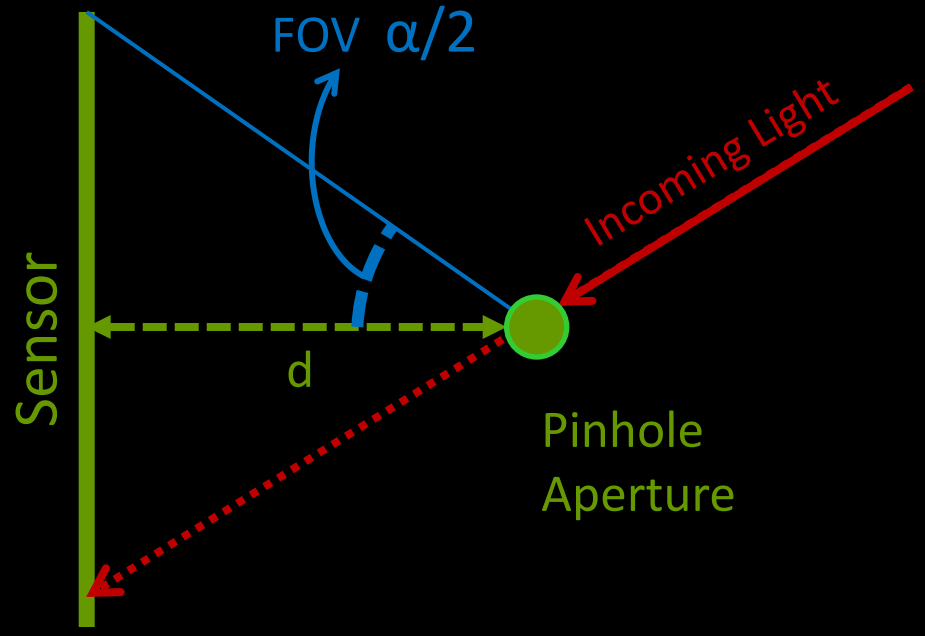
Relativistic Effects – **Camera deformation**

Old camera model:



Relativistic Effects – **Camera deformation**

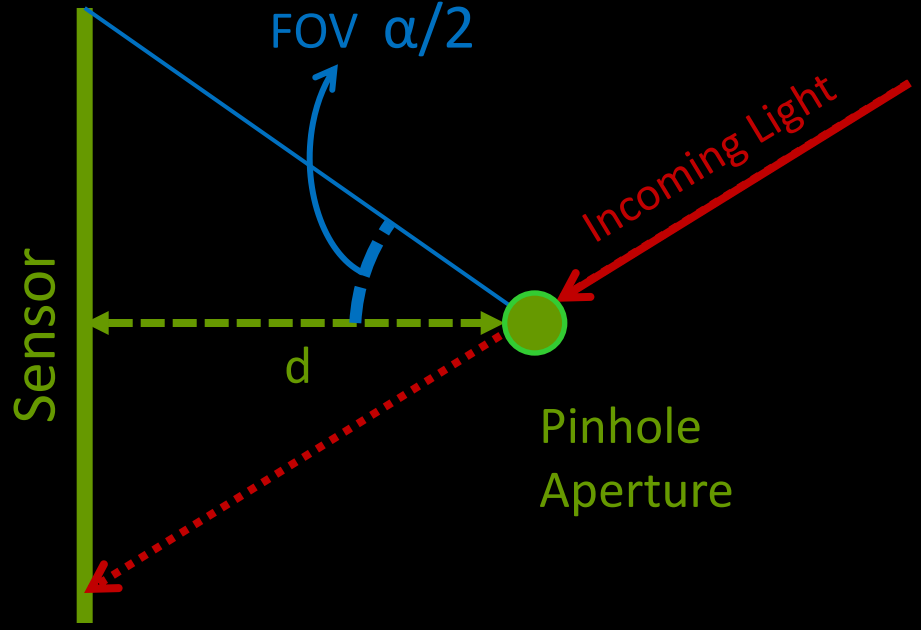
Pinhole camera model:



Relativistic Effects – **Camera deformation**

$v = \beta c$

Lorentz contraction $d = \frac{d'}{\gamma}$

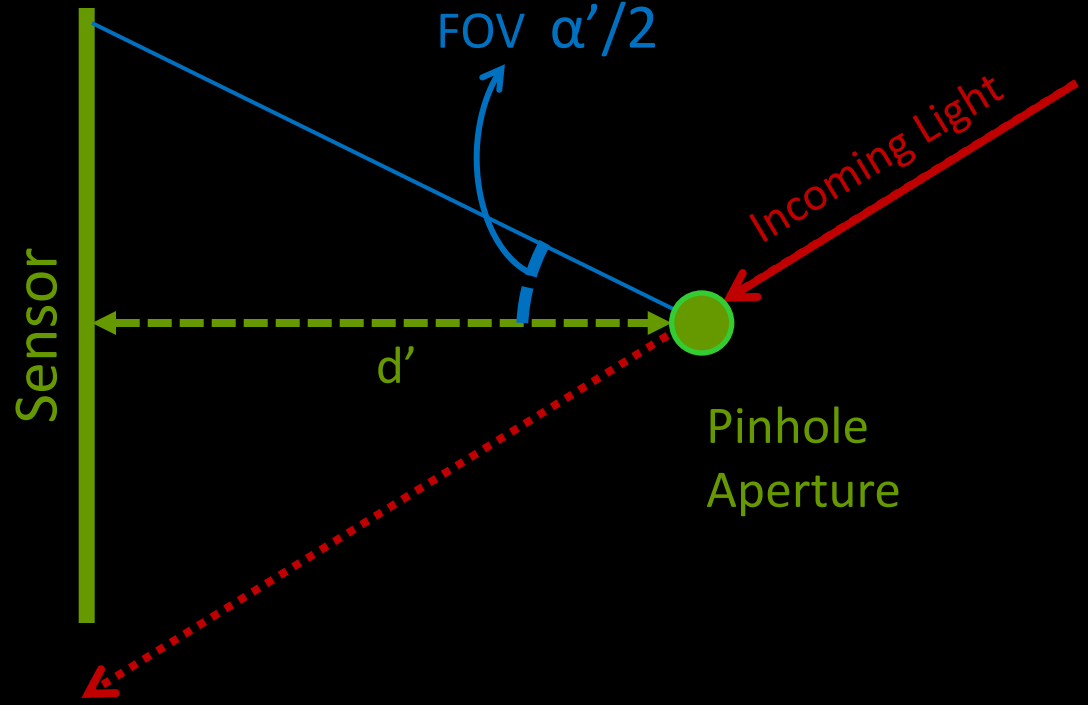


Relativistic Effects – **Camera deformation**

$v = \beta c$

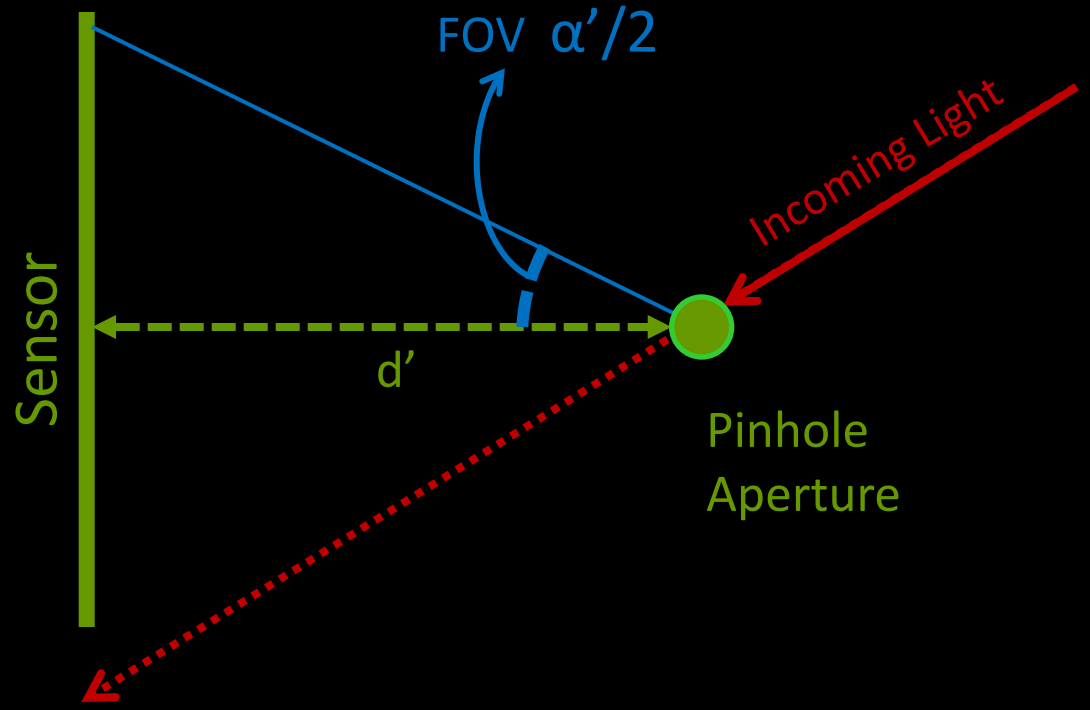
Lorentz contraction

$$d = \frac{d'}{\gamma}$$



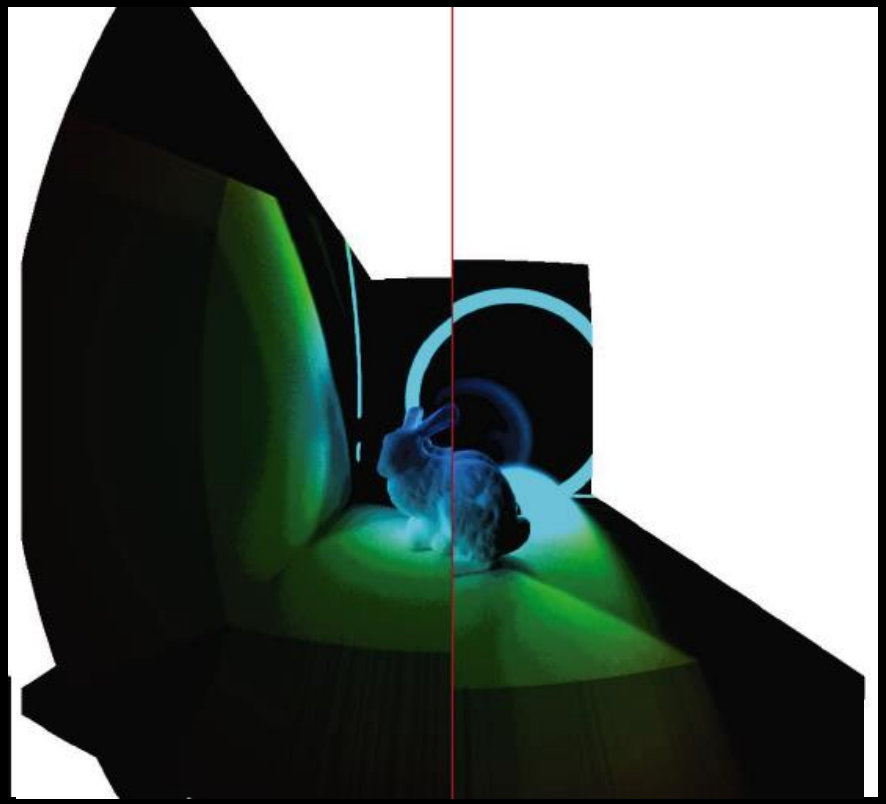
Relativistic Effects – **Camera deformation**

