

# Multidimensional Adaptive Sampling and Reconstruction for Ray Tracing

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Richard Peter Weistroffer† Kevin Dale‡  
Greg Humphreys†  
Matthias Zwicker\* Henrik Wann Jensen\*

\*University of California, San Diego

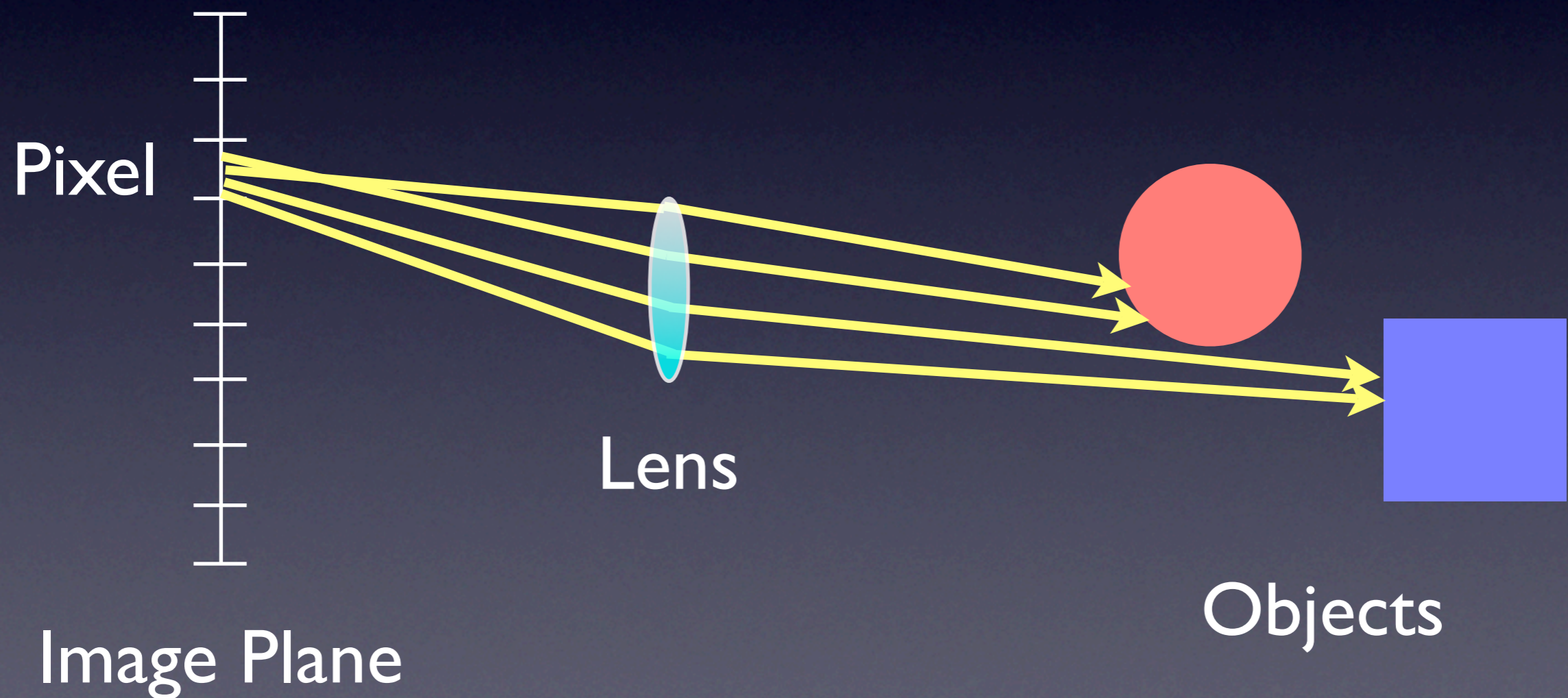
†University of Virginia ‡Harvard University



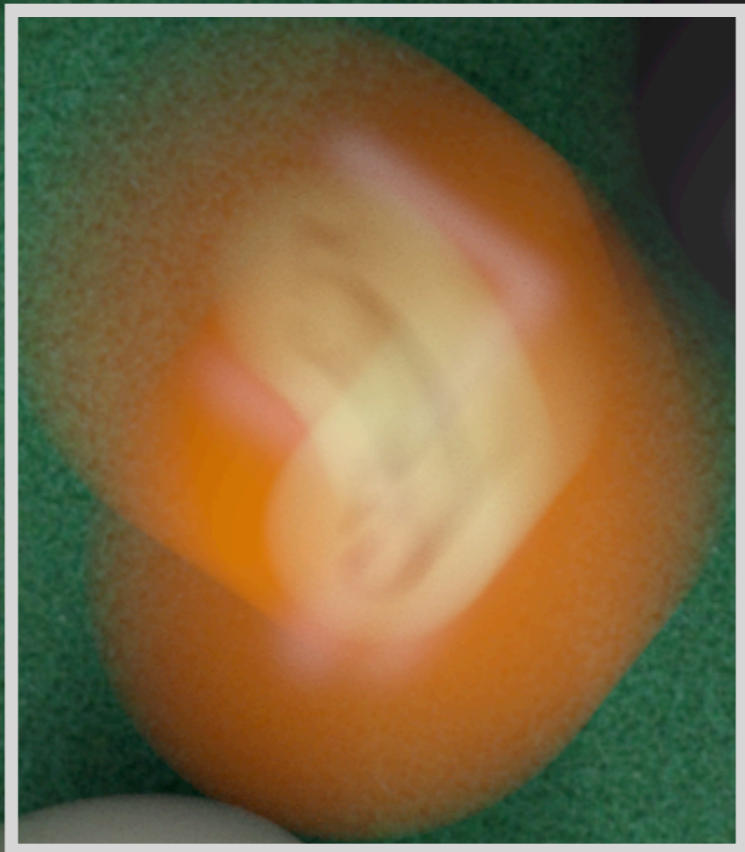


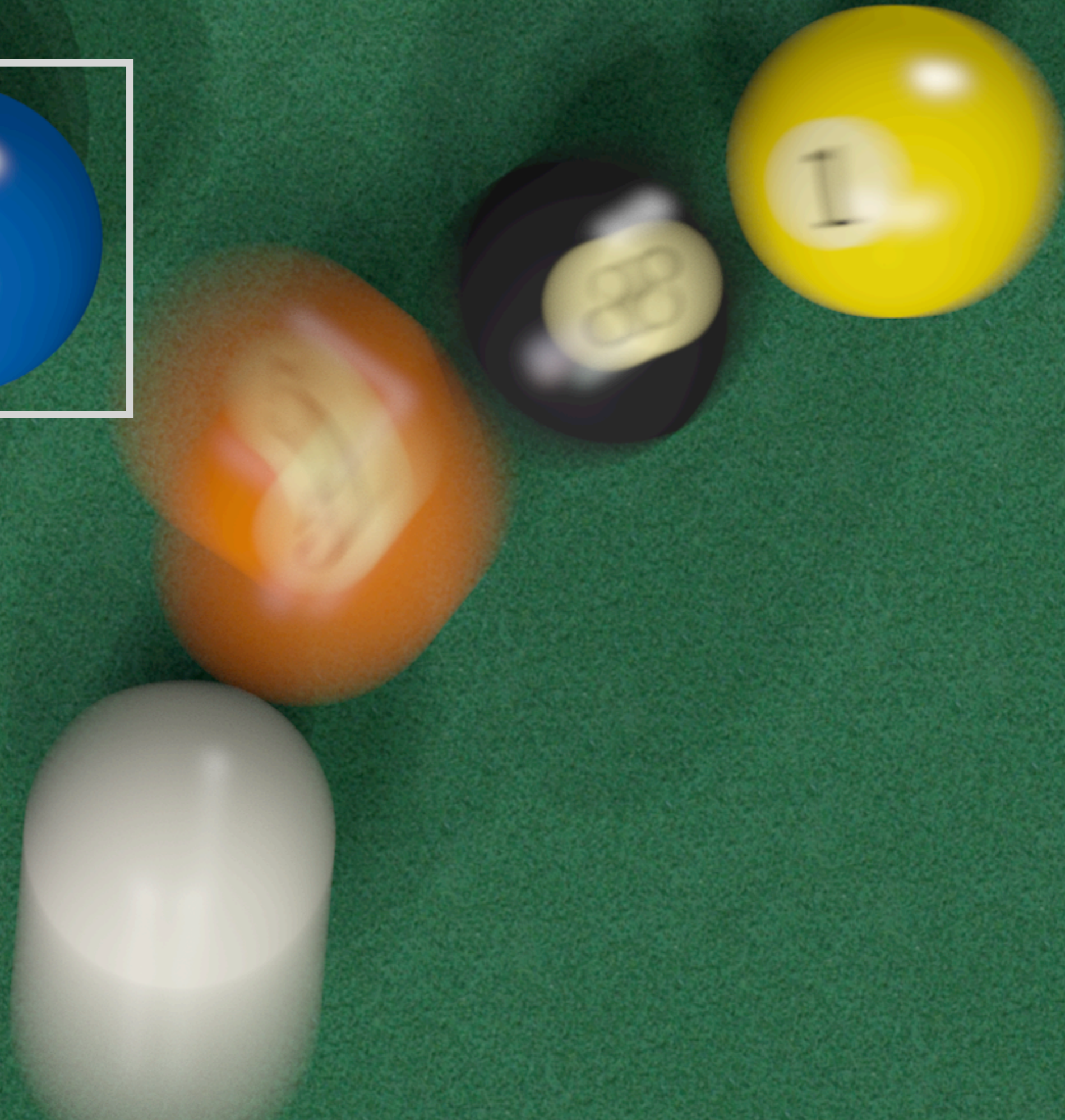
# Sampling and Realistic Rendering

- Distributed ray tracing [Cook et al. 84]









# Adaptive Sampling

## Image based adaptive sampling

- Recursive subdivision [Whitted 80]
- Stochastic adaptive sampling [Mitchell 87, 91]
- Perceptually based criterion [Bolin and Meyer 98]
- Divergence based criterion [Rigau et al. 03]
- MISER [Press and Farrar 90] [Leeson 03]

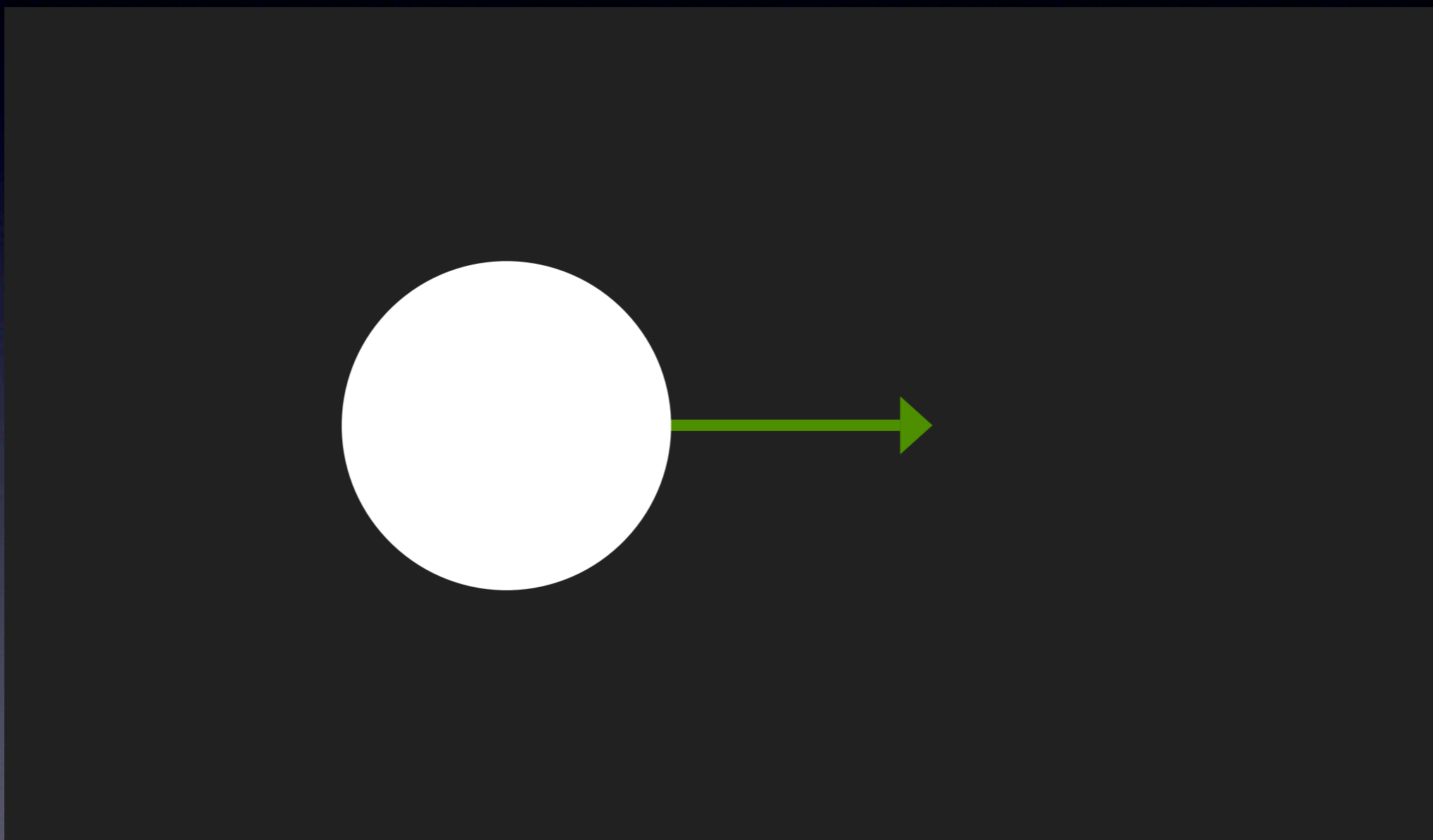


# Adaptive Sampling

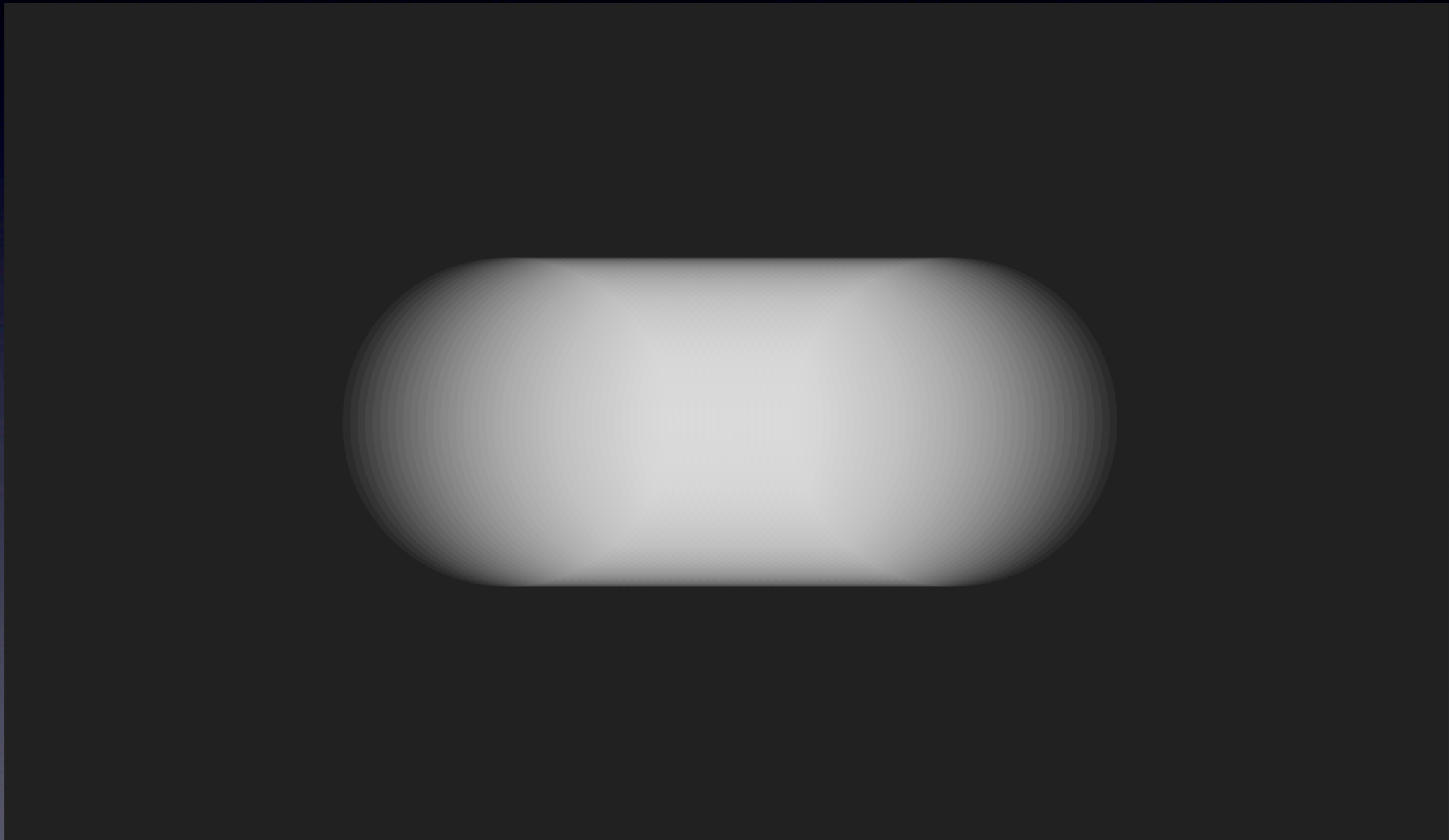
## Image based adaptive sampling

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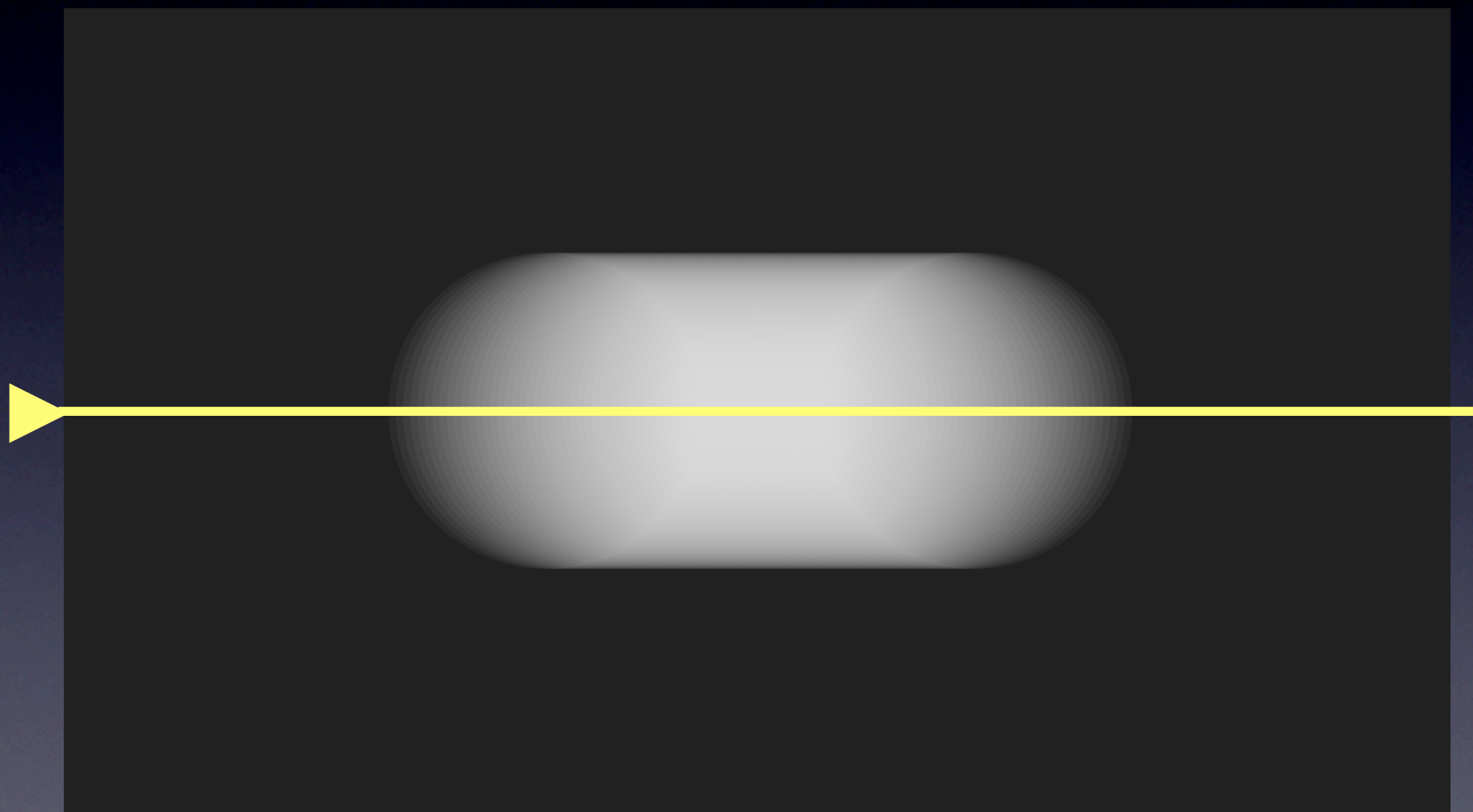
# Motion Blur



