Imaging In Challenging Weather Conditions

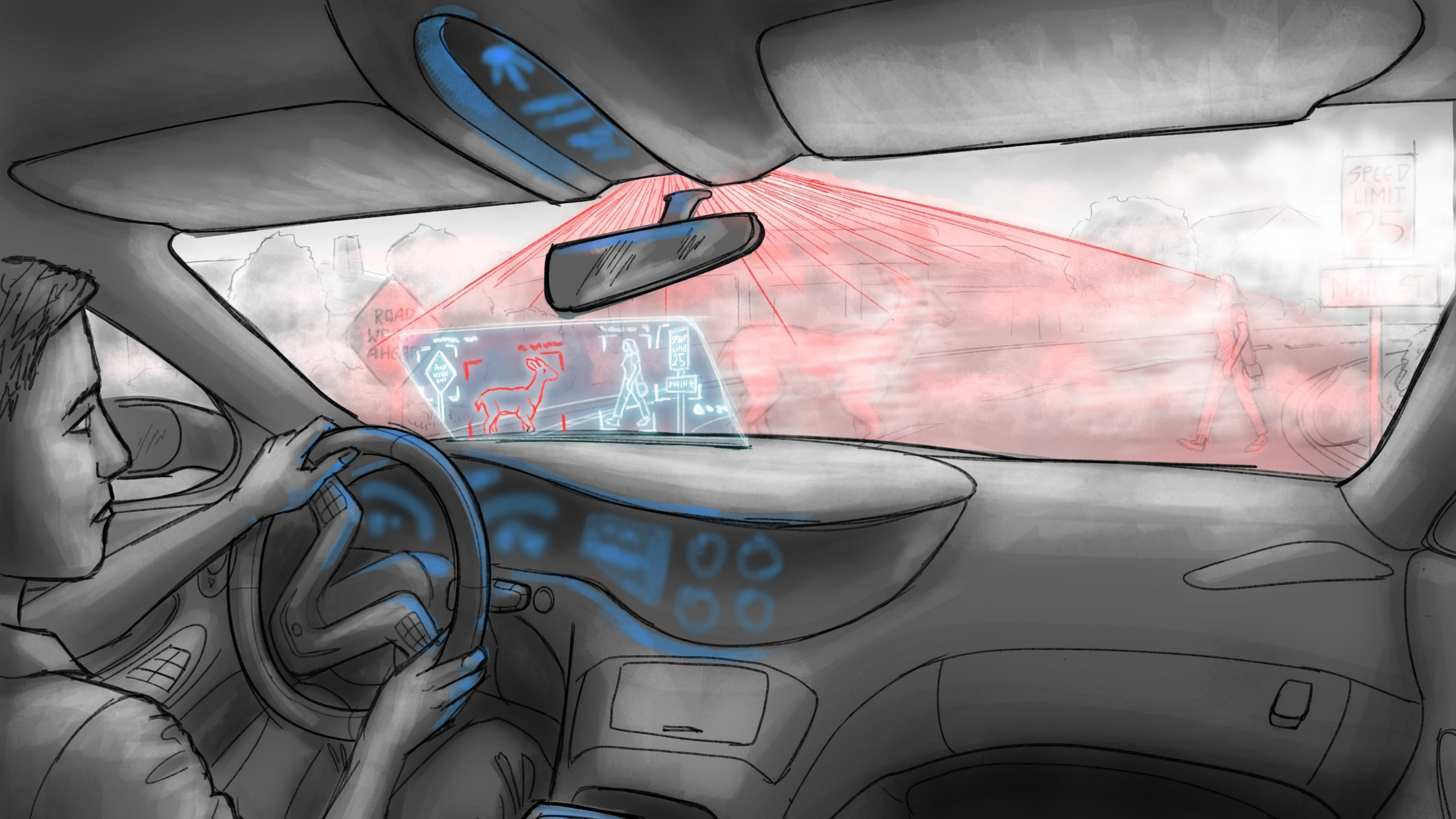
Guy Satat

Computational Imaging for Self-Driving Vehicles @ CVPR 2018

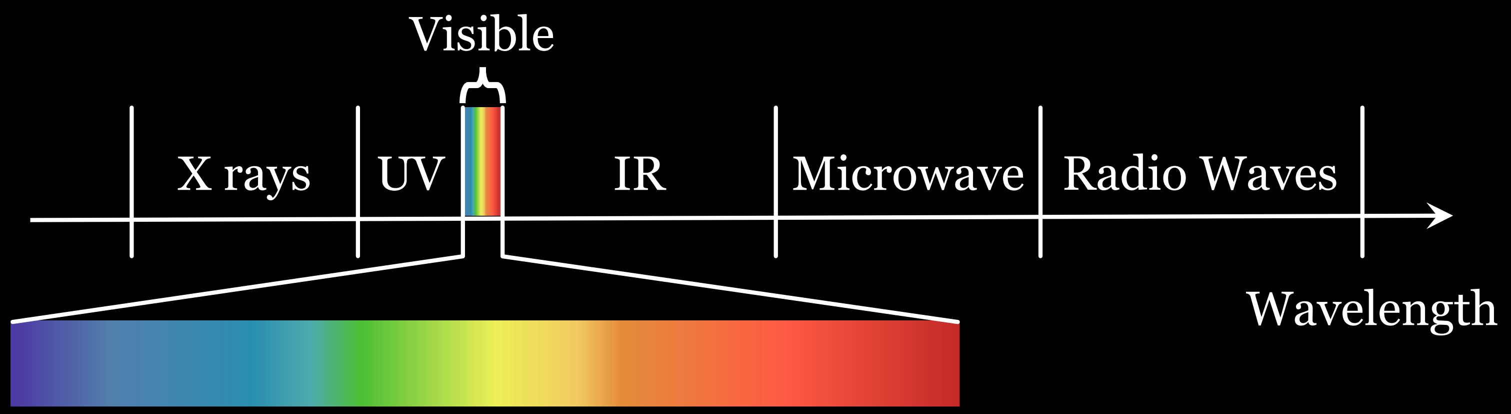


HYATT

Imaging Through Fog == Imaging Through Scattering?


ROAD
SPEED
LIMIT
25
MAIN ST

Why not RADAR ?



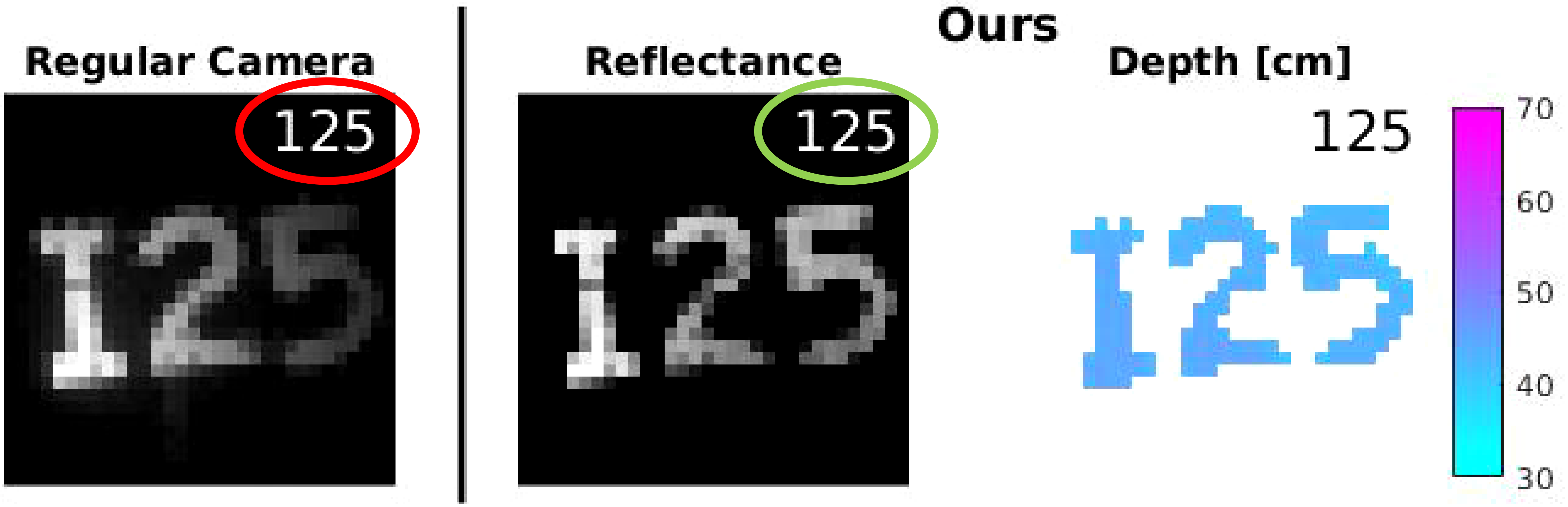
- Resolution
- Optical contrast

Different Strategies to Drive in Fog

Fog Sensor Detects Fog → Stop the Car!

Fog Sensor Detects Fog Level i → Drive with Foggy Algorithm i

Fog Invariant Computational Imaging System → Drive Normal As if the Fog were Not There



Estimated visiblity: 80 cm

Information Carried by Light

- The plenoptic function:

$$I(r, \lambda, t, \theta, P, n, \Phi)$$

Irradiance | Position | Wavelength | Time | Angle | Polarization | Bounce | Phase

Information Carried by Light

- The plenoptic function:

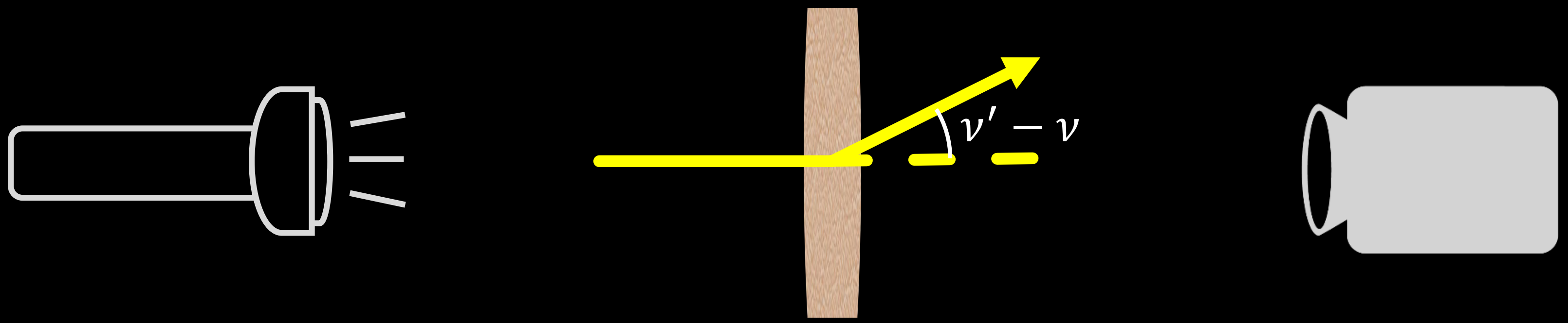
$$I(r, \lambda, t, \theta, P, n, \Phi)$$

Irradiance | Position | Wavelength | Time | Angle | Polarization | Bounce | Phase

Scattering Types

Sparse Scattering

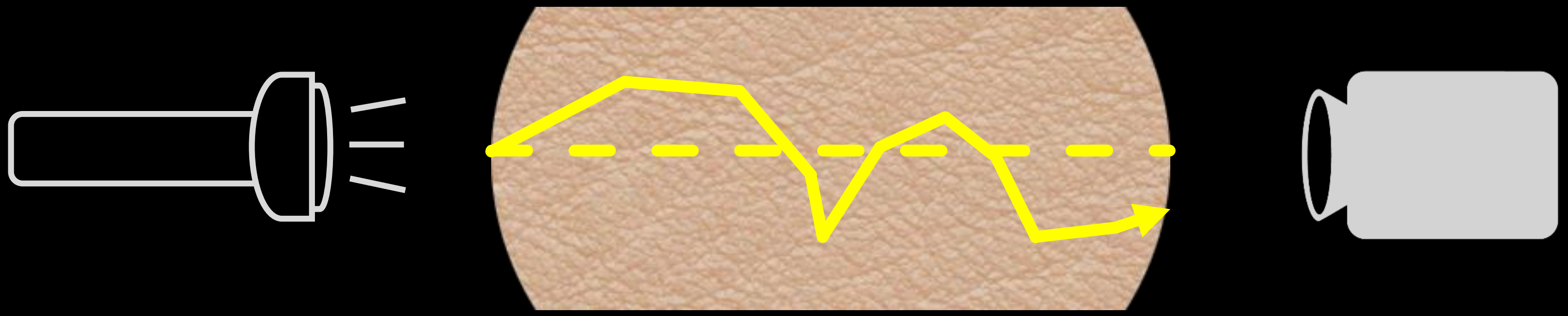
- Milky glass
- Paper
- Lensless imaging