$$\alpha' = 2 \arctan\left(\frac{\tan(\alpha/2)}{\gamma}\right)$$



Relativistic Effects – **Camera deformation**

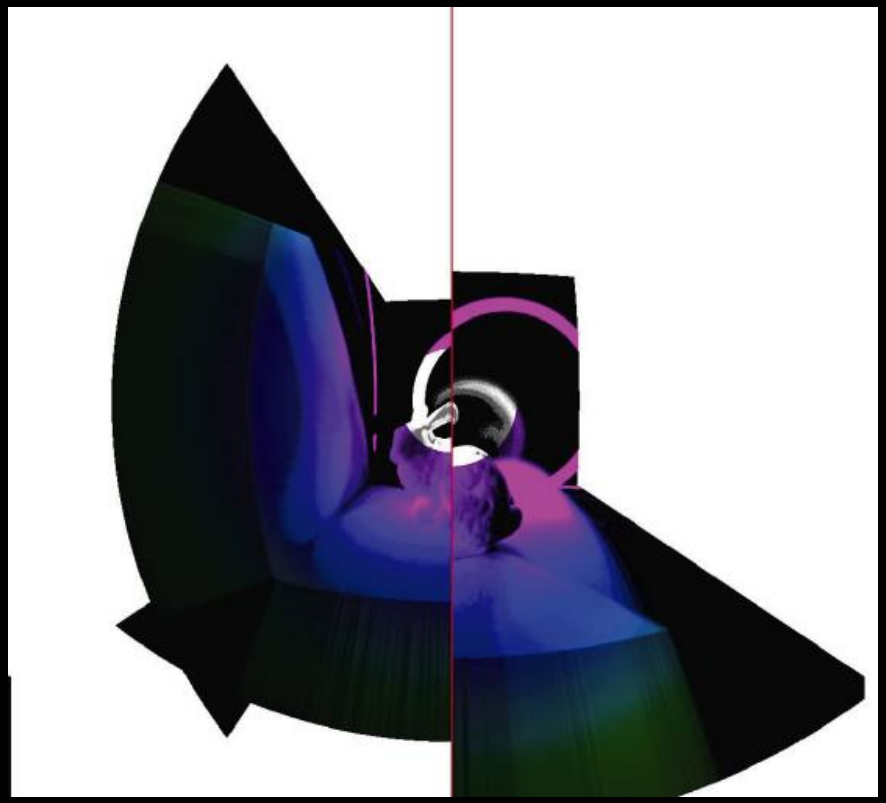
Without With



$\beta = 0.35$

Relativistic Effects – **Camera deformation**

Without With



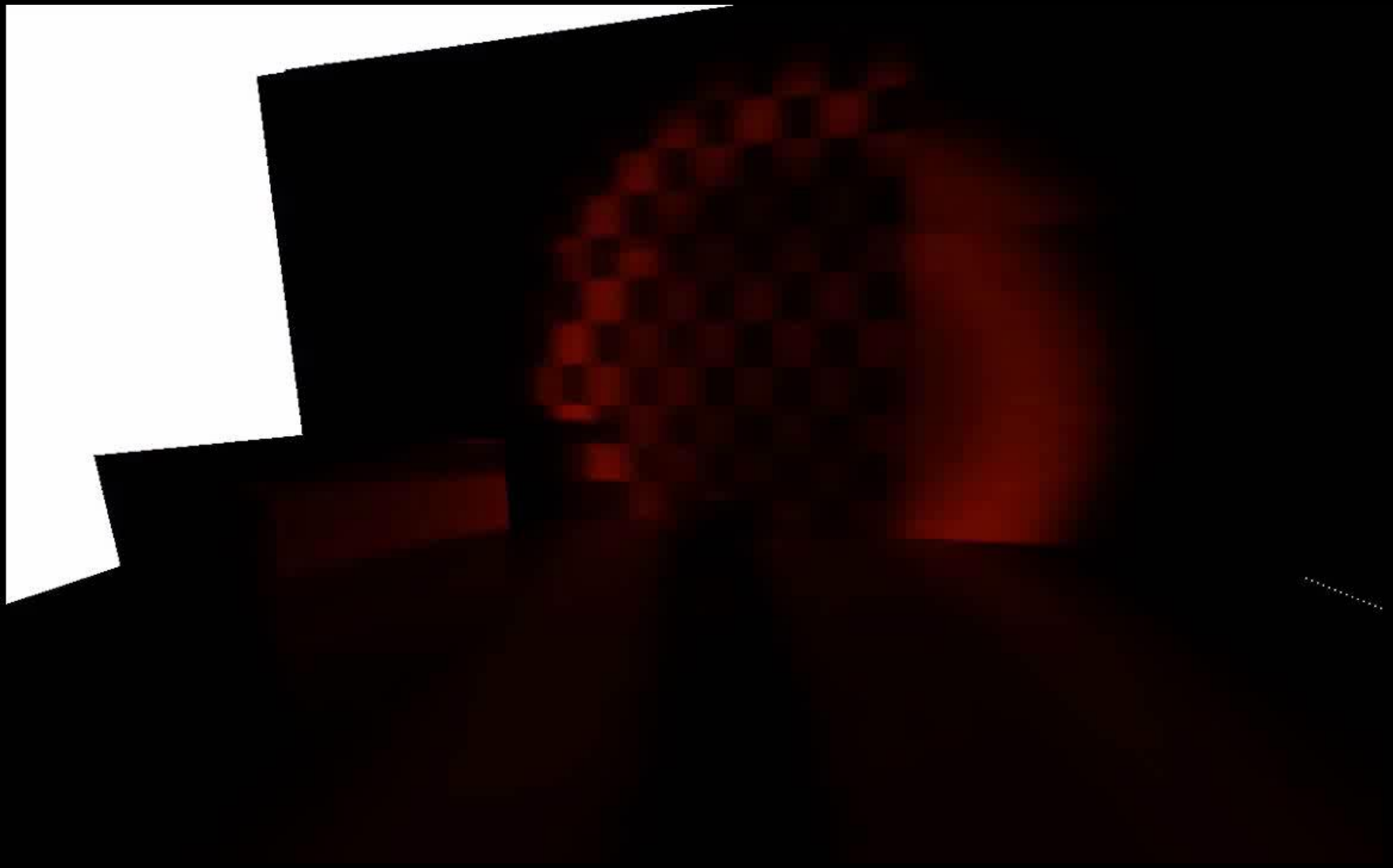
$\beta = 0.50$

Rendering Relativistic Effects

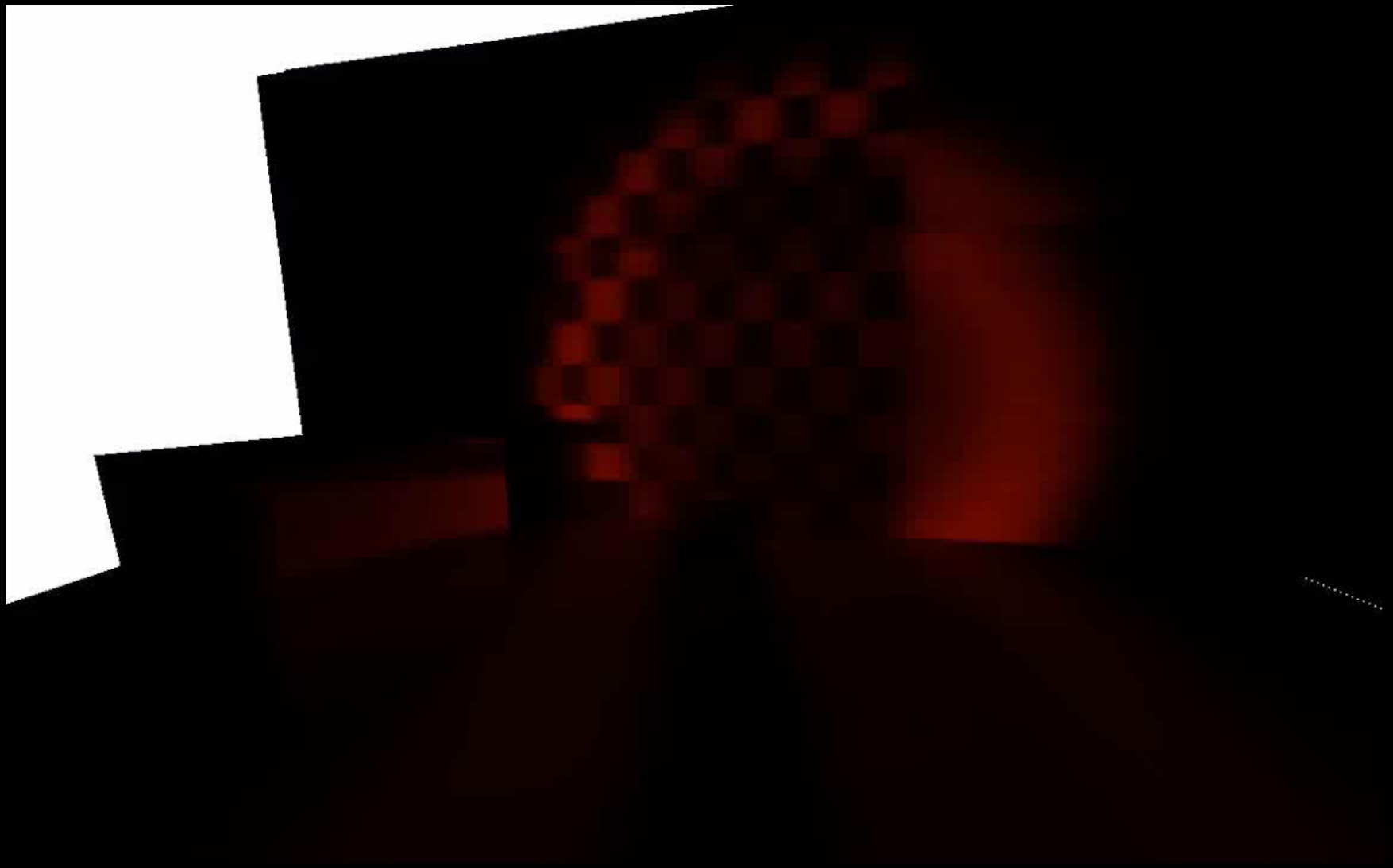
Five main phenomena:

- Light aberration
- Doppler effect
- Searchlight effect
- Time dilation
- Camera deformation

Relativistic Effects – **All together…**



Relativistic Effects – **All together…**

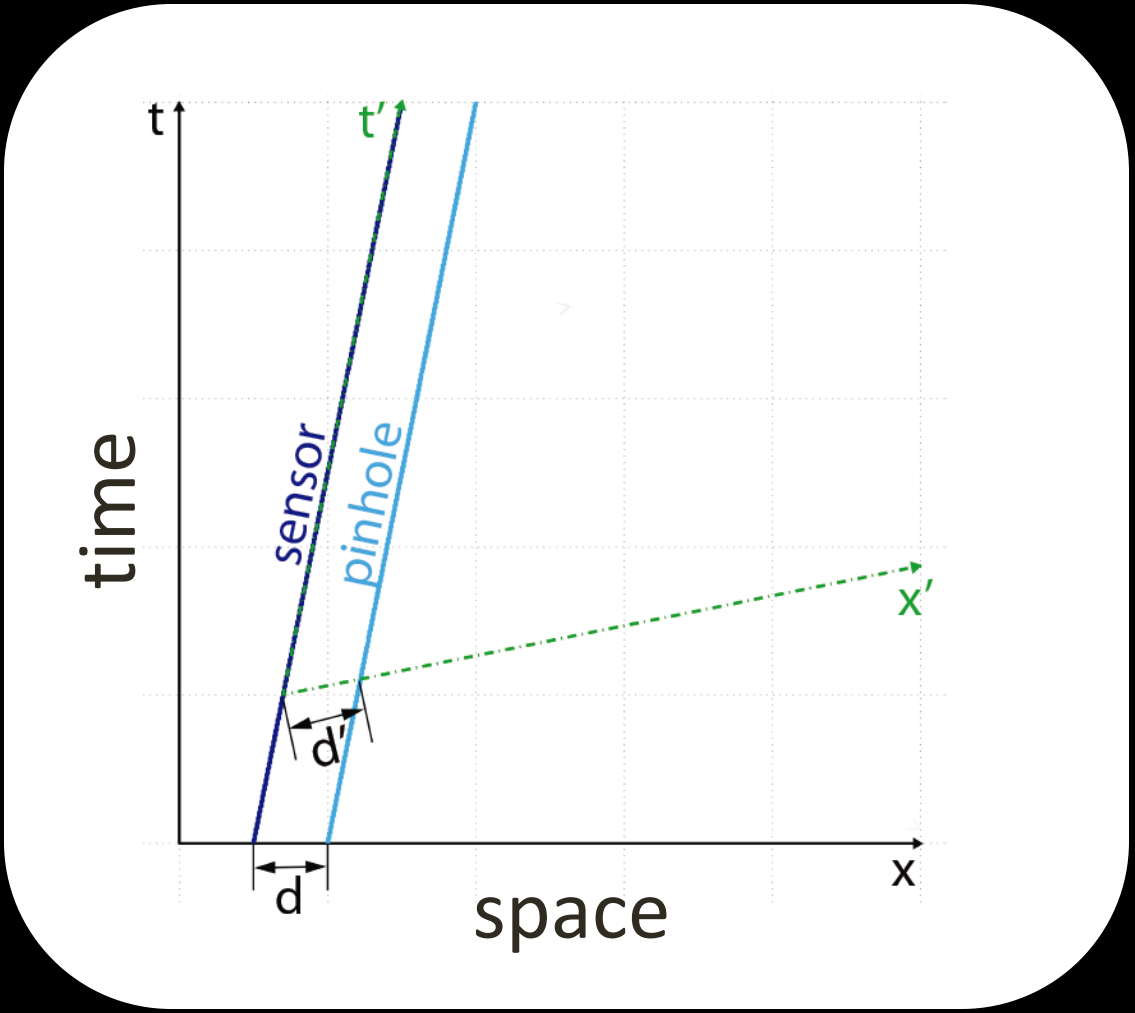


Rendering Relativistic Effects

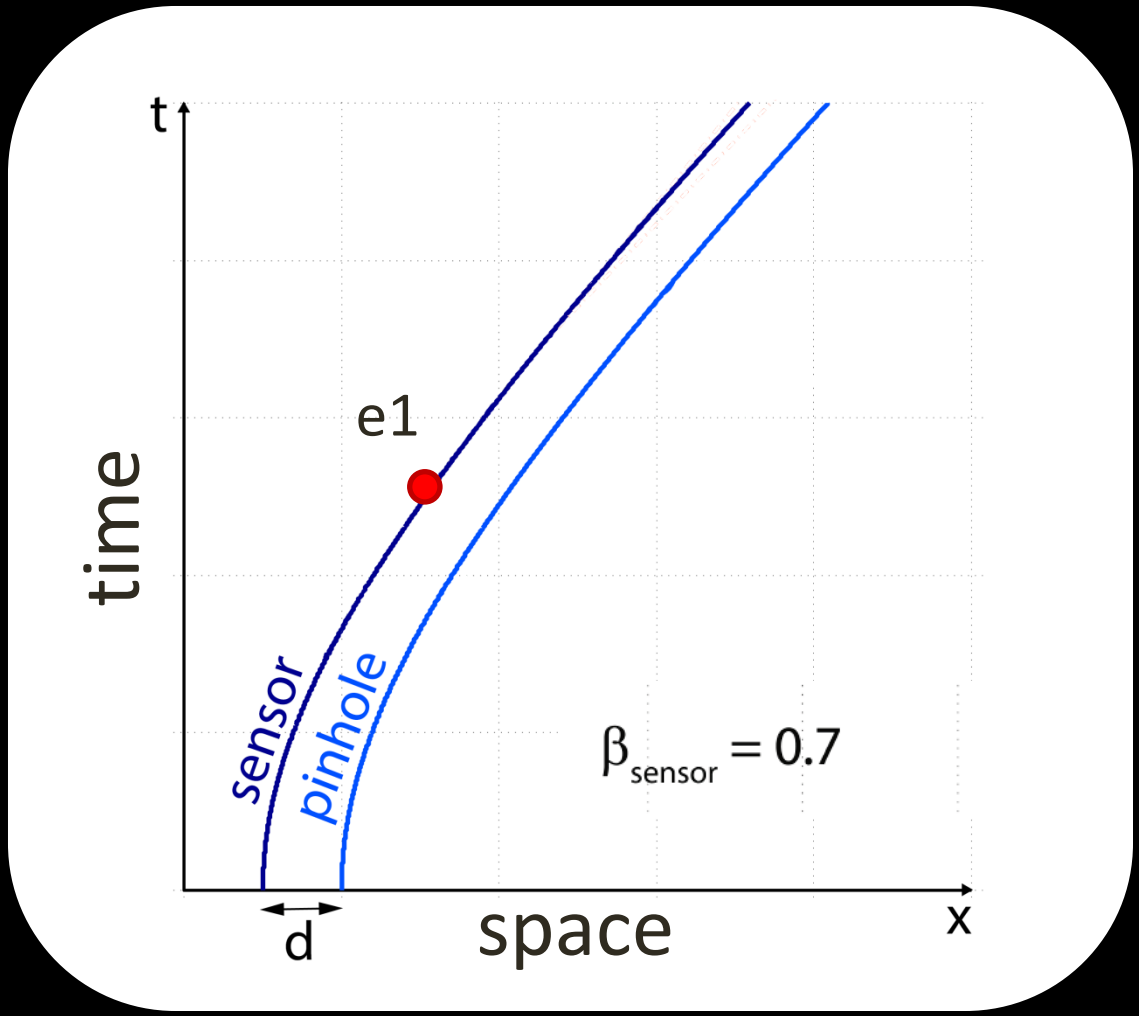
More than just linear non-accelerated motion…