# Motion Blur

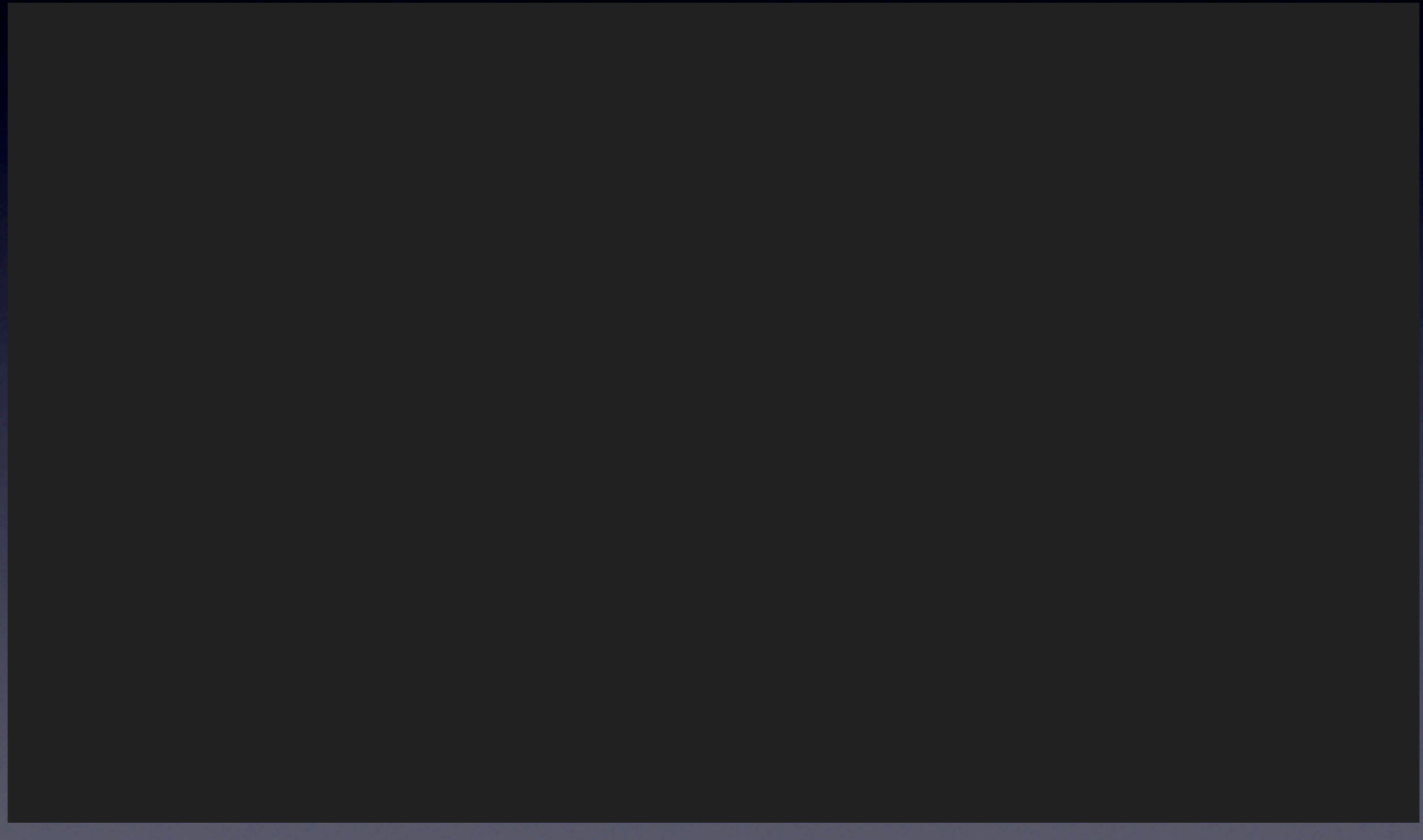


# Motion Blur



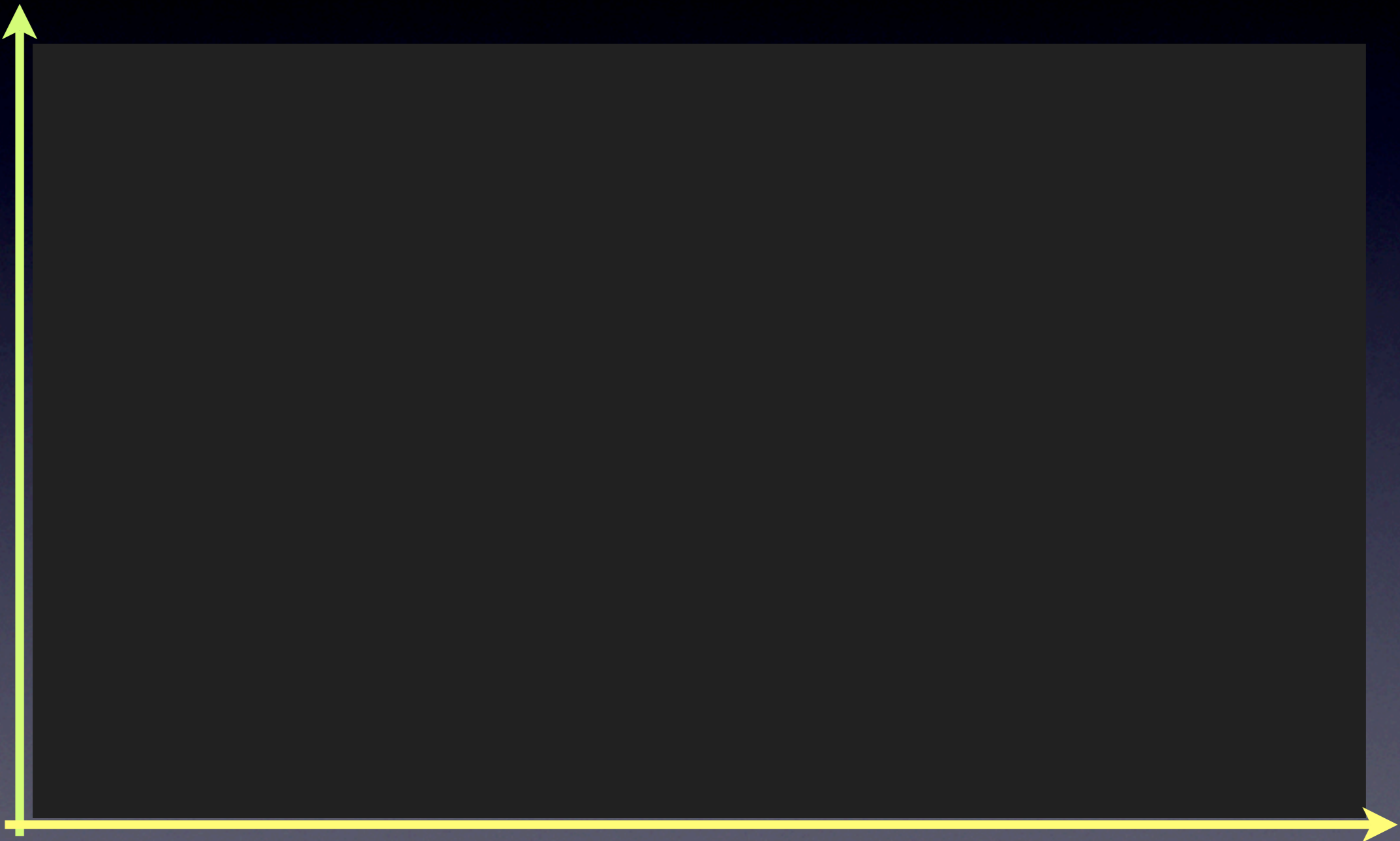
# Motion Blur

Time ↑



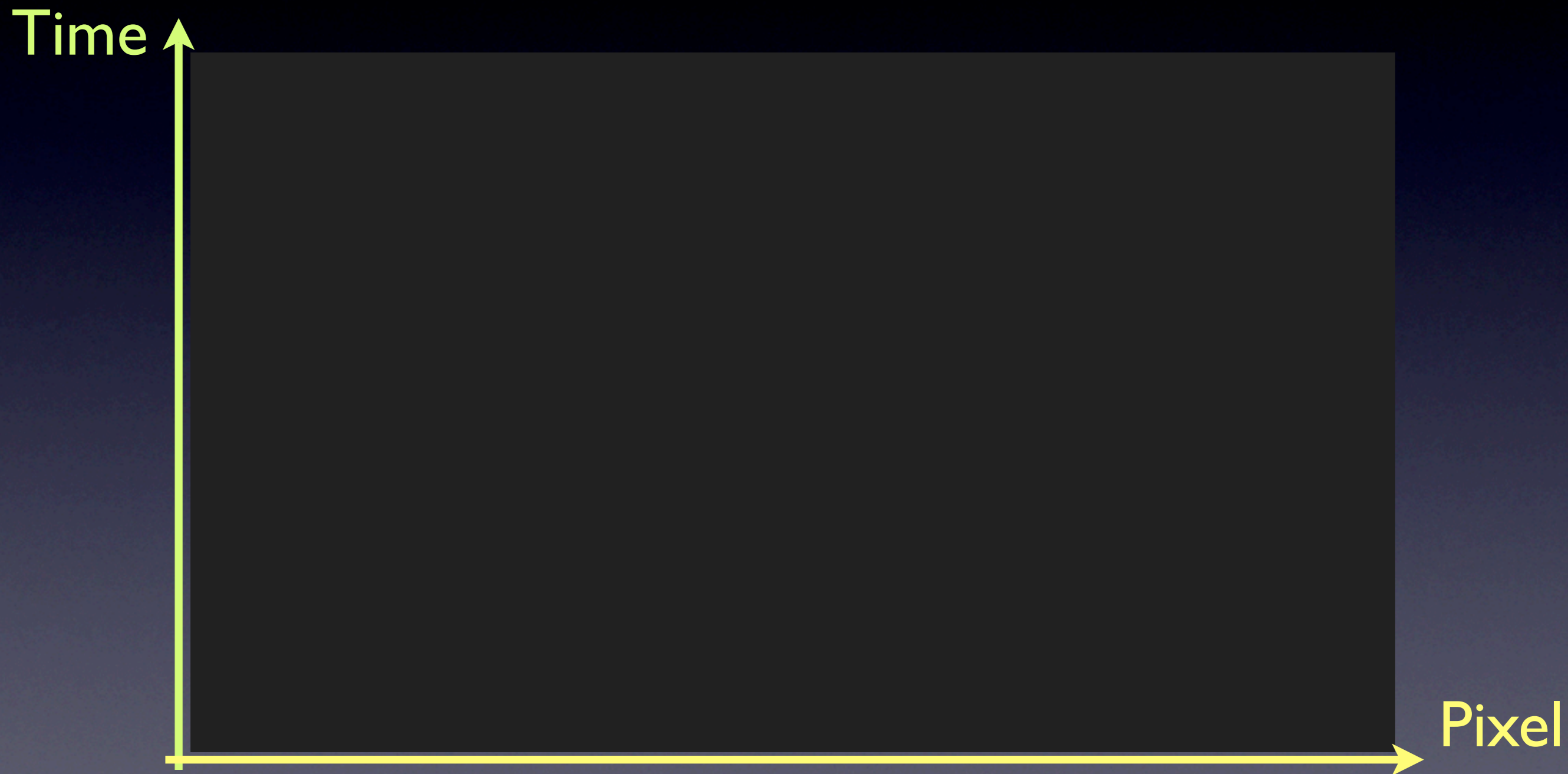
# Motion Blur

Time

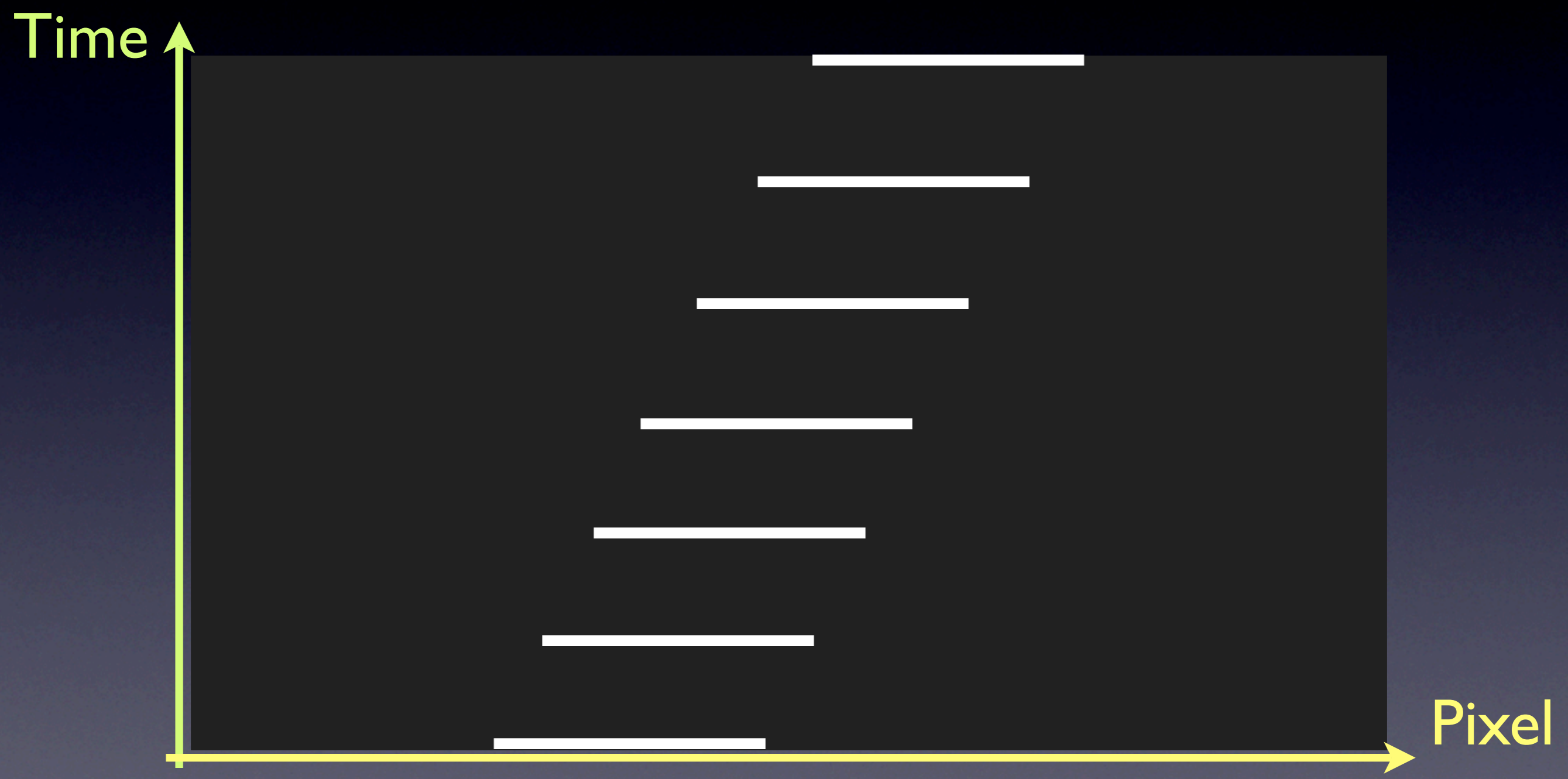


Pixel

# Motion Blur



# Motion Blur

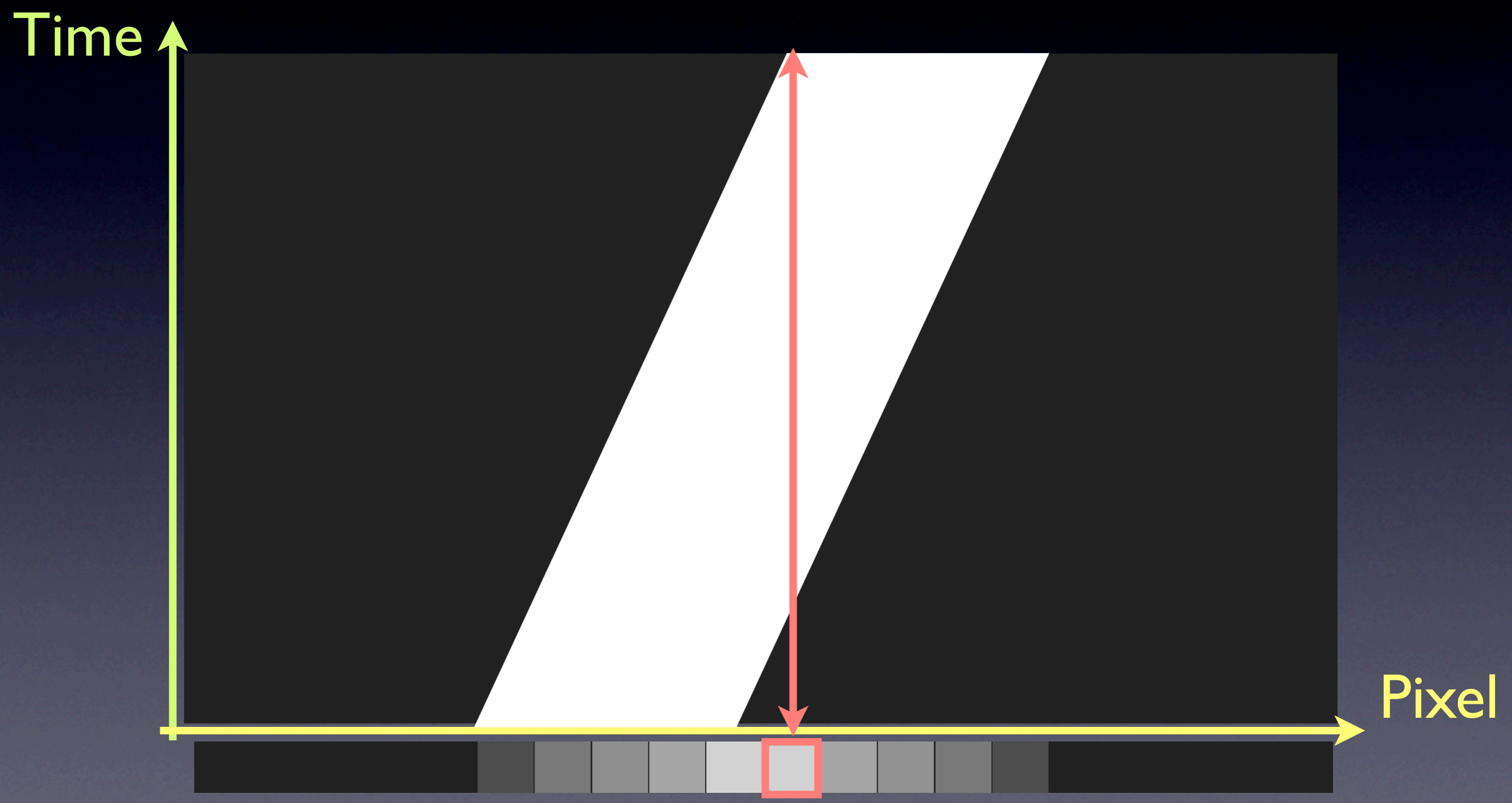




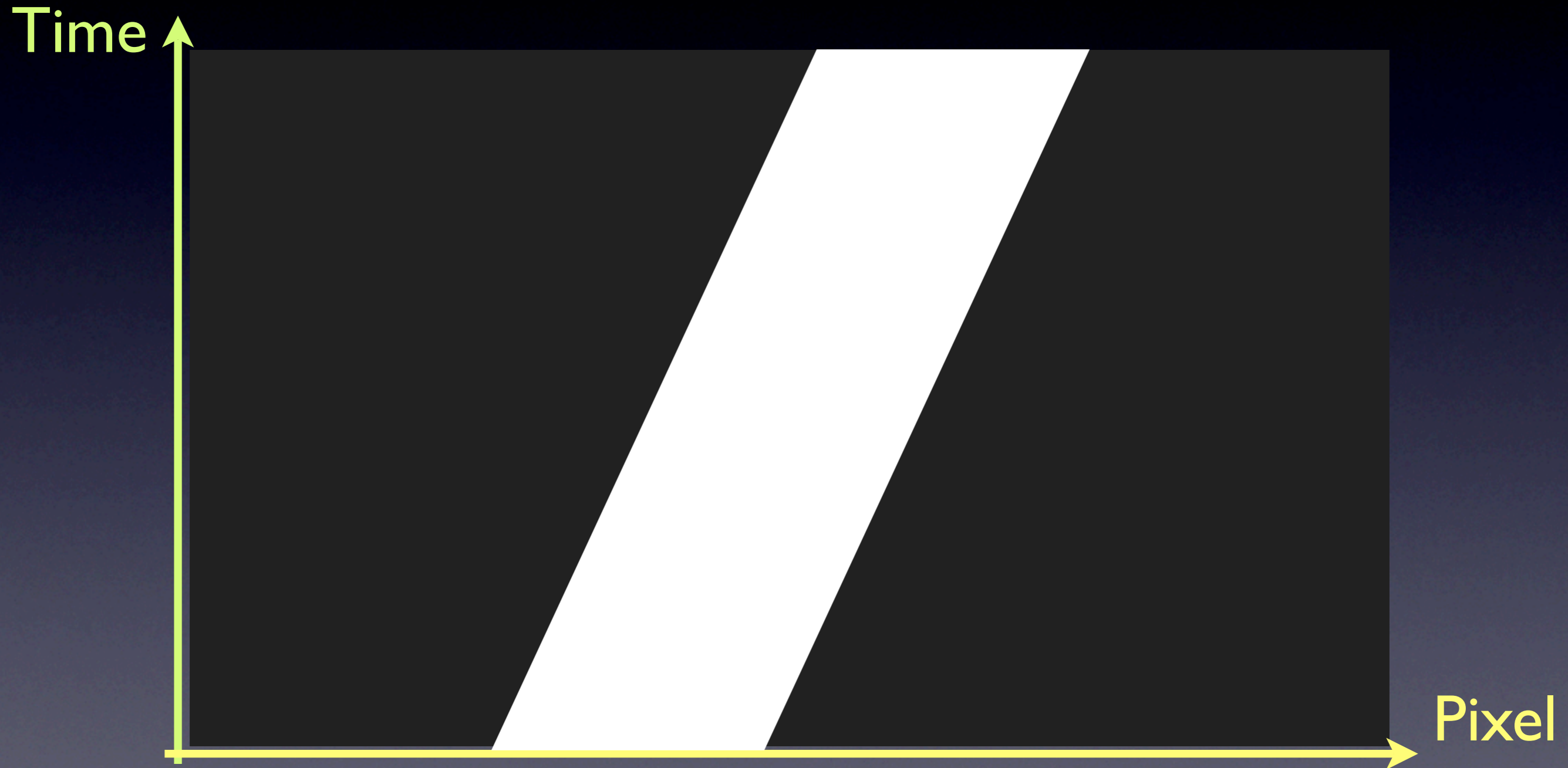
# Motion Blur



# Motion Blur



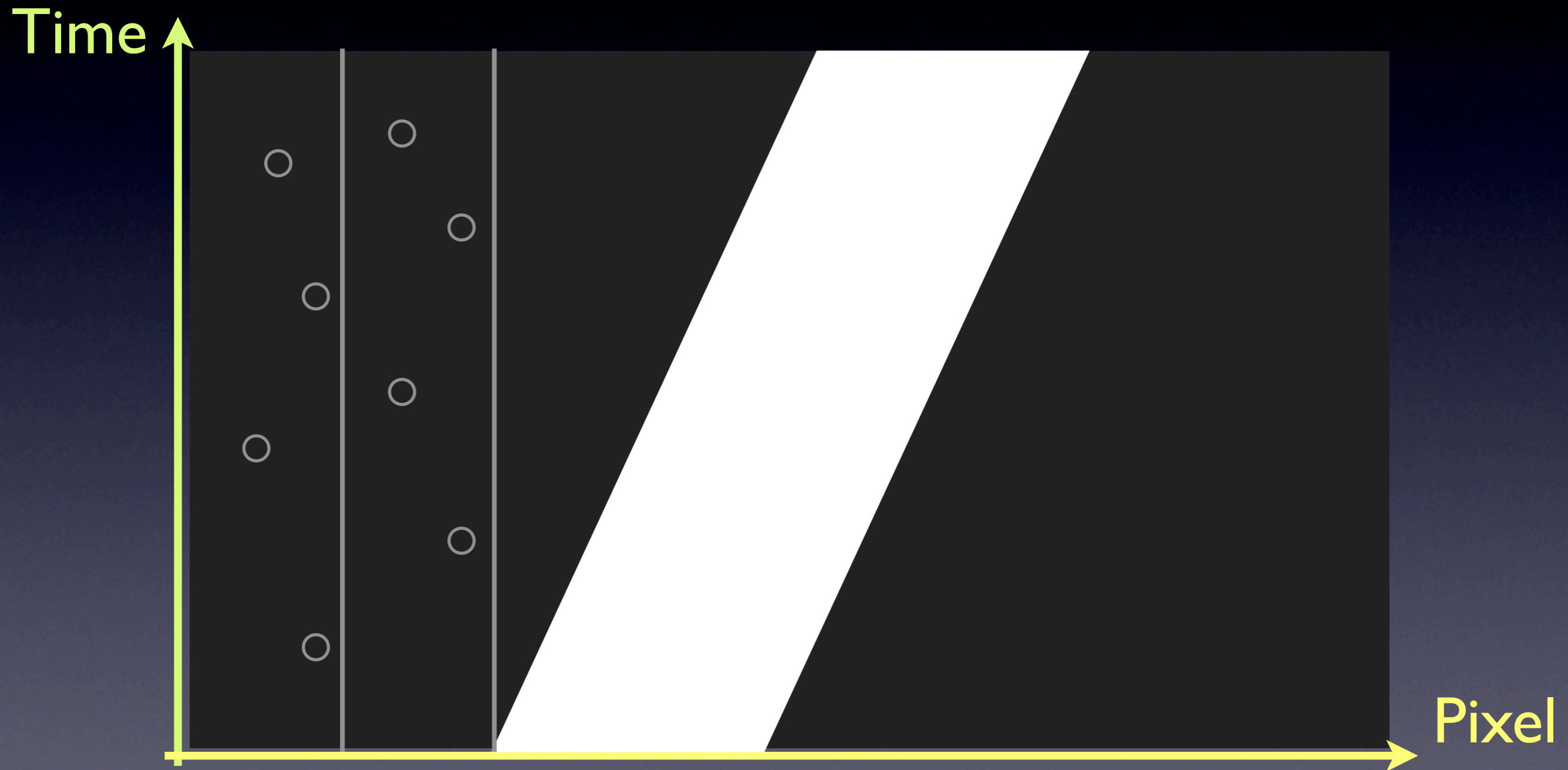
# Adaptive Sampling [Mitchell 91]



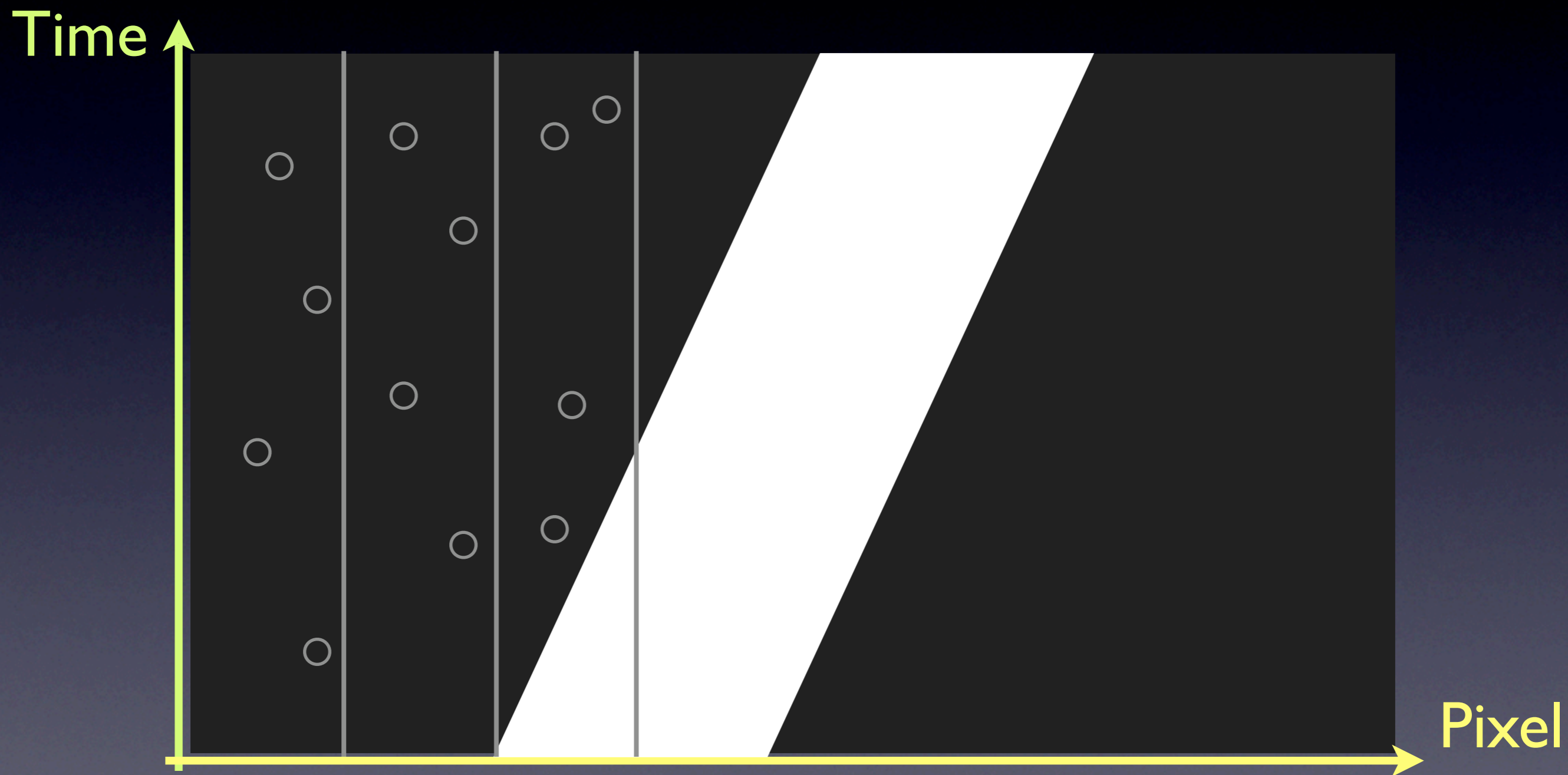
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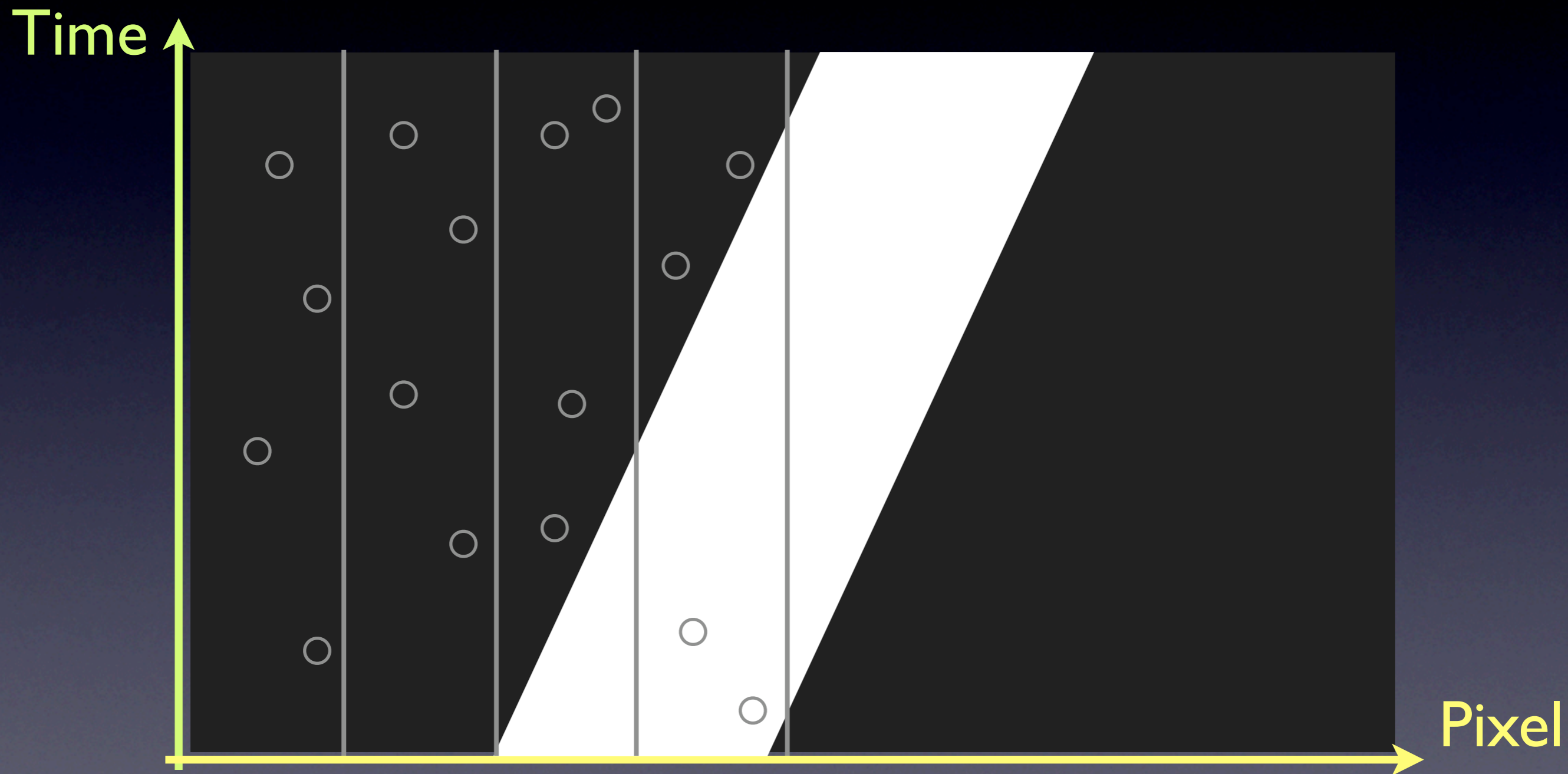
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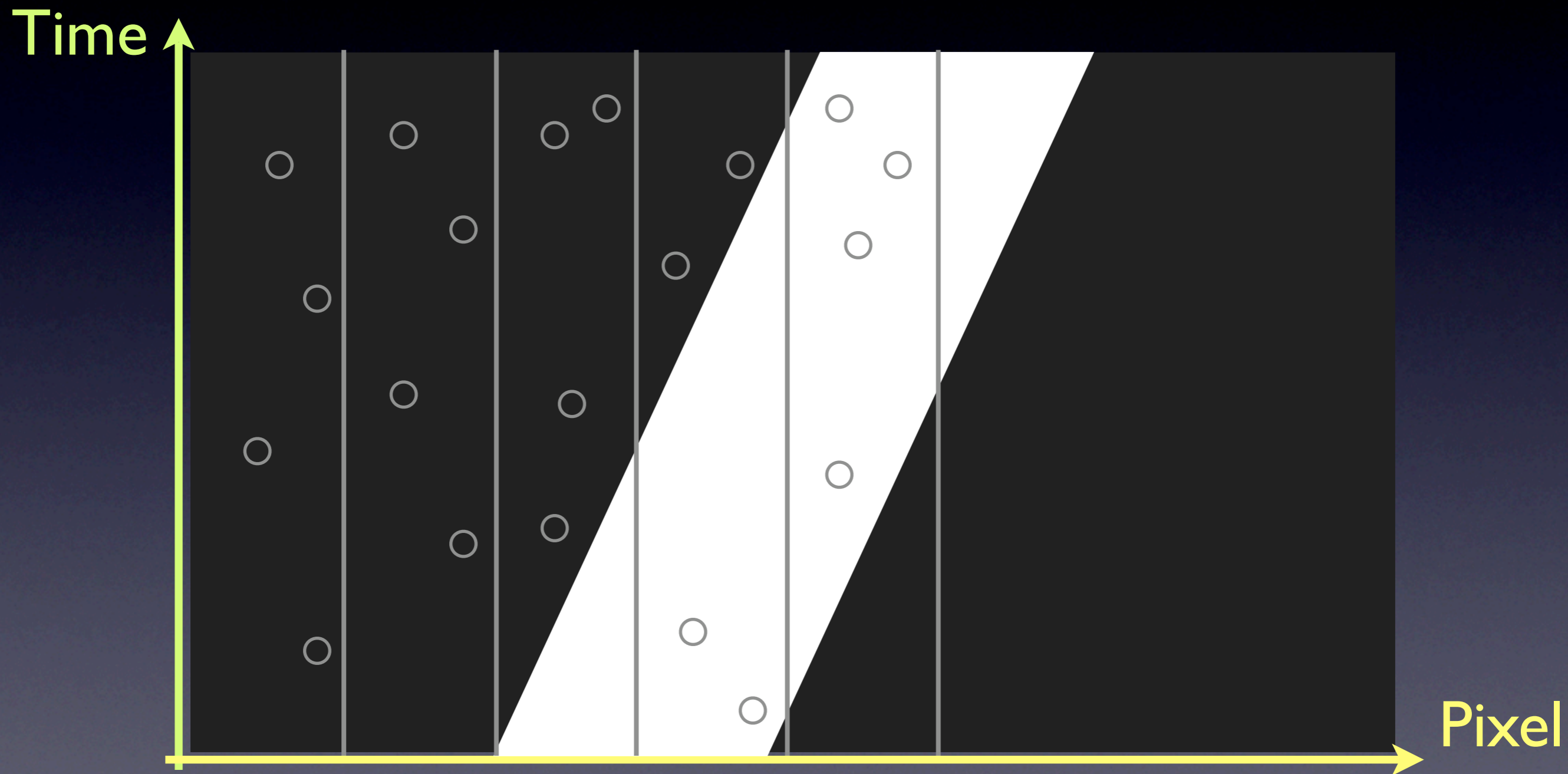
# Adaptive Sampling [Mitchell 91]



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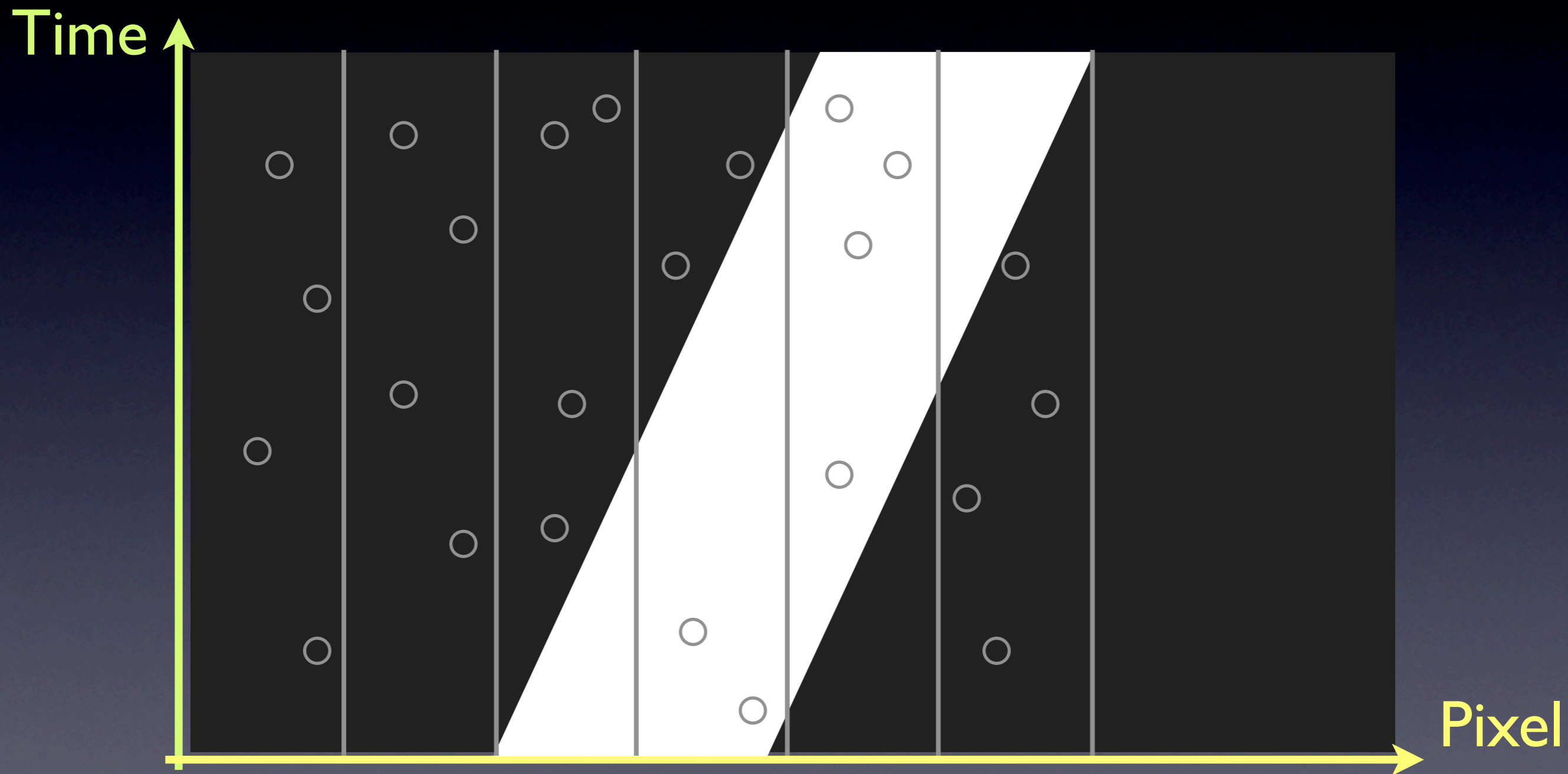


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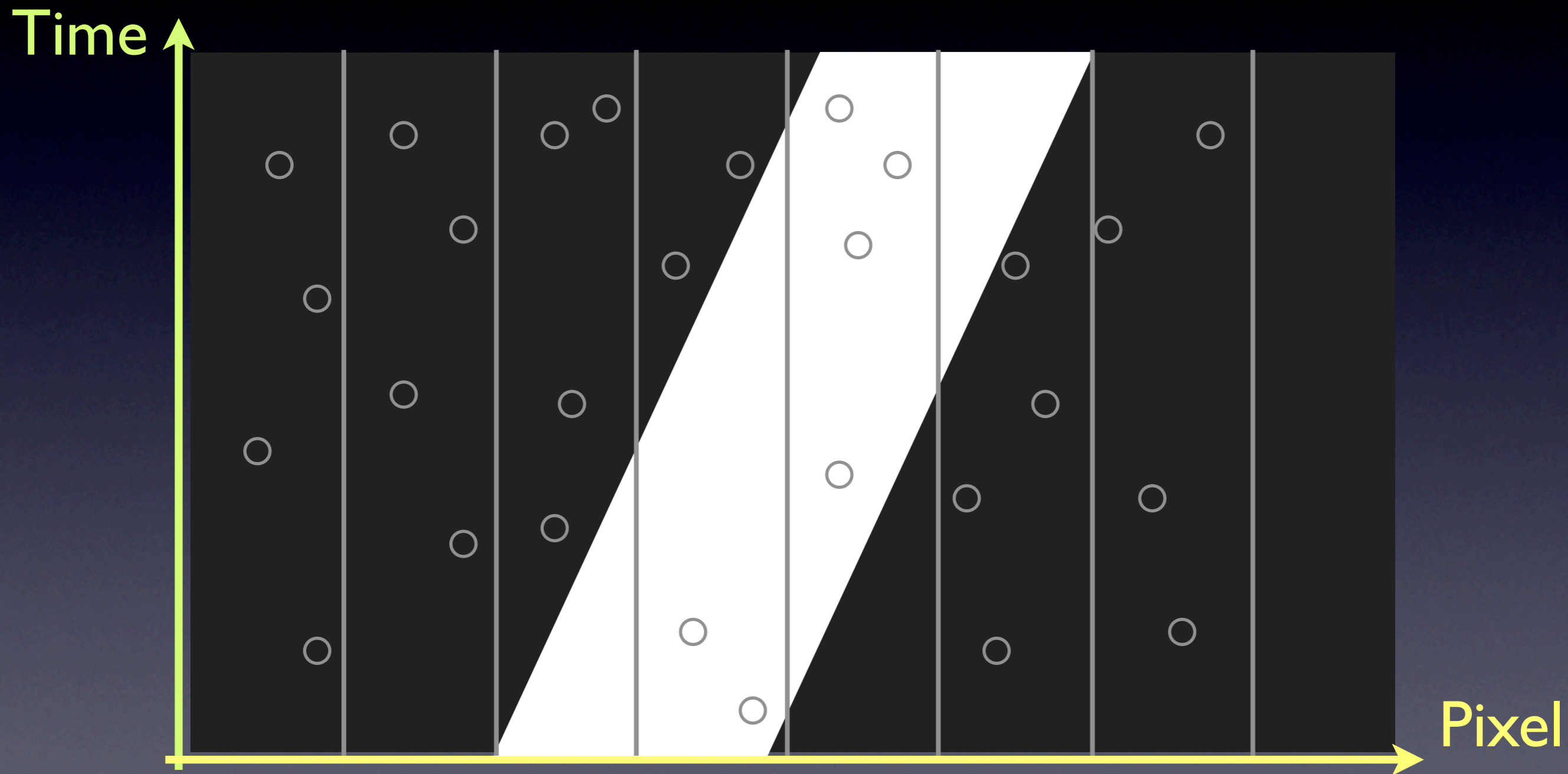




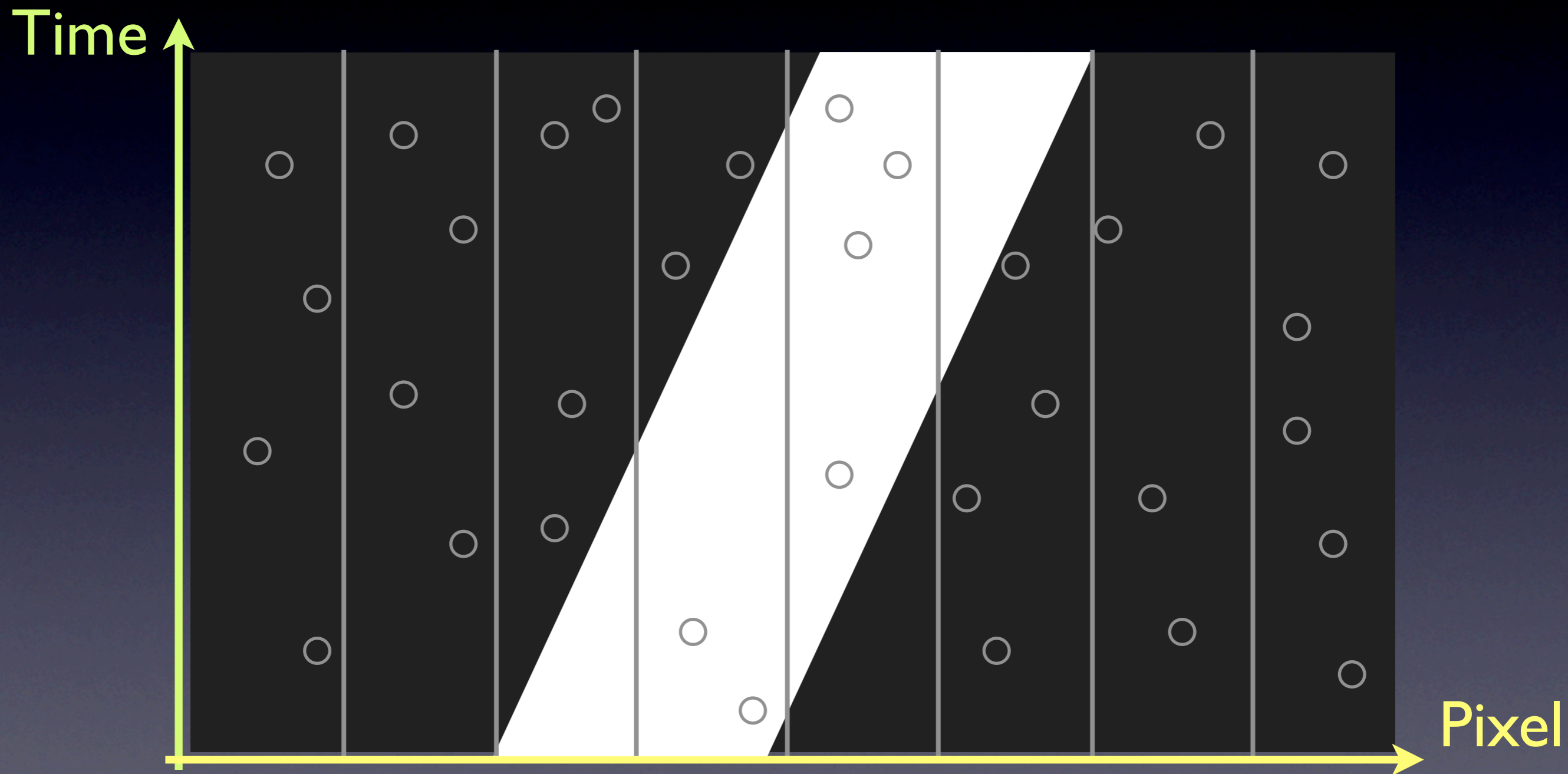
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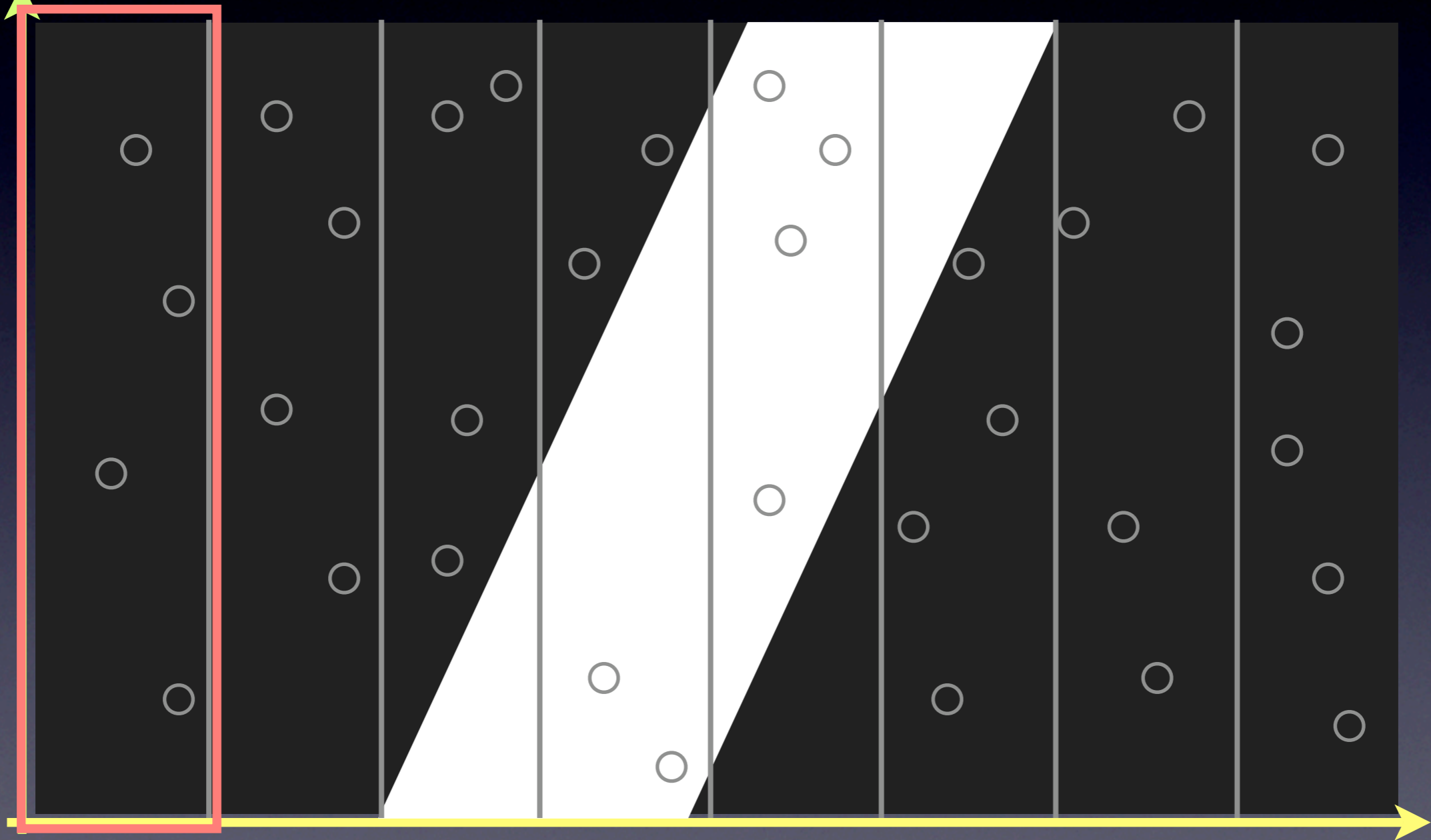


# Adaptive Sampling [Mitchell 91]



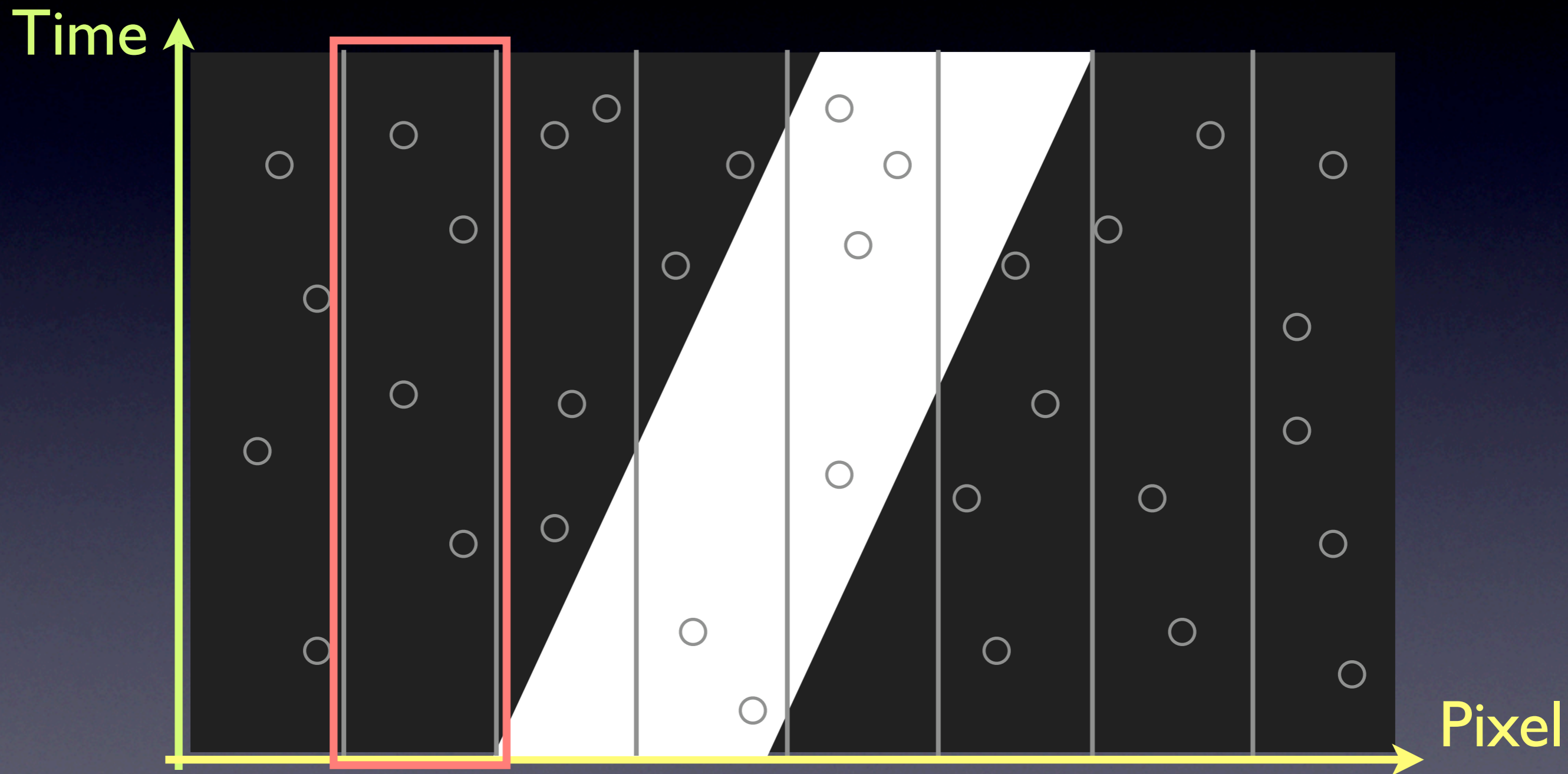
# Adaptive Sampling [Mitchell 91]