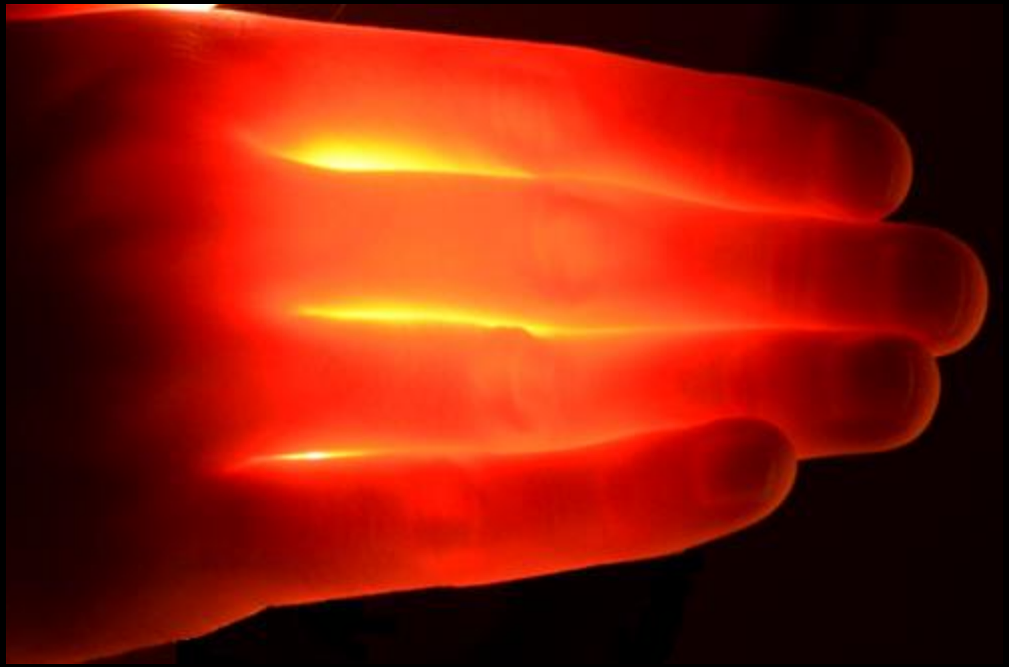
$$(x, \nu, t) \rightarrow (x, \nu', t)$$

Volumetric Scattering

- Tissue
- Fog

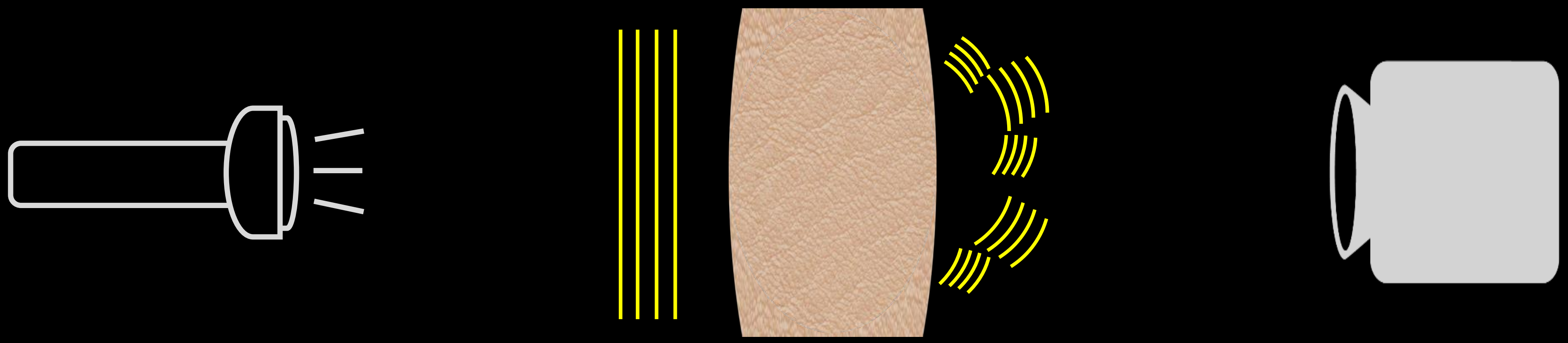


$$(x, \nu, t) \quad \rightarrow \quad (x', \nu', t')$$

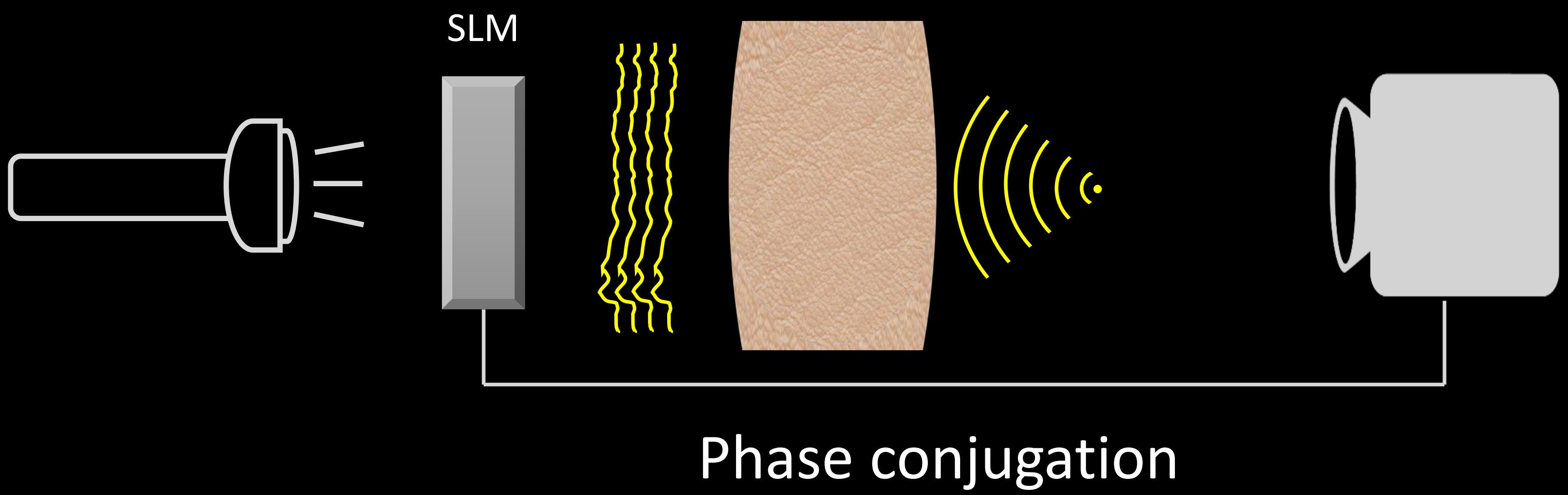


Lessons learned from seeing into the body

Phase Conjugation



Phase Conjugation



Long iterative process
Requires Guide Star

Diffuse Optical Tomography

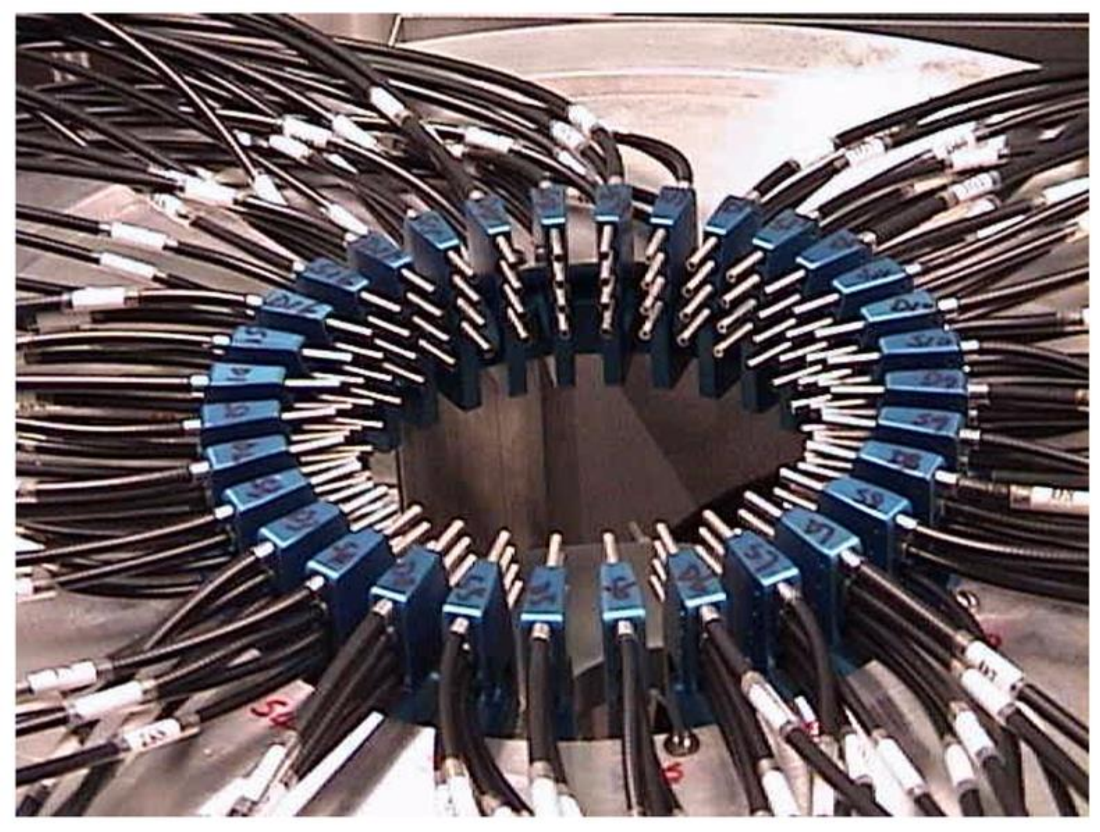
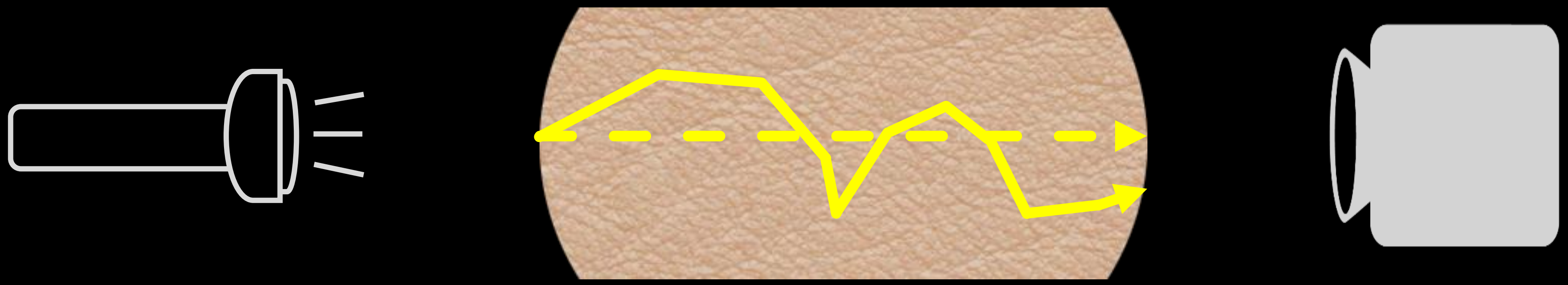