- Relativistic Acceleration
- Relativistic Rotation

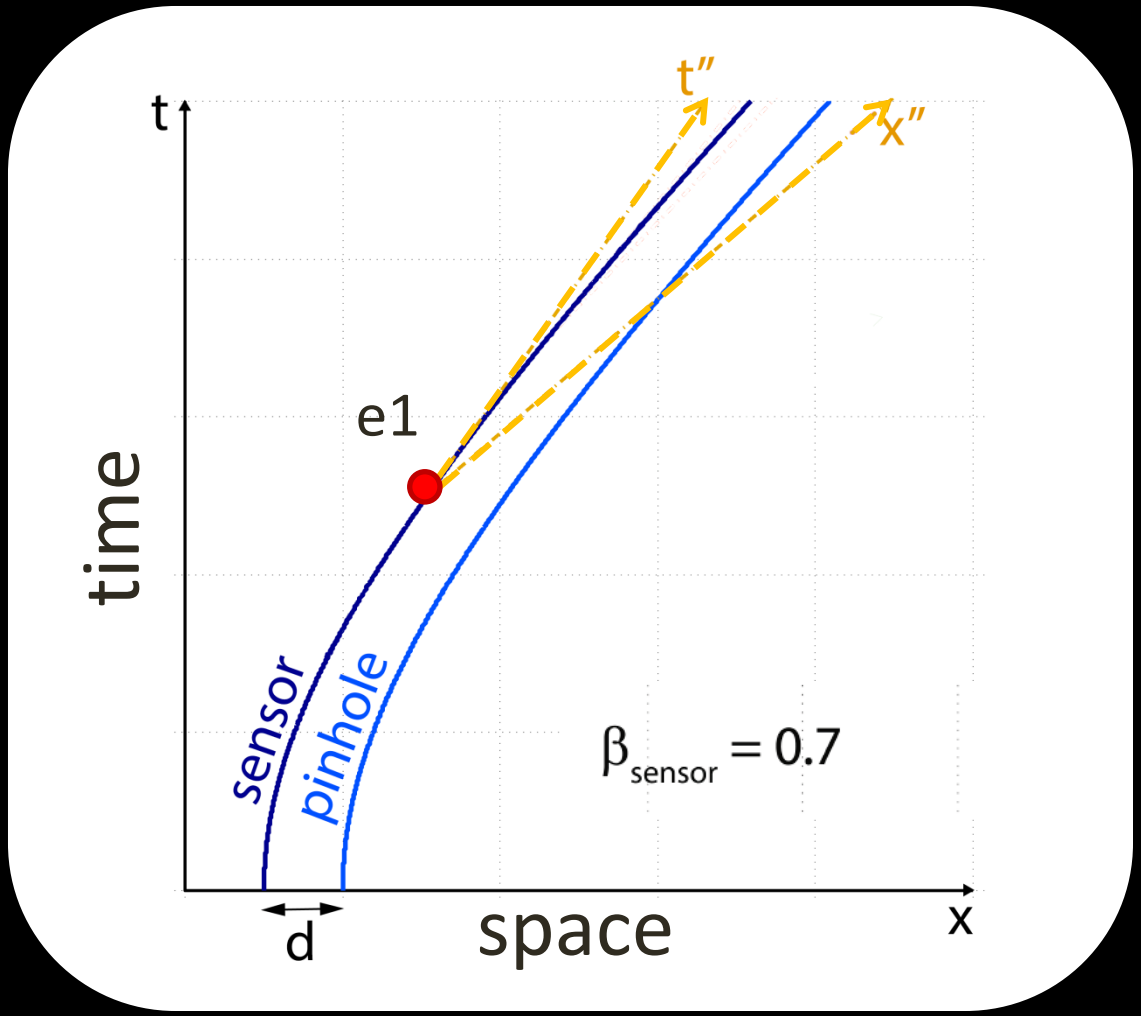
Relativistic **Acceleration**



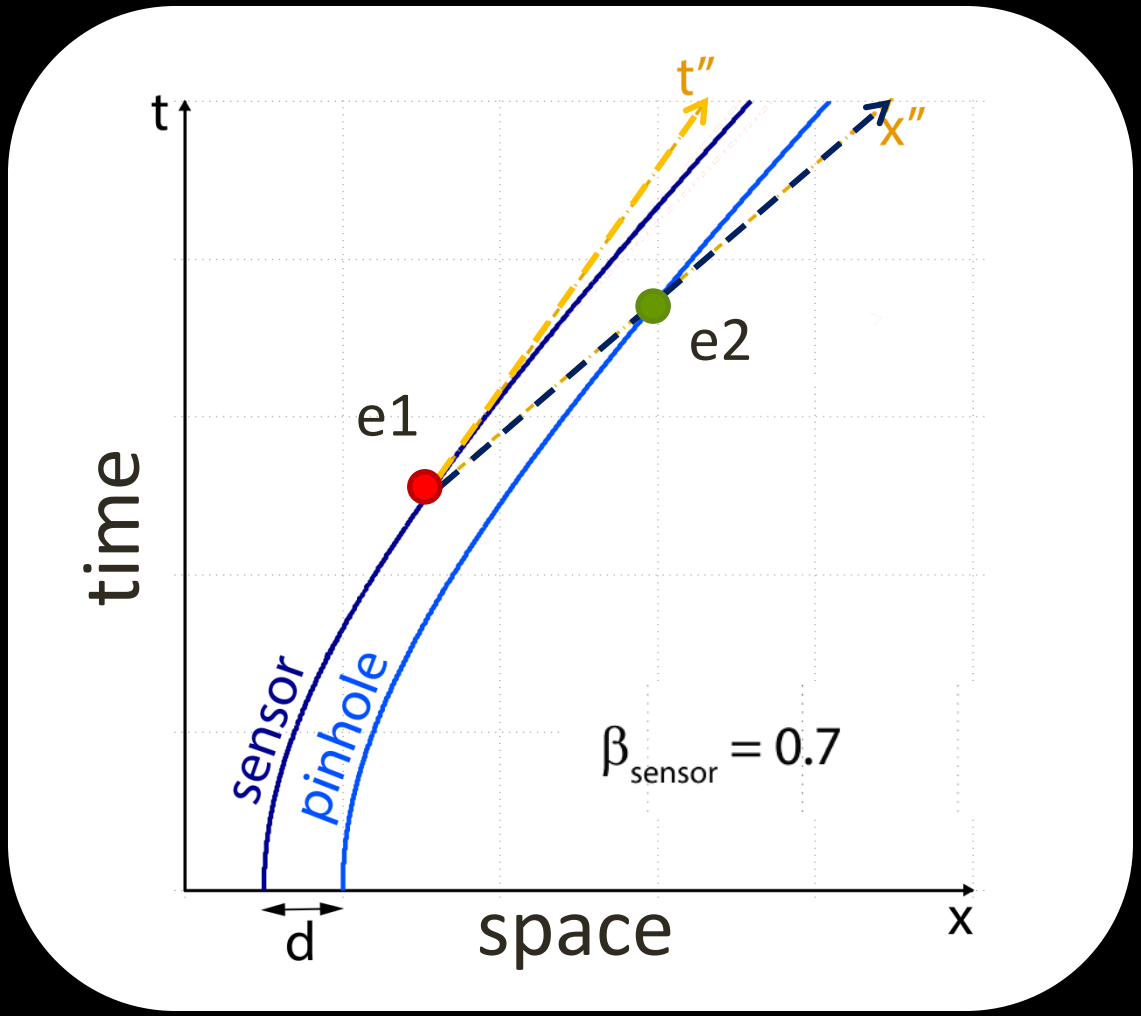
Relativistic **Acceleration**



Relativistic **Acceleration**

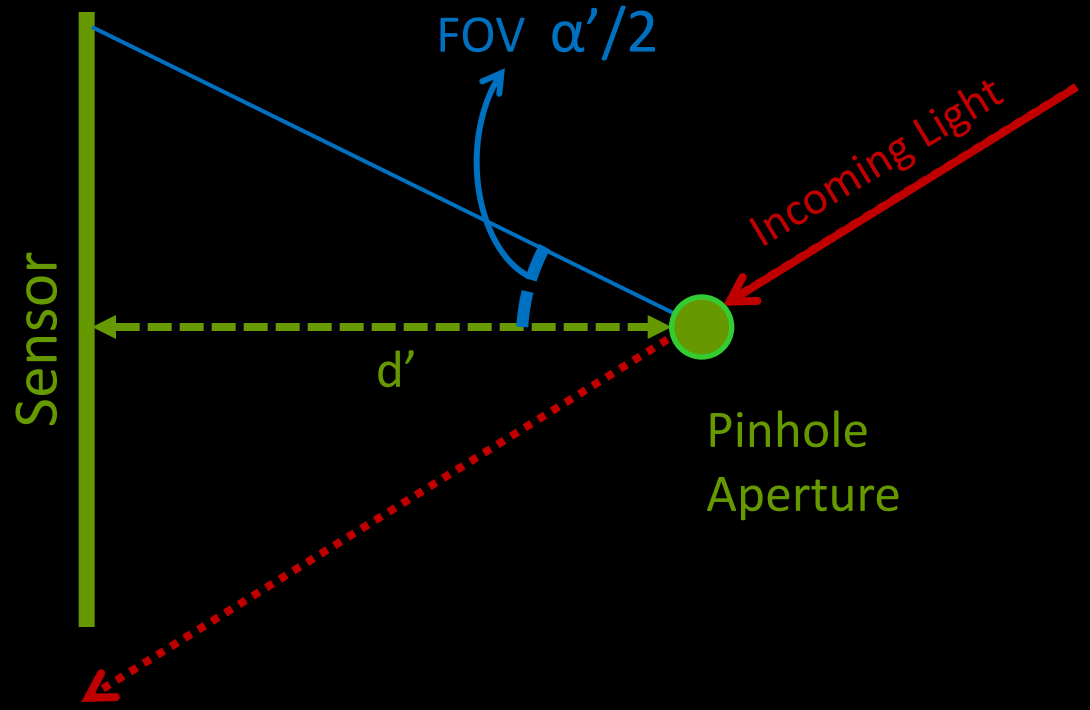


Relativistic **Acceleration**



Relativistic Effects – **Camera deformation**

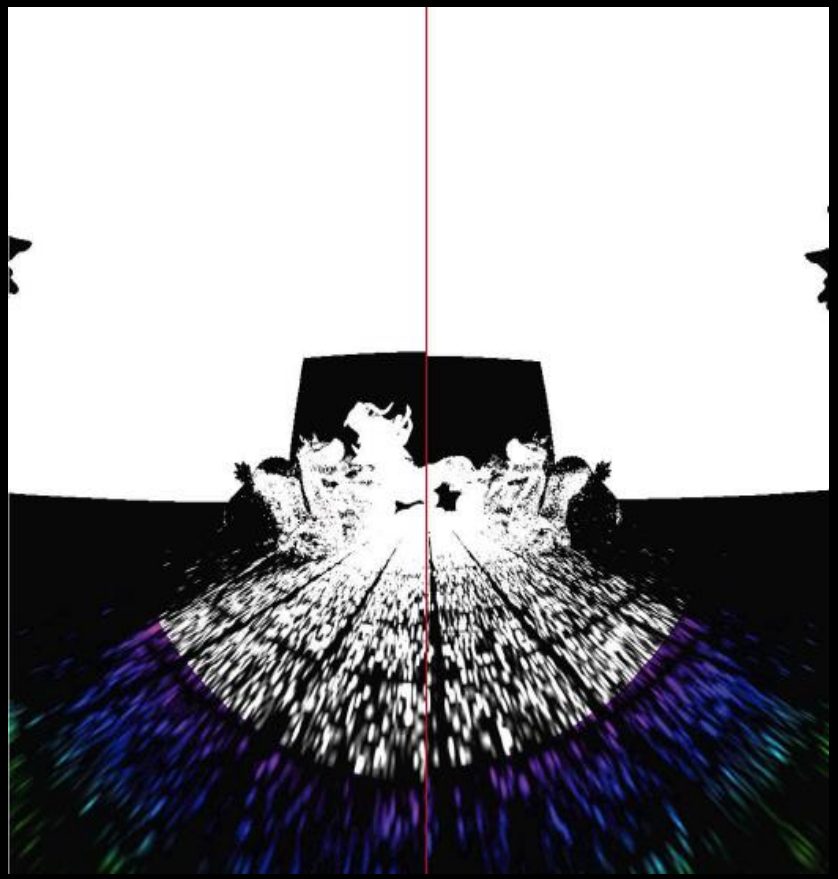
$$\alpha' = 2 \arctan\left(\frac{\tan(\alpha/2)}{\gamma}\right)$$