Time ↑

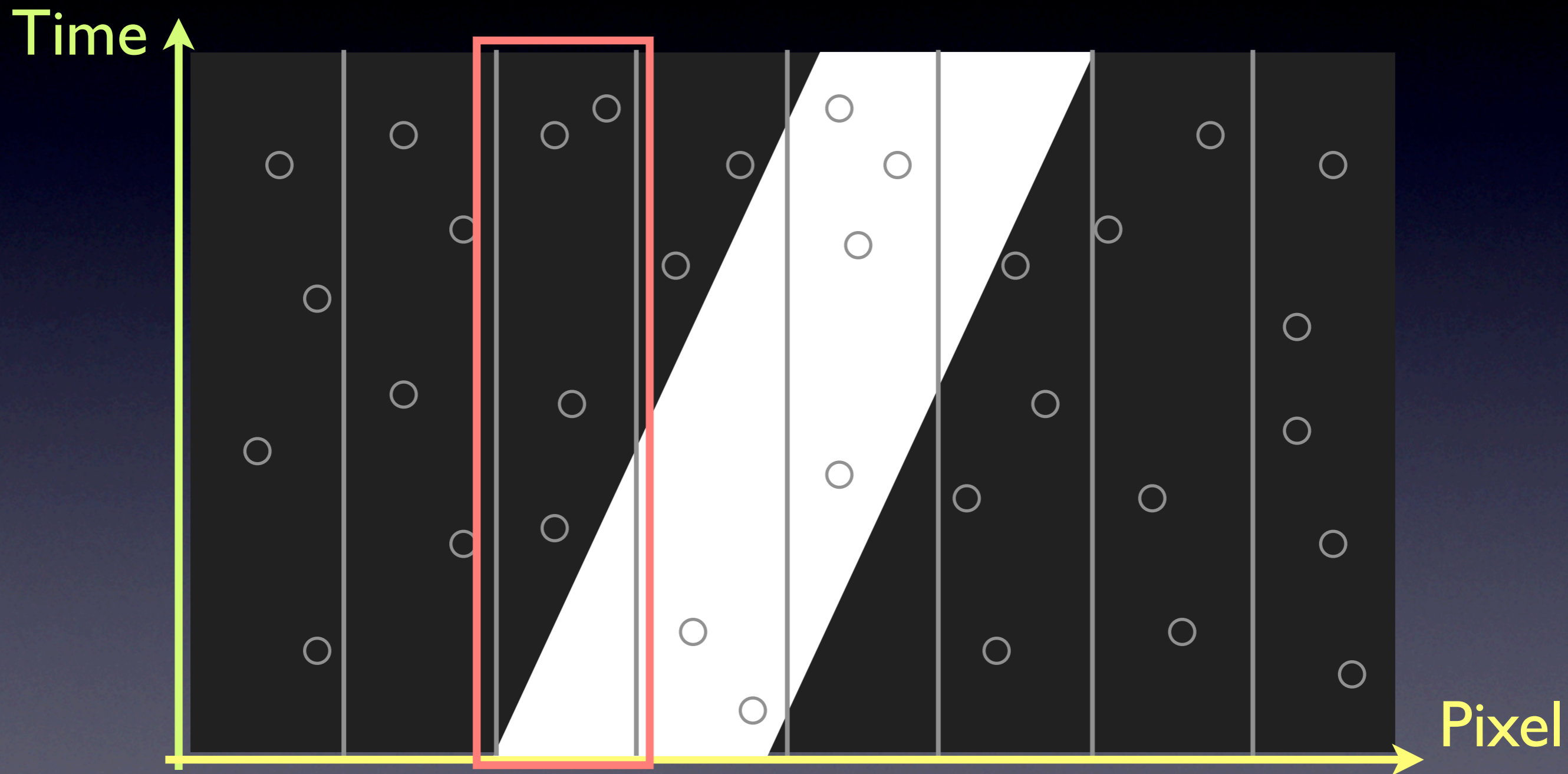


Pixel →

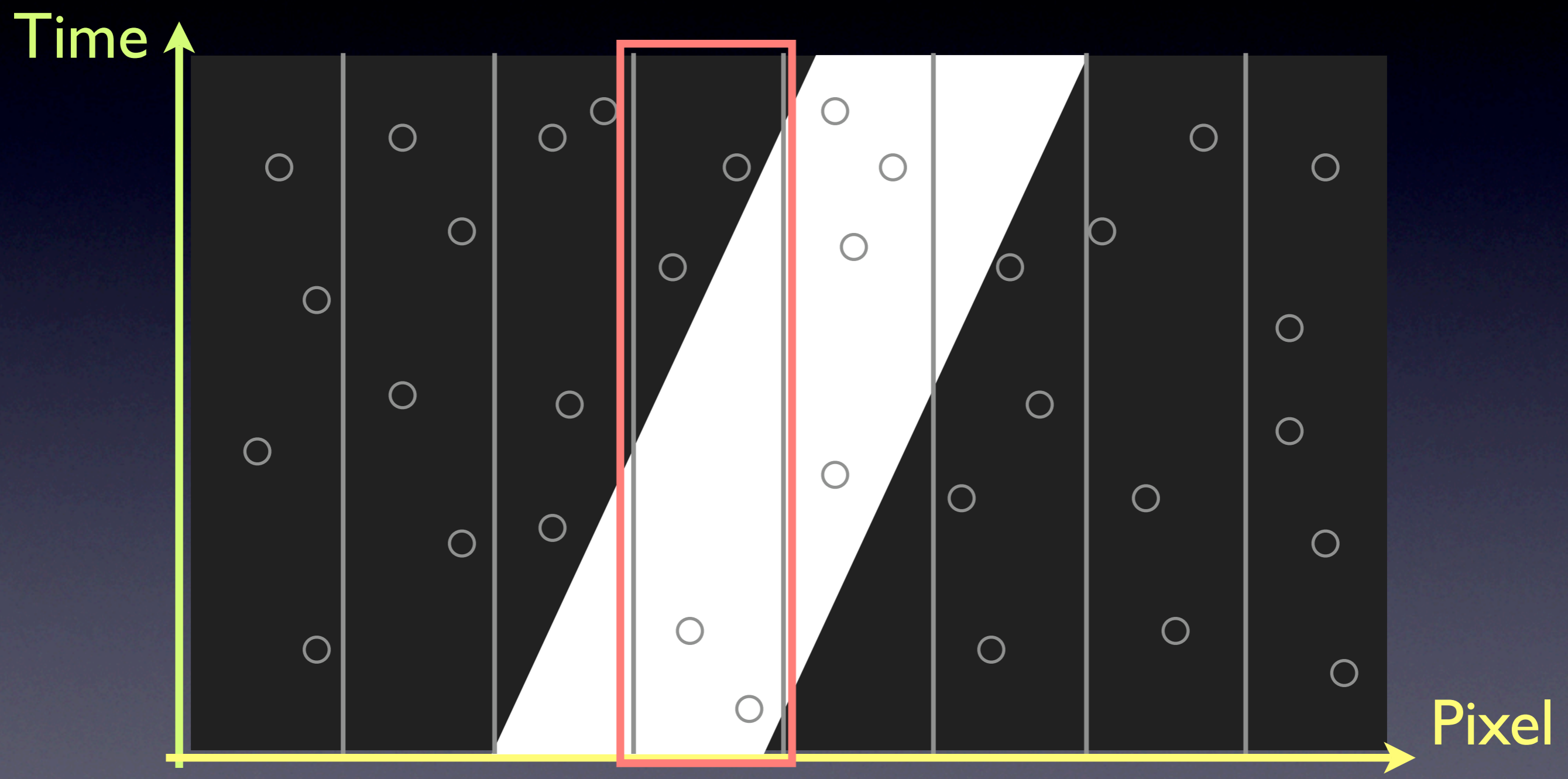
# Adaptive Sampling [Mitchell 91]



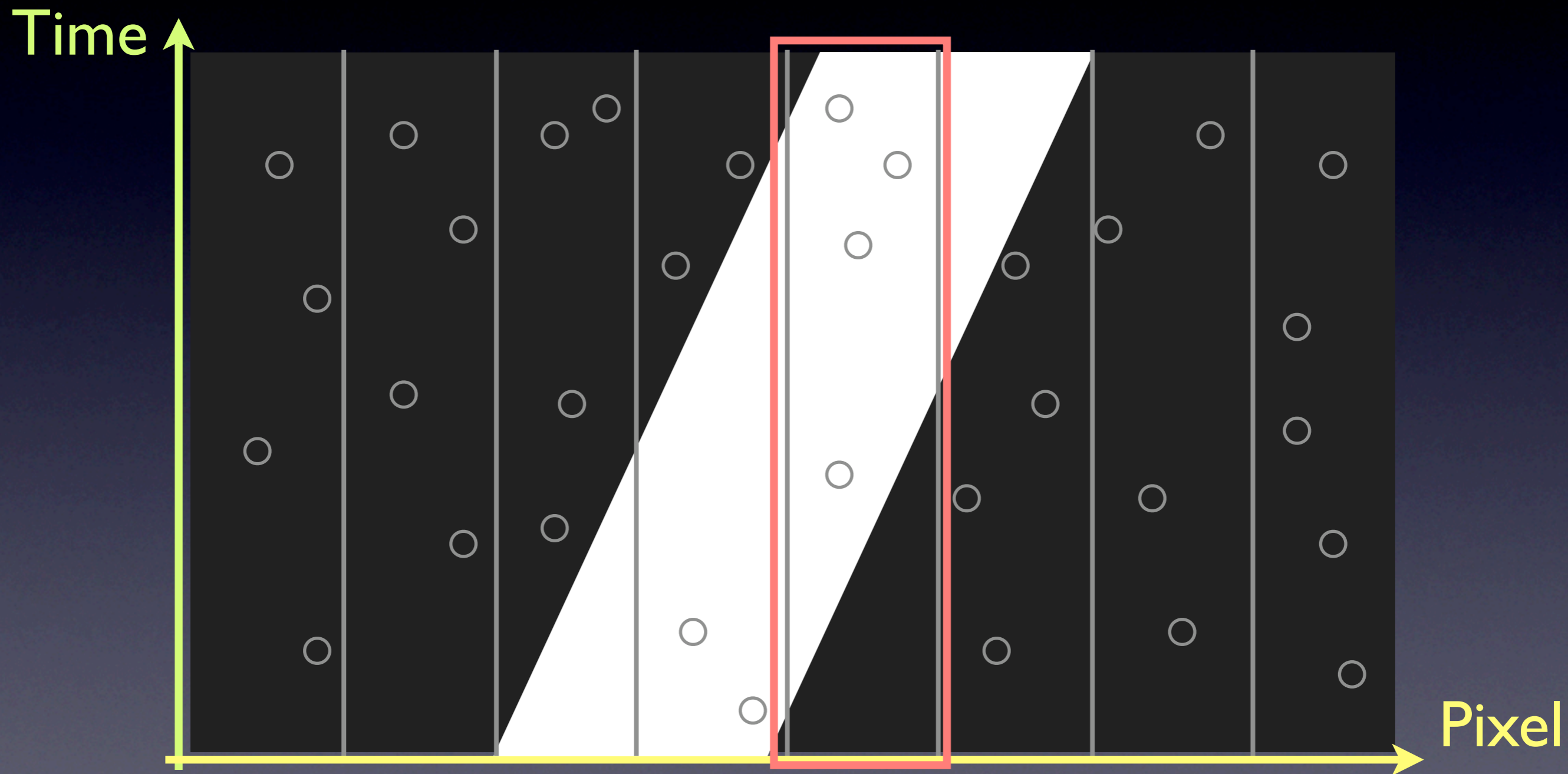
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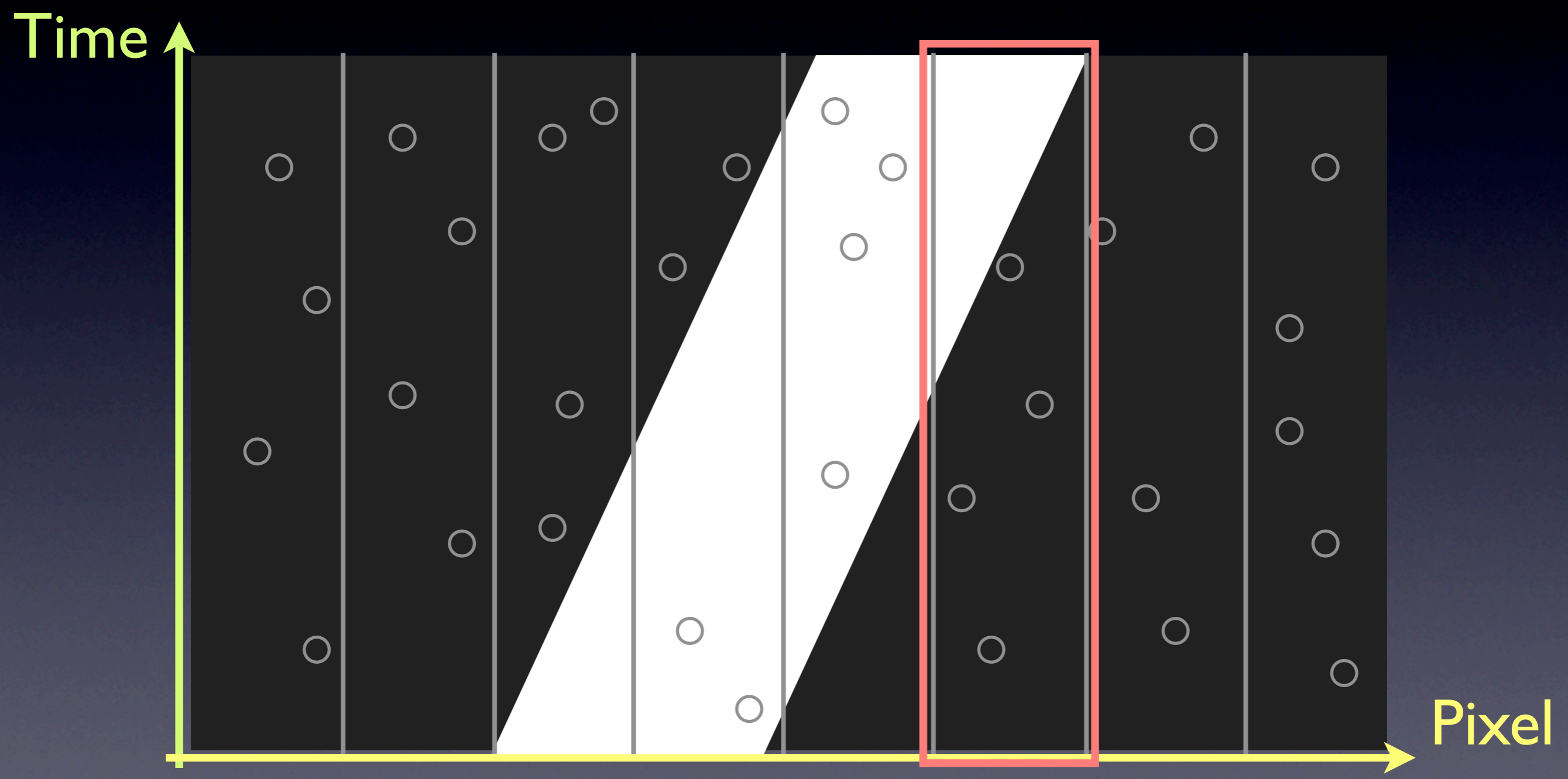


# Adaptive Sampling [Mitchell 91]

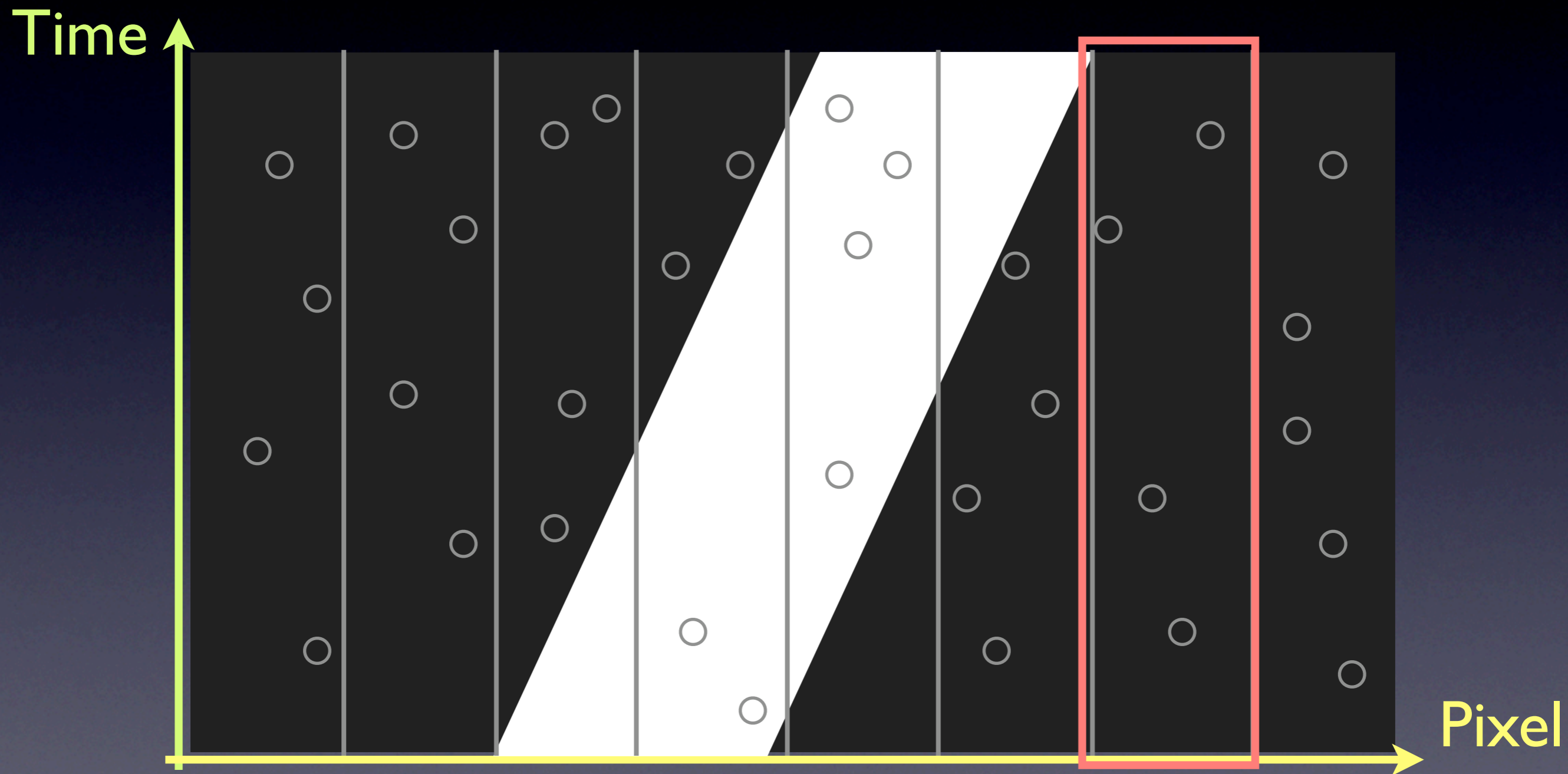




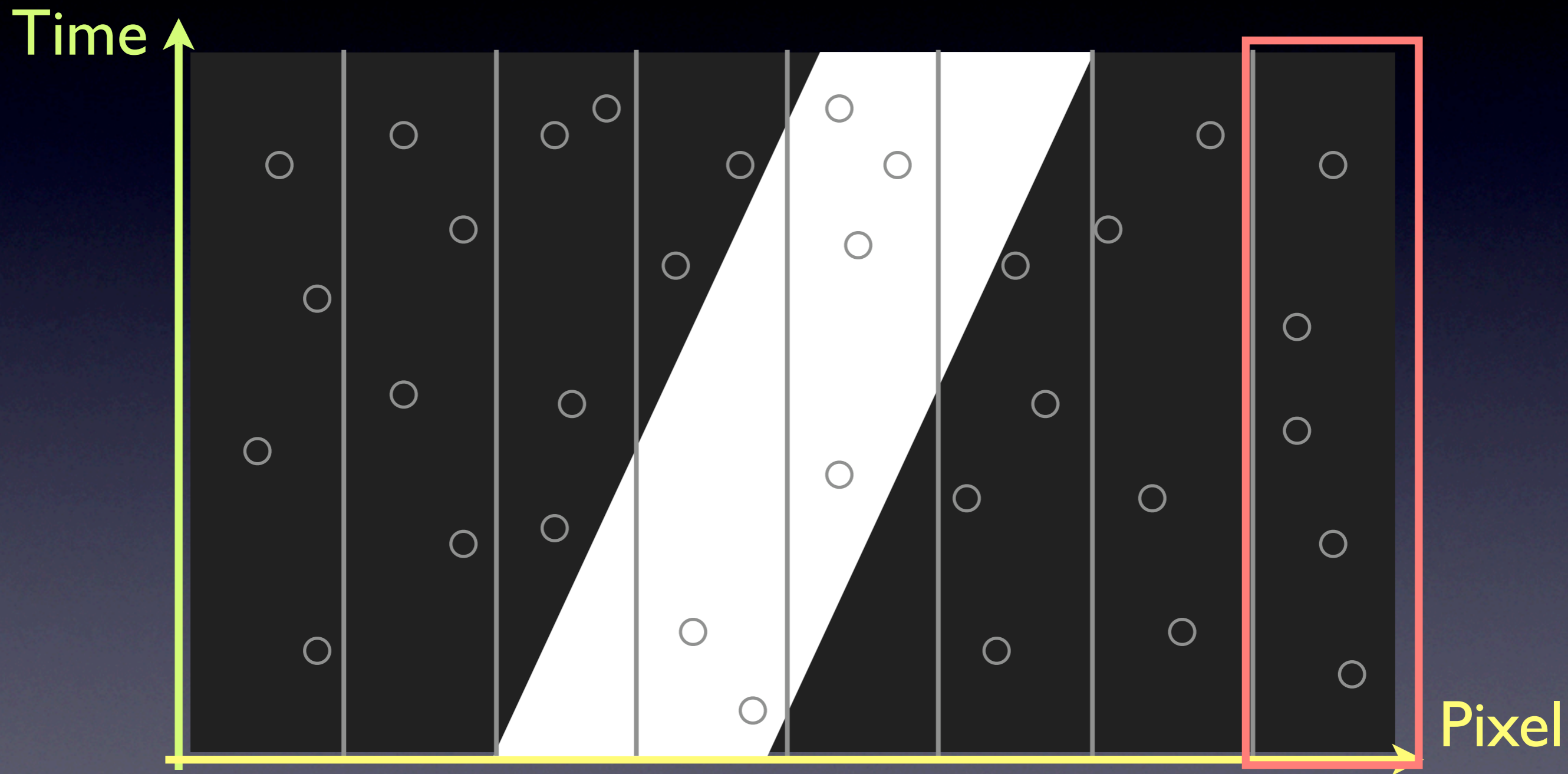
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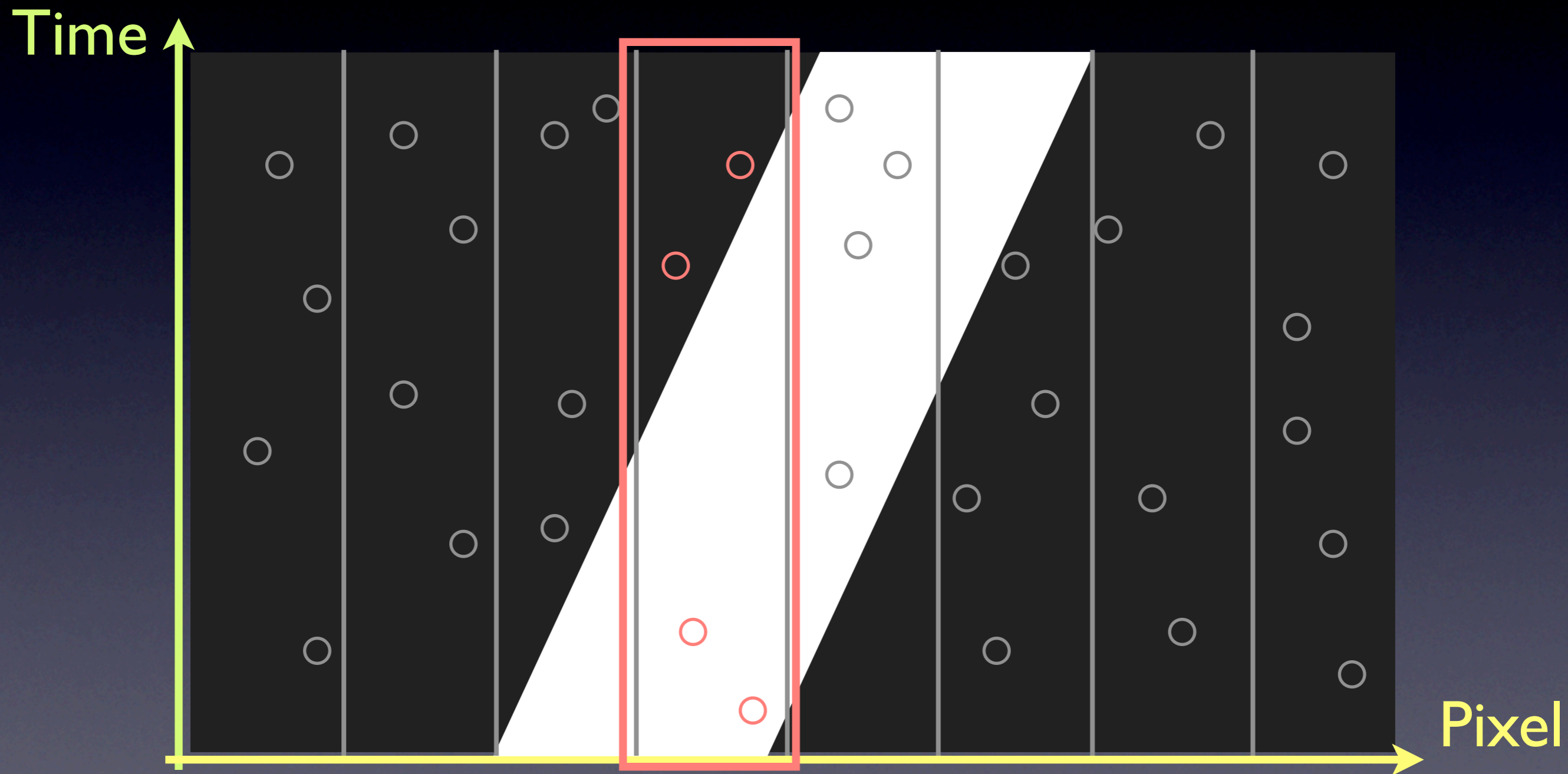
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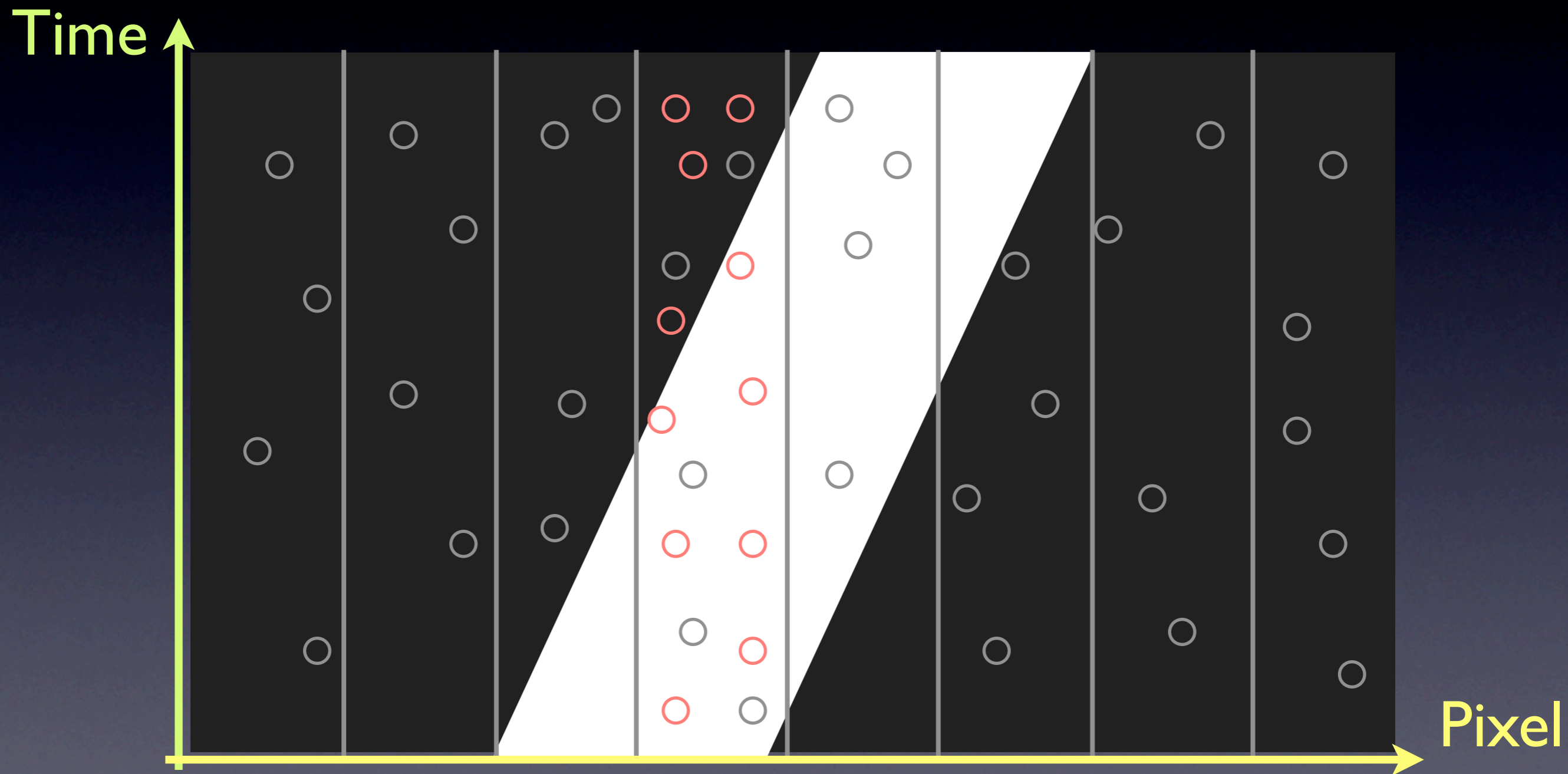
# Adaptive Sampling [Mitchell 91]



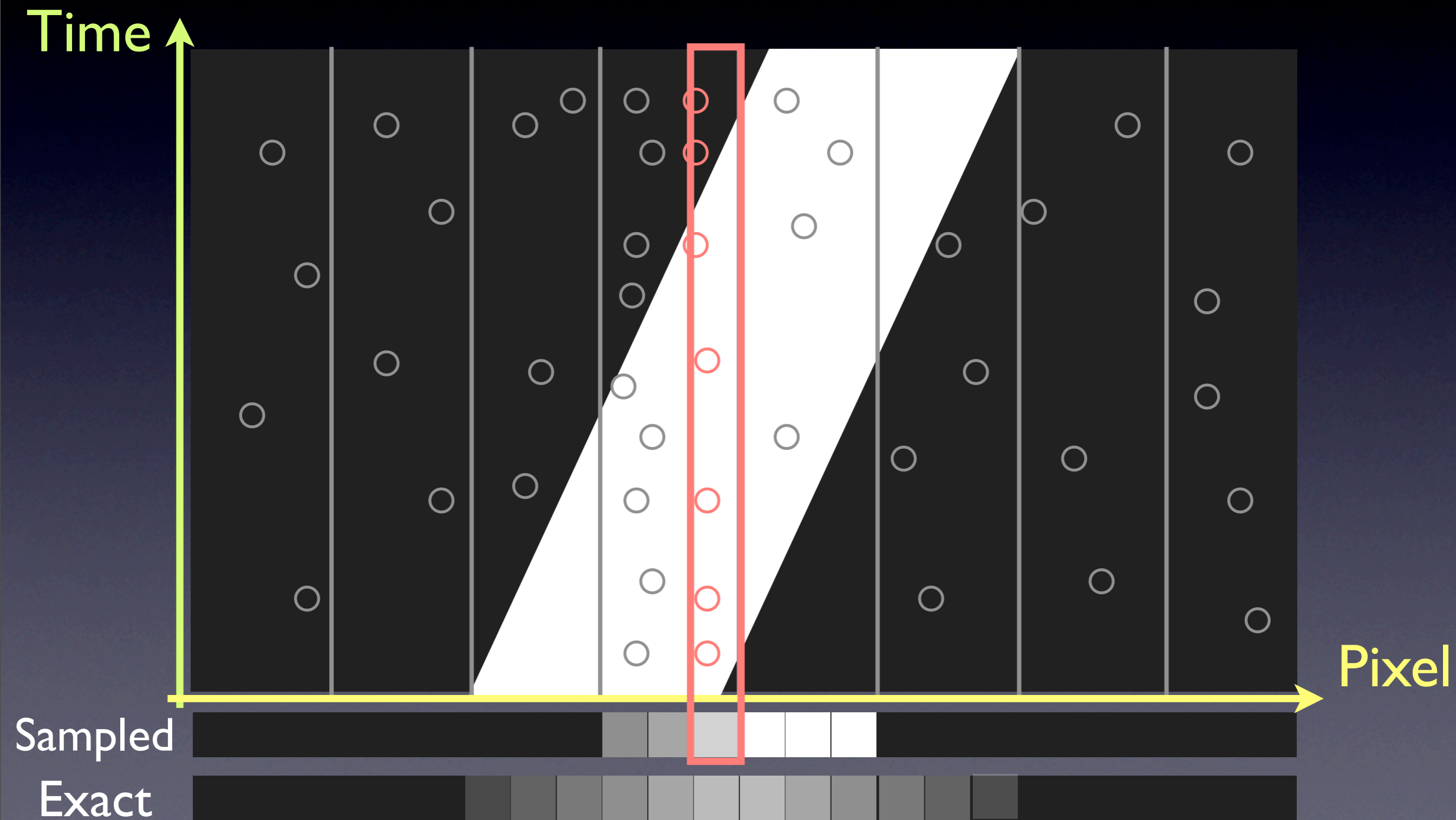
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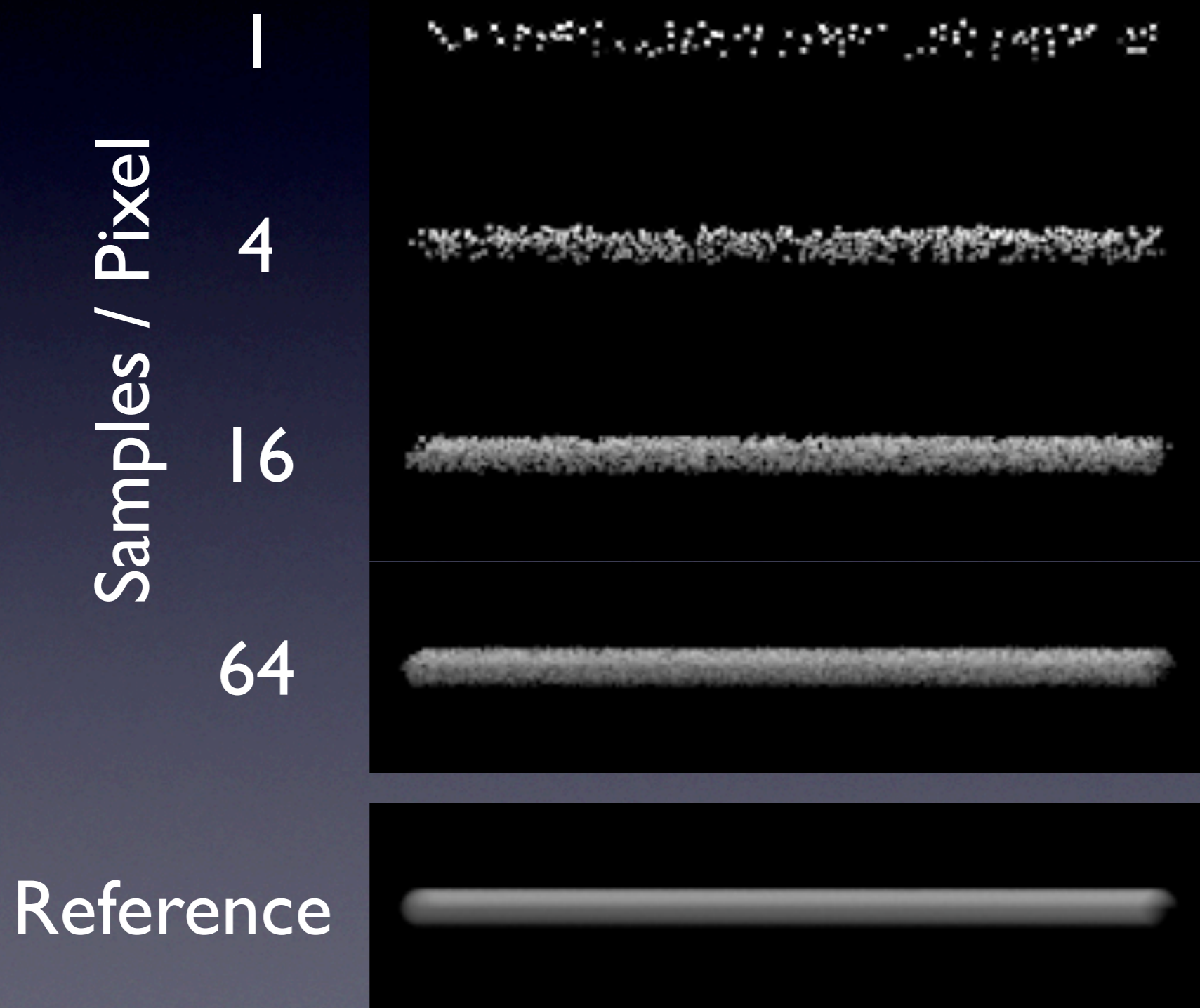
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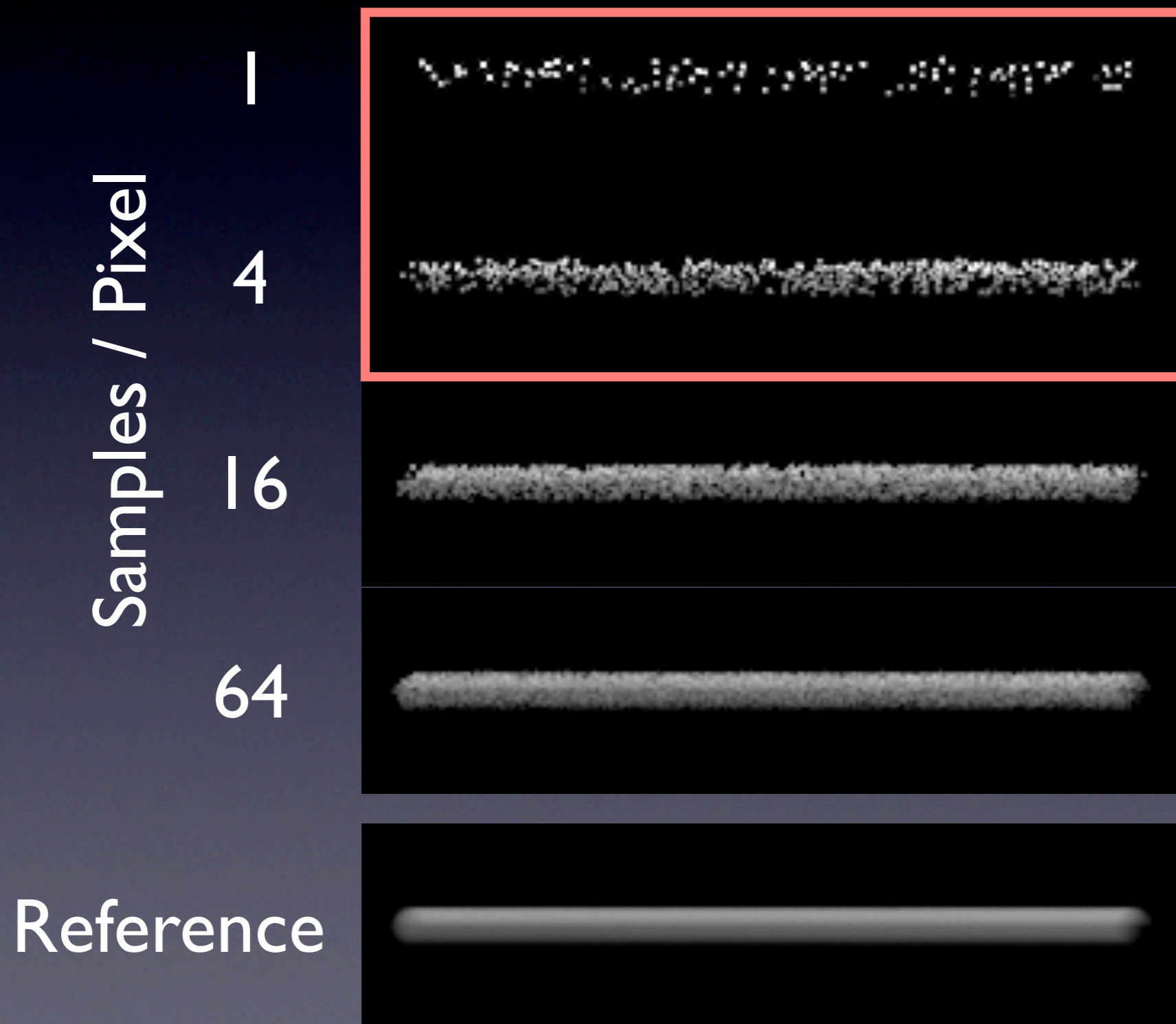
# Adaptive Sampling [Mitchell 91]