Photo credit: Wikipedia

Constrained
Imaging Geometry

Descattering with Photon Gating



Angle Time Polarization Coherence

Not enough photons

Doesn't reject all scattered light

No computation

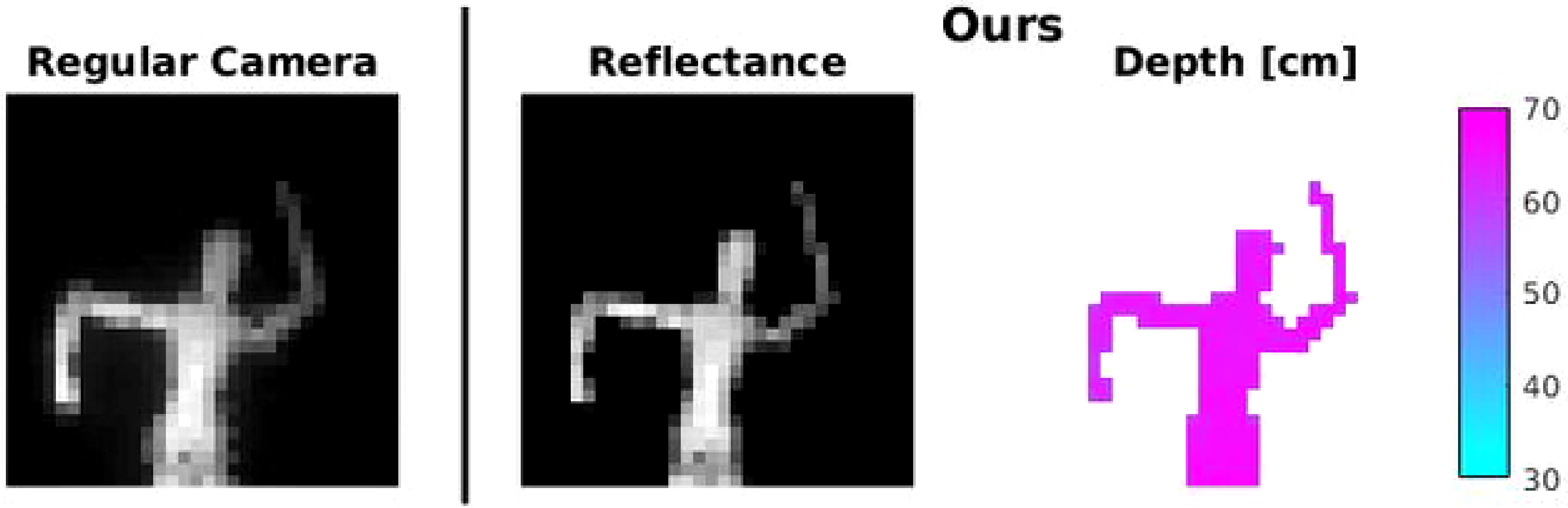
Constrained Imaging Geometry

Continuum of possible densities
Patchy (heterogeneous)
Moving platform

Towards Photography Through Realistic Fog

Guy Satat, Matthew Tancik, Ramesh Raskar

ICCP 2018



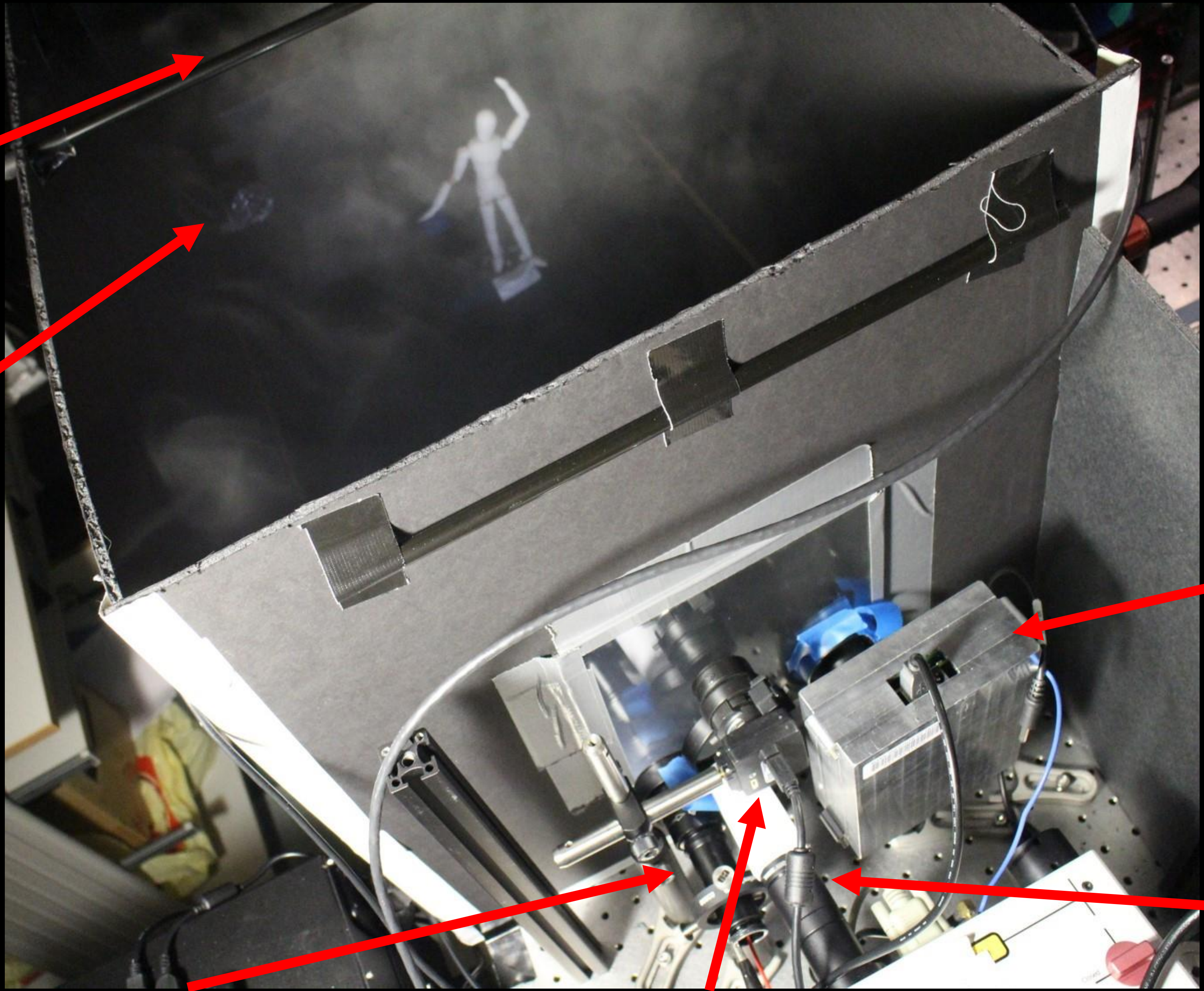
Estimated visiblity: 80 cm

Dense, Dynamic, Heterogeneous

Key Idea

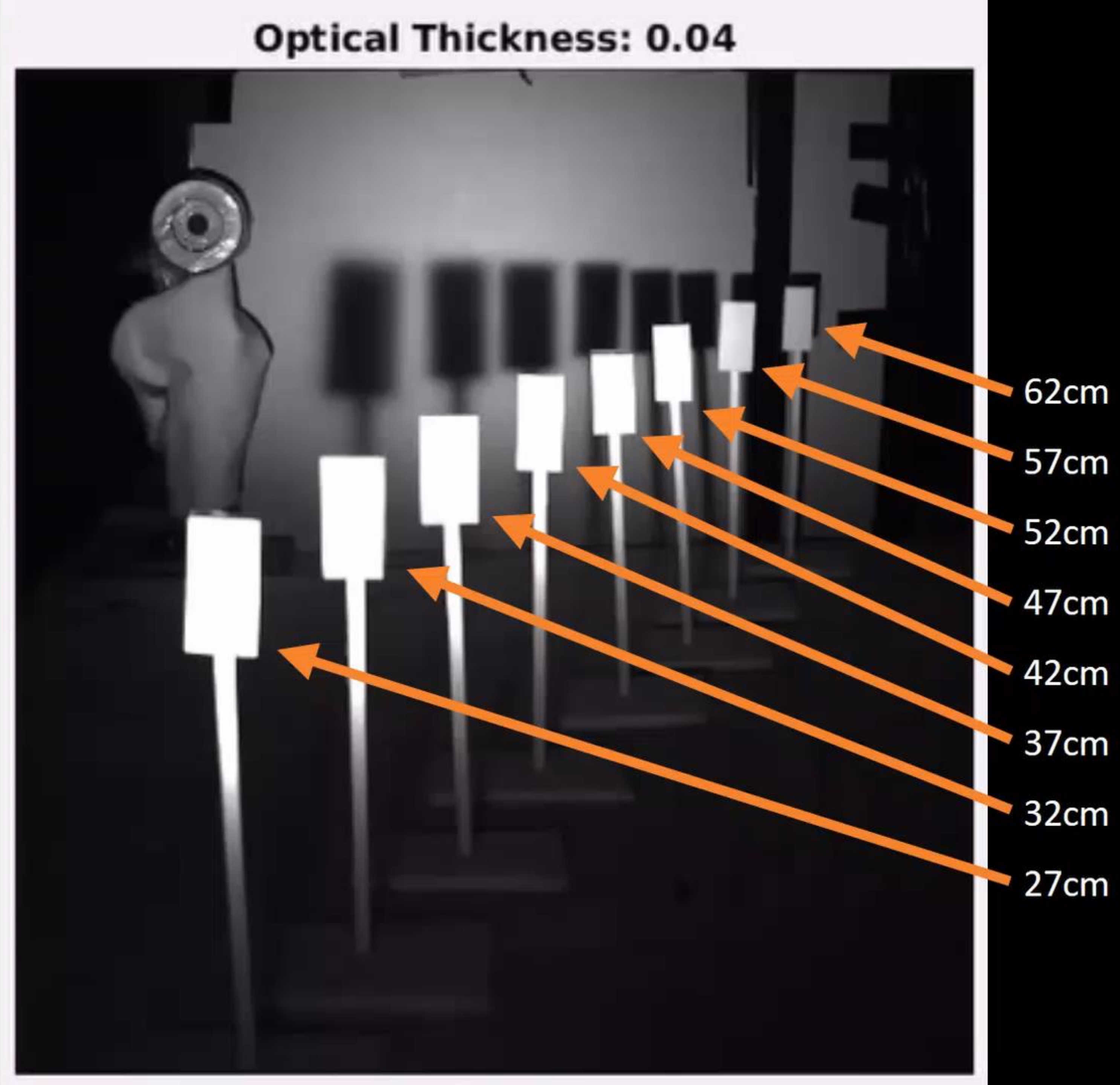
- Observation:
  - Photons reflected from fog and those reflected from target obey different statistics

- Solution:
  - A probabilistic technique to reject the backreflected photons

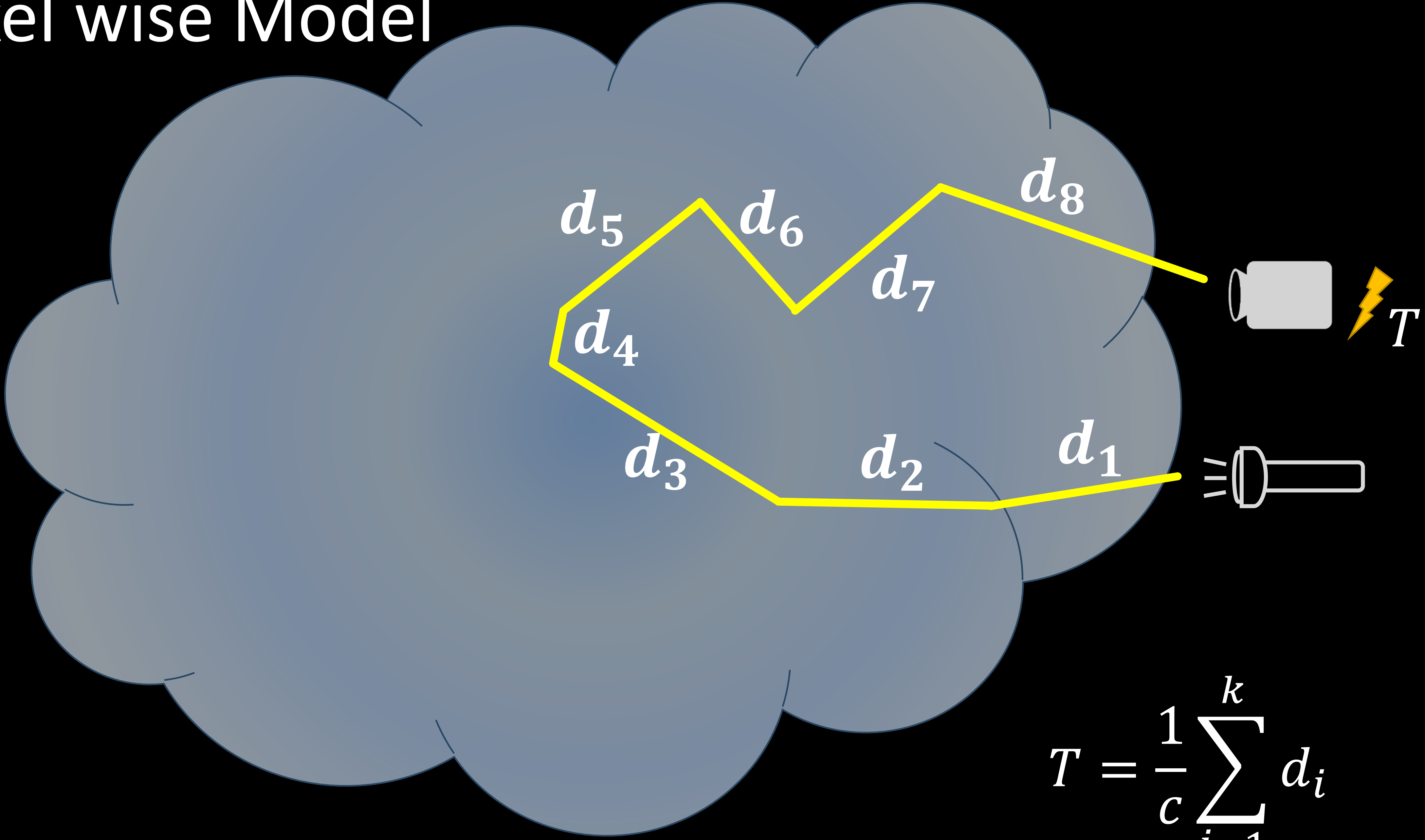

Fog
Generator
Power
Meter
SPAD
Camera
Diffused
Pulsed
Laser
IR flashlight
Regular Camera

Optical Thickness:

$$OT_t = -\log\left(\frac{P_0}{P_t}\right)$$

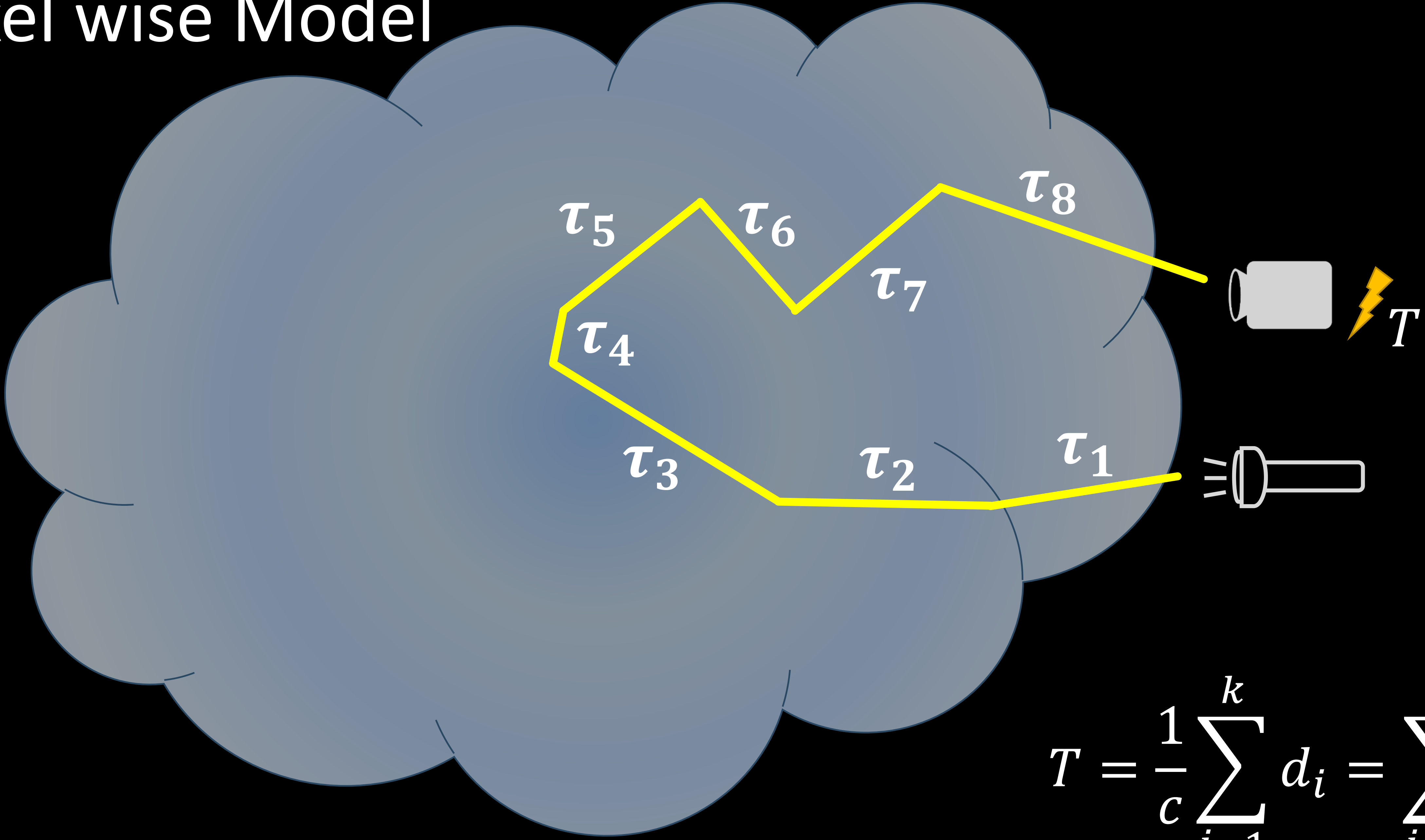


Pixel wise Model



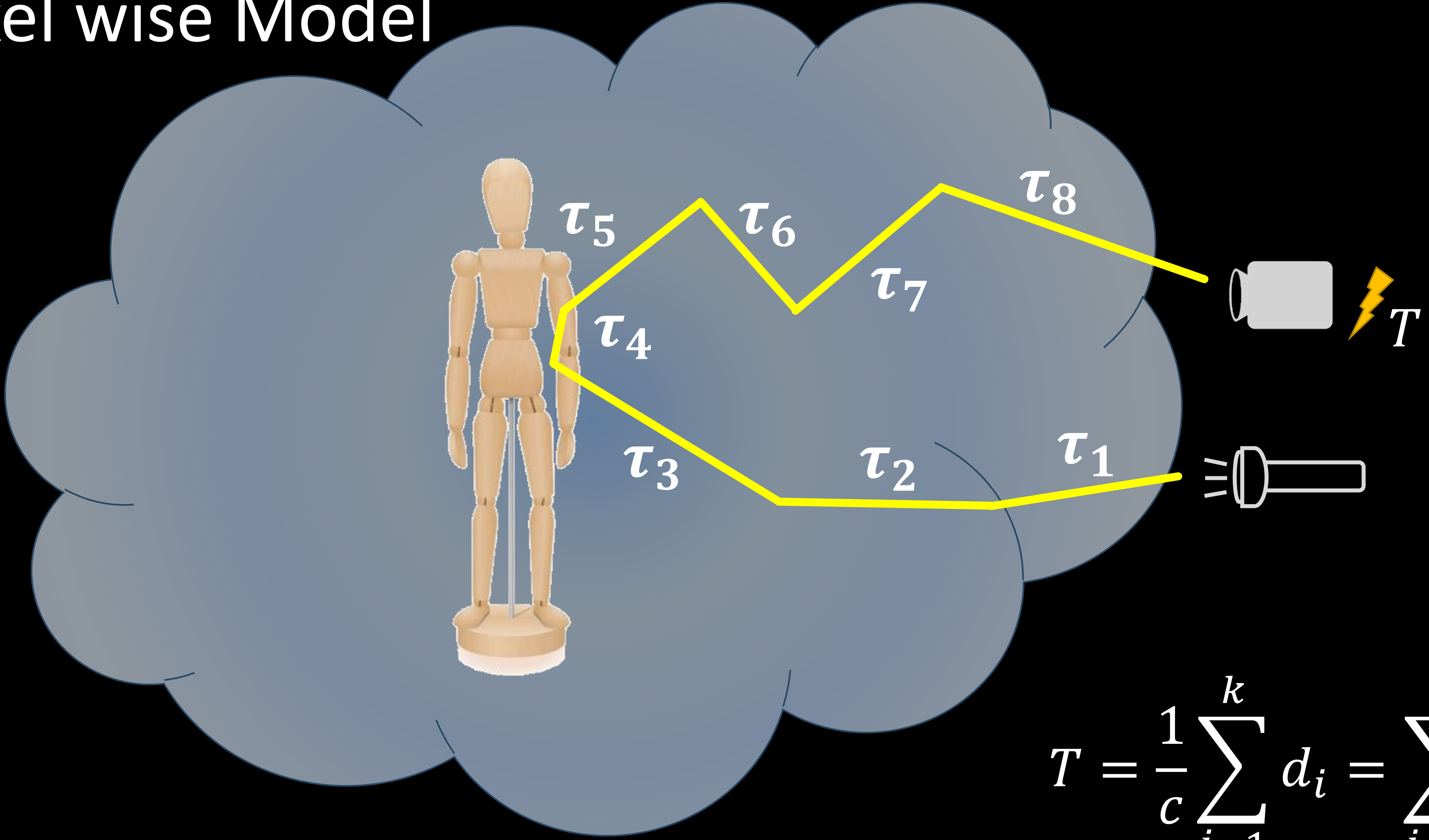
$$T = \frac{1}{c}\sum_{i=1}^{k} d_i$$

Pixel wise Model



$$T = \frac{1}{c}\sum_{i=1}^{k} d_i = \sum_{i=1}^{k} \tau_i$$

Pixel wise Model



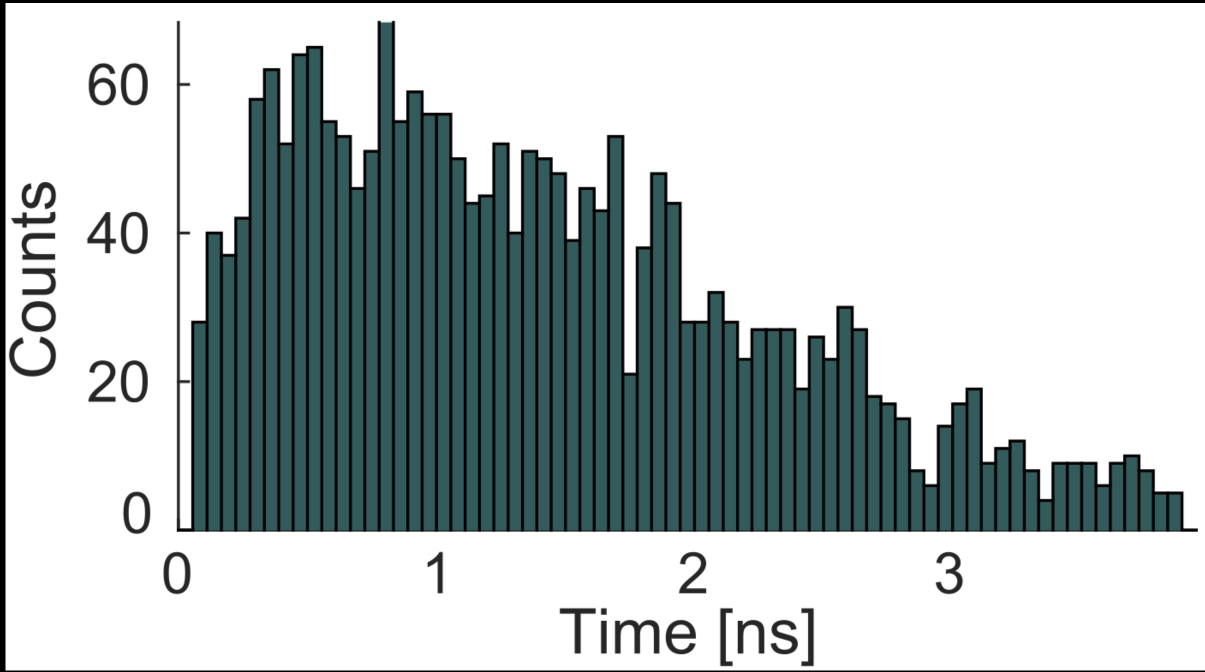
$$T = \frac{1}{c}\sum_{i=1}^{k} d_i = \sum_{i=1}^{k} \tau_i$$

Photon Classes

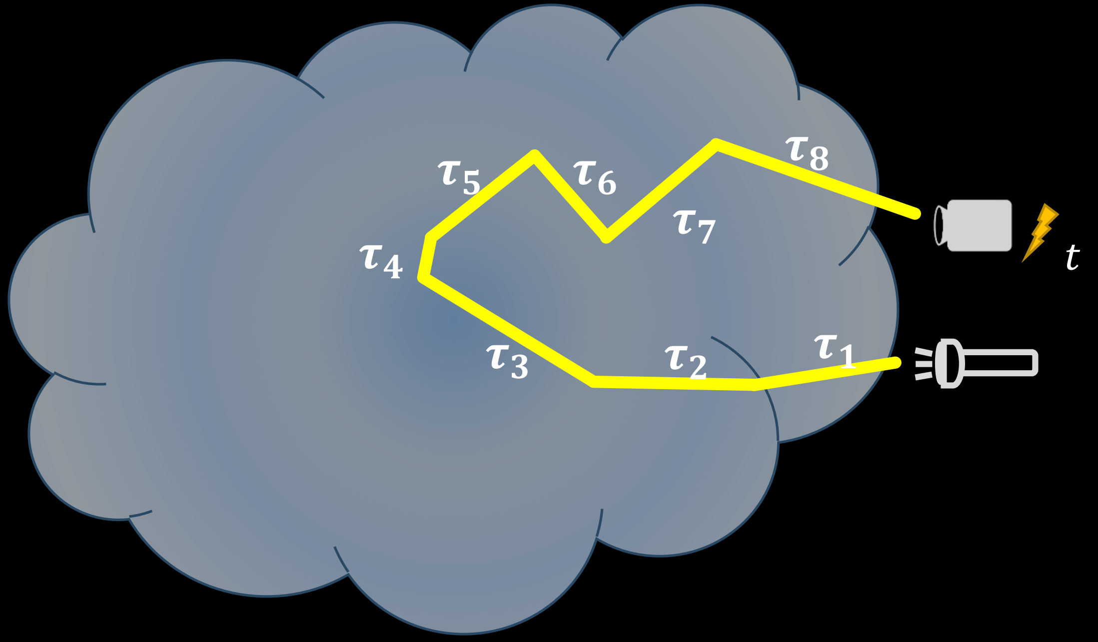
Background

Signal

Dark Count



Fog Model



- $T = \sum_{i=1}^{k} \tau_i$
- $\tau_i \sim Exp\{\mu_s\}$
  - $1/\mu_s$ - mean time between scattering events
- $T \sim Gamma\{\mu_s, k\}$
- $f_T(t|B) = \frac{\mu_s^k}{\Gamma(k)} t^{k-1} \exp\{-\mu_s t\}$