Relativistic **Acceleration**

Constant Speed

Acceleration

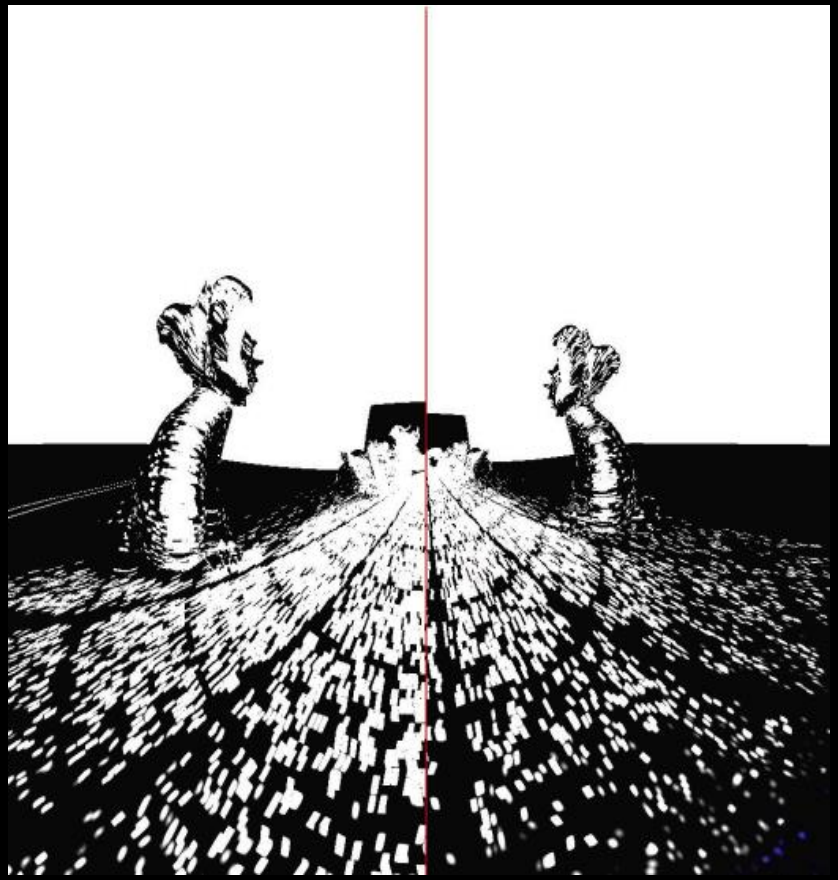


$\beta = 0.6$

Relativistic **Acceleration**

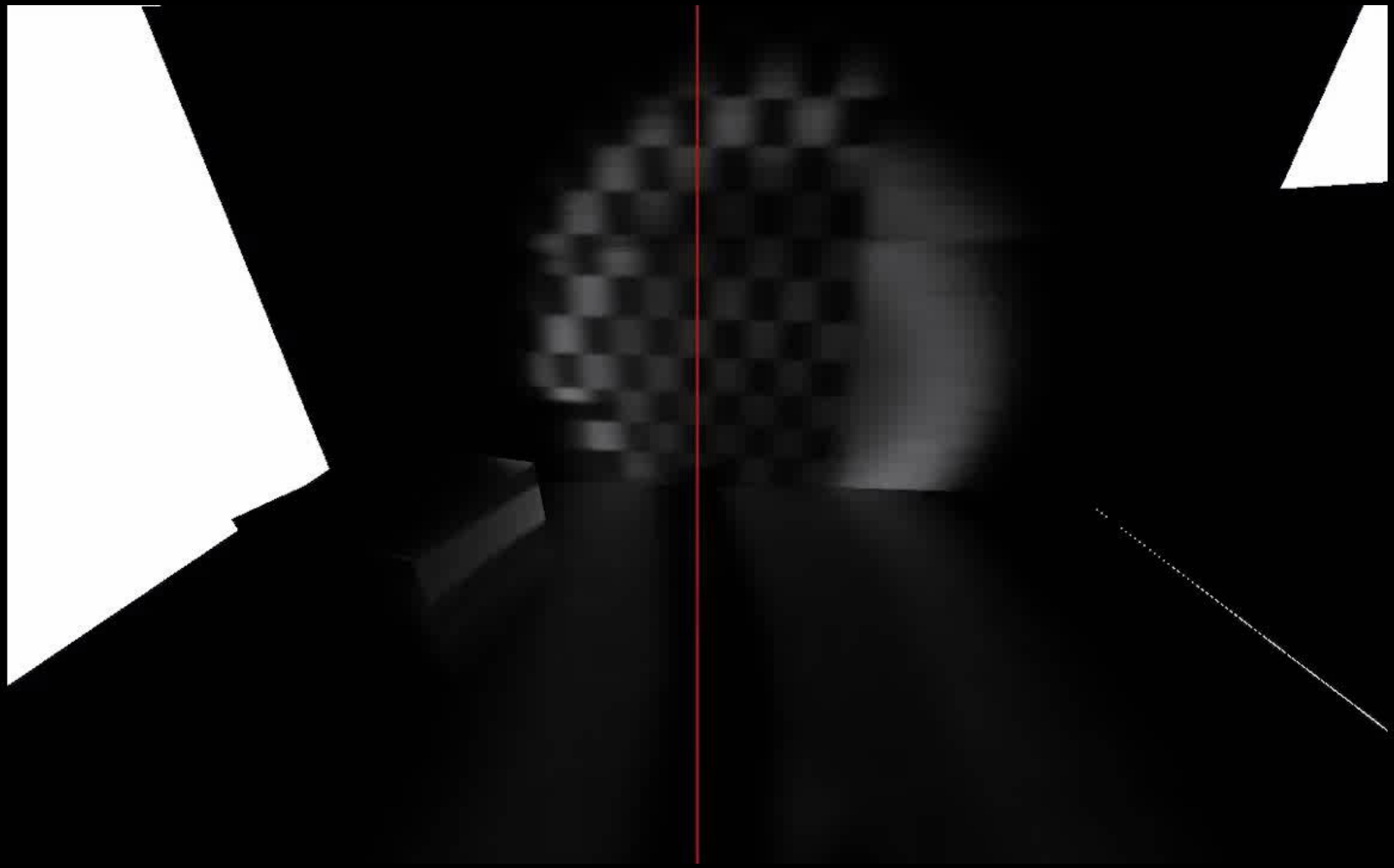
Constant Speed

Acceleration



$\beta = 0.9$

Relativistic **Acceleration**



Constant Speed

Acceleration

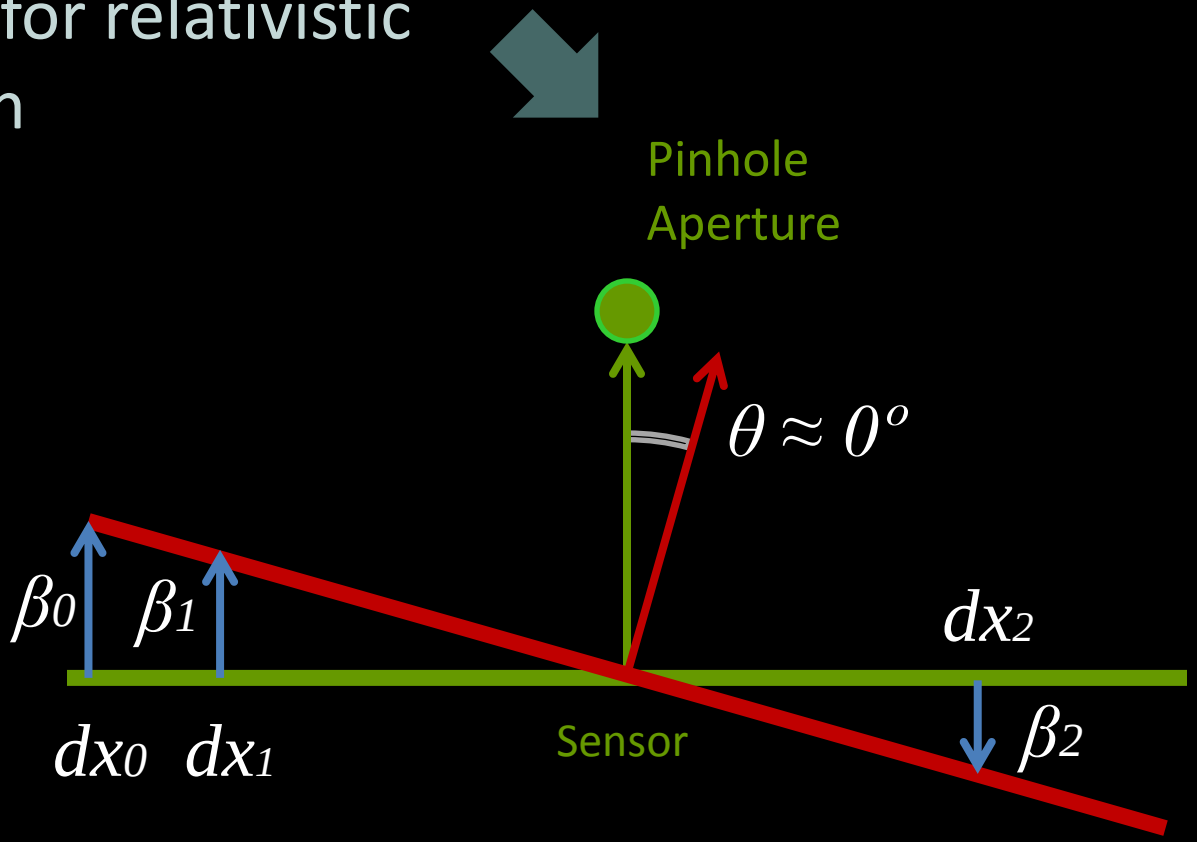
Rendering Relativistic Effects

More than just linear non-accelerated motion…

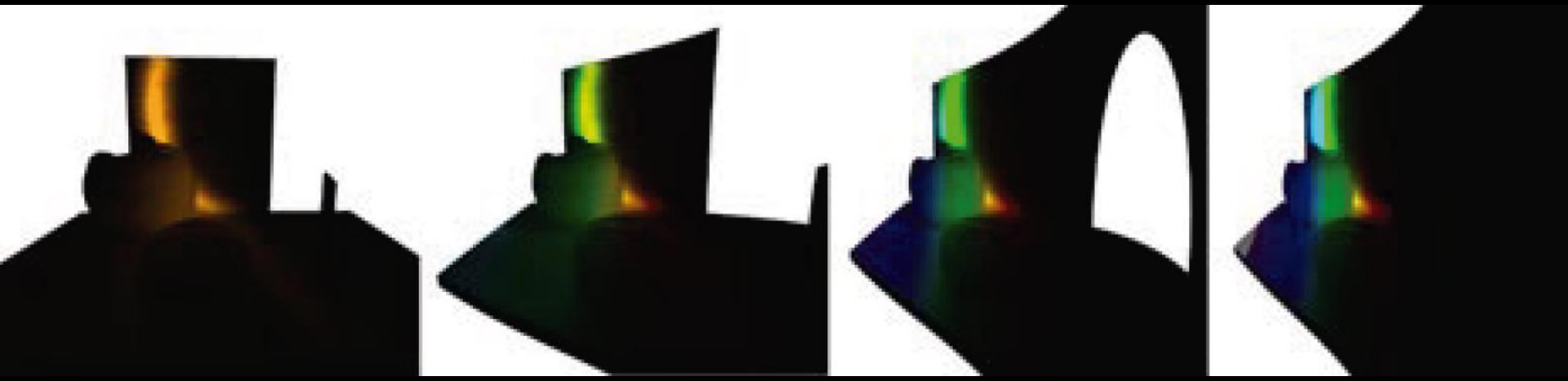
- Relativistic Acceleration
- Relativistic Rotation

Relativistic **Rotation**

No commonly accepted theory for relativistic rotation

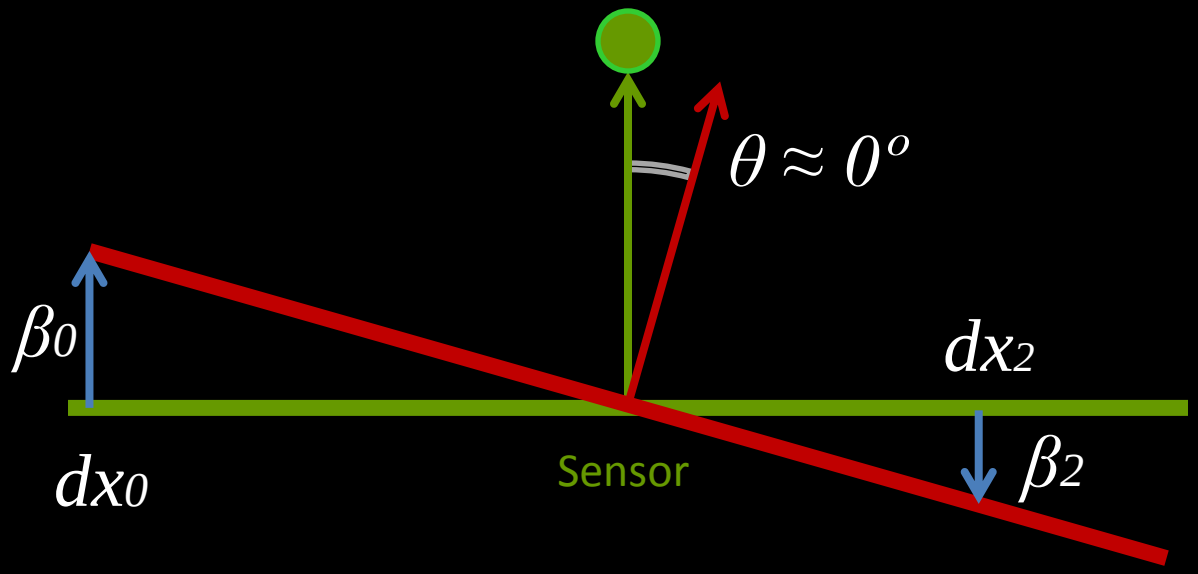


Relativistic **Rotation**