# Motion Blurred Sphere

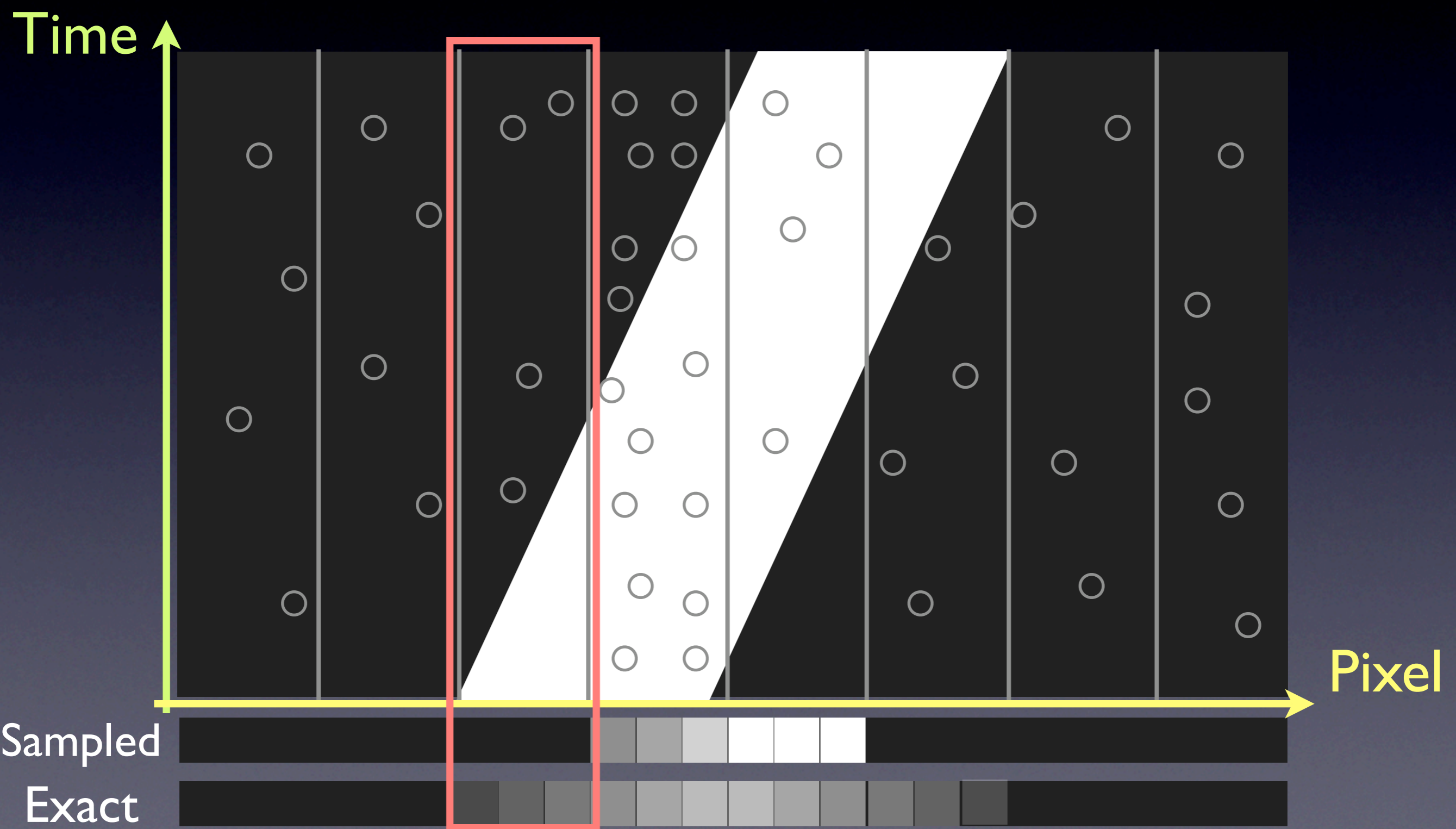


# Motion Blurred Sphere





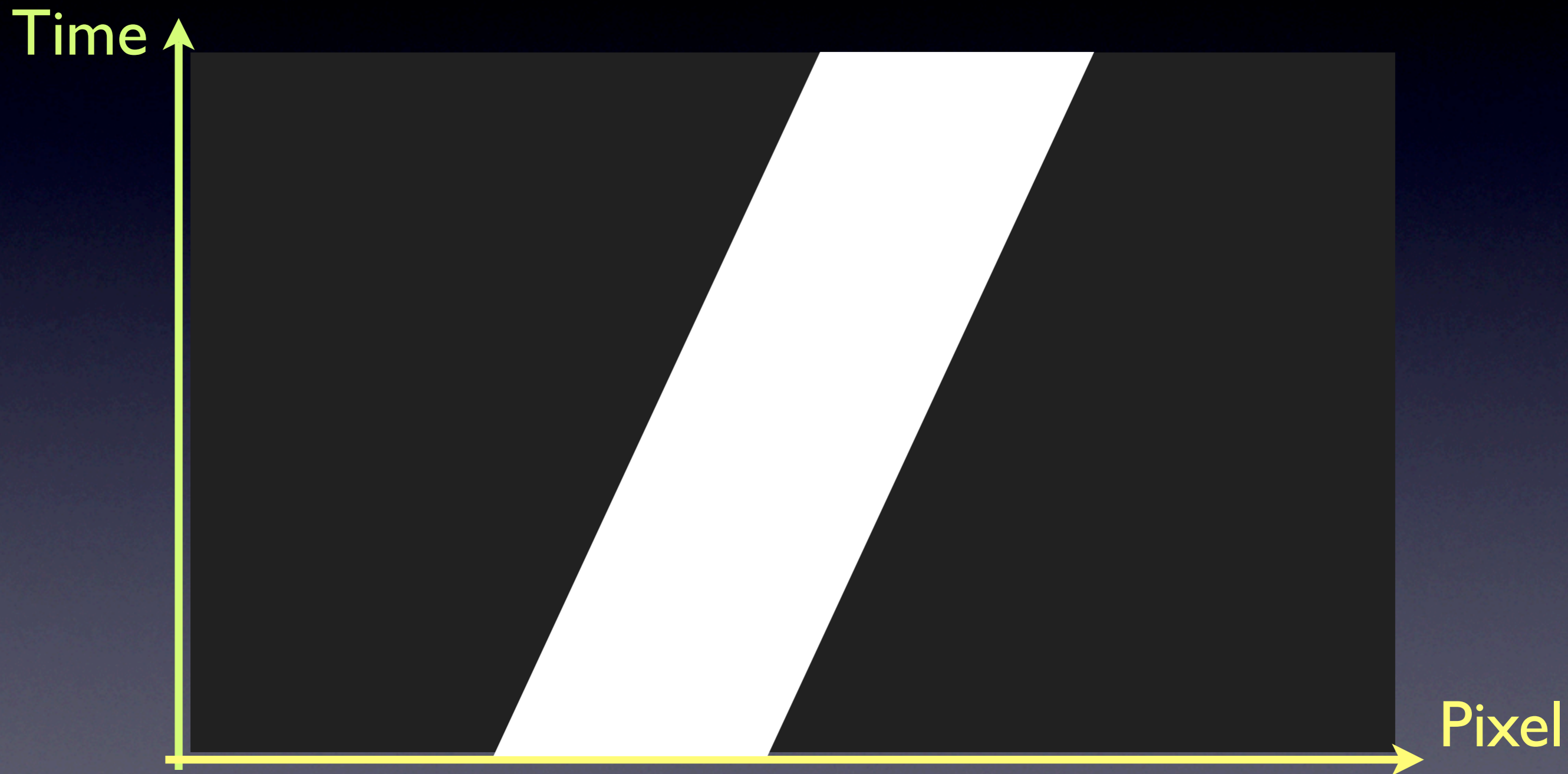
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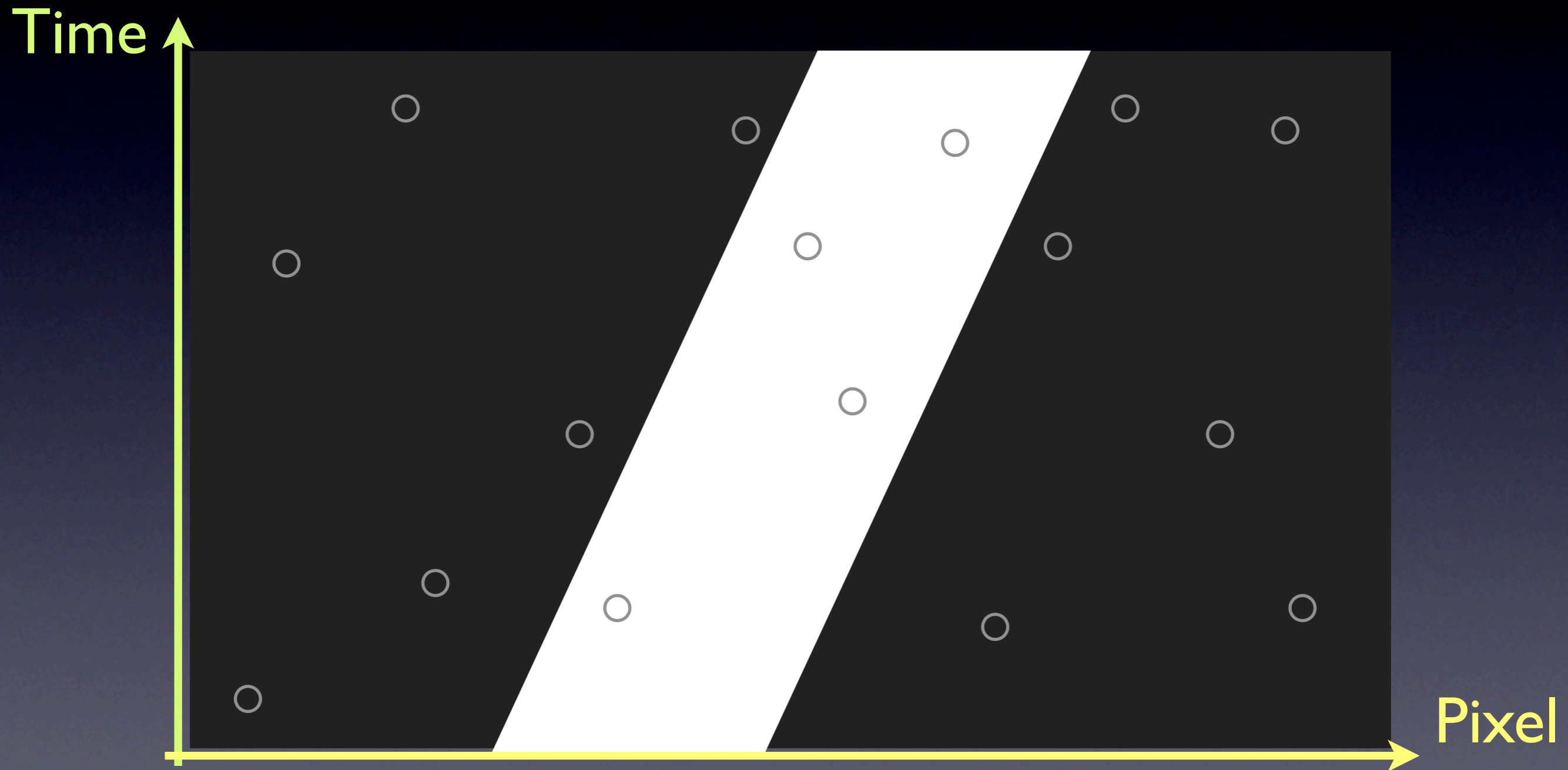
# Key Idea of Our Work

- Conventional adaptive sampling
  - Only adaptive on pixel axis
- Multidimensional adaptive sampling
  - Adaptive on all axes

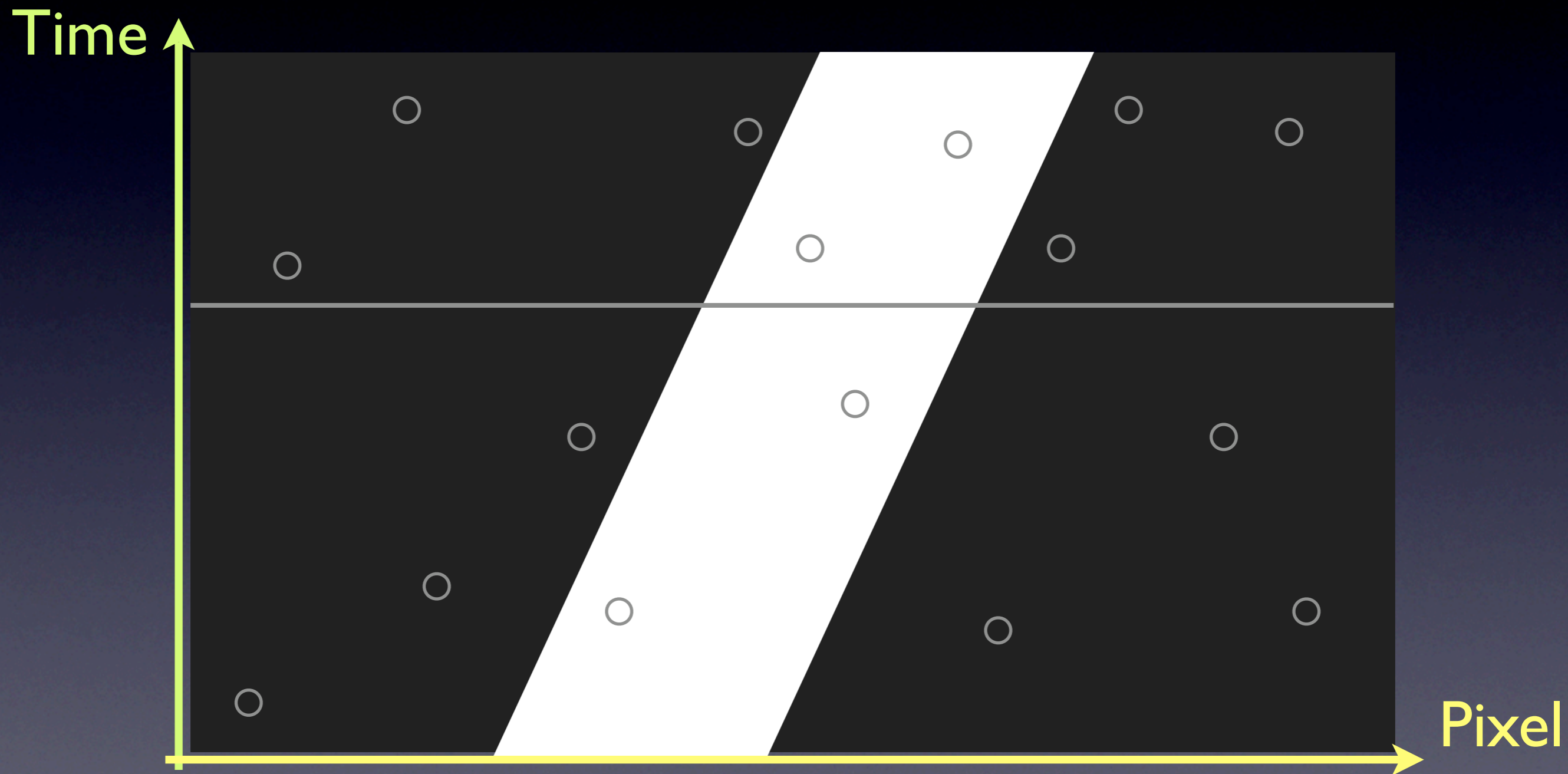
# Multidimensional Adaptive Sampling



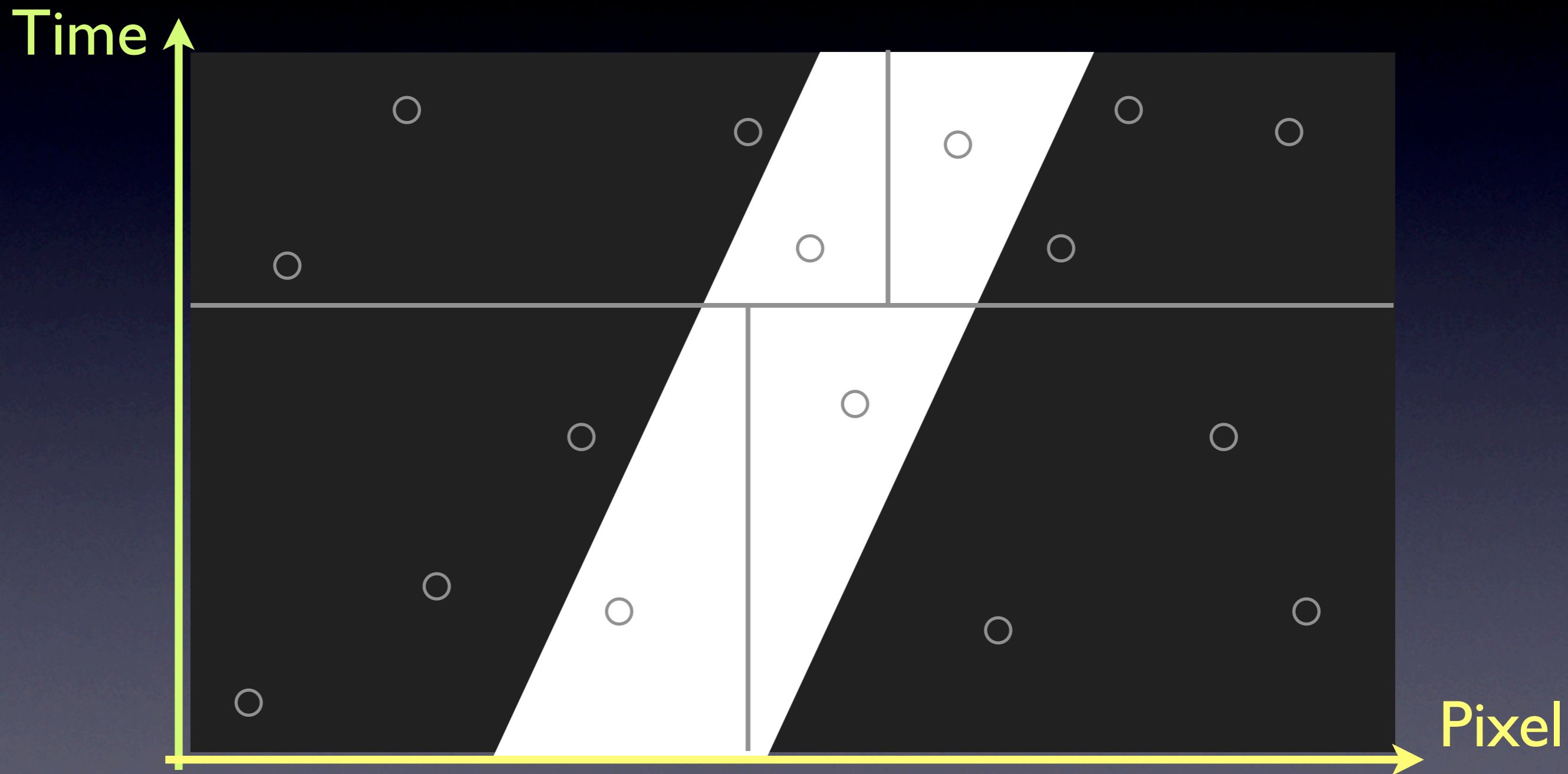
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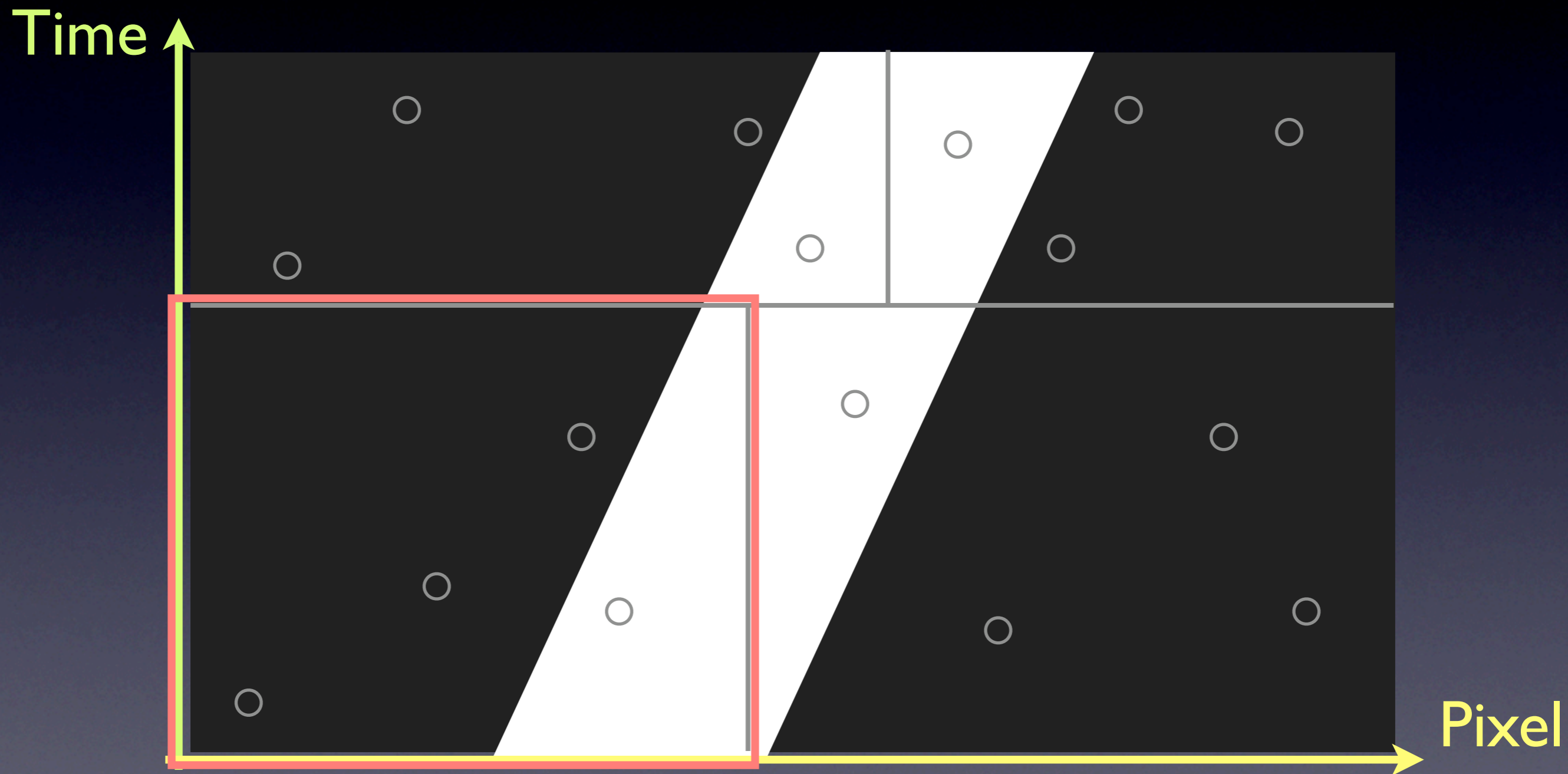
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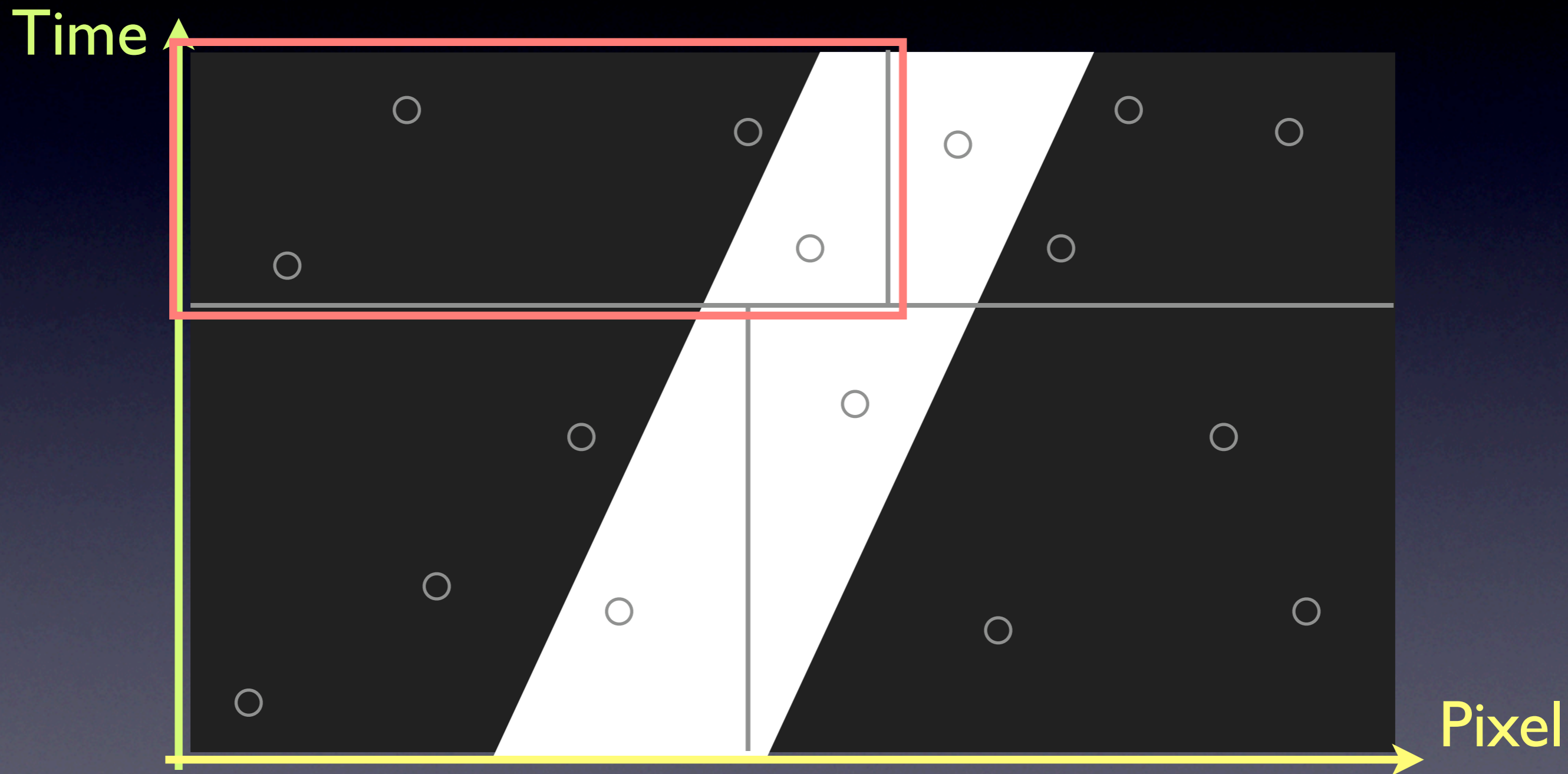
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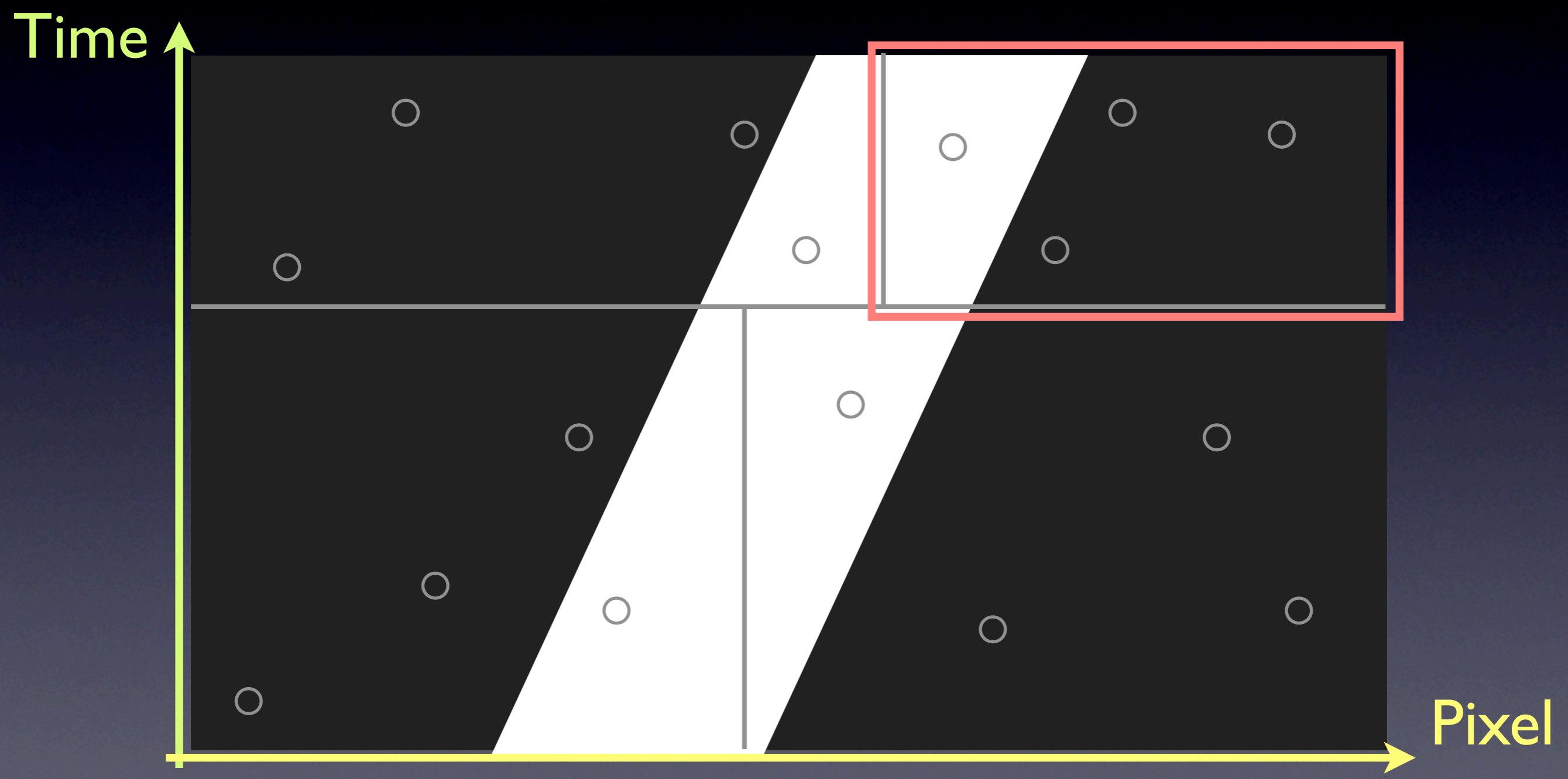