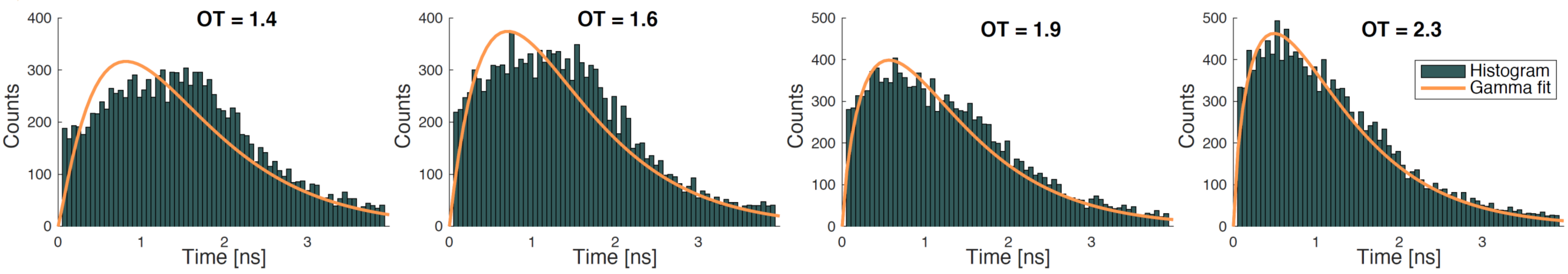
Fog Model

$$T = \Sigma\tau_i$$

$$\tau_i \sim Exp\{\mu_s\}$$

$$T \sim Gamma\{\mu_s, k\}$$

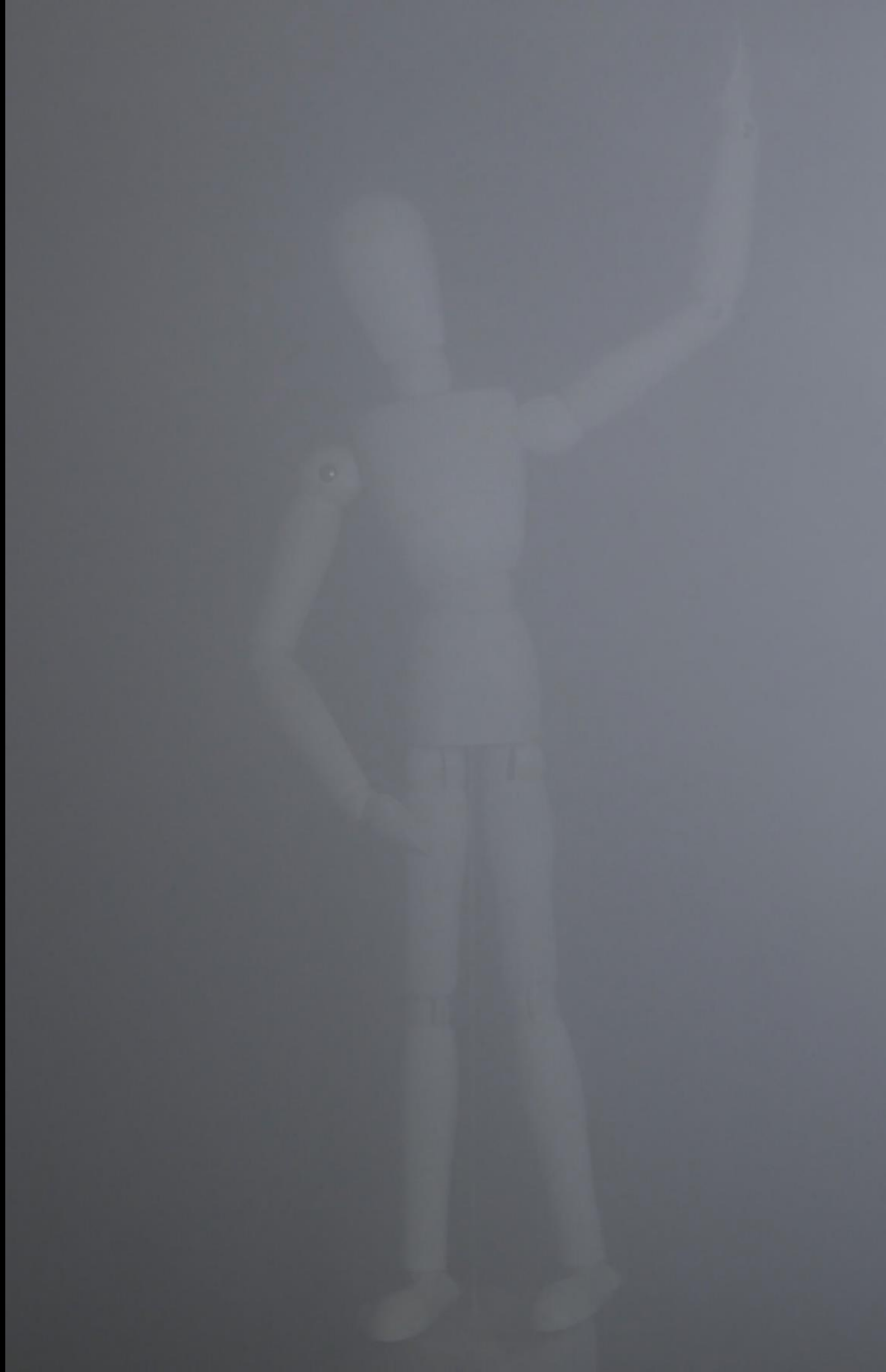
$$f_T(t|B) = \frac{\mu_s^k}{\Gamma(k)} t^{k-1} \exp\{-\mu_s t\}$$



Signal Model

- Another Gamma?

- $f_T(t|S) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left\{-\frac{(t-\mu)^2}{\sigma}\right\}$



Measurement Model

$$f_T(t) = P(B)f_T(t|B) + P(S)f_T(t|S)$$

Probability to measure a photon at time t

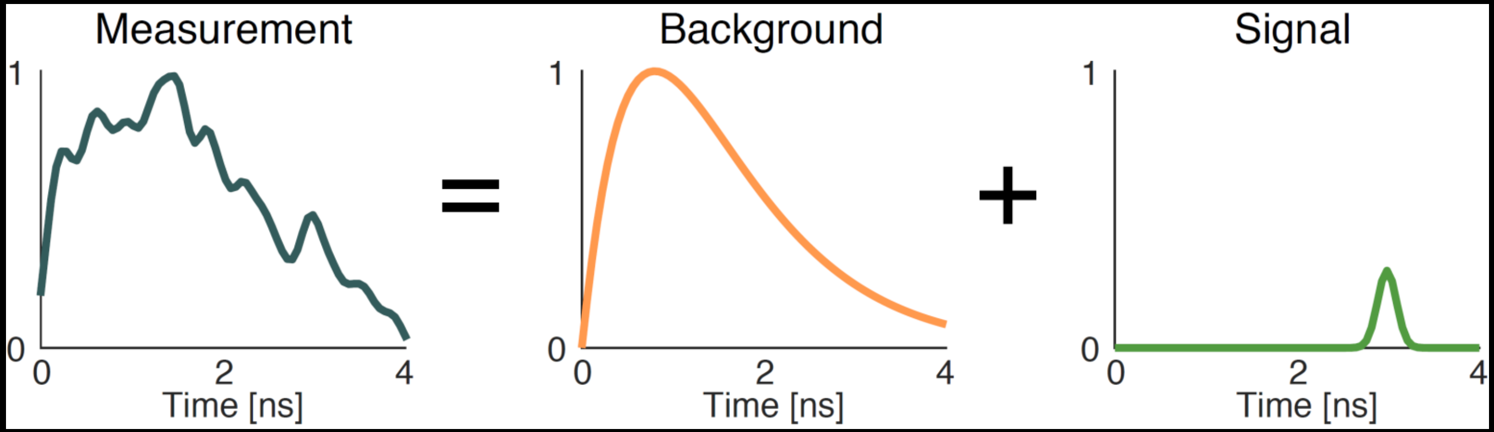
Probability to measure a background photon

Gamma distribution

Probability to measure a signal photon

Normal distribution

Encodes the target depth and reflectance



Model Estimation

$$f_T(t) = \underbrace{P(B)f_T(t|B)}_{\text{Fog}} + \underbrace{P(S)f_T(t|S)}_{\text{Signal}}$$

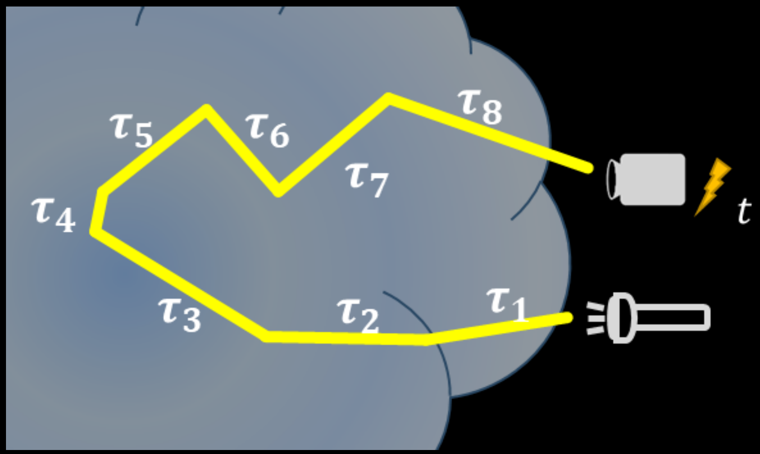
$$f_T(t) = \underbrace{P(B)f_T(t|B)}_{\text{Fog}} + \underbrace{P(S)f_T(t|S)}_{\text{Signal}}$$

Model Estimation

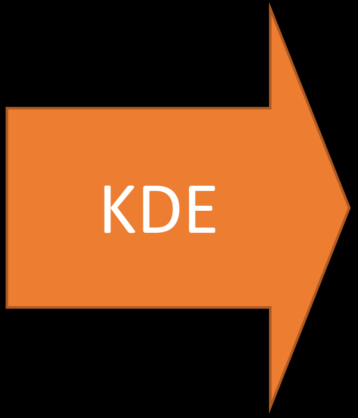
Time Profile → Background → Signal → Target

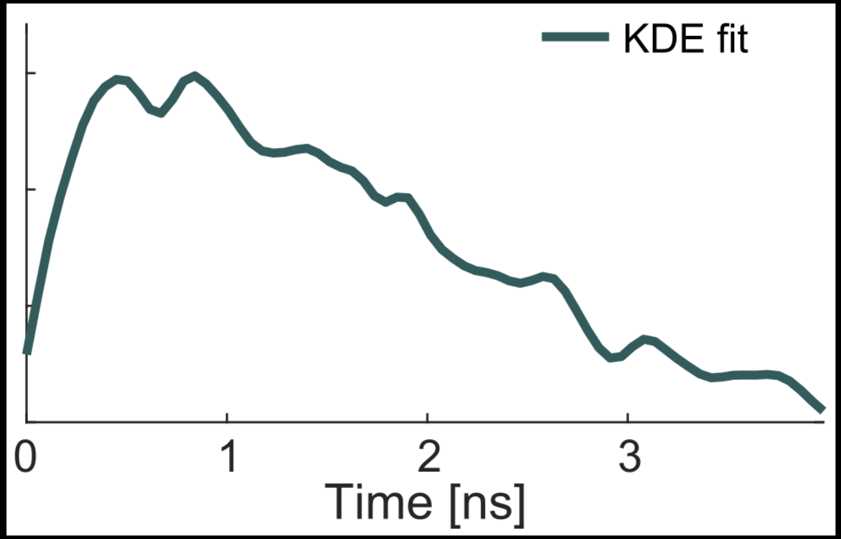
$$f_T(t) = \underbrace{P(B)f_T(t|B)}_{\text{Fog}} + \underbrace{P(S)f_T(t|S)}_{\text{Signal}}$$

Time Profile Estimation



0.7
1.1
1.1
1
3
1.9
3.8
1.7
0.5
0.6
3.8
3.9
3.4
1.4
3.8
3.2
3.3
2.7



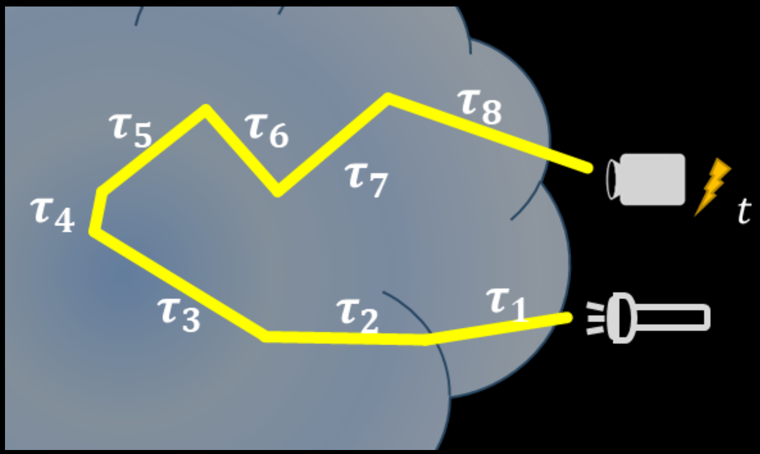


KDE (Kernel Density Estimator):

- Works well with a few sampling points

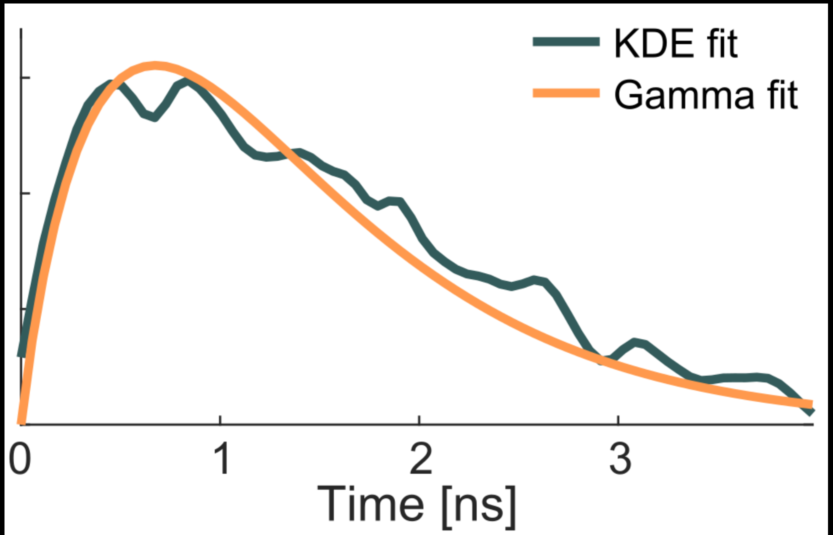
$$f_T(t) = \underbrace{P(B)f_T(t|B)}_{\text{Fog}} + \underbrace{P(S)f_T(t|S)}_{\text{Signal}}$$