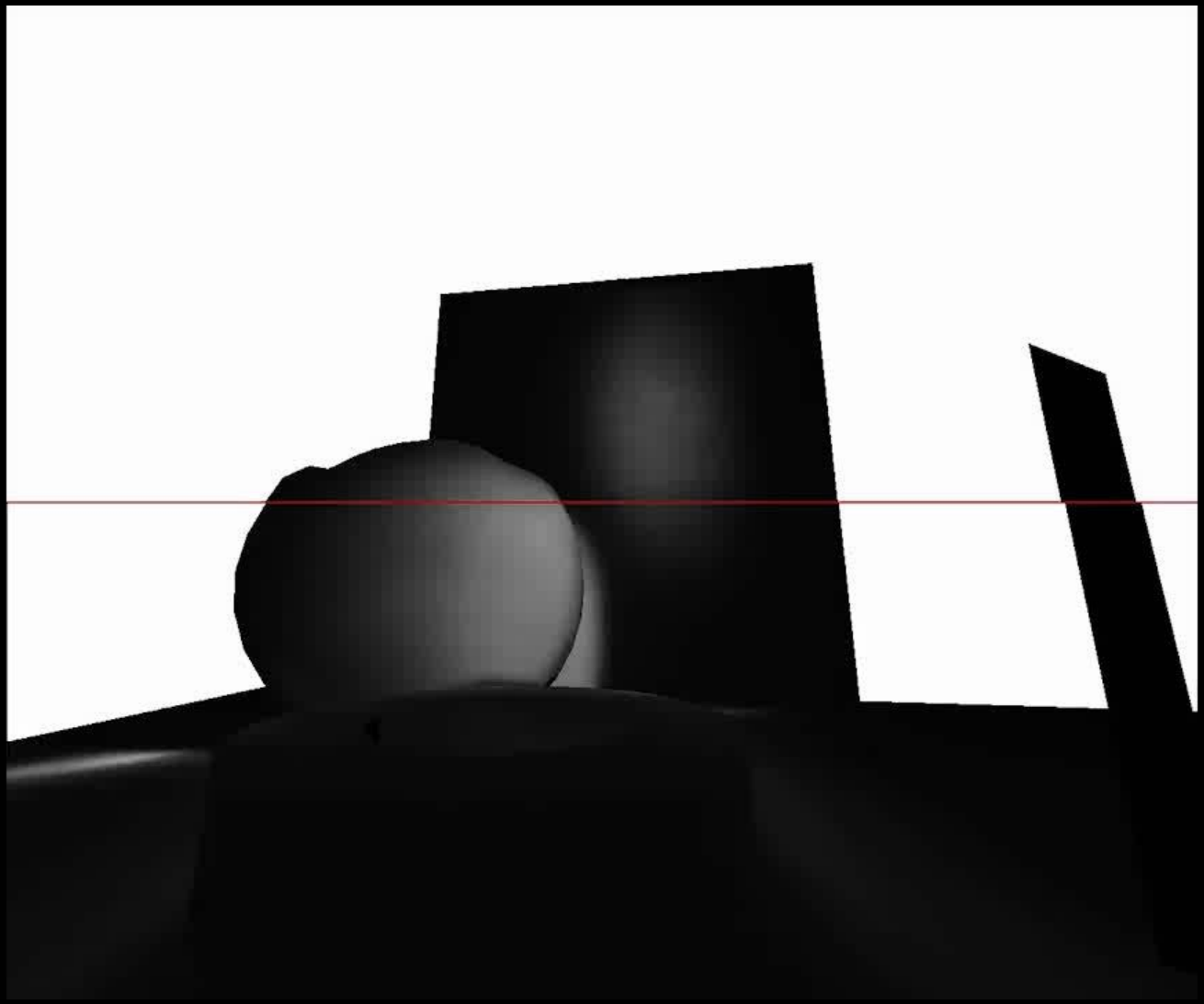


$\beta = 0.2$ $\beta = 0.4$ $\beta = 0.8$ $\beta = 0.99$

Relativistic **Rotation**



Relativistic Effects – **Rotation**



Conclusion & Future Work

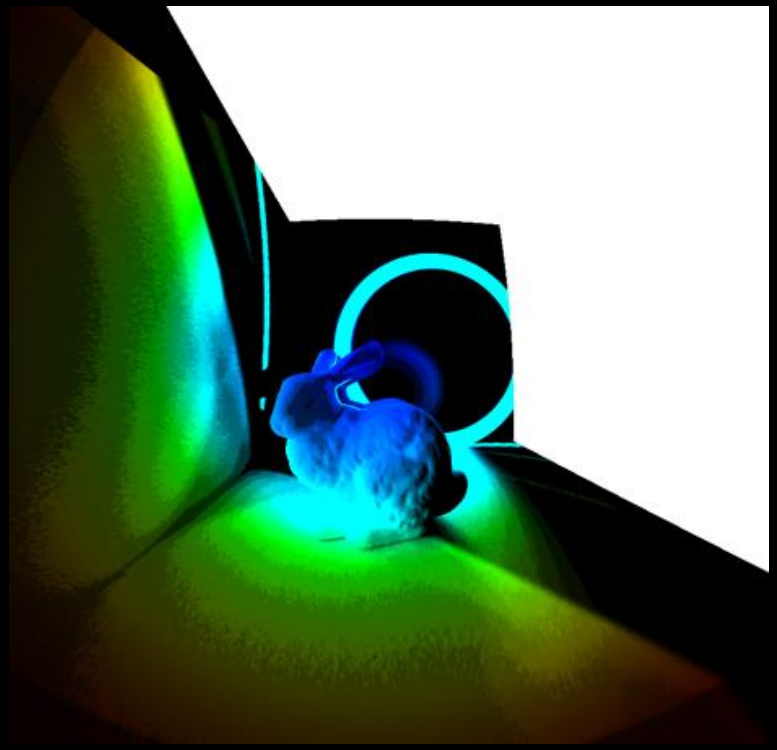
Relativistic rendering framework of time-resolved data:

- **non-constant** time-resolved radiance
- **acceleration** and **rotation** for visualization
- **pinhole camera** model with **camera deformation**

Future Work:

- General relativity -> Gravitational Forces
- More sophisticated camera models
- Lift Lambertian surface assumption

Relativistic Effects for Time-Resolved Light Transport



THANKS!