# Multidimensional Adaptive Sampling

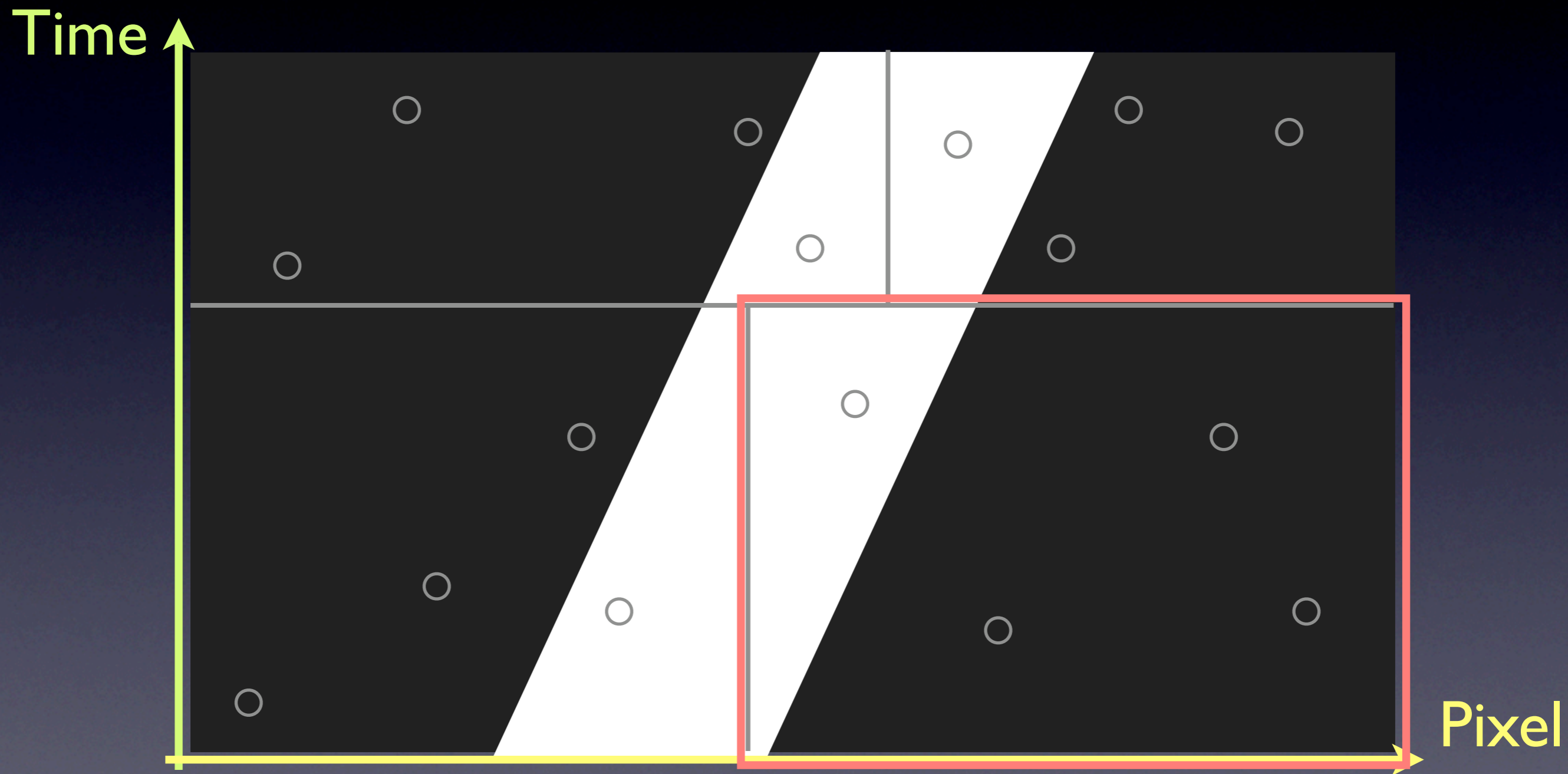




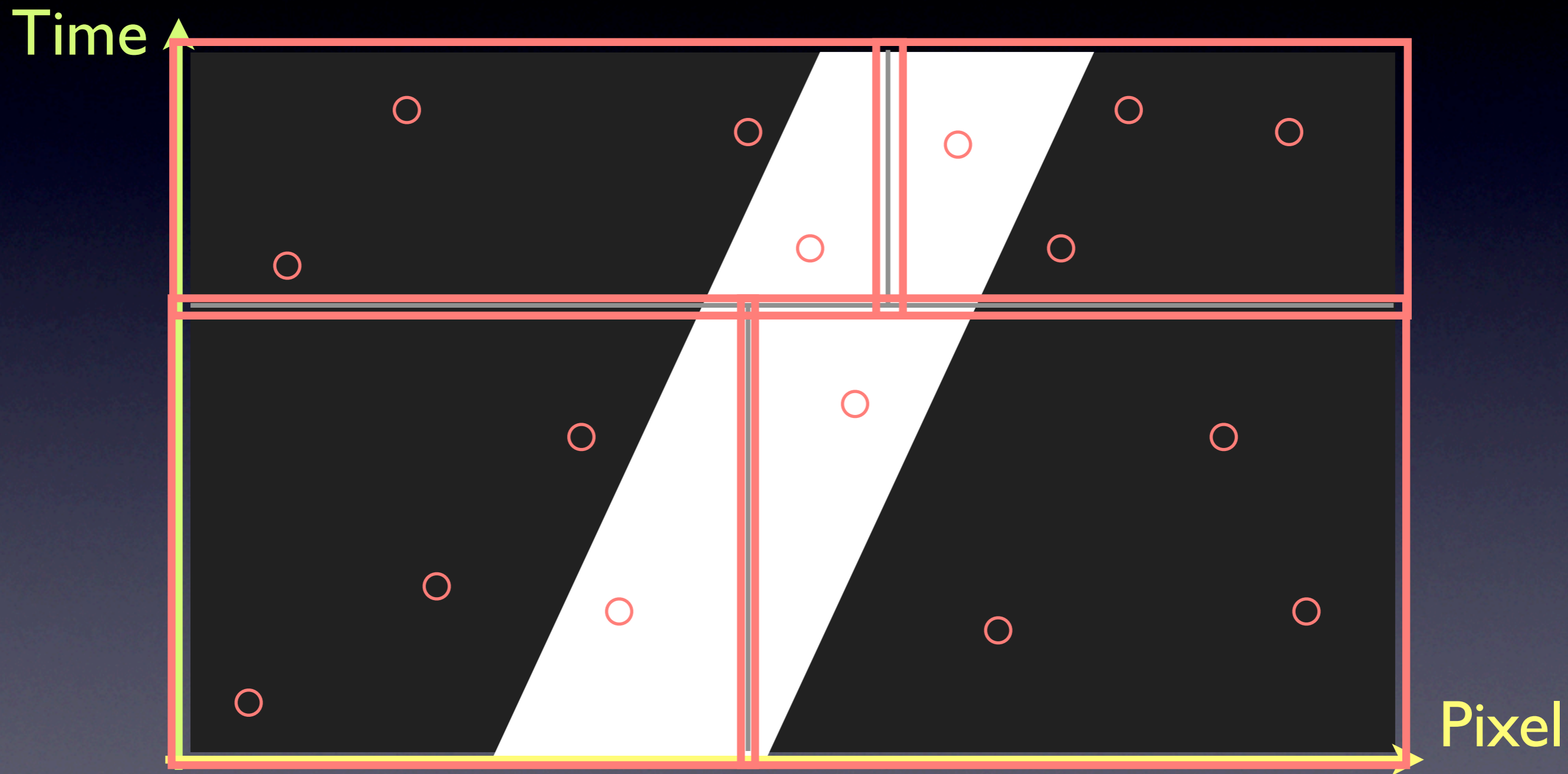
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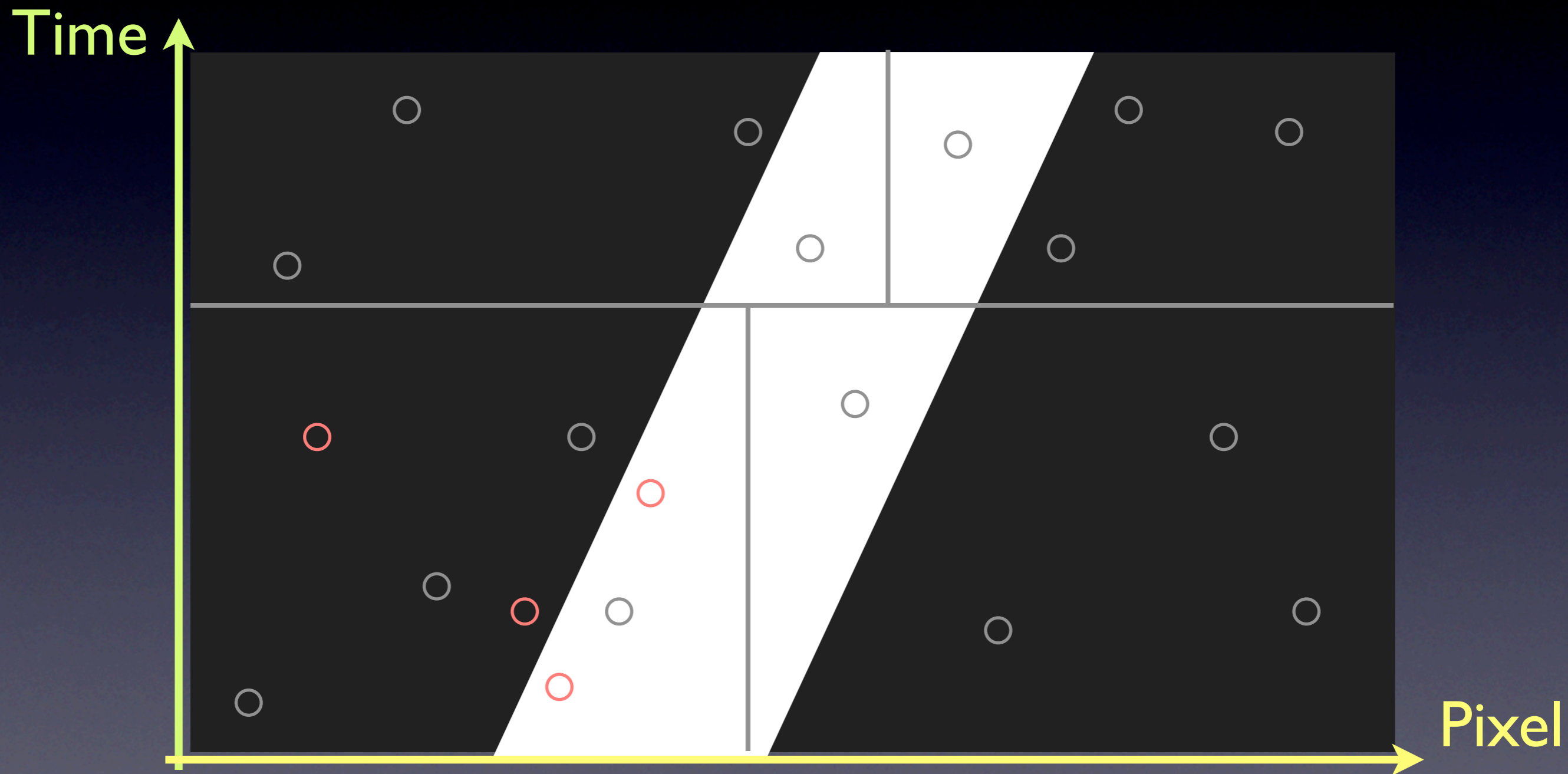
# Multidimensional Adaptive Sampling



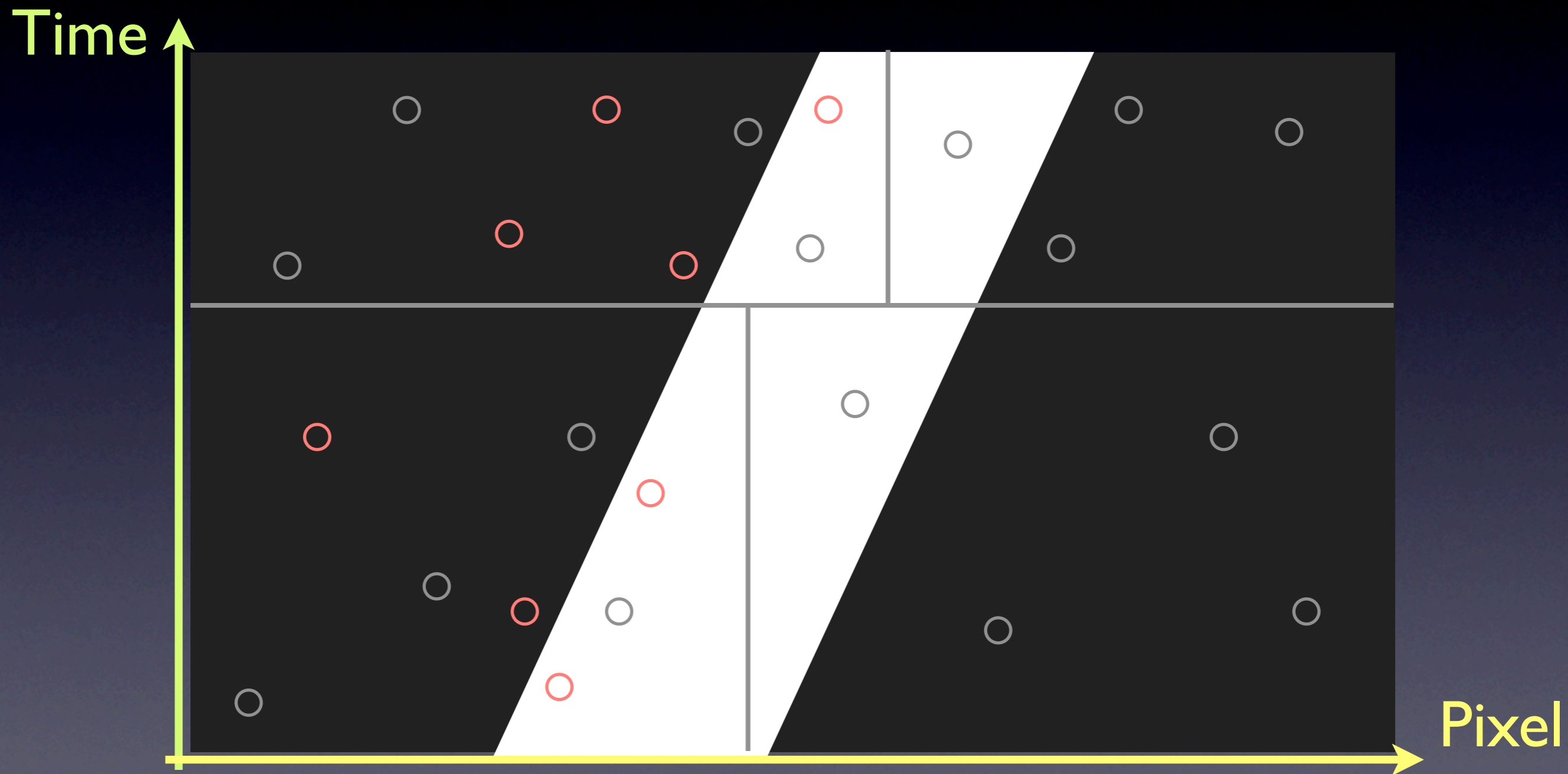
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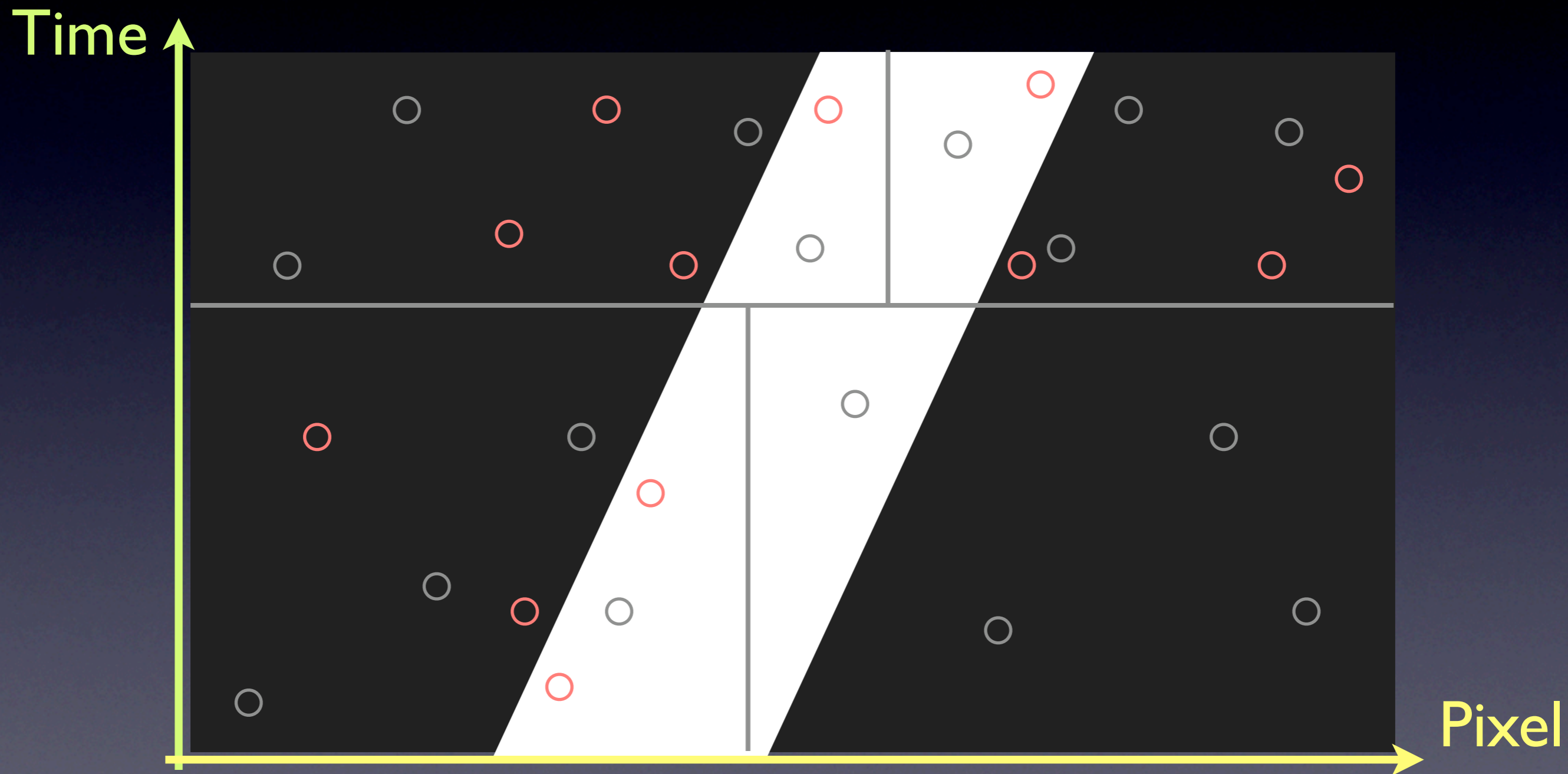
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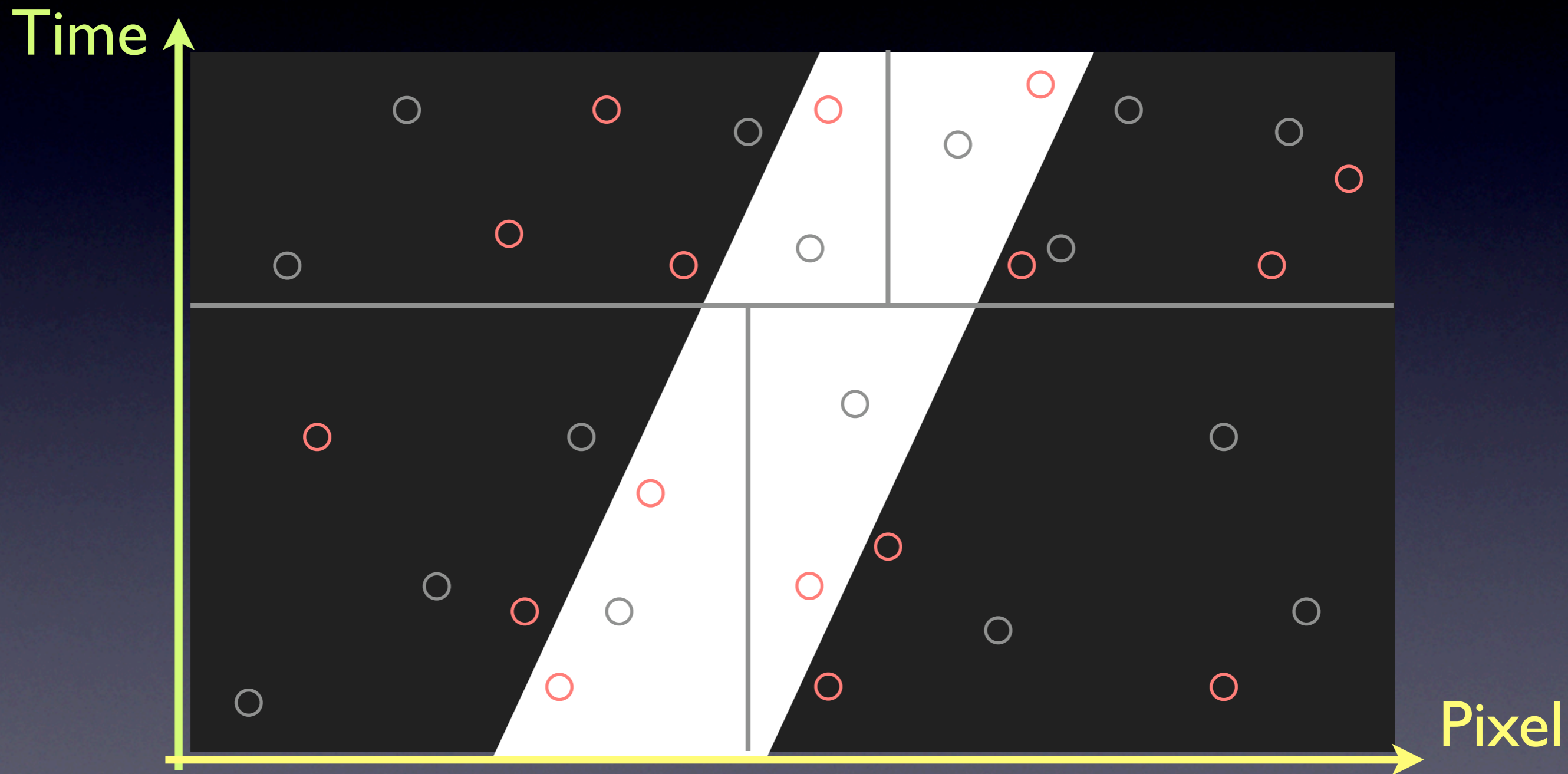
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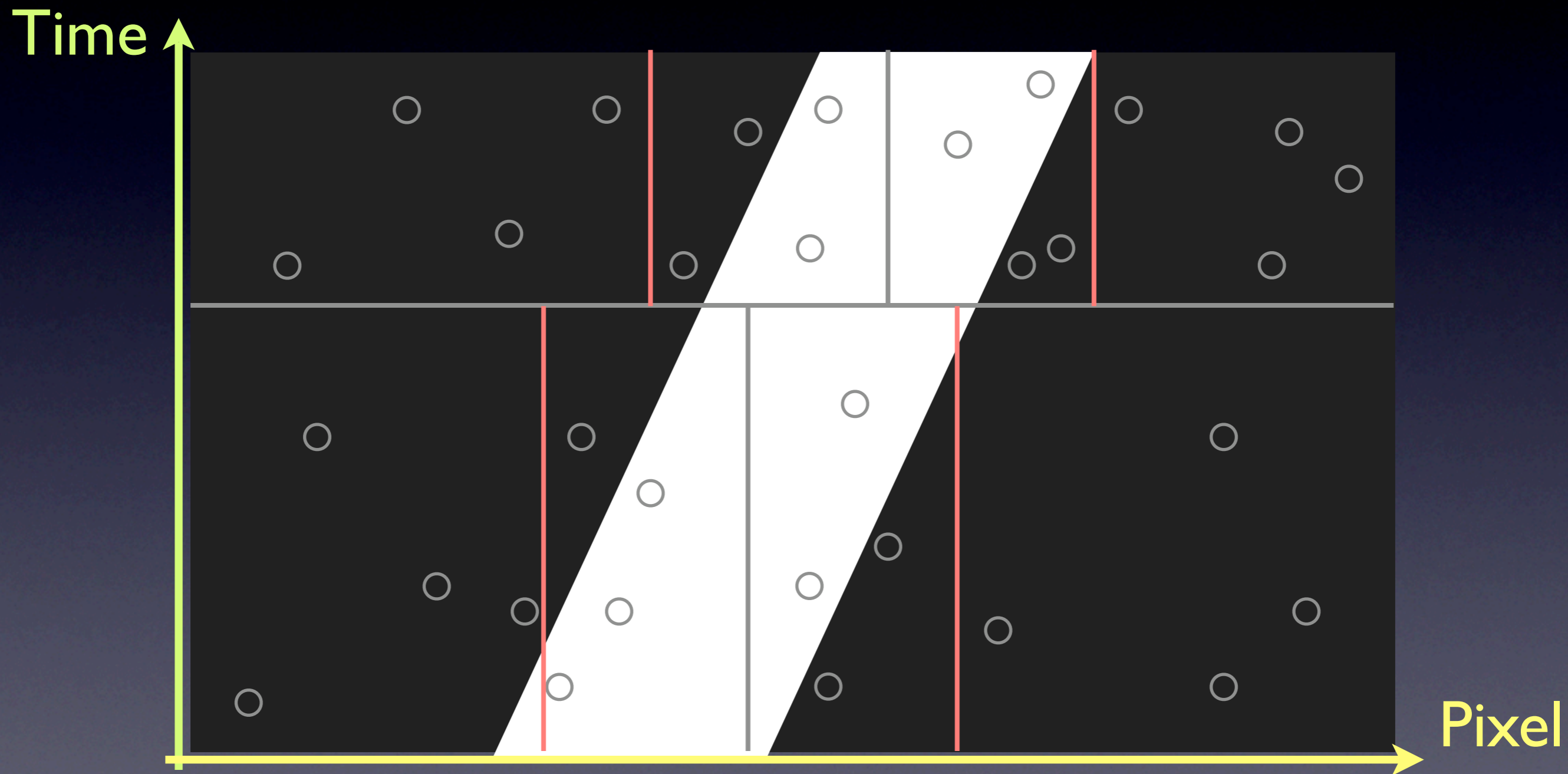
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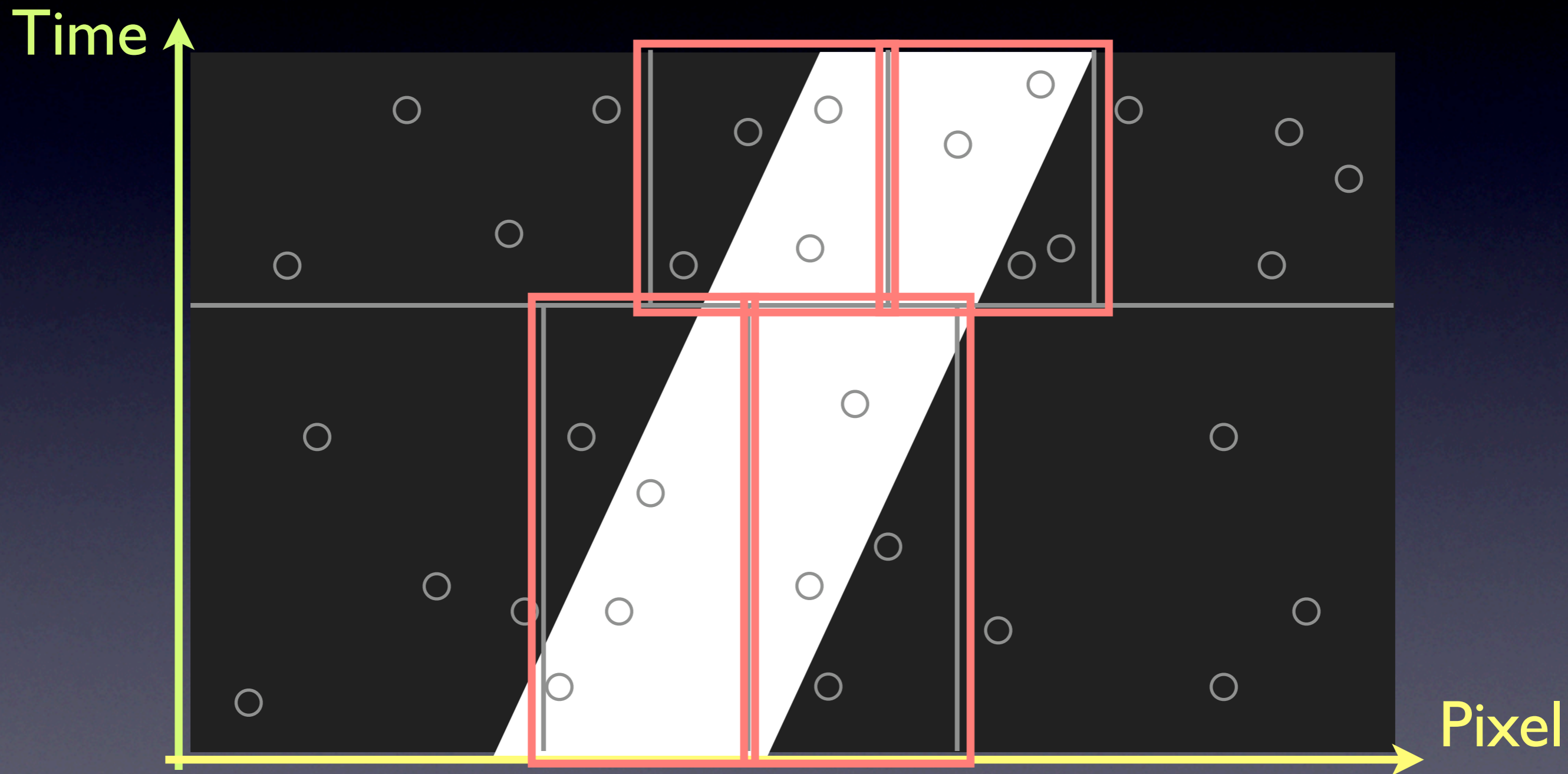