Background Estimation



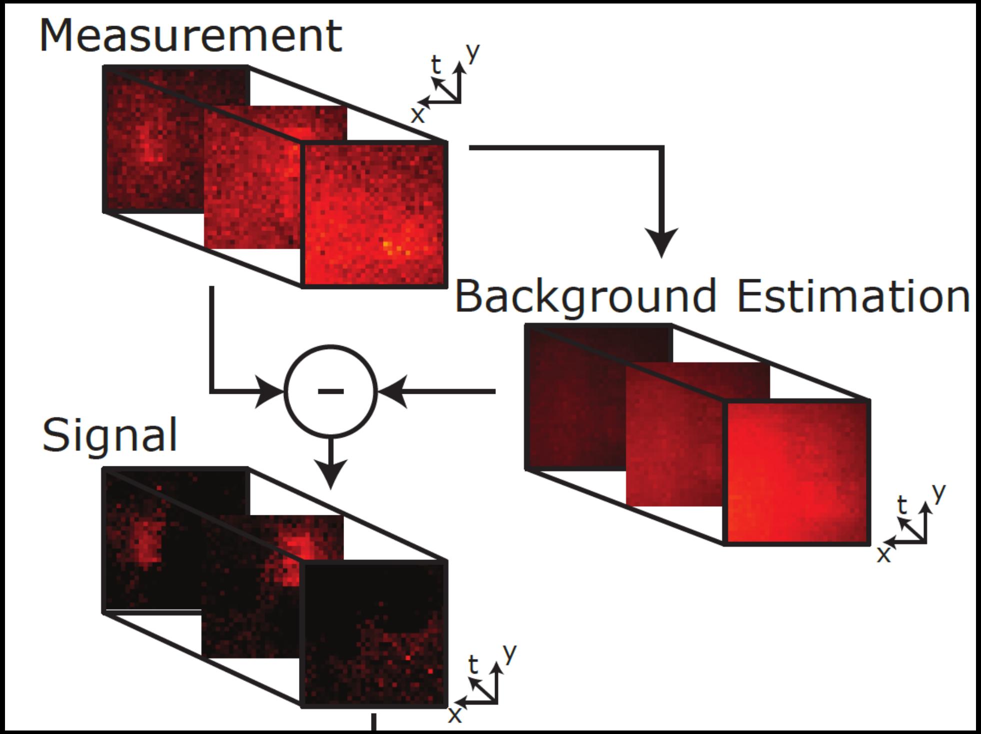
0.7
1.1
1.1
1
3
1.9
3.8
1.7
0.5
0.6
3.8
3.9
3.4
1.4
3.8
3.2
3.3
2.7

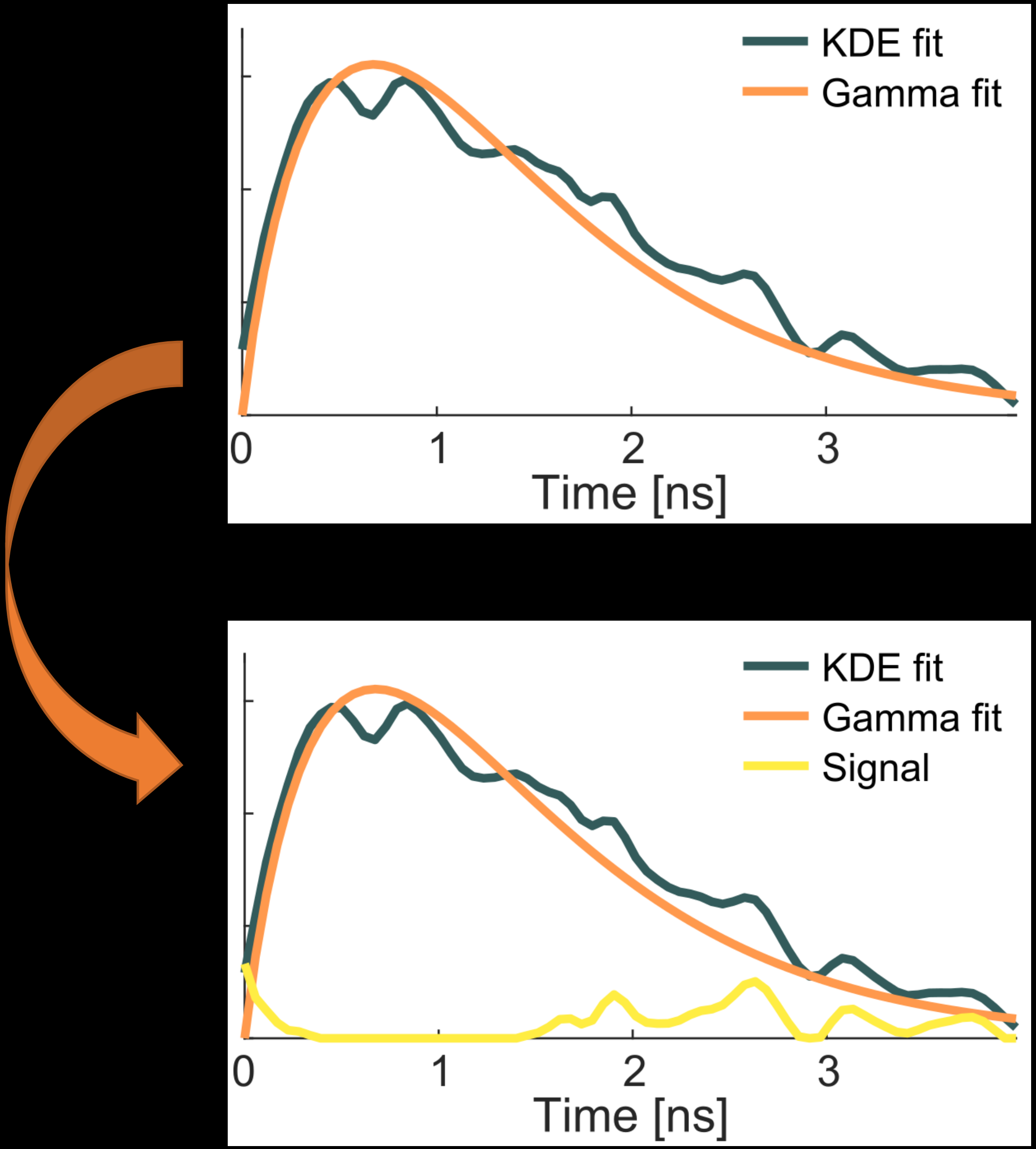
Gamma fit



$$f_T(t) = \underbrace{P(B)f_T(t|B)}_{\text{Fog}} + \underbrace{P(S)f_T(t|S)}_{\text{Signal}}$$

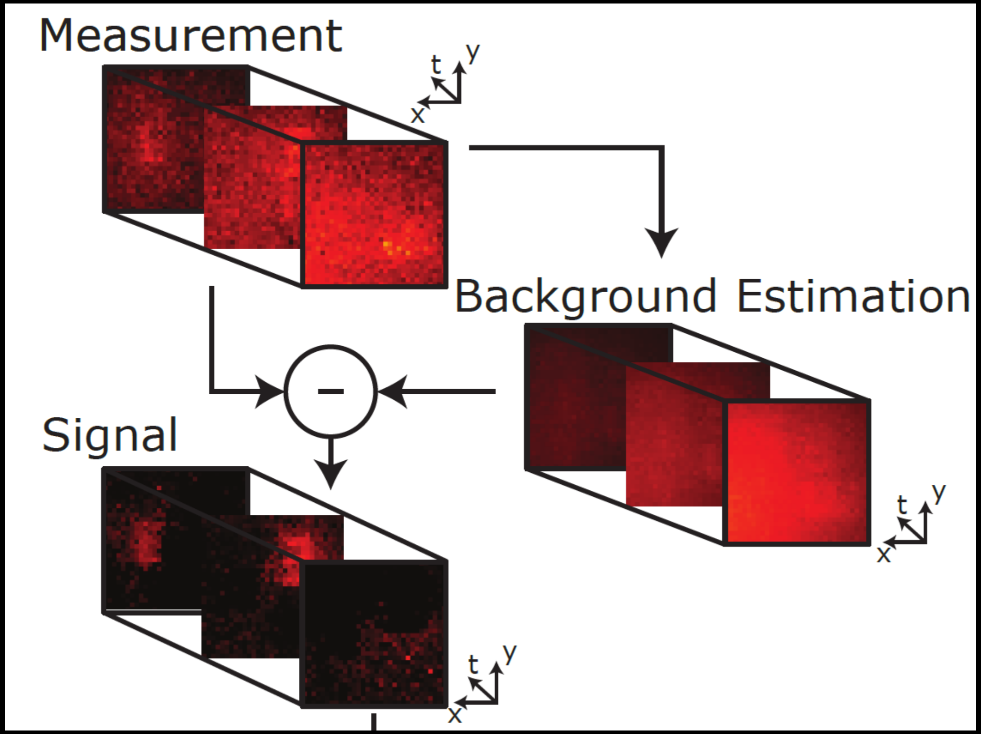
Signal Estimation

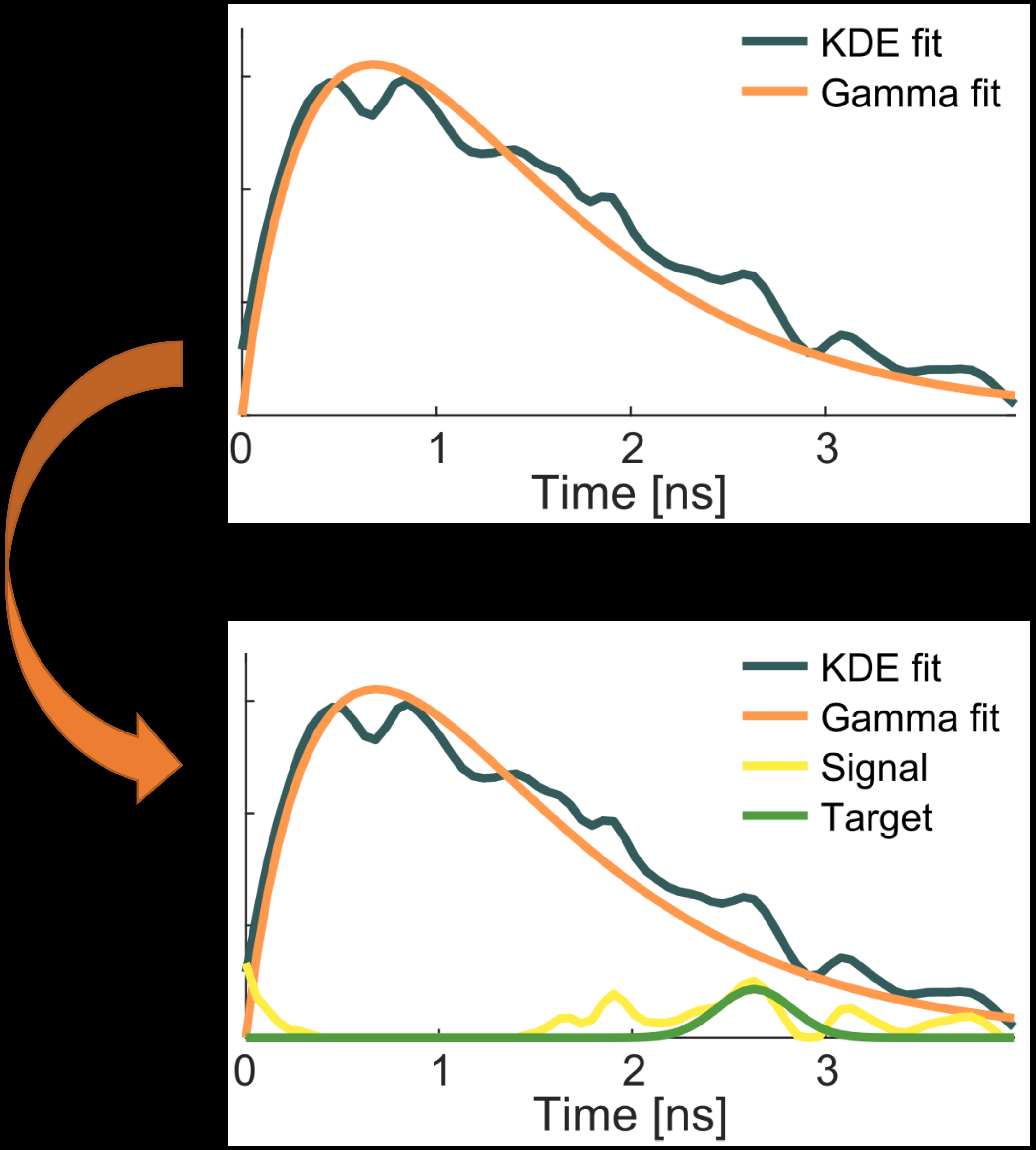




$$f_T(t) = \underbrace{P(B) f_T(t|B)}_{\text{Fog}} + \underbrace{P(S) f_T(t|S)}_{\text{Signal}}$$