Adrian Jarabo[1] Belen Masia[1,2,3] Andreas Velten[4]
Christopher Barsi[2] Ramesh Raskar[2] Diego Gutierrez[1]

[1]Universidad de Zaragoza [2]MIT Media Lab [3]I3A [4]Morgridge Institute for Research

Implementation Details

Standalone app., **real-time**, OpenGL

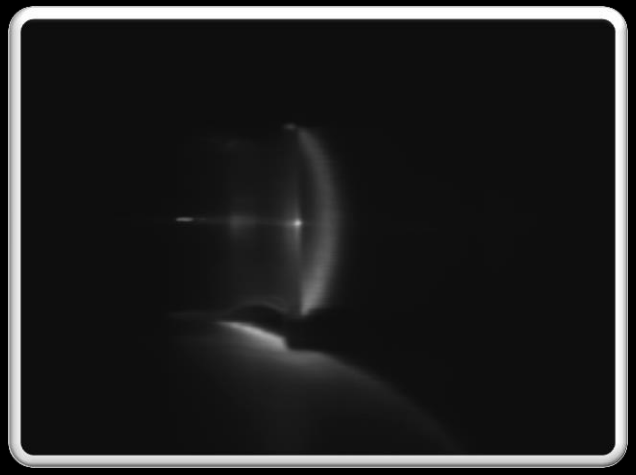
x-y-t data => 3D texture in GPU in world time

Light aberration => geometry needs to be **re-tessellated**

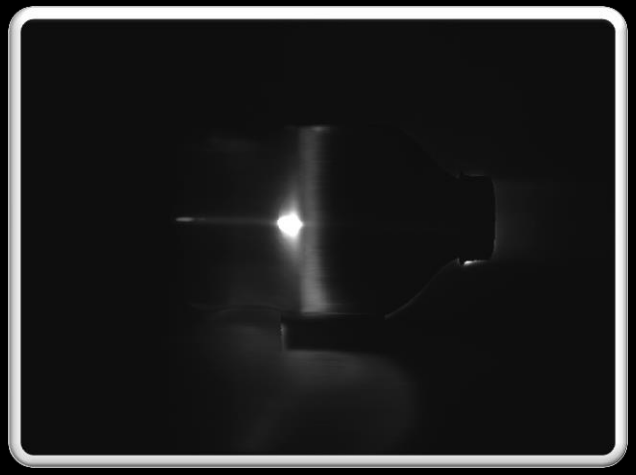
Doppler effect => wavelength-to-RGB 1D texture

Searchlight effect => pre-integrate (in time) irradiance values & **anisotropic mipmapping** to later access them

Time Unwarping



Captured
(camera time)



Corrected
for depth

Corrected for depth
and scattering

Femto-photography Setup System Parameters

Time Resolution	2 ps (0.6 mm)
Spatial Resolution	672 by up to 1000 pixels
Time gating contrast	100% (sensor)
Sensitivity	Photon counting ~10% quantum efficiency
Illumination Power	500 mW
Capture Time	About 1 hour for presented videos (limited by camera SNR and amount of available photons)

Femto-Photography Setup

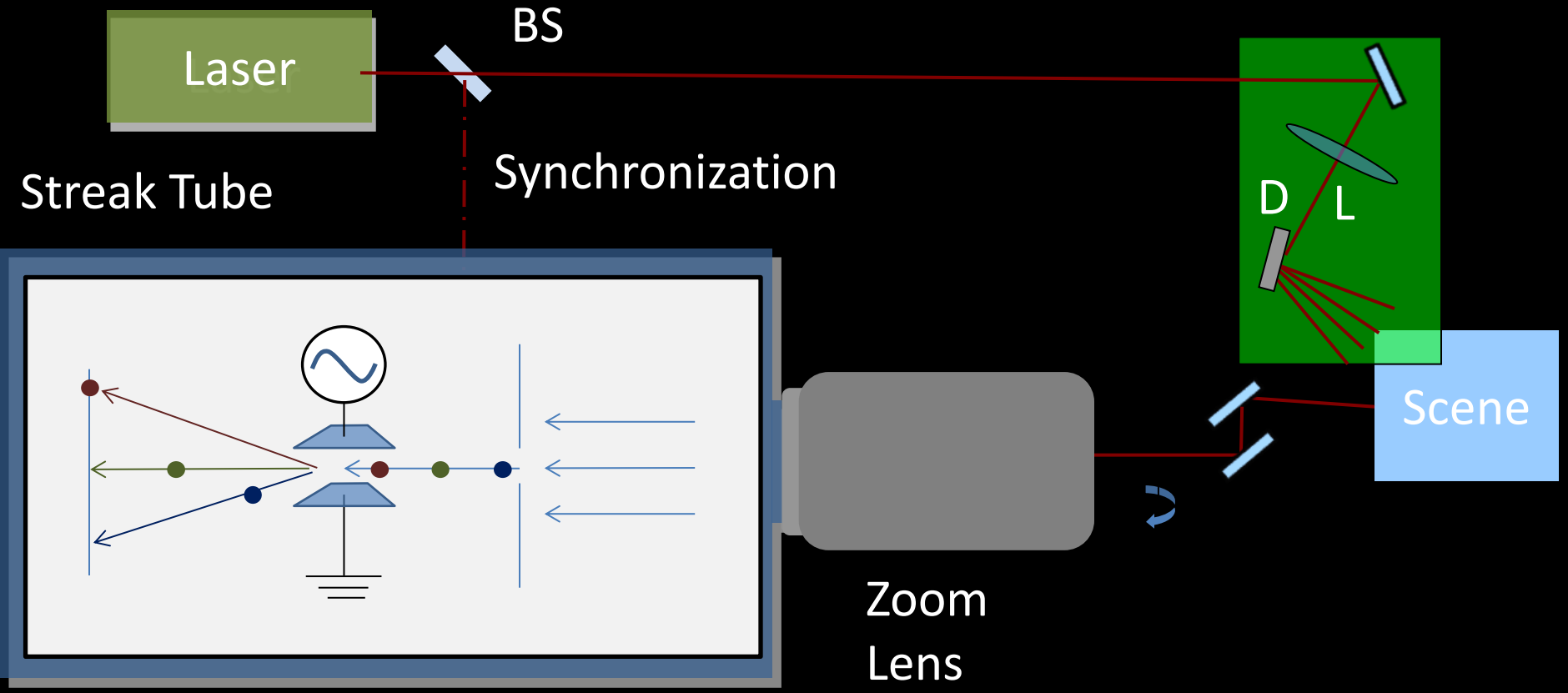
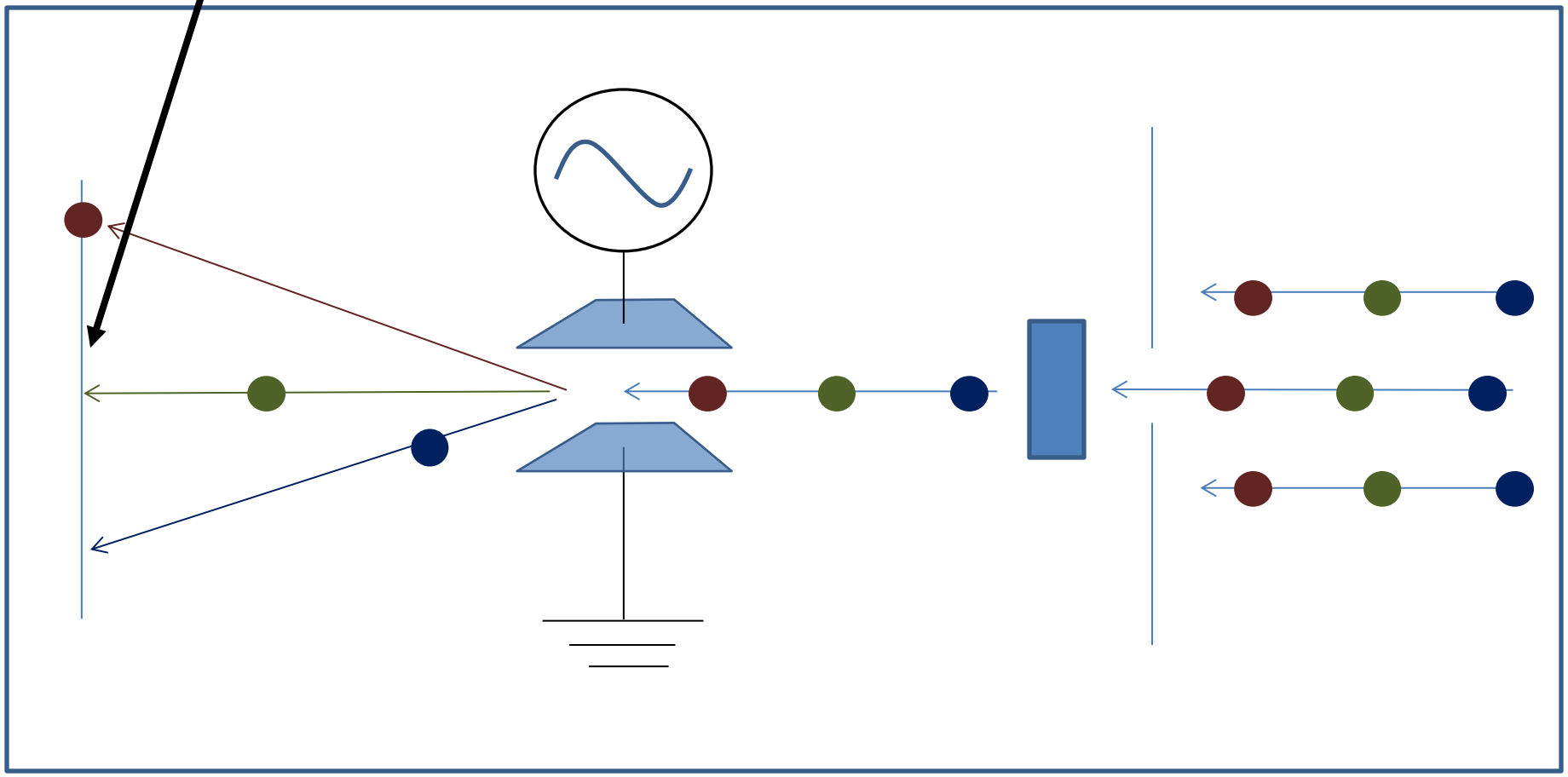
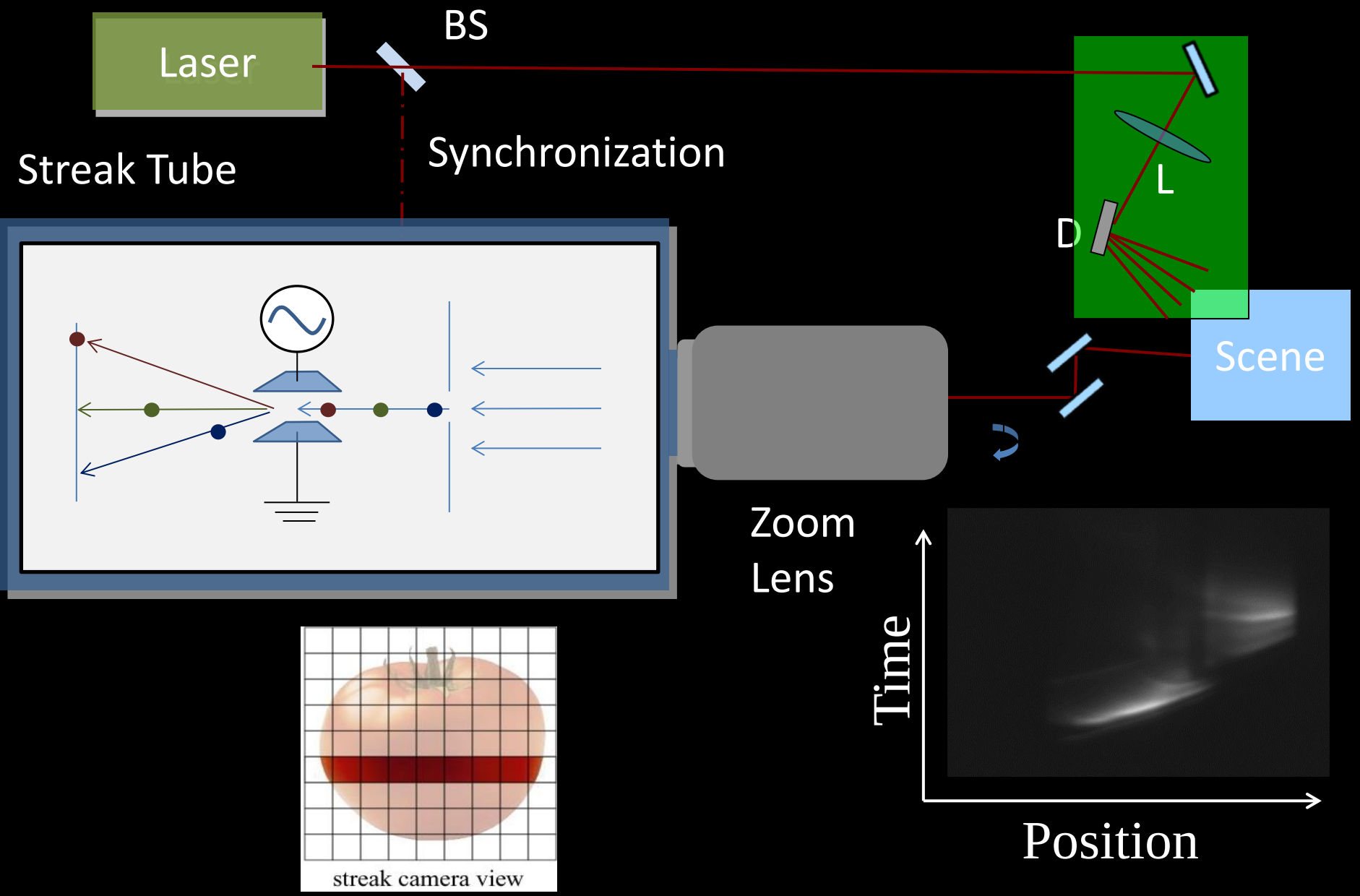