# Multidimensional Adaptive Sampling

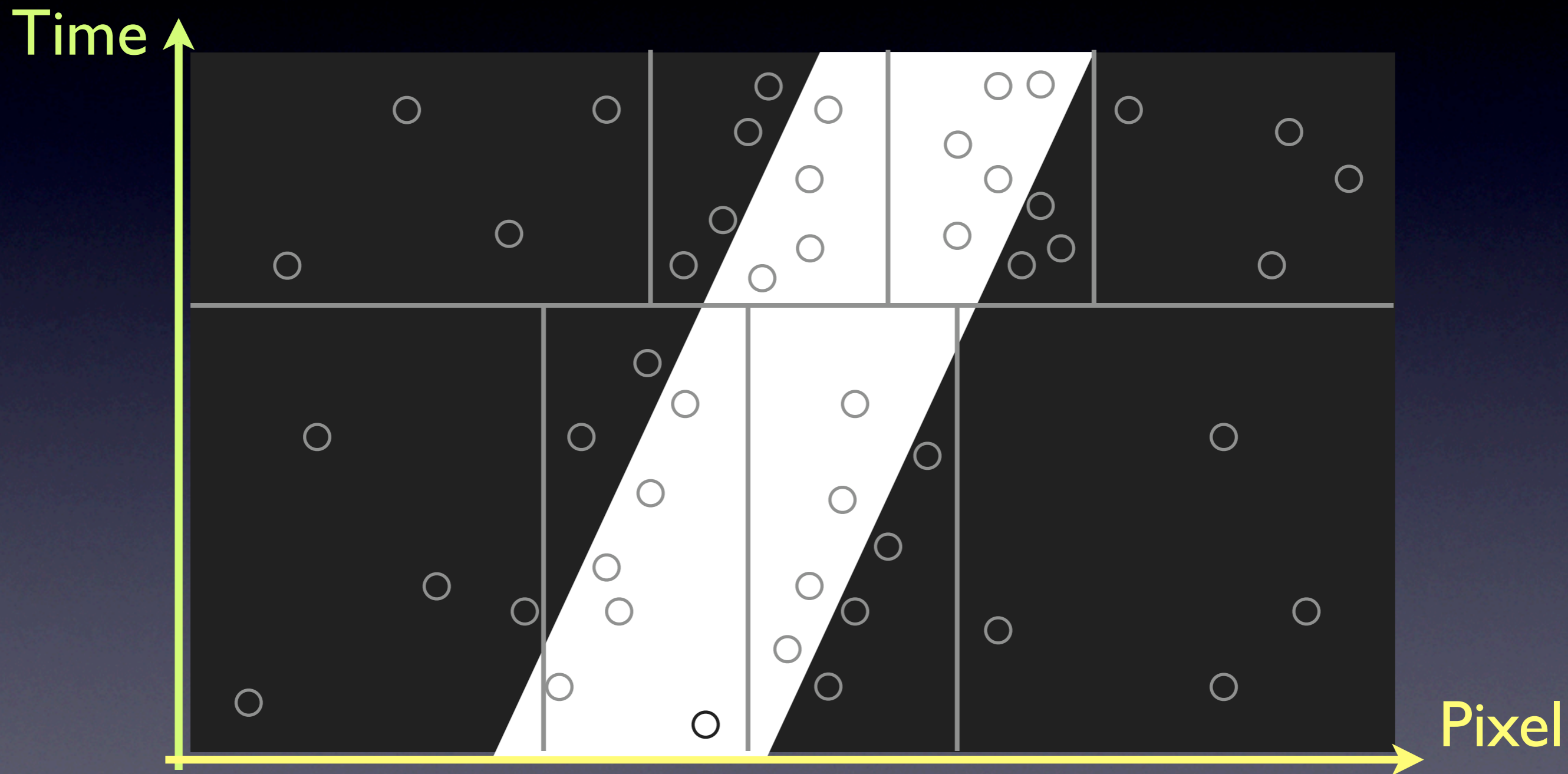




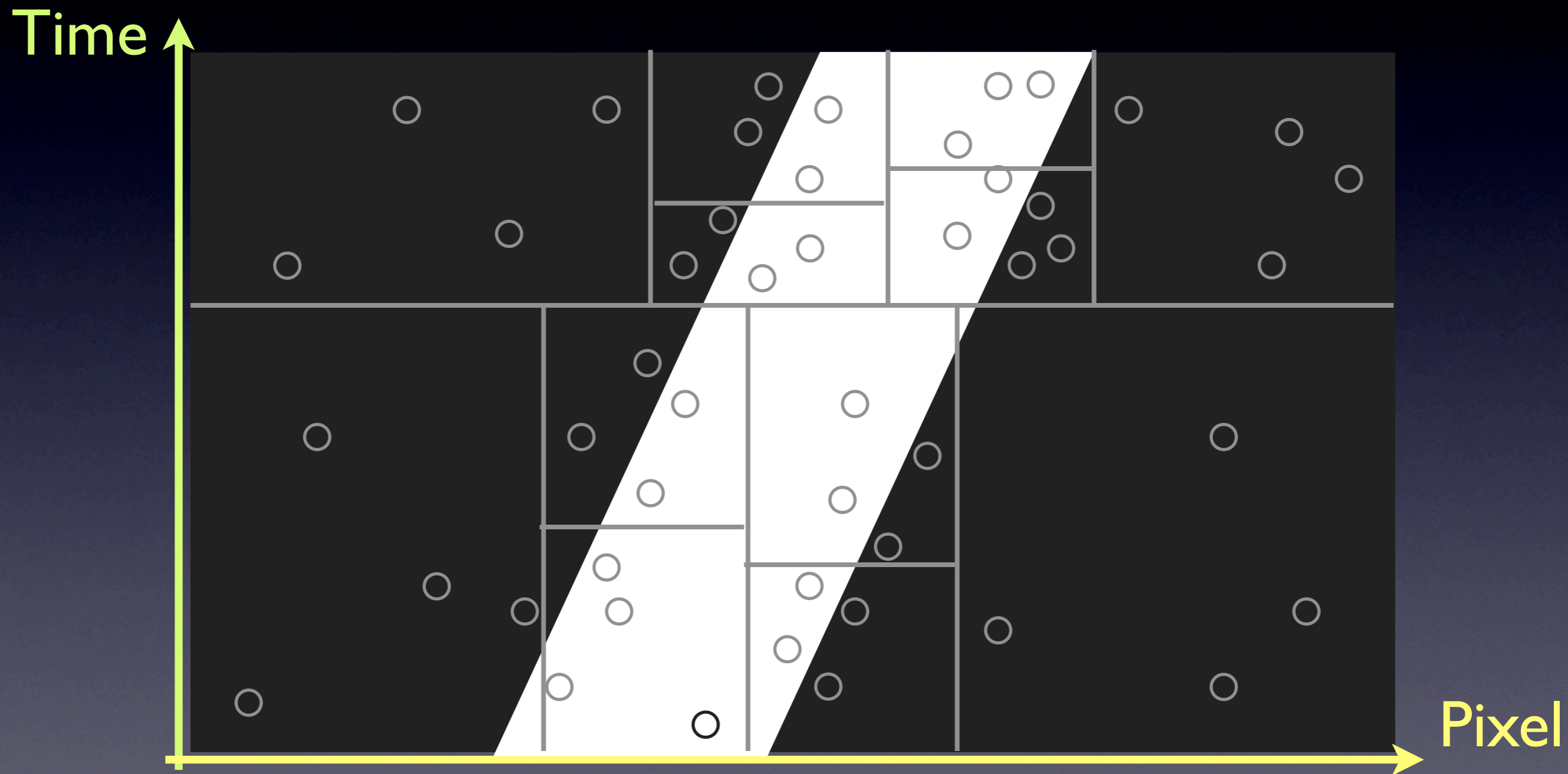
# Multidimensional Adaptive Sampling



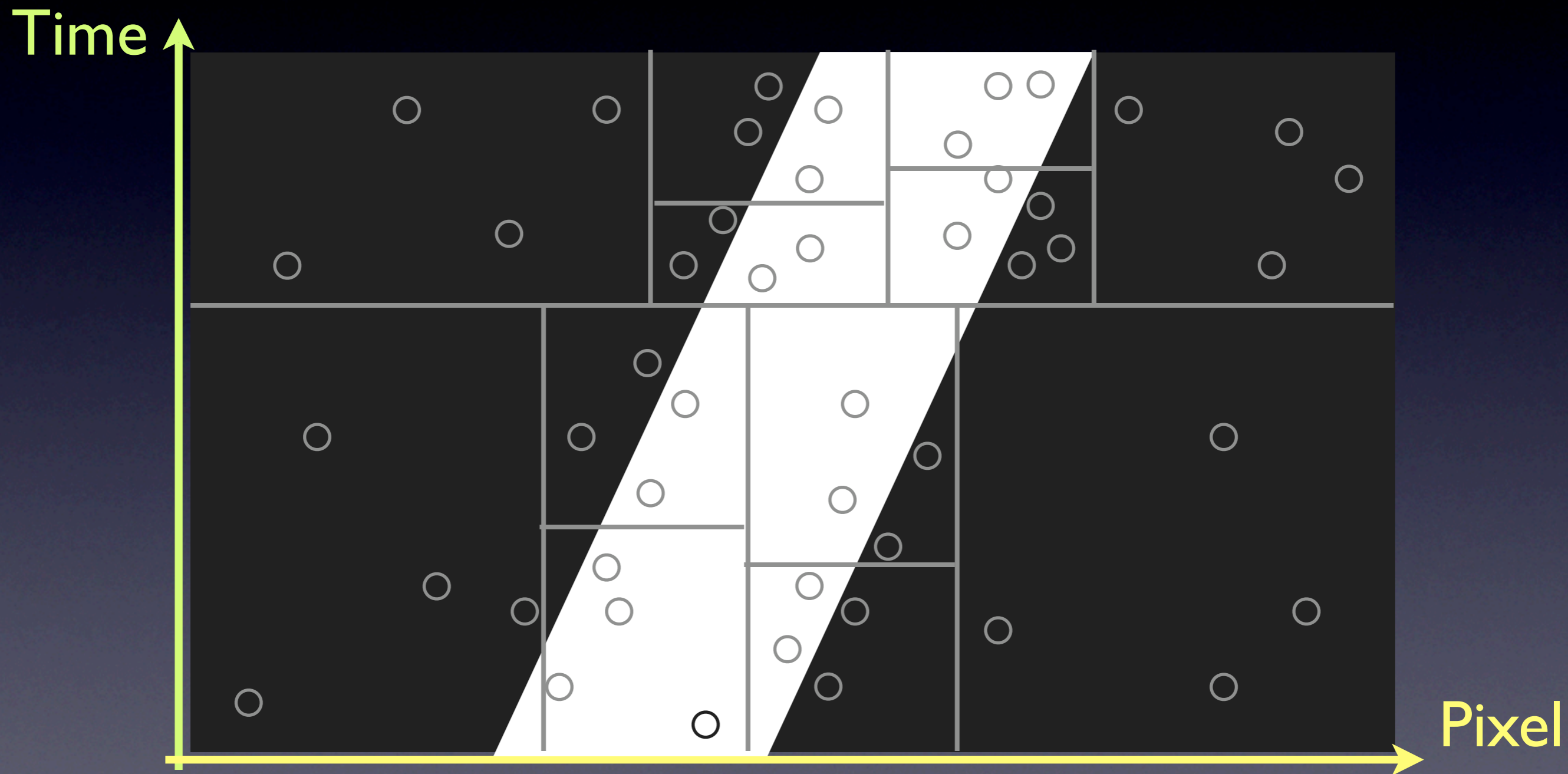
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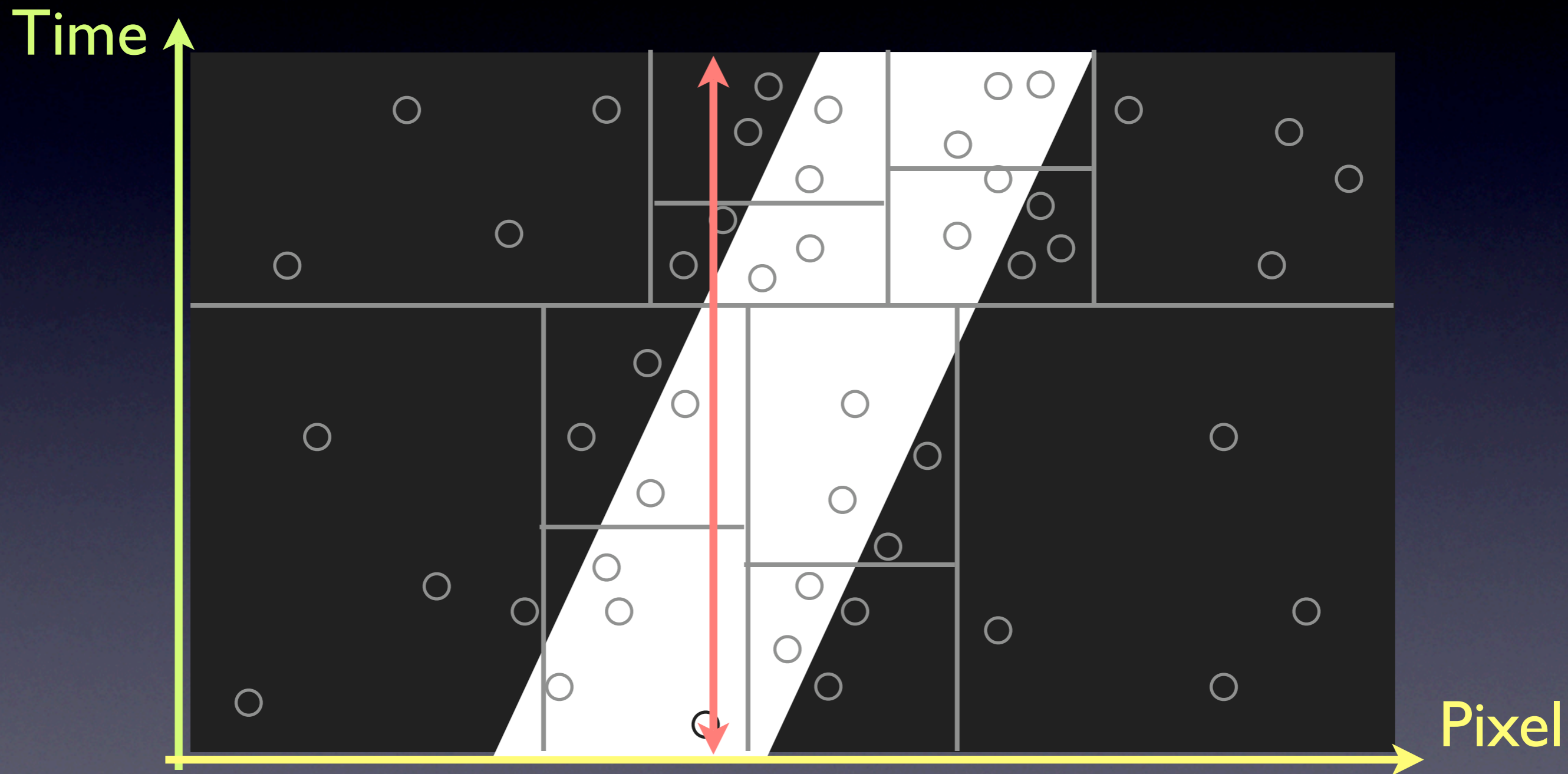
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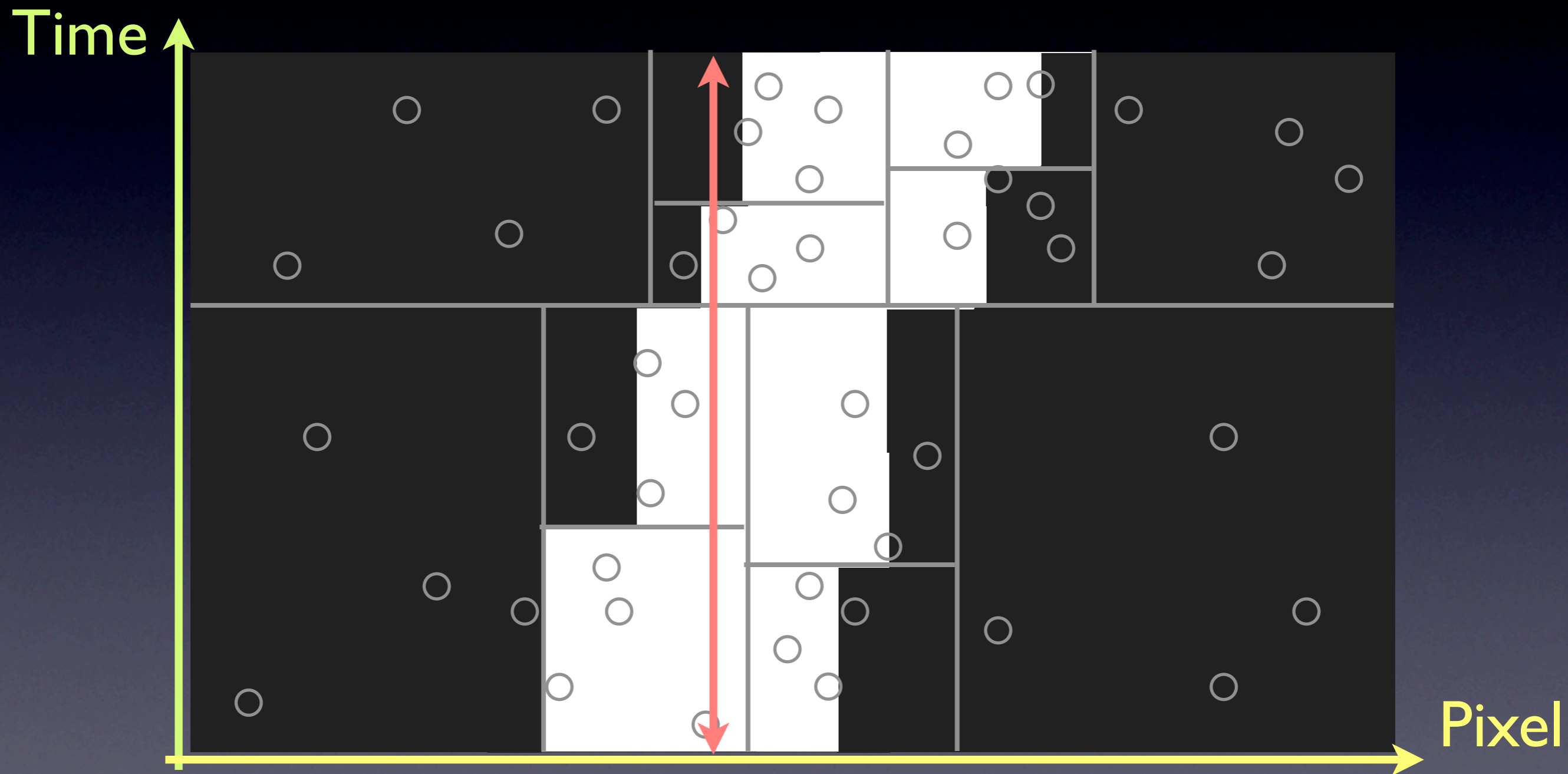
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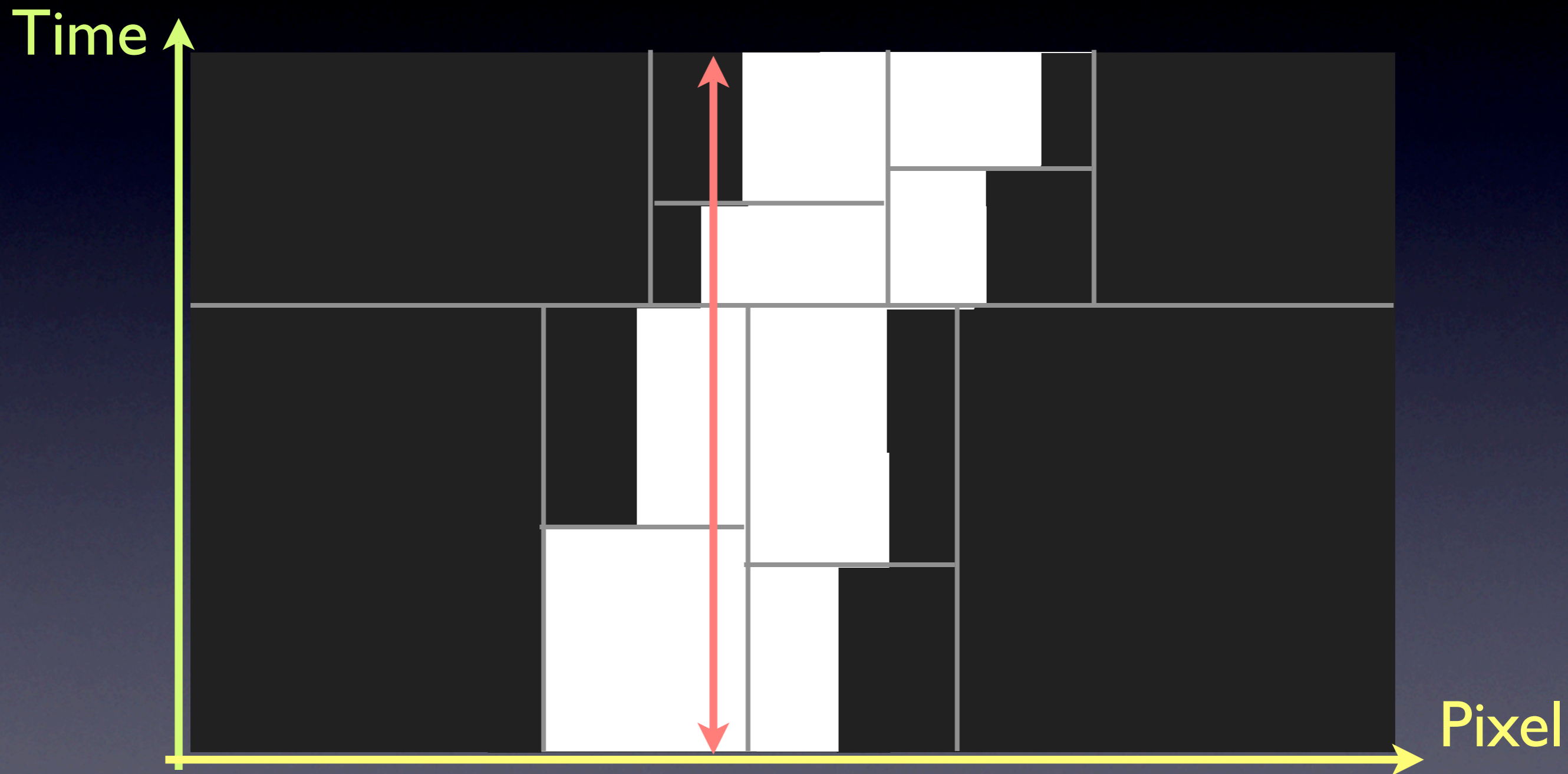
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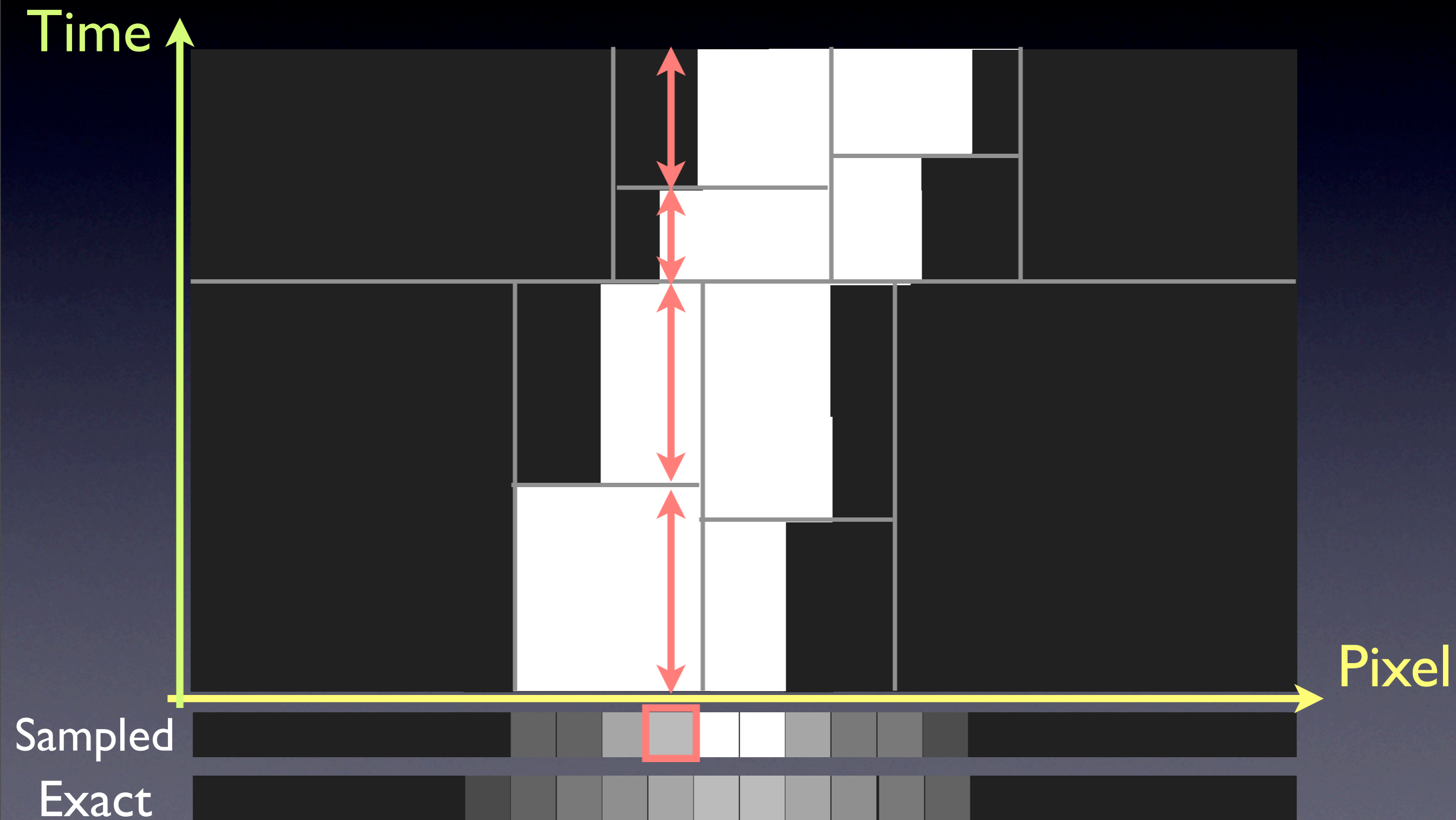
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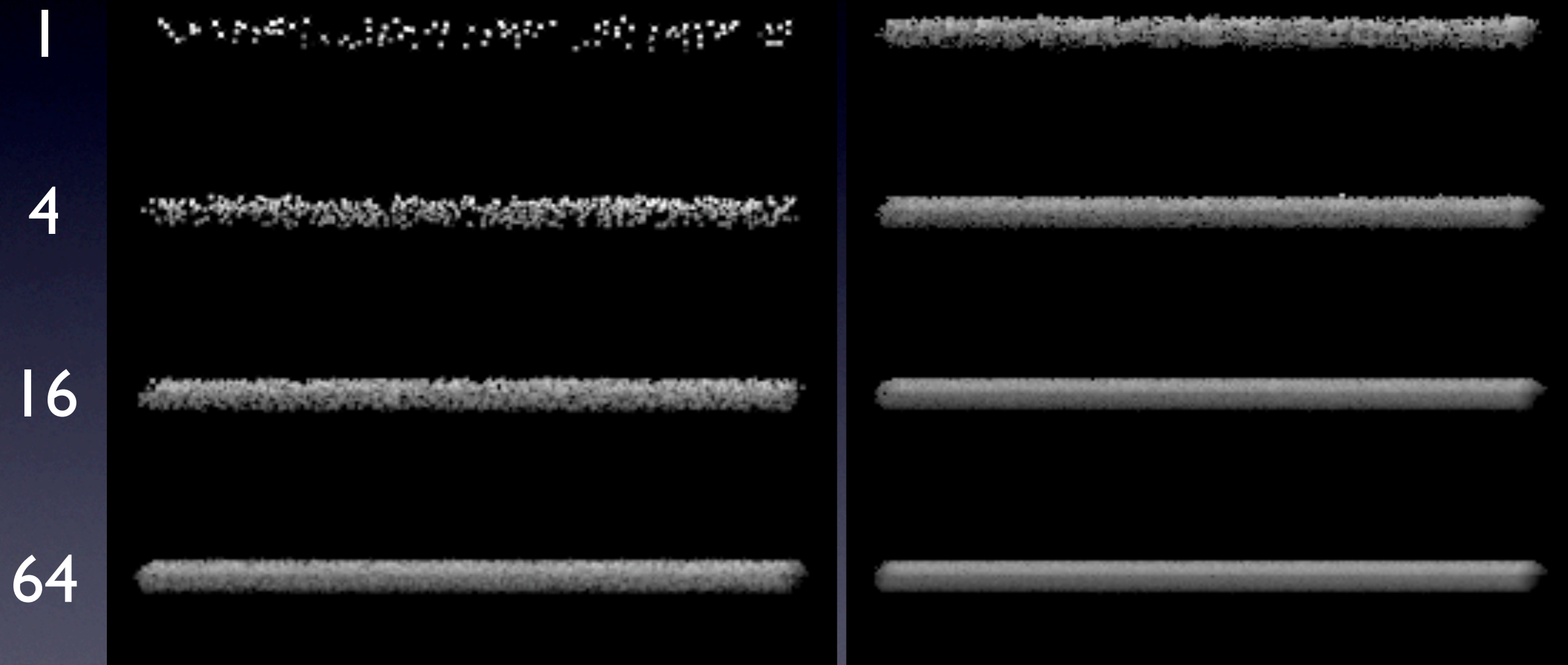




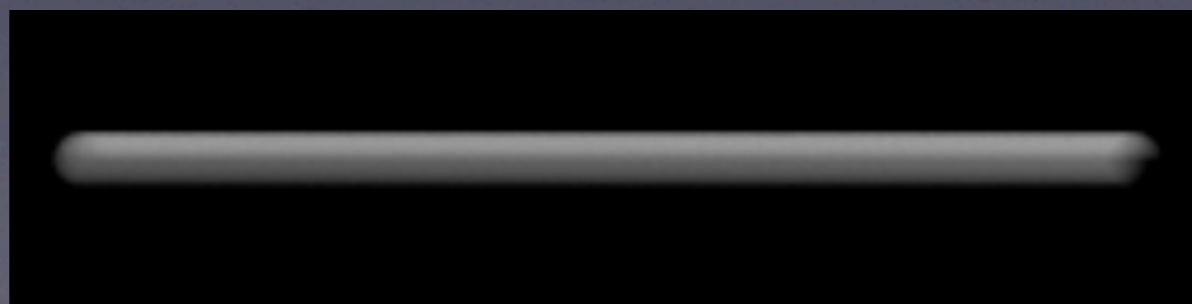
# Motion Blurred Sphere - Comparison

[Mitchell 91]

Our method



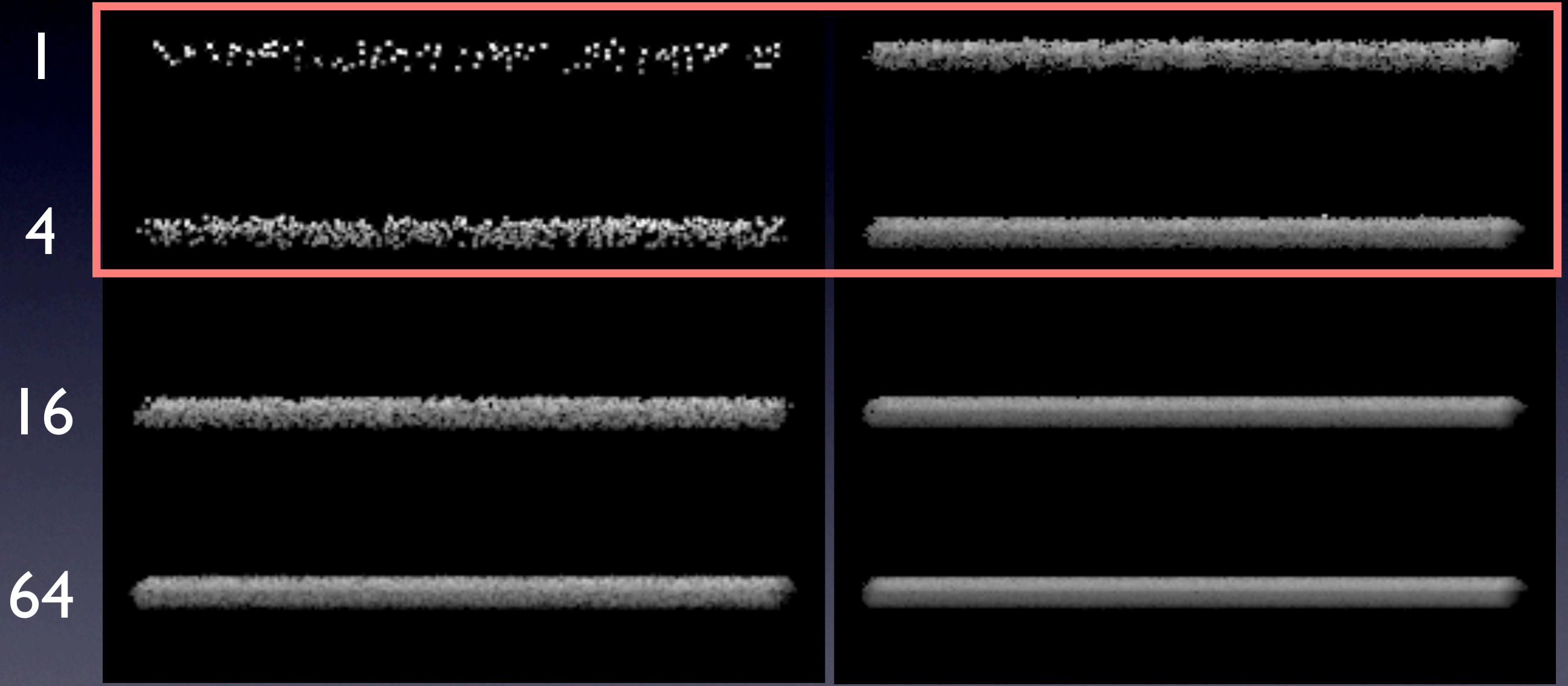
Reference



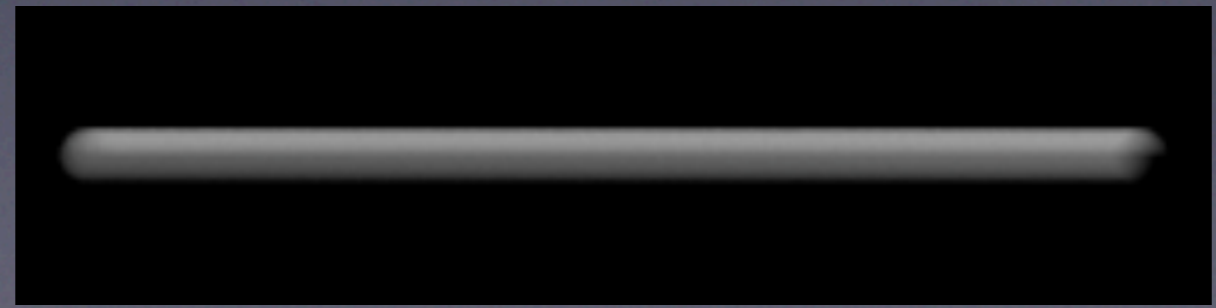
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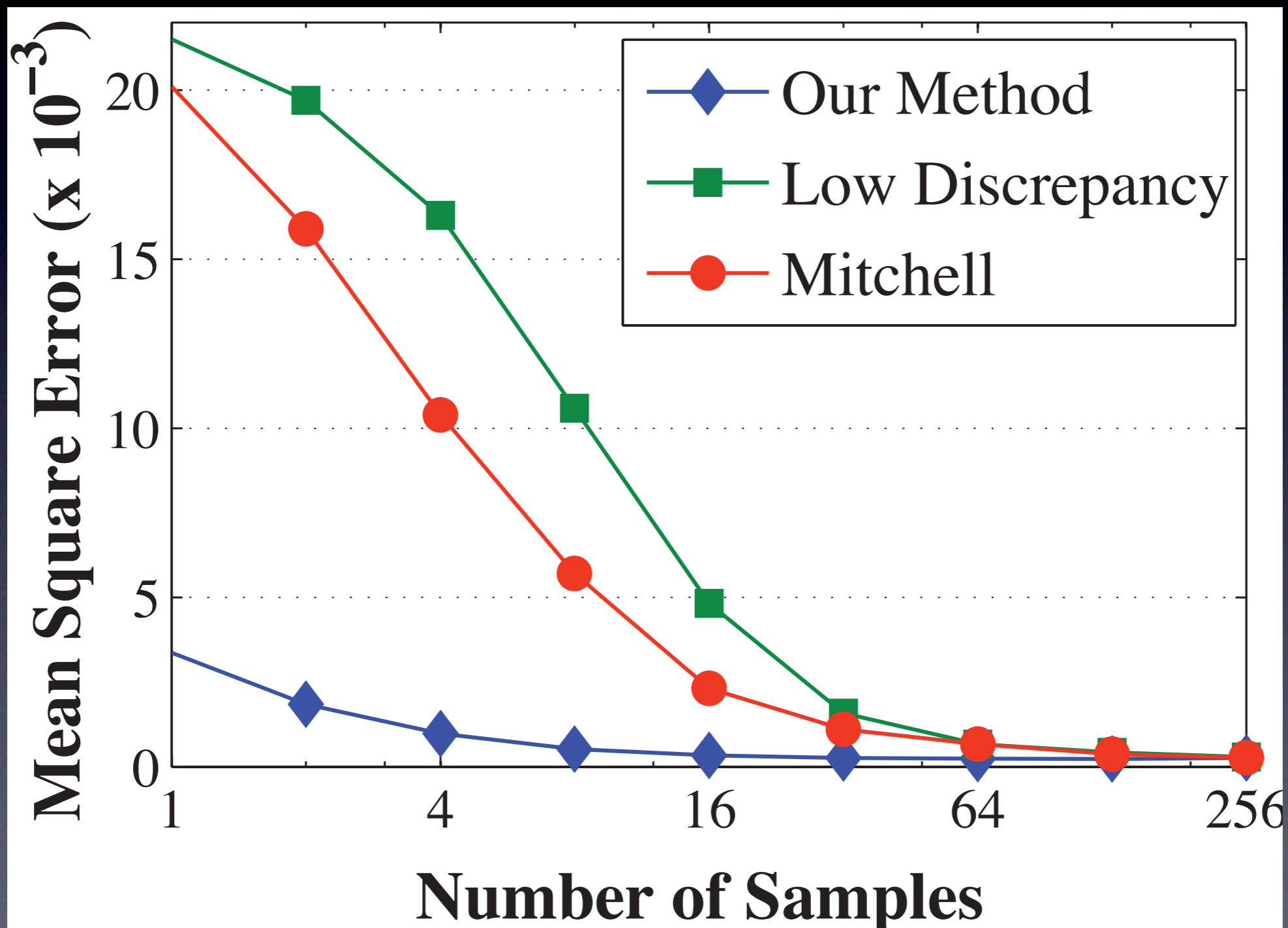
Our method



Reference



# Motion Blurred Sphere



# Rendering is Integration

- Each pixel value,  $L(x, y)$ , is defined as multidimensional integration

$$L(x, y) = \int \cdots \int f(x, y, u_1, \dots, u_n) du_1 \dots du_n$$

# Rendering is Integration

- Motion blur is 1D integration over time (t)

$$L(x, y) = \int f(x, y, t) dt$$



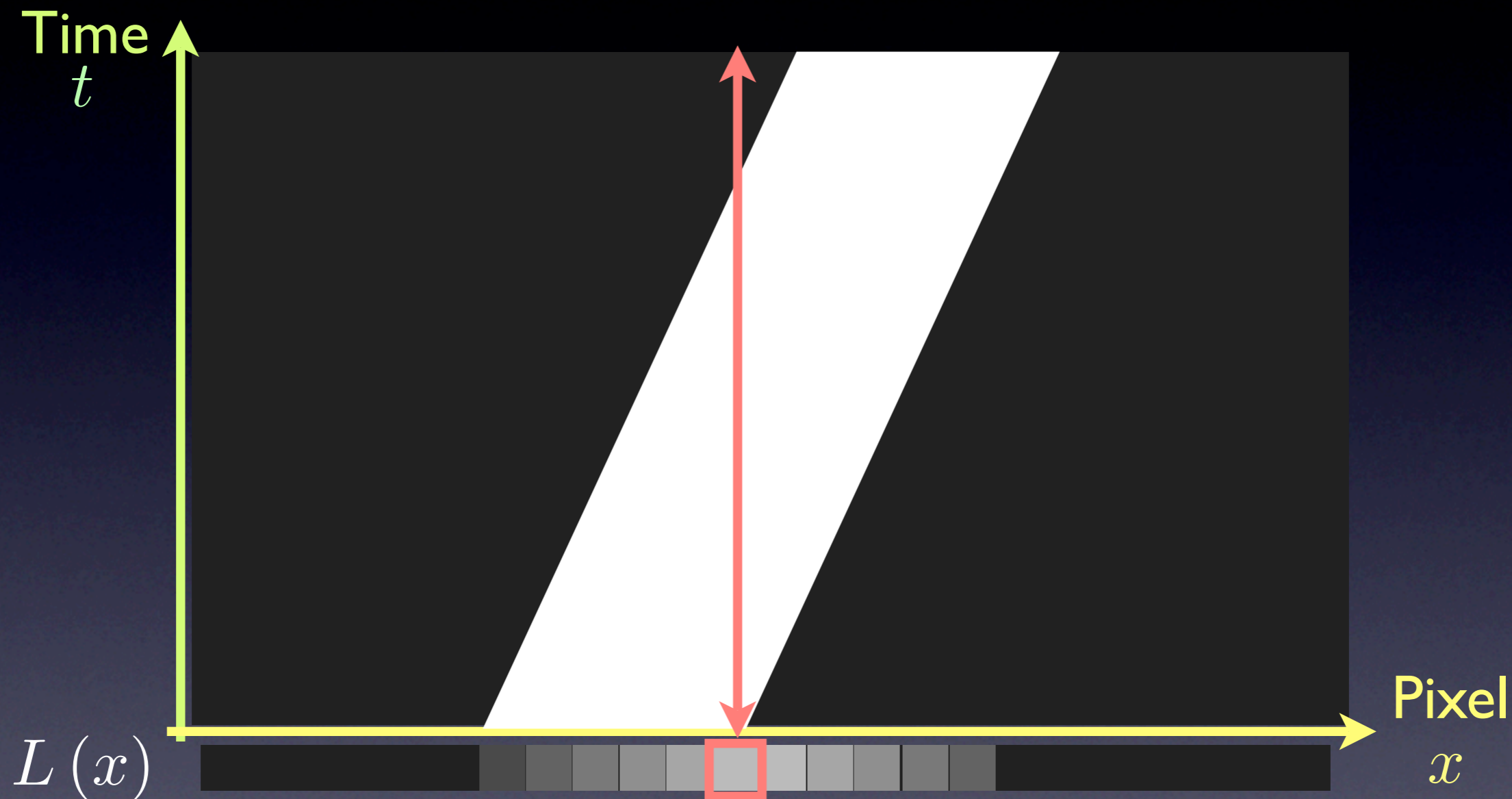
# Rendering is Integration

- DOF is 2D integration over lens ( $u, v$ )