Signal Estimation

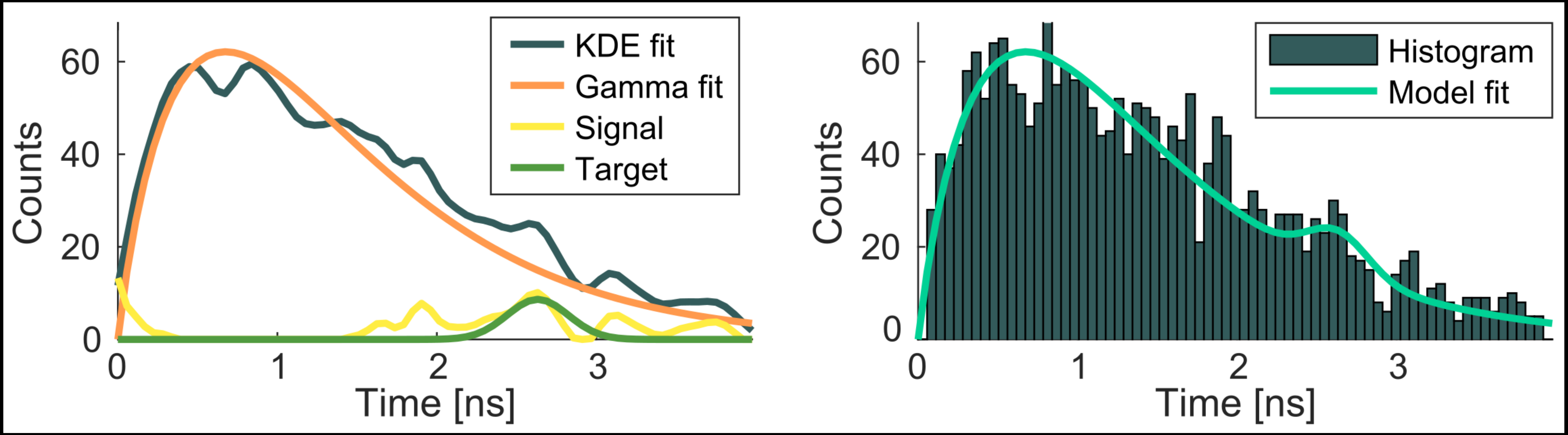


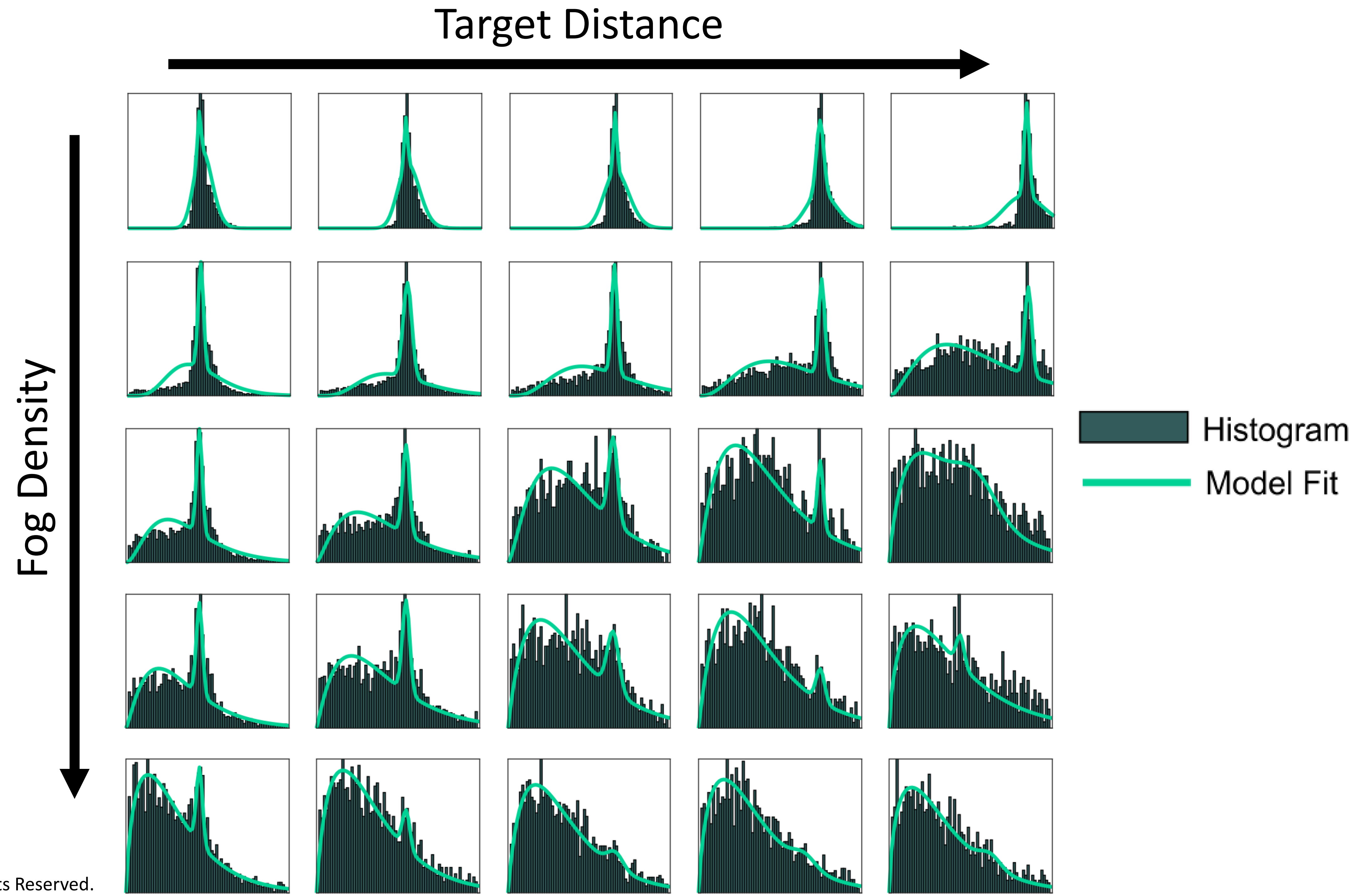


$$f_T(t) = \underbrace{P(B) f_T(t|B)}_{\text{Fog}} + \underbrace{P(S) f_T(t|S)}_{\text{Signal}}$$

Signal Estimation

$$\left[\hat{P}(S), \hat{P}(B)\right] = \underset{[P(S),P(B)]}{\operatorname{argmin}} \sum_t \left[P(B)\widehat{f_T}(t|B) + P(S)\widehat{f_T}(t|S) - \widehat{f_T}(t)\right]^2$$




Target Distance
Fog Density
Histogram
Model Fit

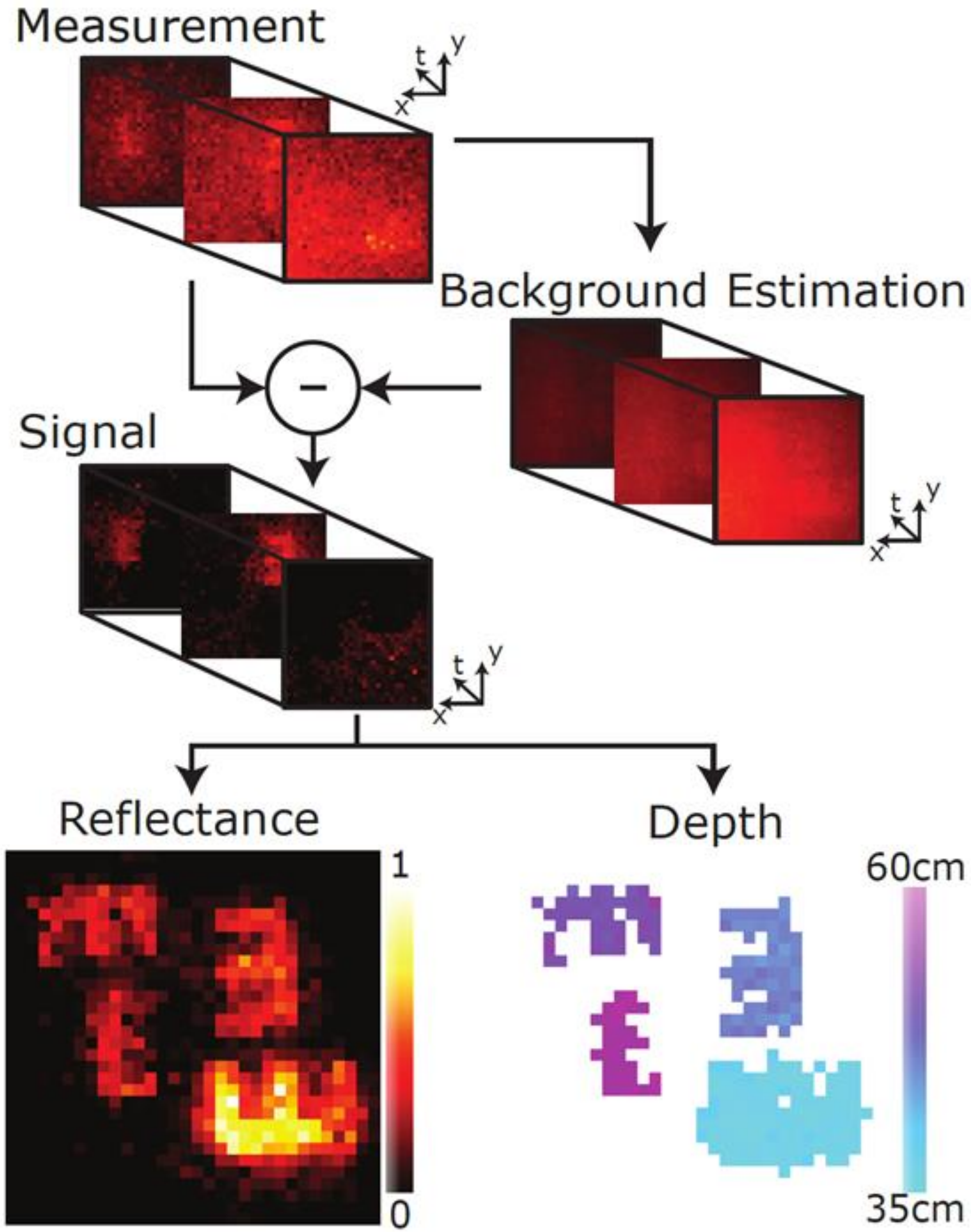
$$f_T(t) = P(B)f_T(t|B) + P(S)f_T(t|S)$$

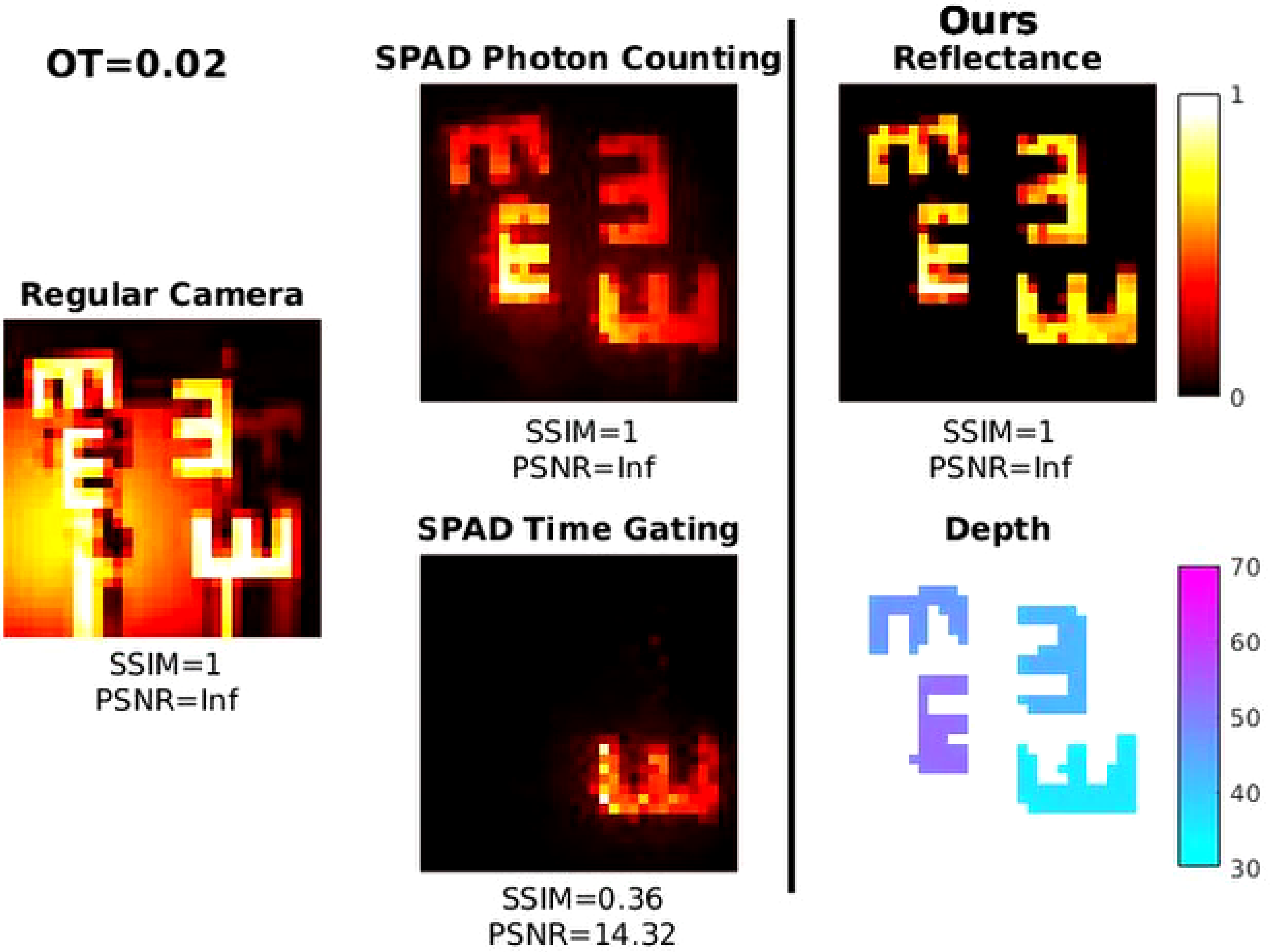
Target Recovery

- $P(S)f_T(t|S) = P(S)\frac{1}{\sqrt{2\pi\sigma^2}}\exp\left\{-\frac{(t-\mu)^2}{\sigma}\right\}$