Image Intensifier

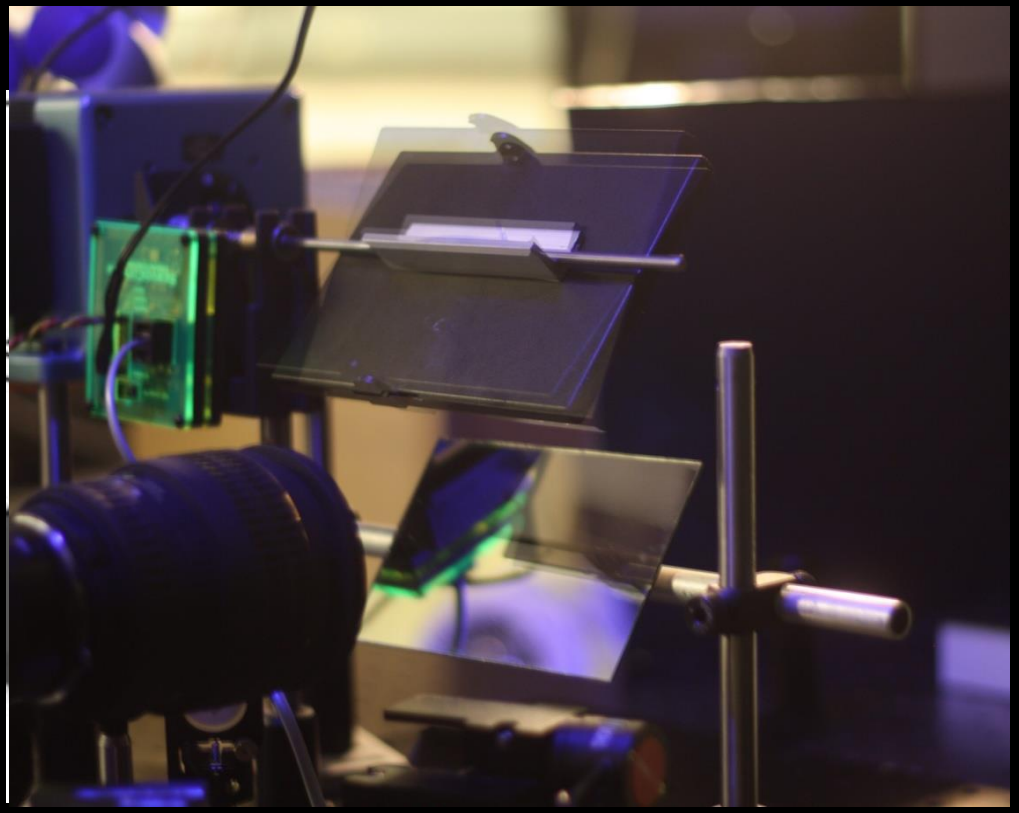


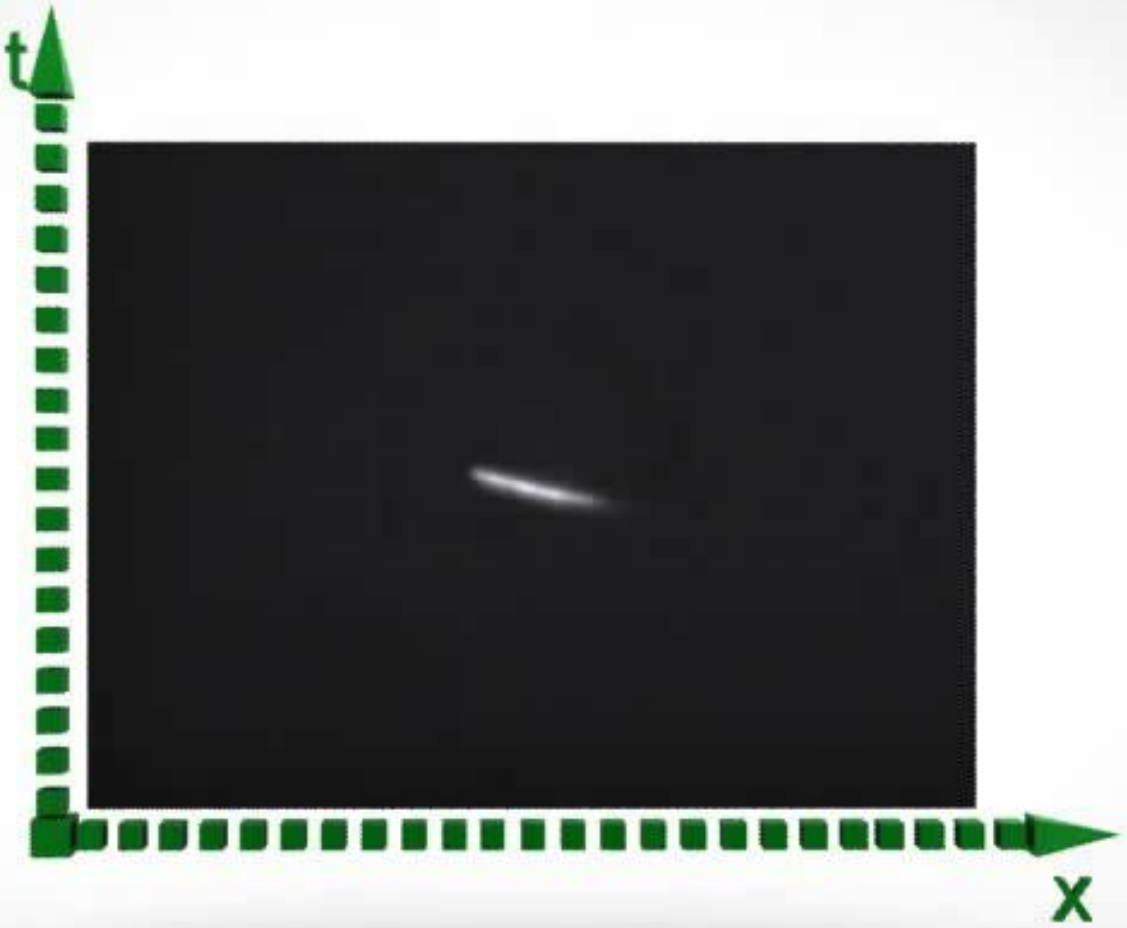
Femto-Photography Setup



Camera Picture – *a 1D Movie*

Going from 1D to 2D

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Coca-Cola
20 FL OZ (1.25 PT) 591 mL