$$L(x, y) = \iint f(x, y, u, v) \, du \, dv$$



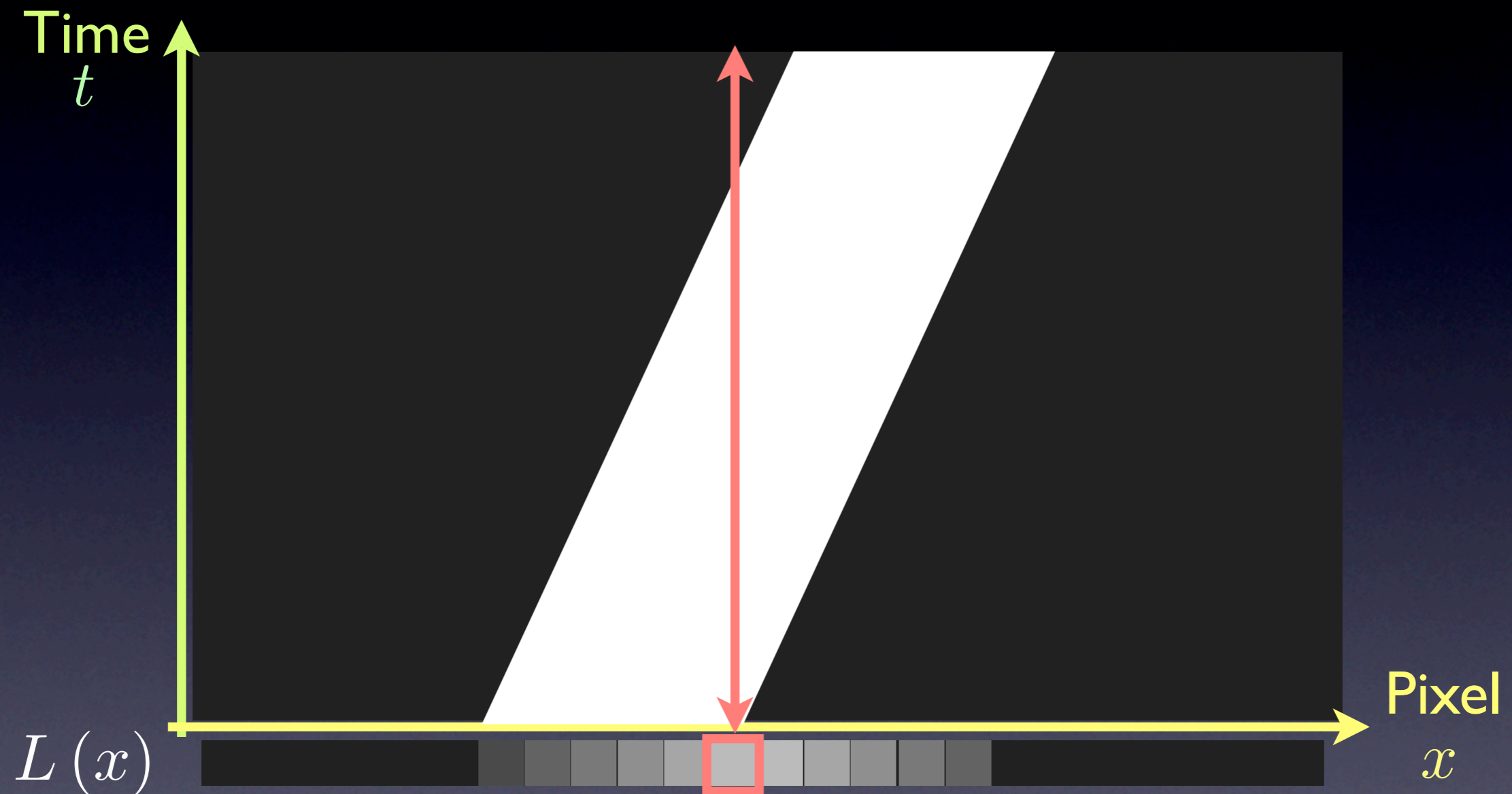
# Analytical Solution

 $L(x)$ 

Pixel  
 $x$

$$L(x) = \int f(x, t) dt$$

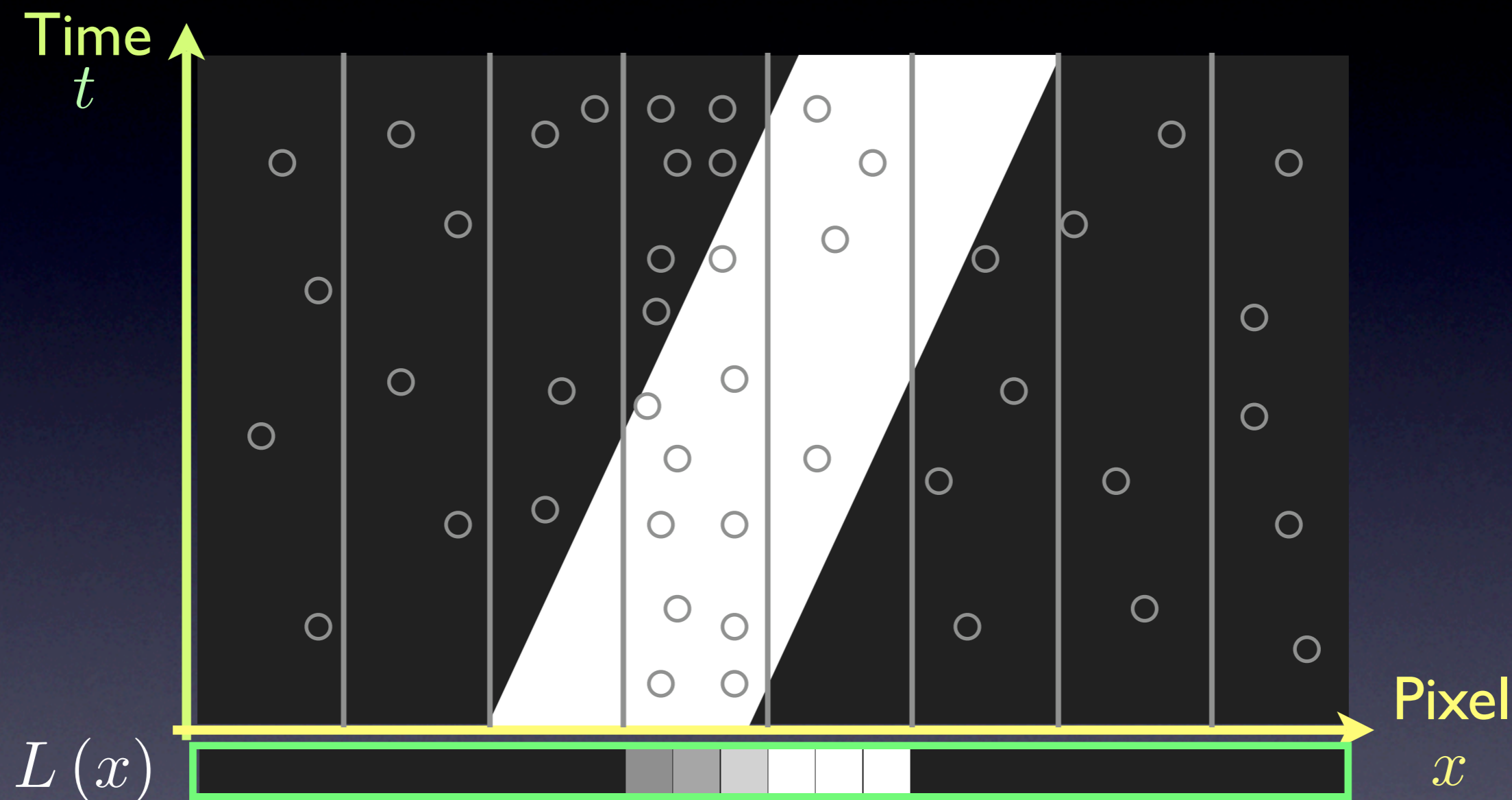
# Analytical Solution



$$L(x) \approx \sum_i w_i f(x, t_i)$$

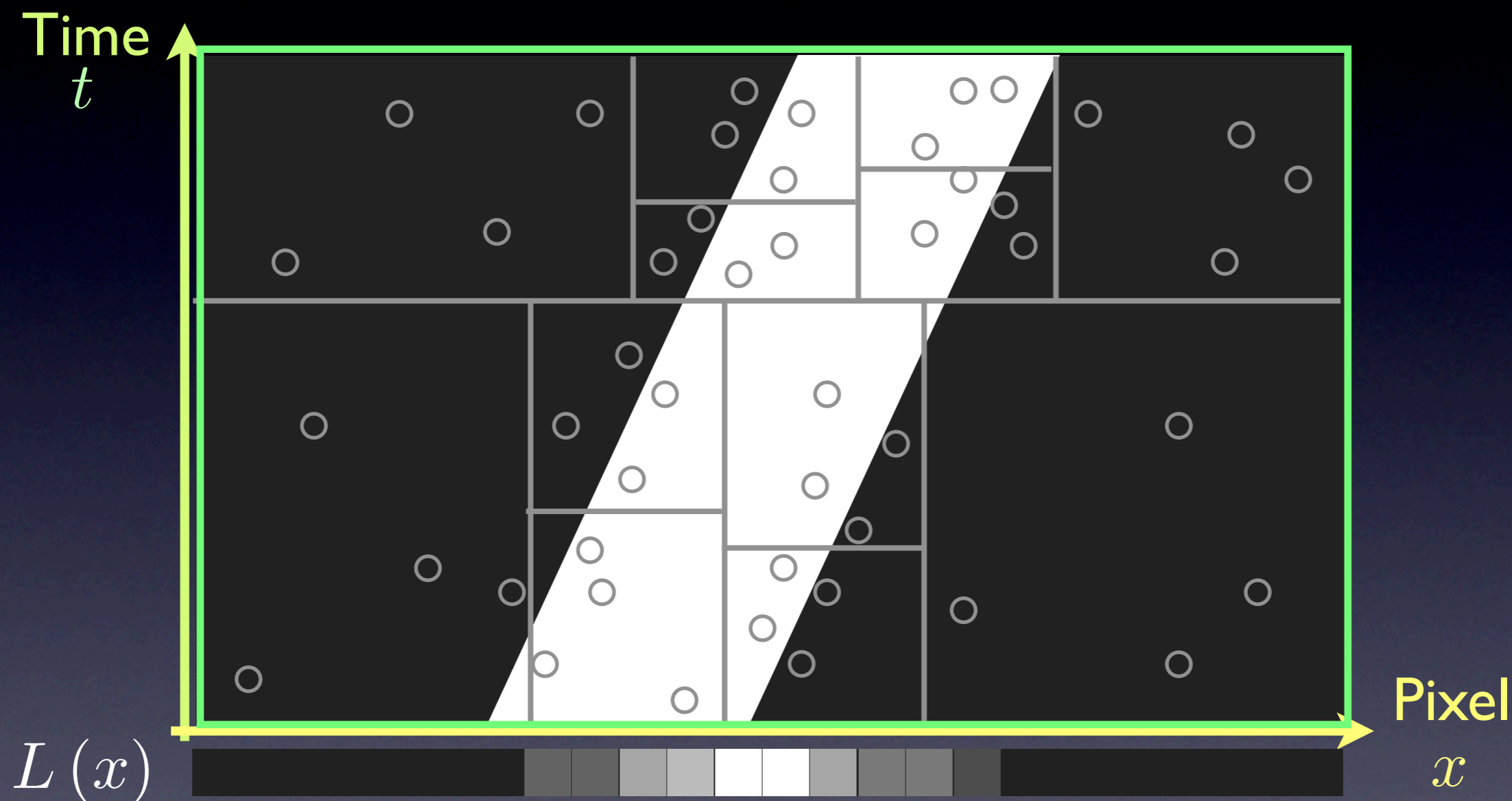


# Conventional Adaptive Sampling



$$L(x) \approx \sum_i w_i f(x, t_i)$$

# Multidimensional Adaptive Sampling



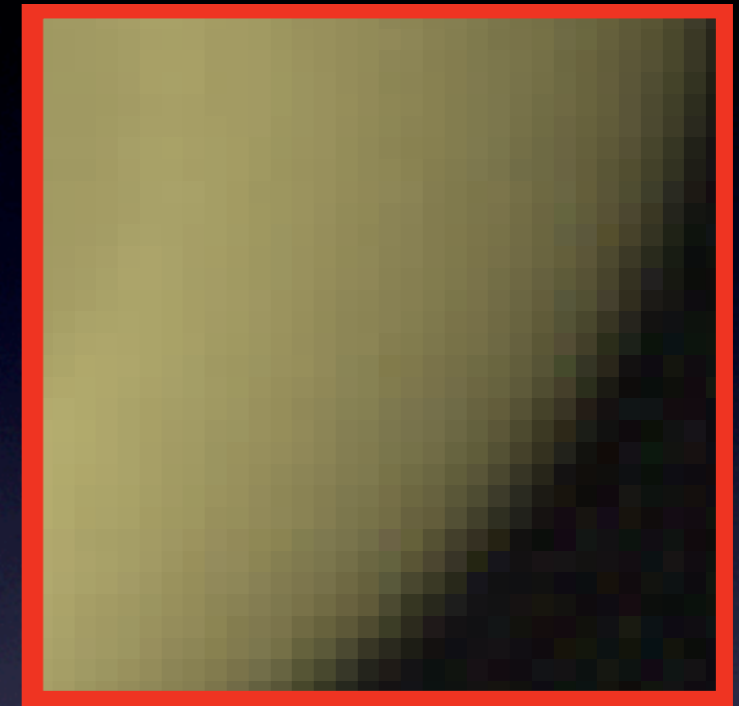
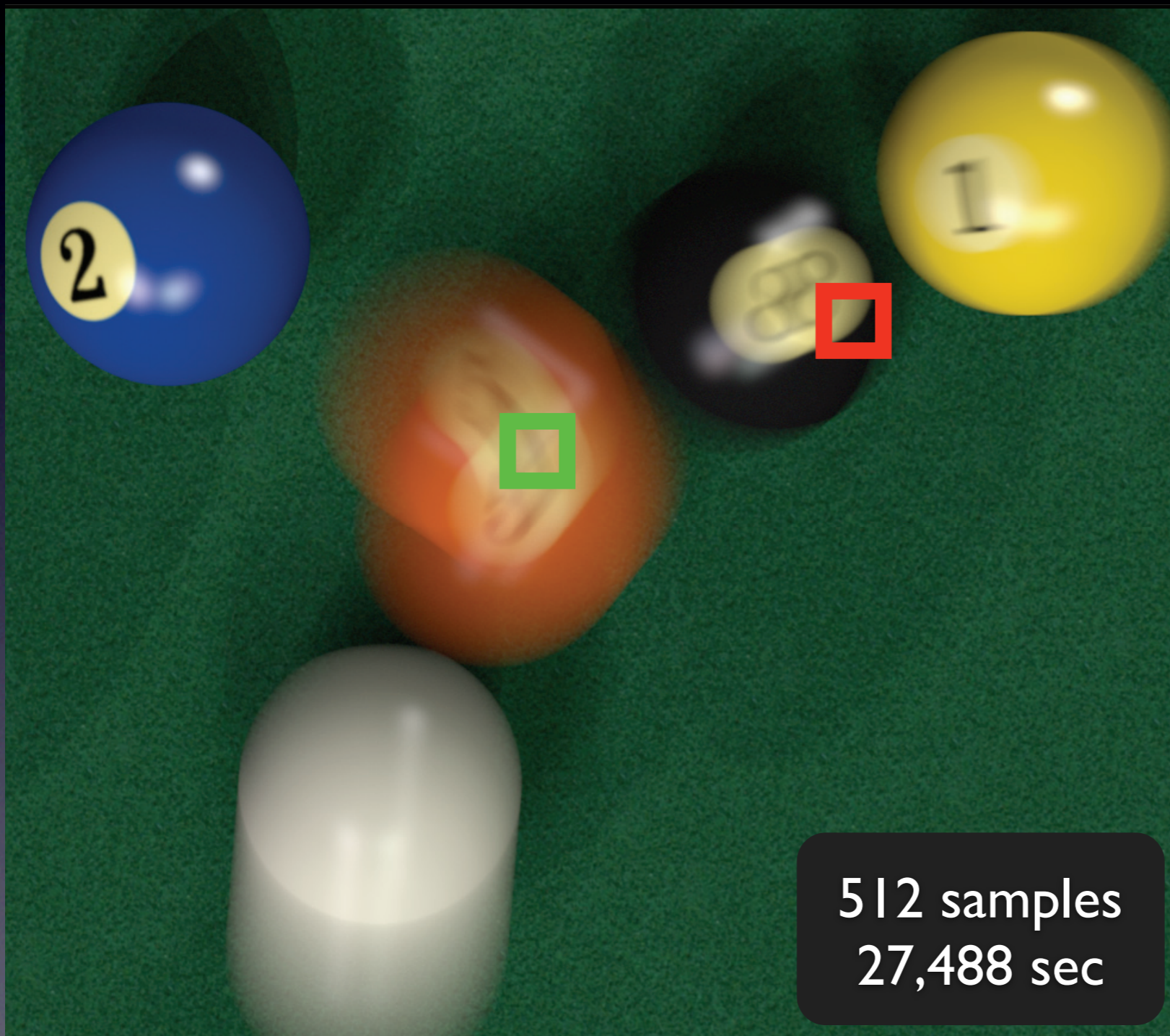
$$L(x) \approx \sum_i w_i f(x, t_i)$$

# Key Features

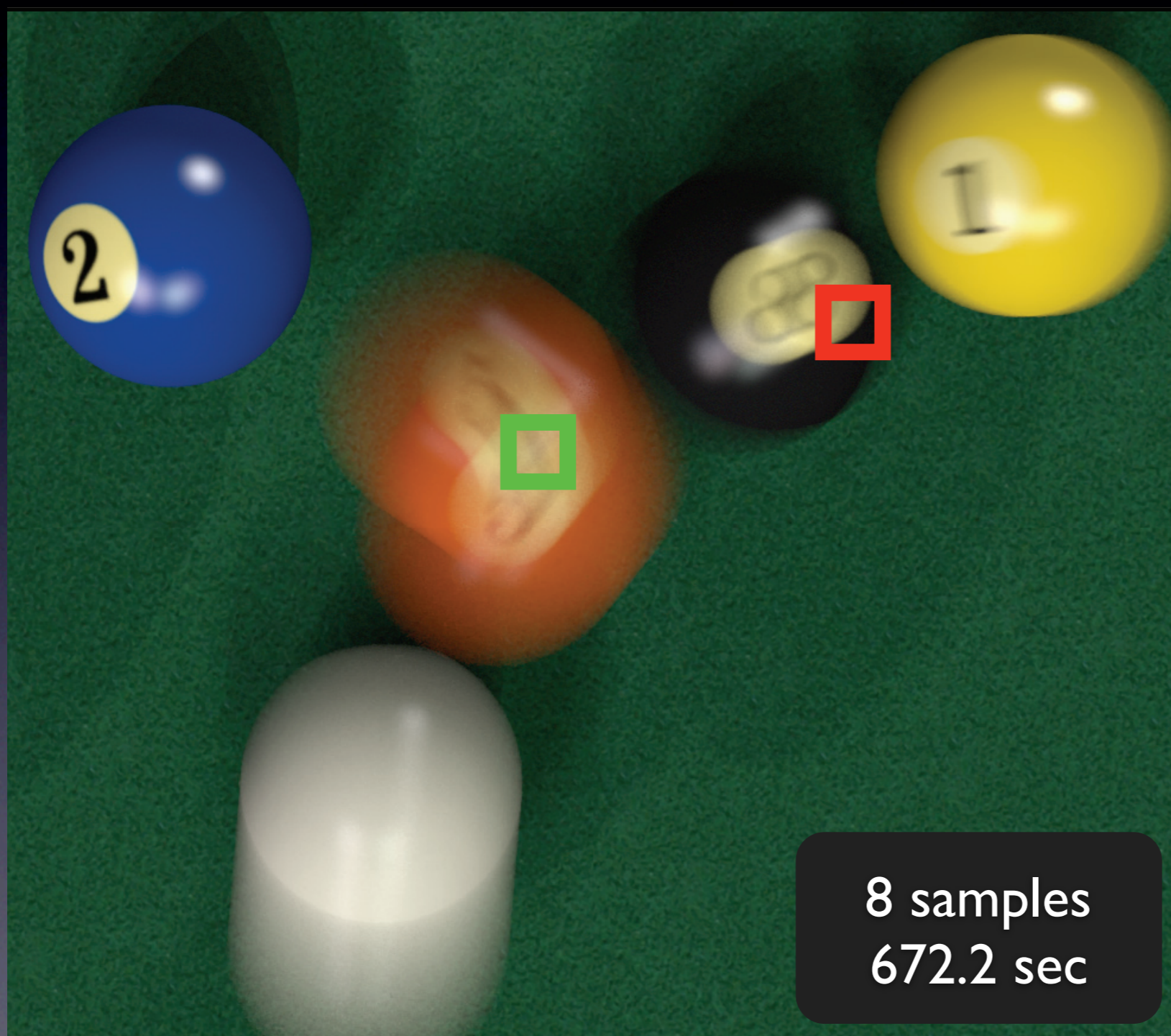
- Exploits coherency **beyond the image plane**
- Adaptive sampling based on **deterministic samples**
- Theory applies to **various effects**

# Results

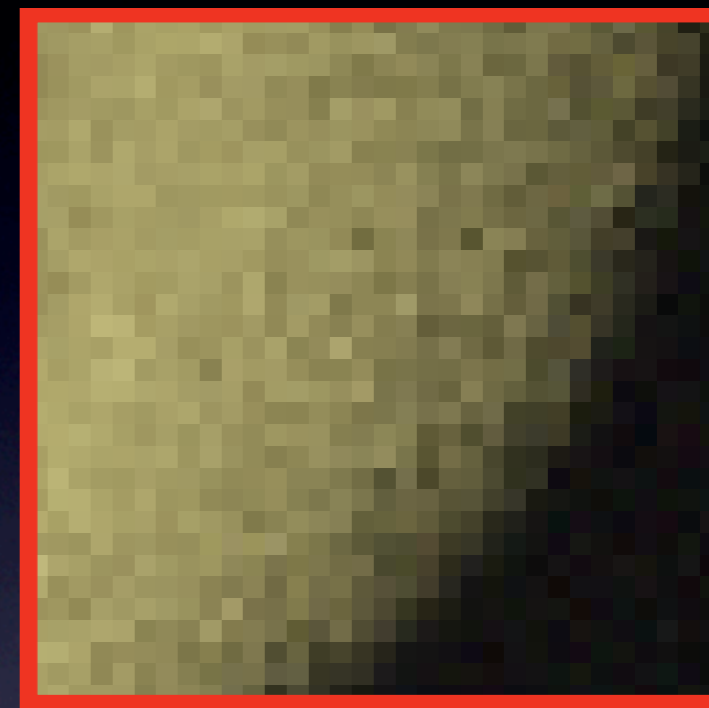
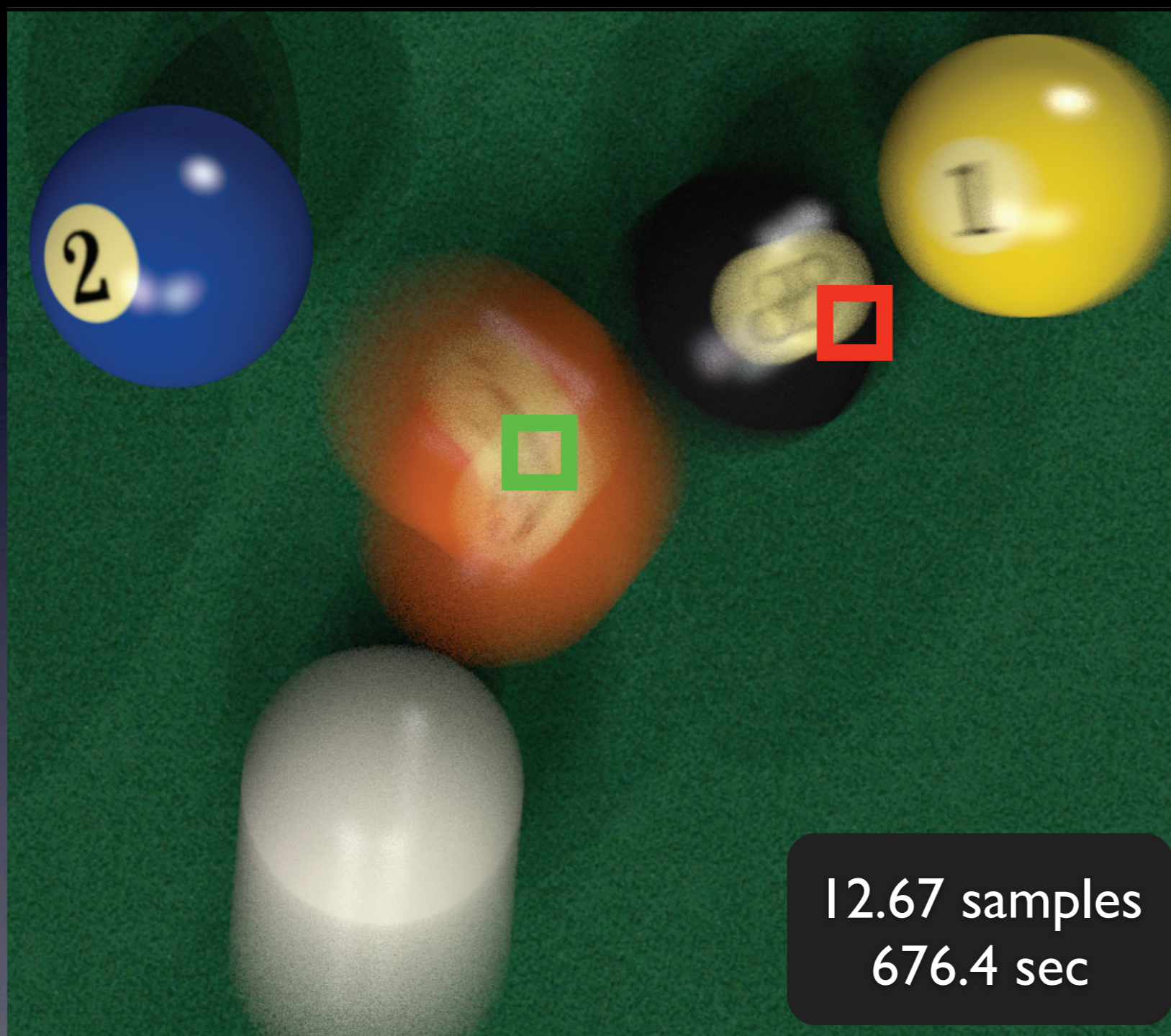
# Motion Blur (3D) - Reference



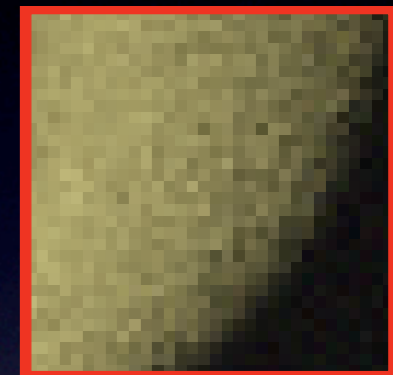
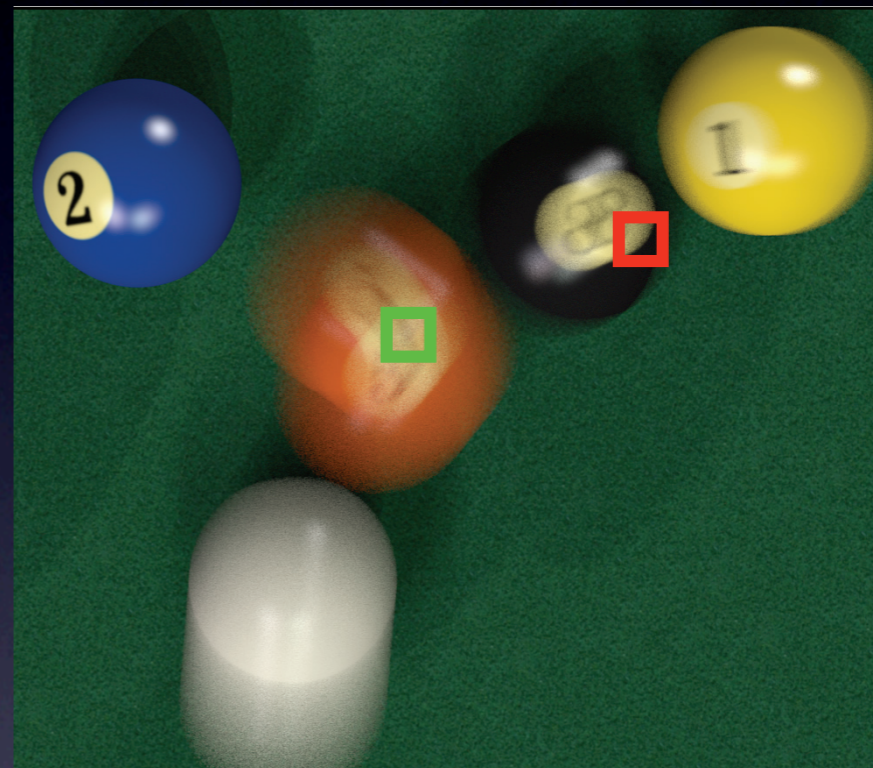
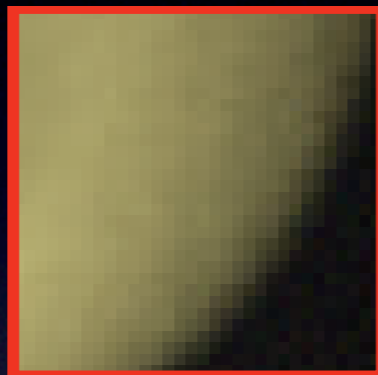
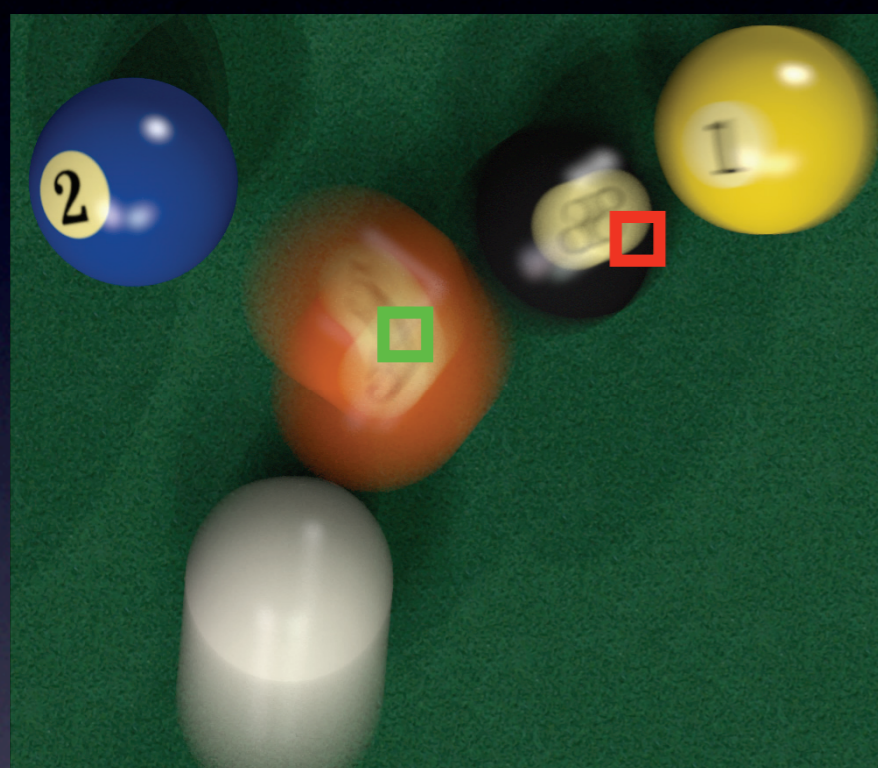
# Motion Blur (3D) - Our Method



# Motion Blur (3D) - [Mitchell 91]



# Motion Blur (3D) - Comparison

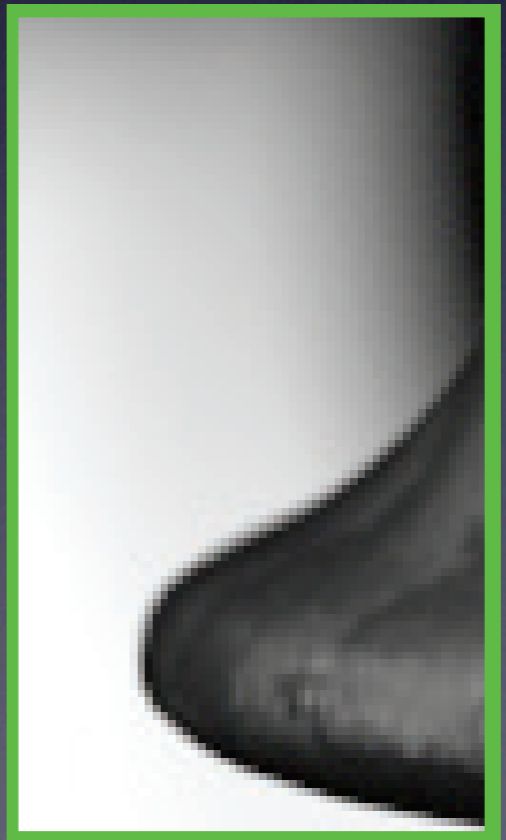
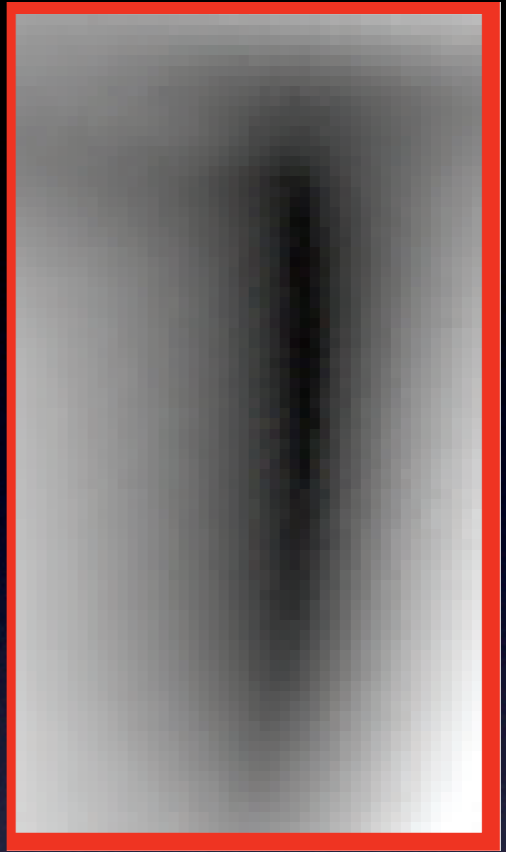


Our method  
8 samples / pixel  
672.2 sec  
RMS: 0.0034

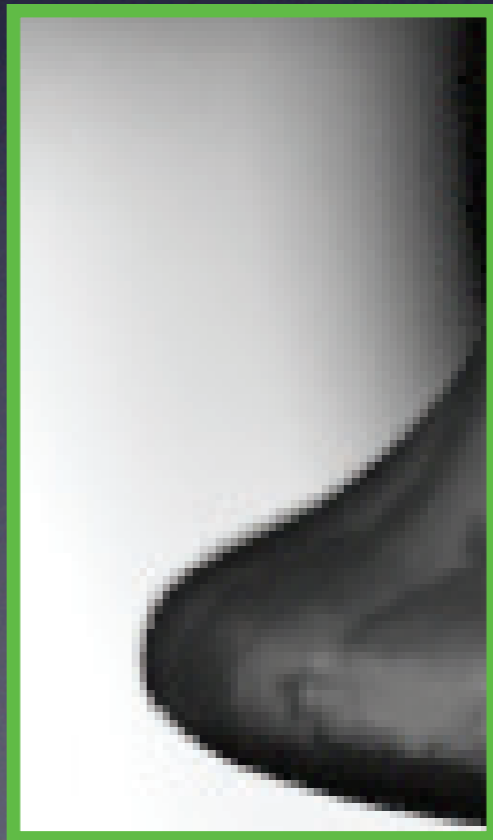
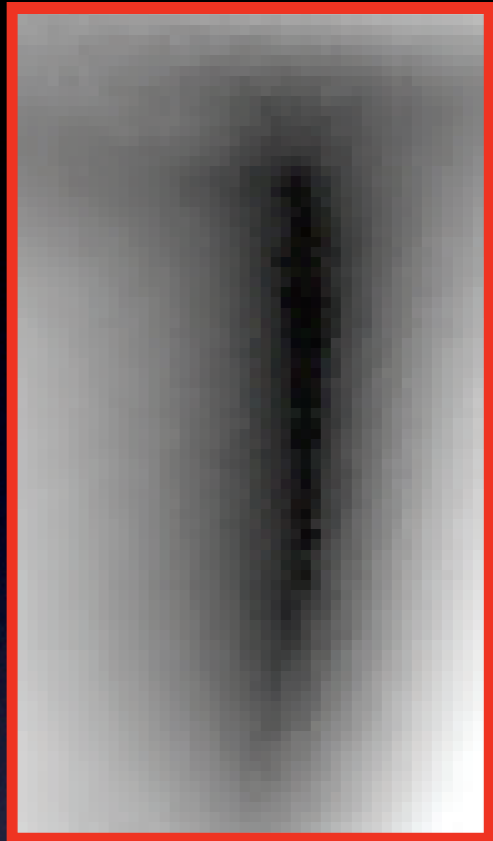
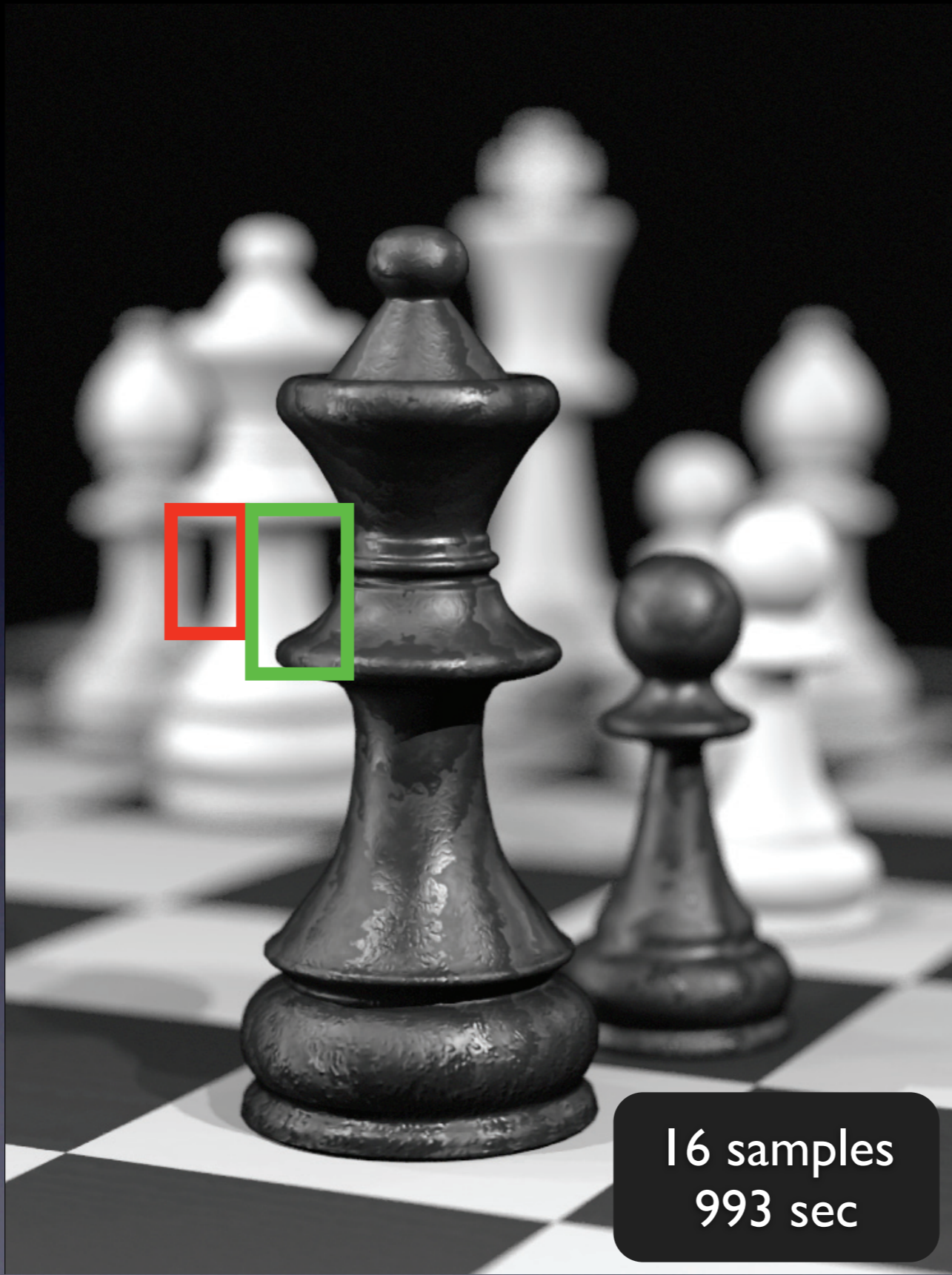
[Mitchell 91]  
12.67 samples / pixel  
676.4 sec  
RMS: 0.0099



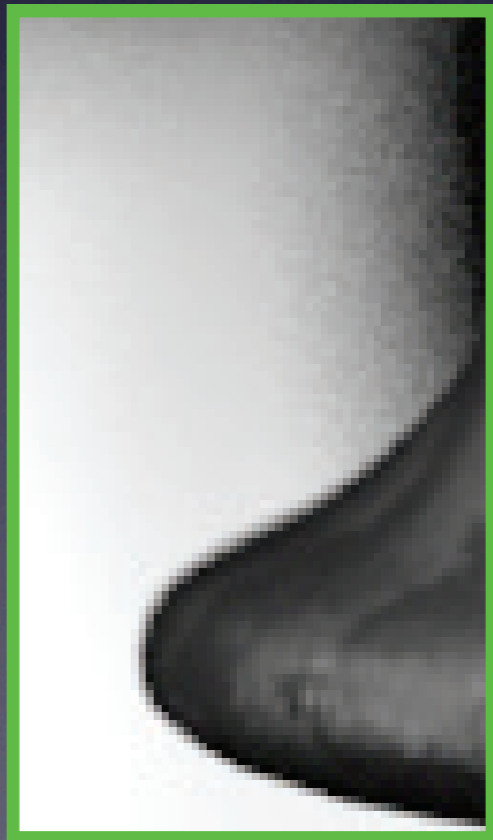
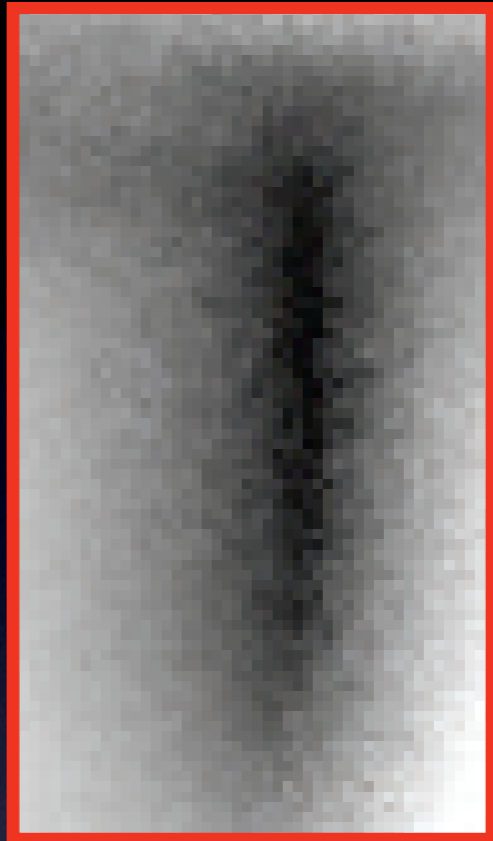
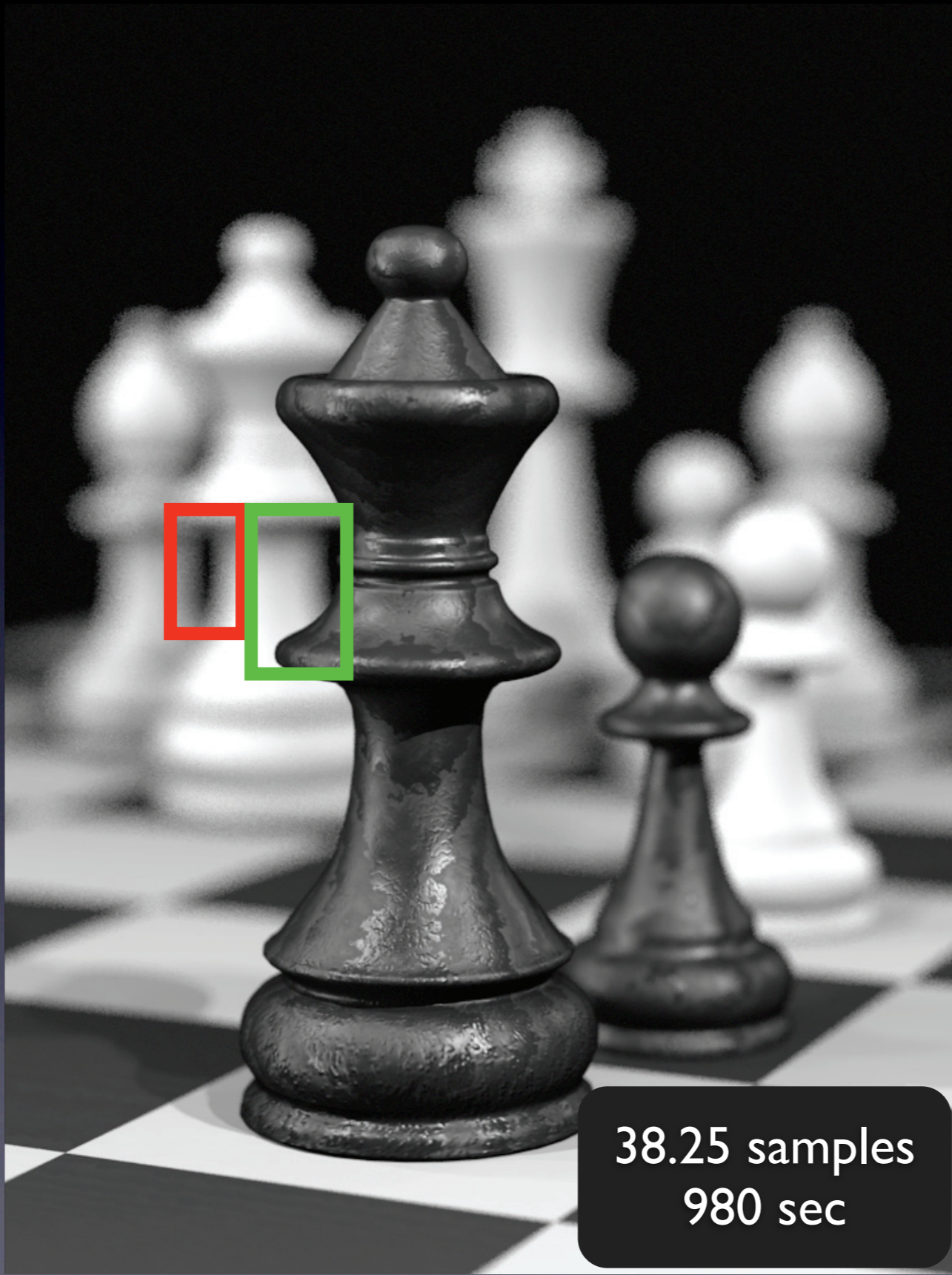
# Depth of Field (4D) - Reference



# Depth of Field (4D) - Our Method

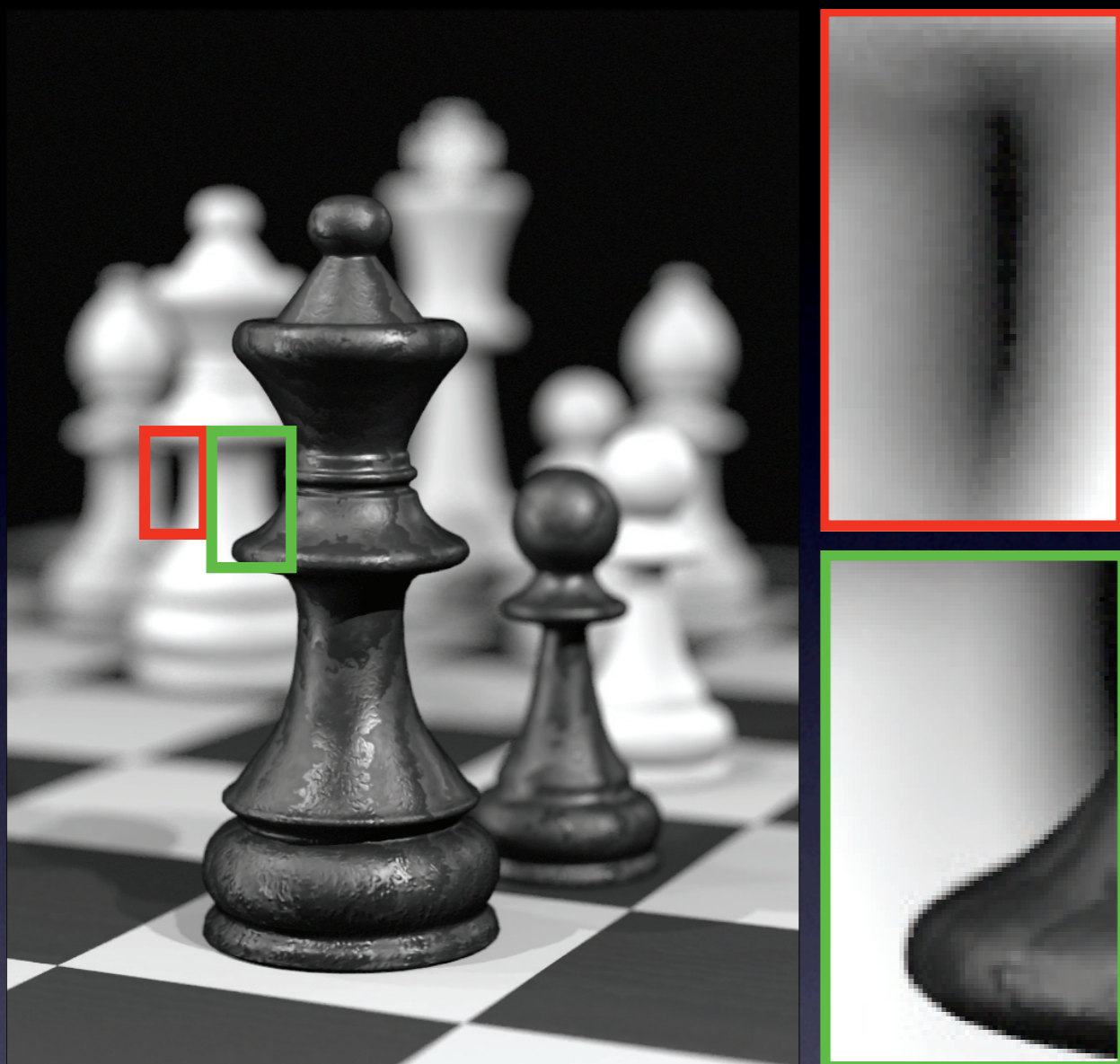


# Depth of Field (4D) - [Mitchell 91]



38.25 samples  
980 sec

# Depth of Field (4D) - Comparison

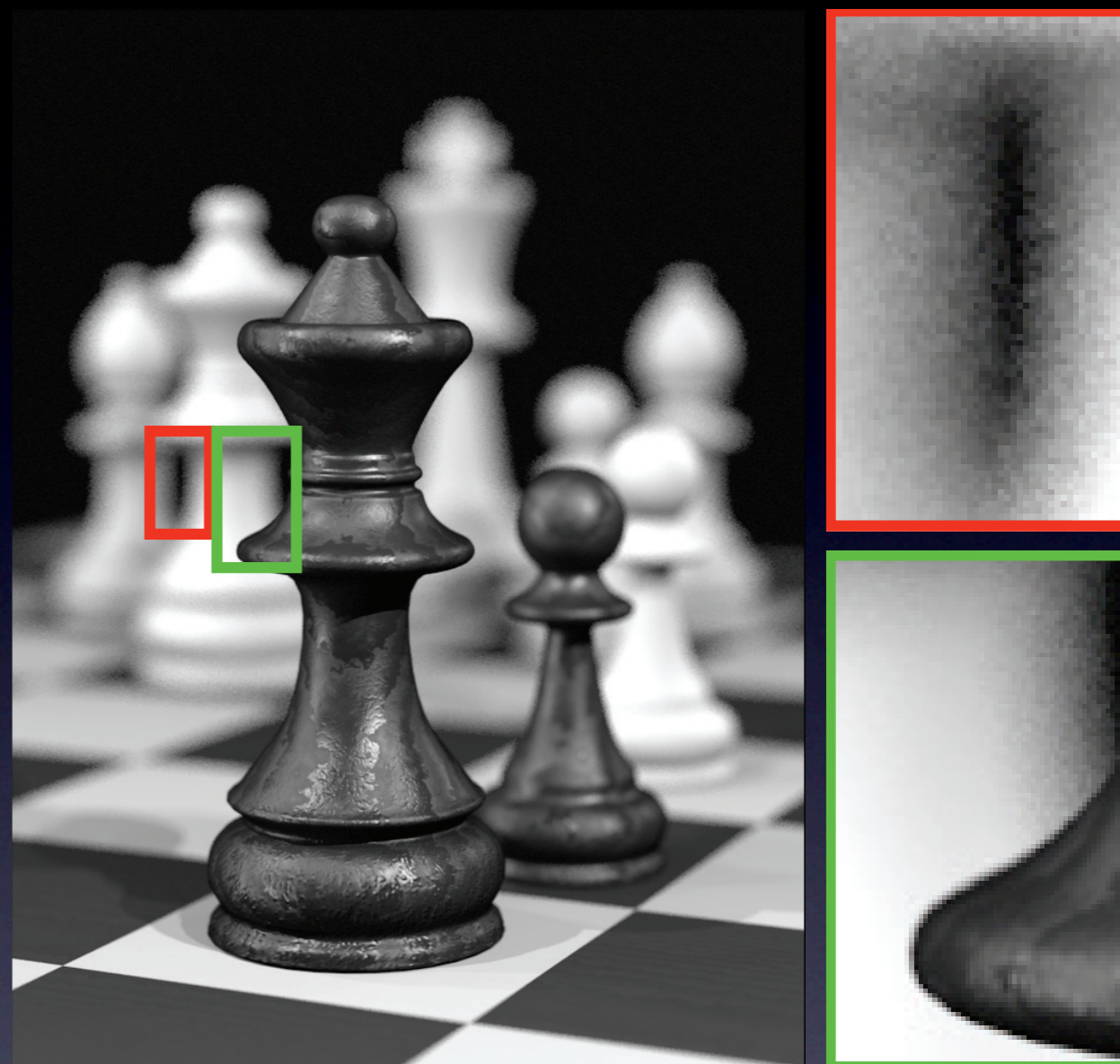


Our method

16 samples / pixel

993 sec

RMS: 0.132



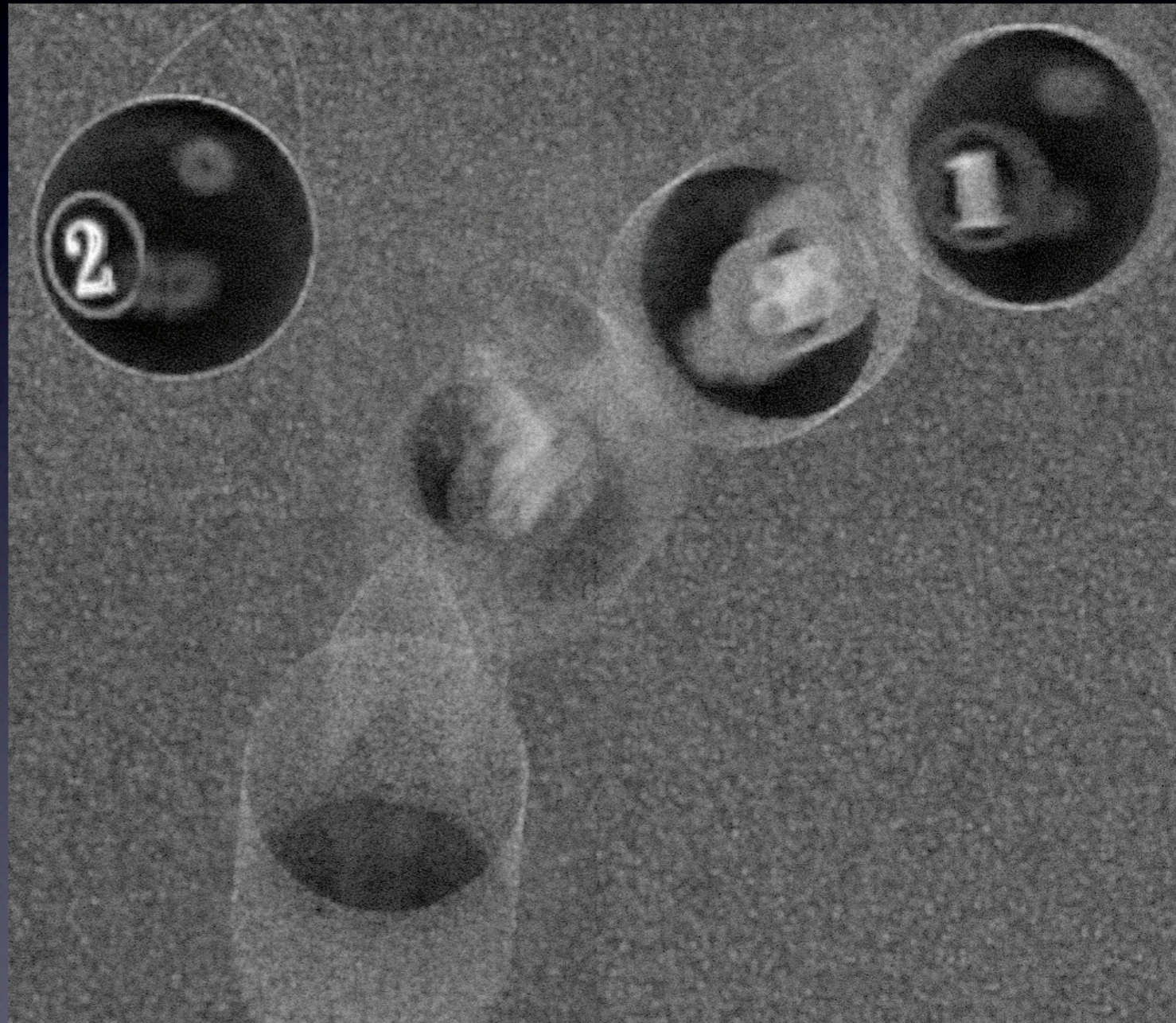
[Mitchell 91]

38.25 samples / pixel

980 sec

RMS: 0.192

# Sampling Density



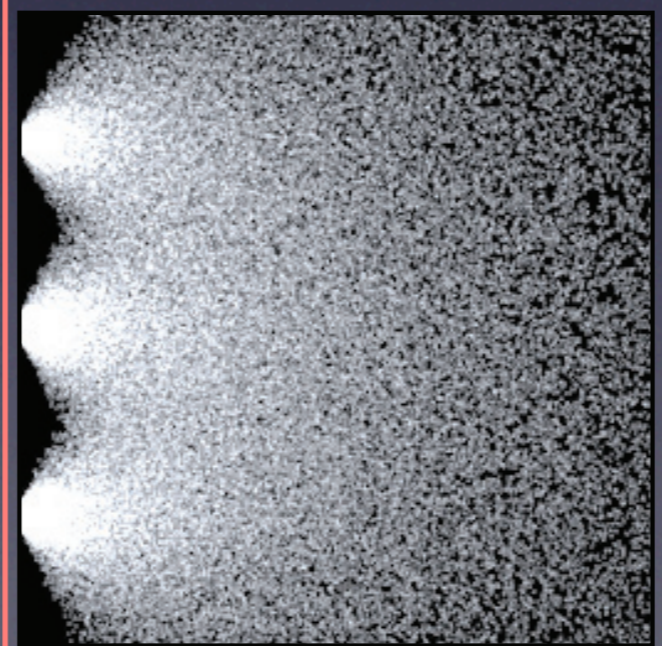
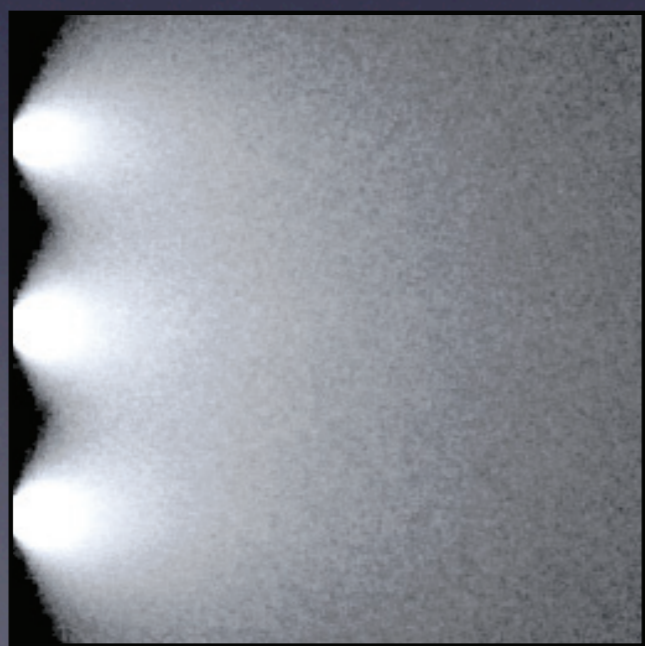
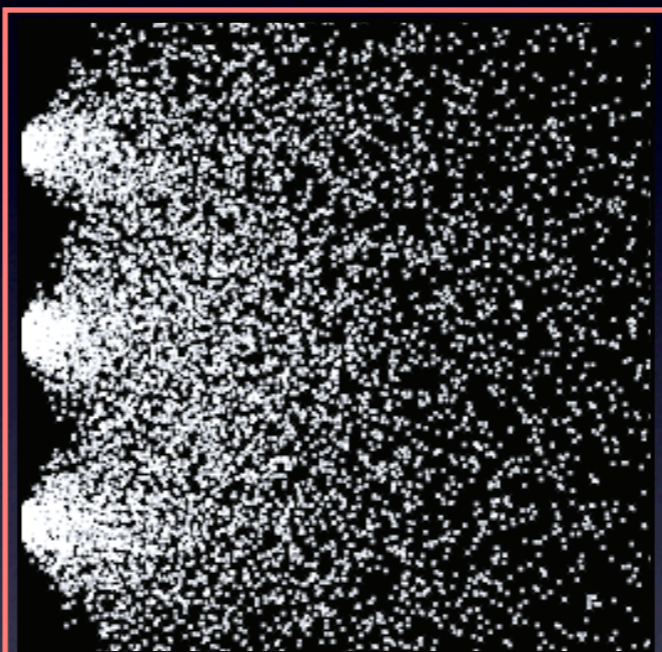
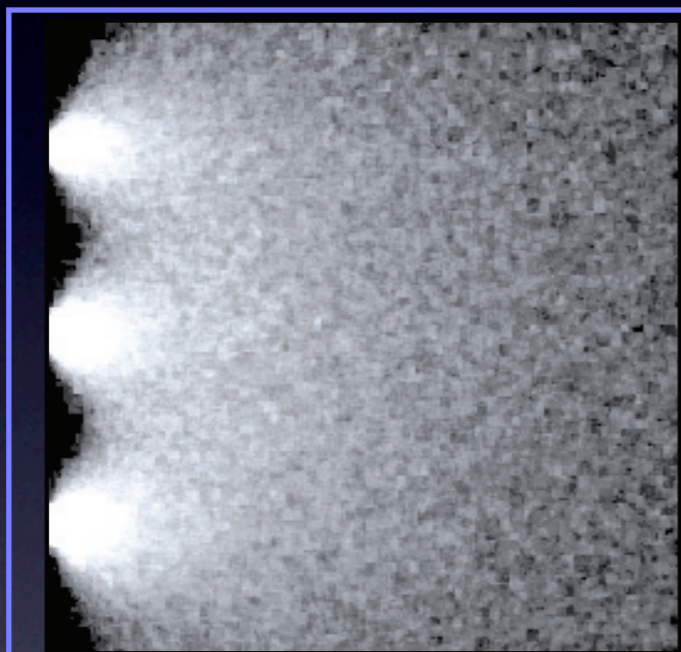
# Area Light Source (4D)

Our method

Mitchell

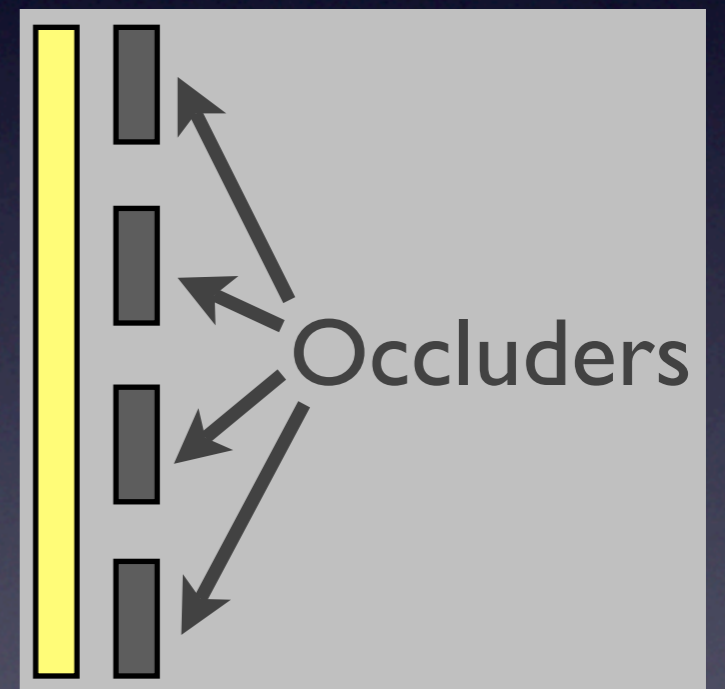
Samples / Pixel

64



Scene Setup

Area Light Source



# Area Light Source (4D)

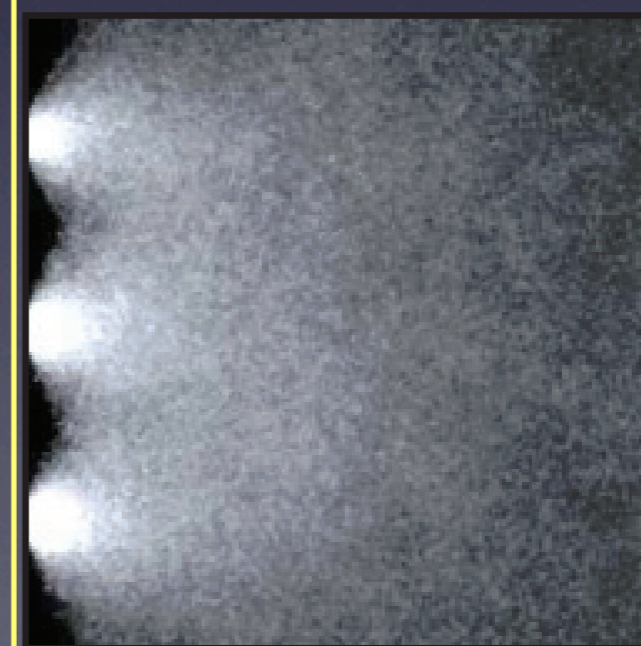
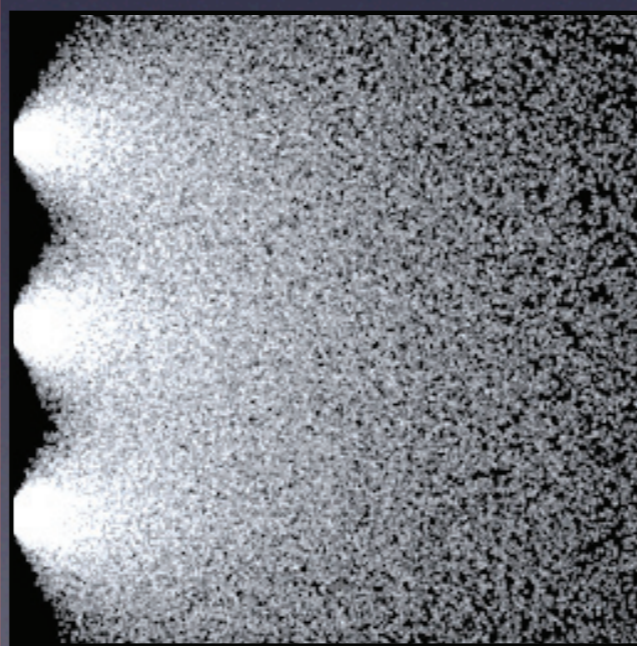
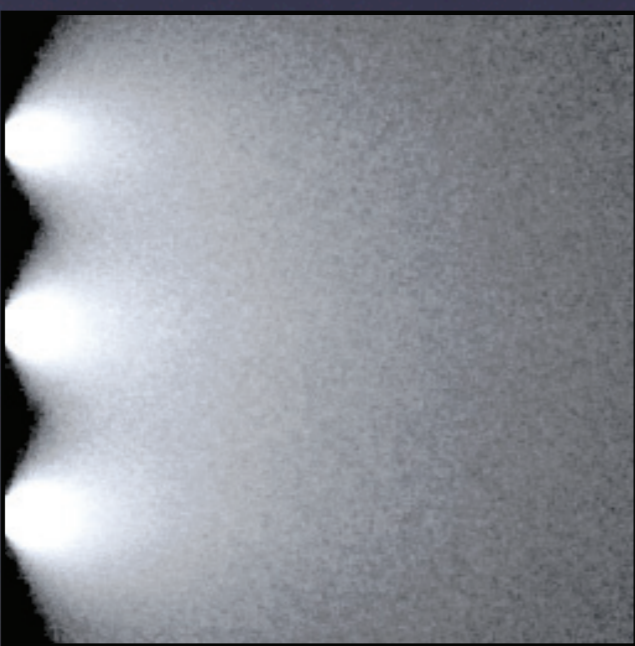
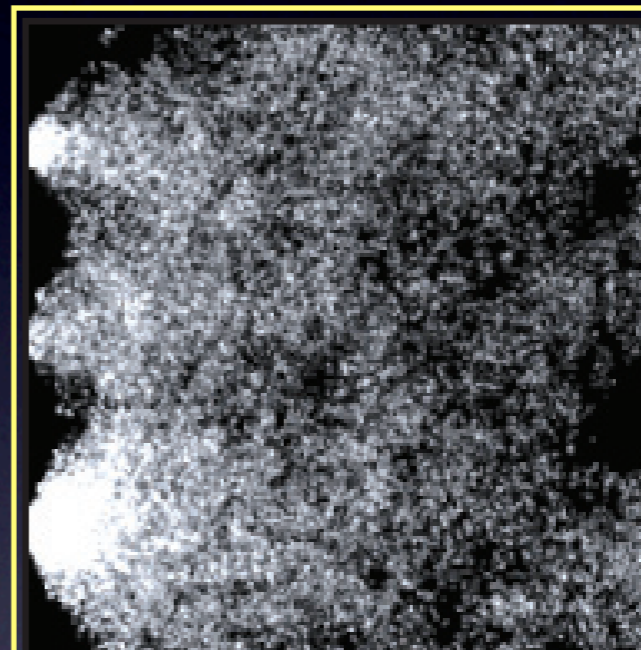
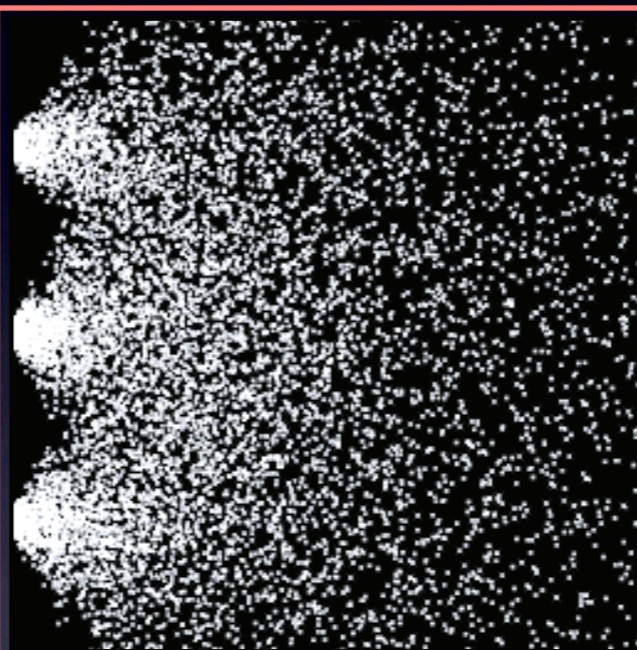
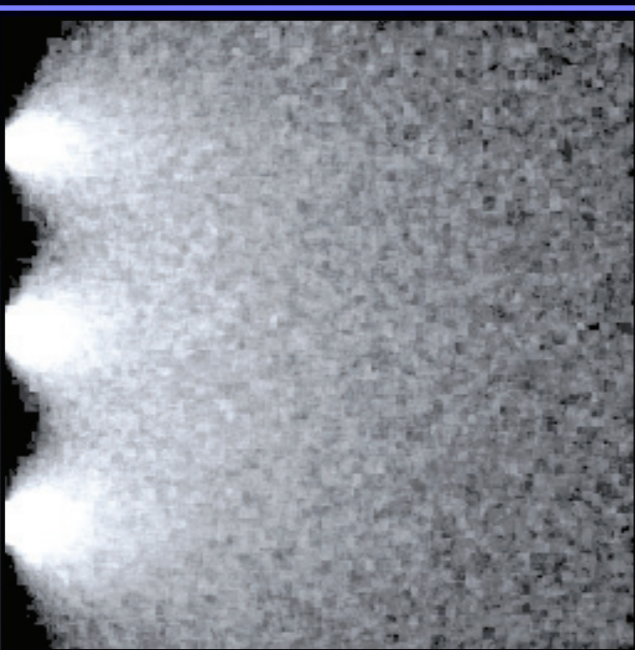
Our method

Mitchell

Metropolis

Samples / Pixel

64



# Area Light Source (4D)

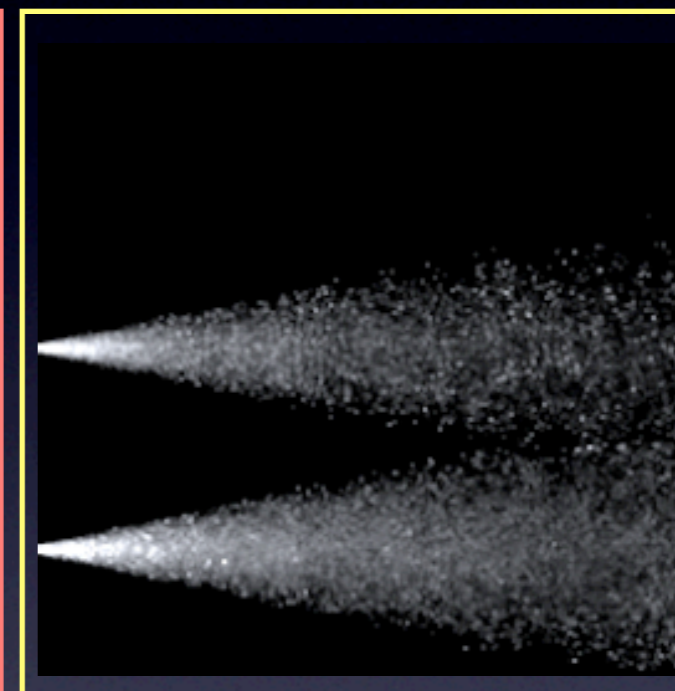
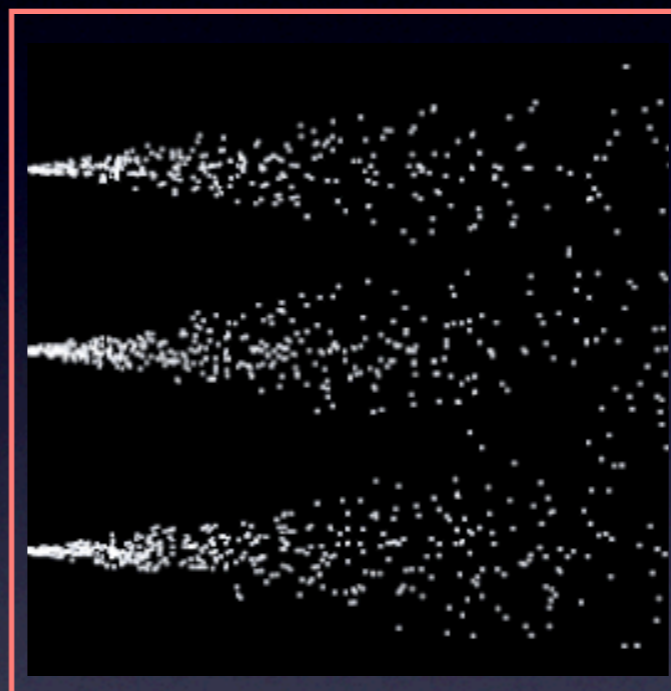
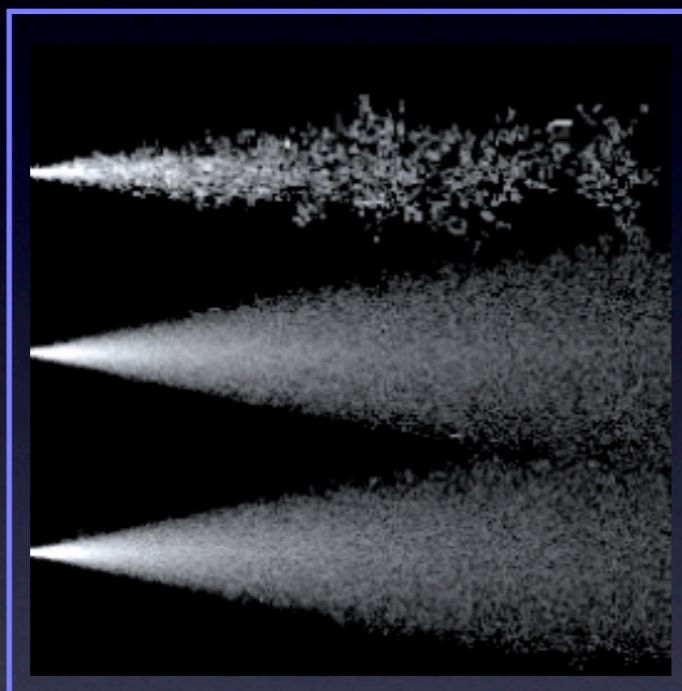
Our method

Mitchell

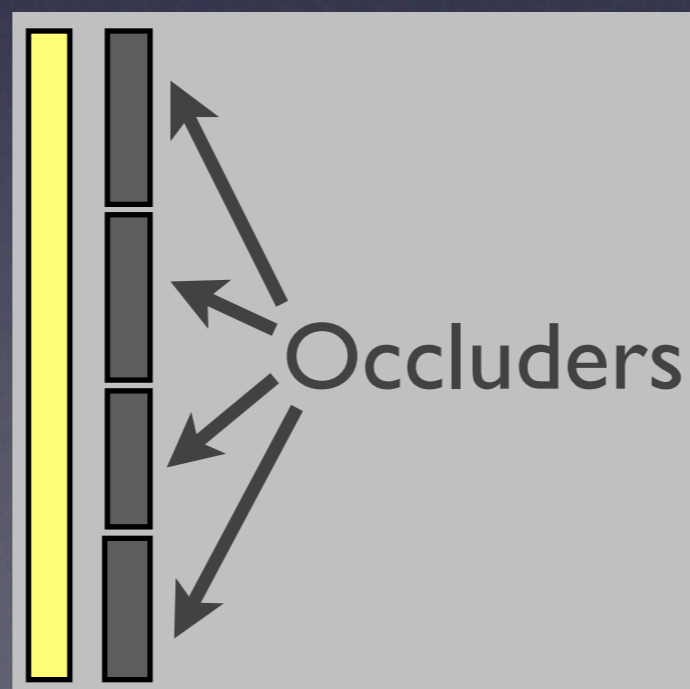
Metropolis

Samples / Pixel

64



Area Light Source





# Motion Blur + DOF (5D)



# Future Work

- More higher dimensional adaptive sampling
- New adaptive sampling criterion
- Application to more complex light transport

# Conclusion

- Produces images with less noise by fewer samples
  - Adaptive sampling in multidimensional space
  - Reconstruction from multidimensional samples
- Applicable to various rendering effects

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# Thanks