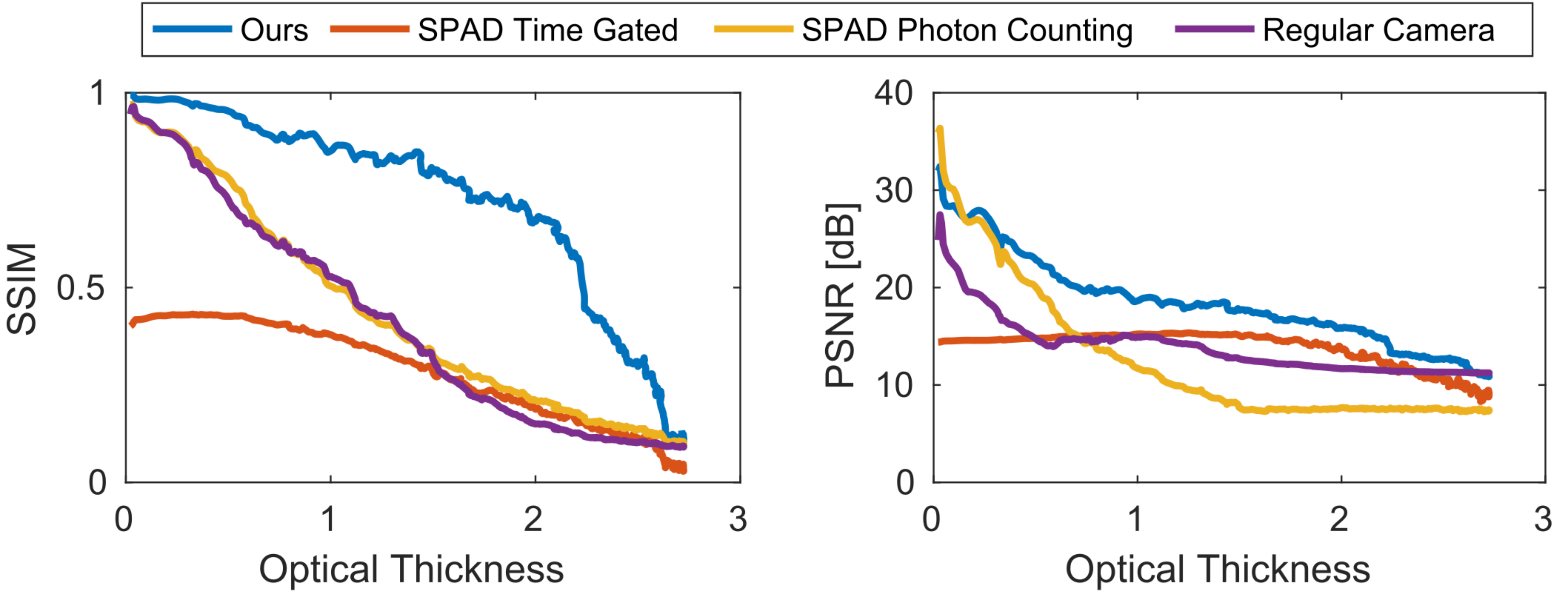
Reflectance

Depth

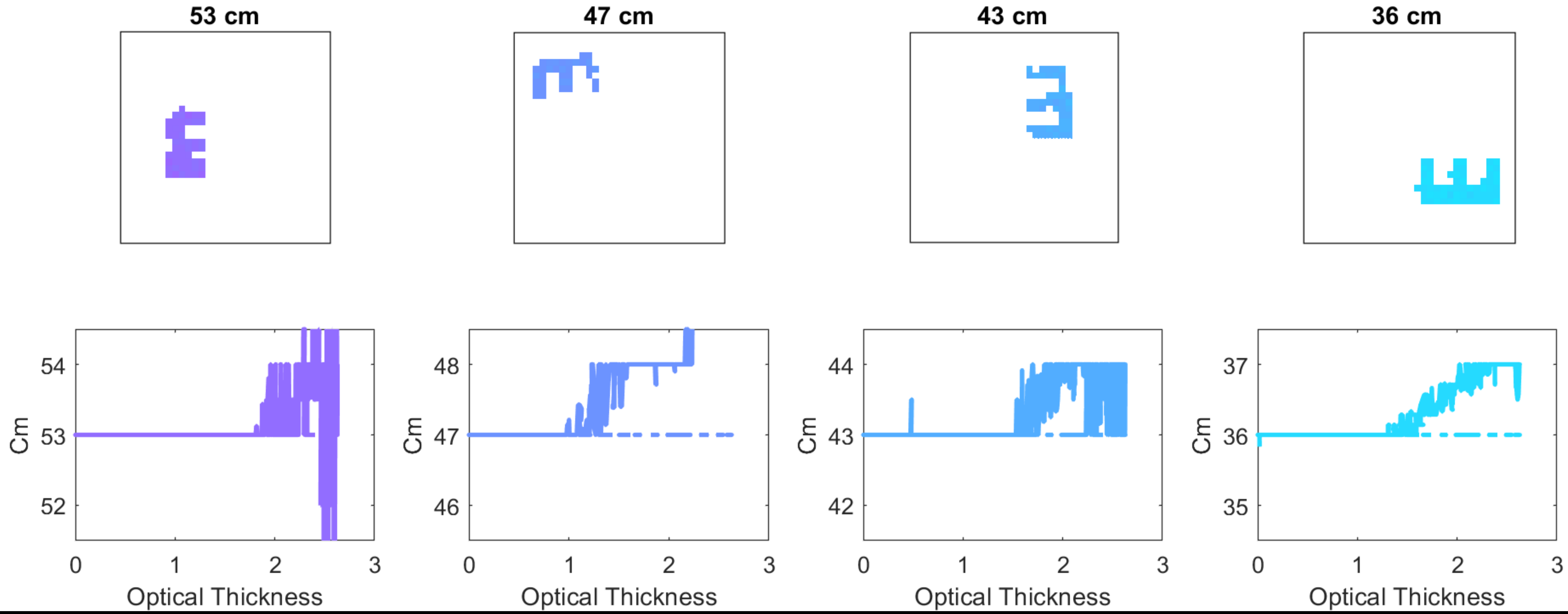

Measurement
t
y
x
Background Estimation
t
y
x
−
Signal
t
y
x
Reflectance
1
0
Depth
60cm
35cm

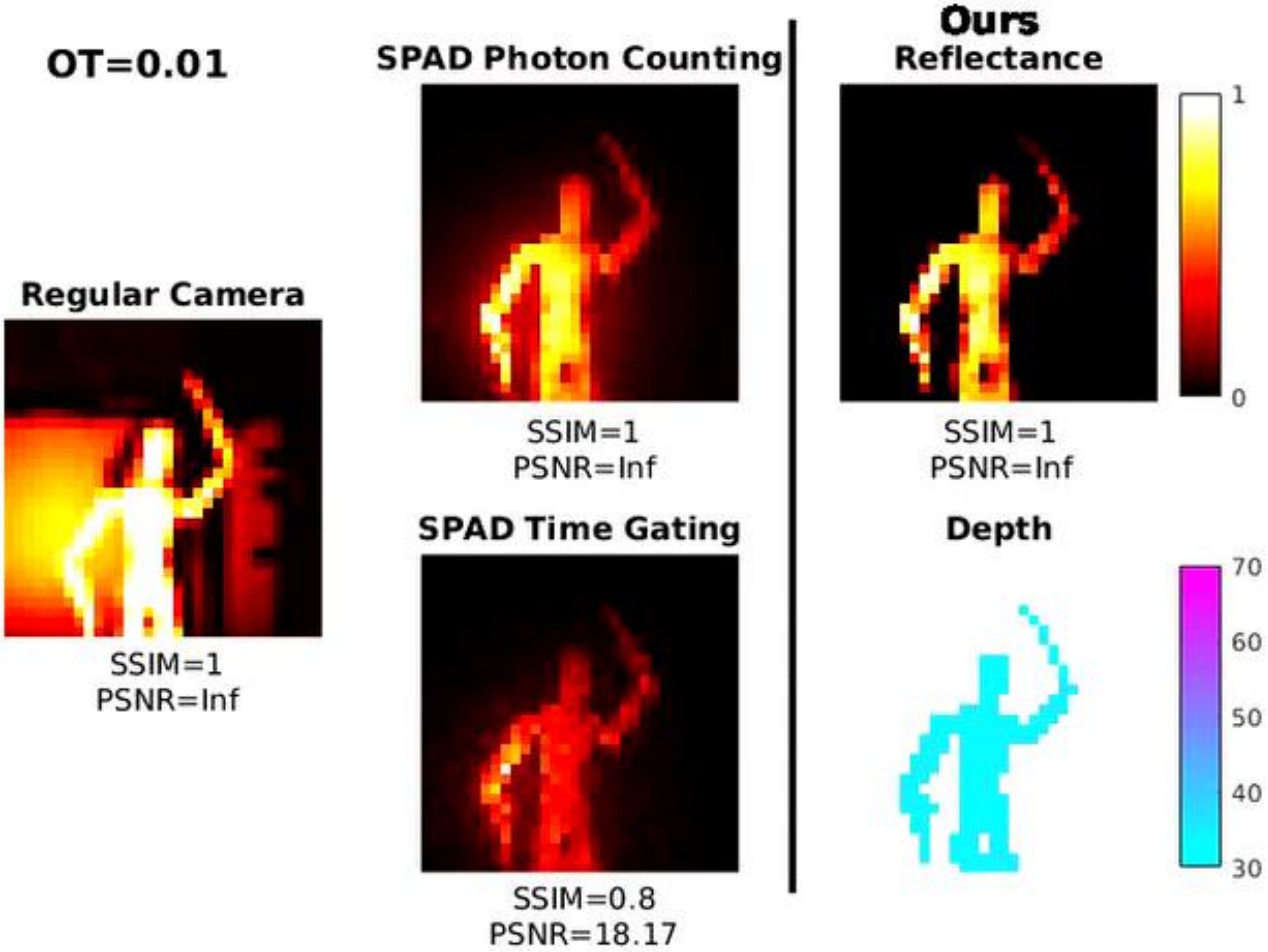

OT=0.02
Regular Camera
SSIM=1
PSNR=Inf
SPAD Photon Counting
SSIM=1
PSNR=Inf
SPAD Time Gating
SSIM=0.36
PSNR=14.32
Ours
Reflectance
1
0
SSIM=1
PSNR=Inf
Depth
70
60
50
40
30

Reflectance Recovery Error

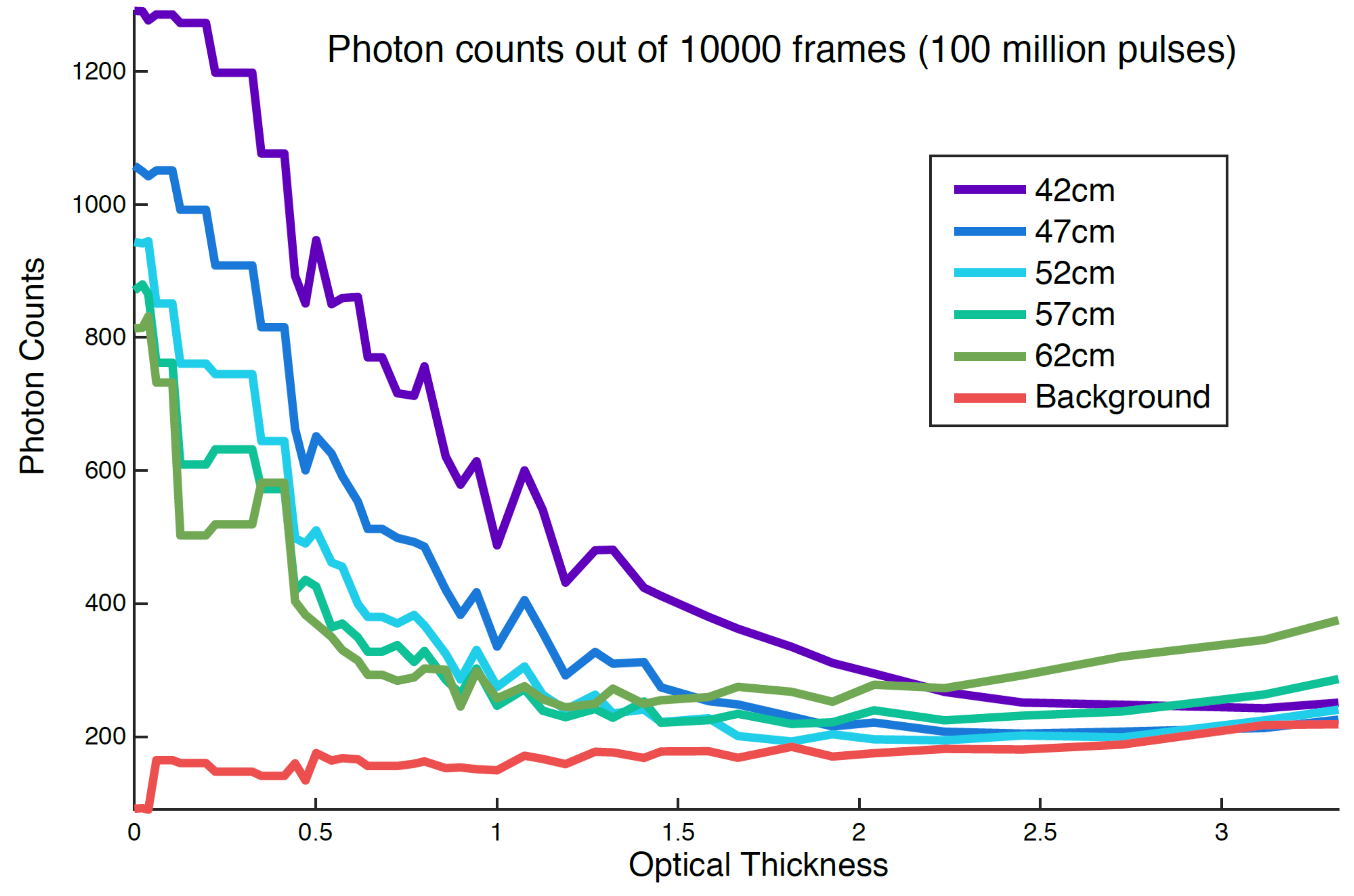


Depth Recovery Error




OT=0.01
Regular Camera
SSIM=1
PSNR=Inf
SPAD Photon Counting
SSIM=1
PSNR=Inf
SPAD Time Gating
SSIM=0.8
PSNR=18.17
Ours
Reflectance
1
0
SSIM=1
PSNR=Inf
Depth
70
60
50
40
30

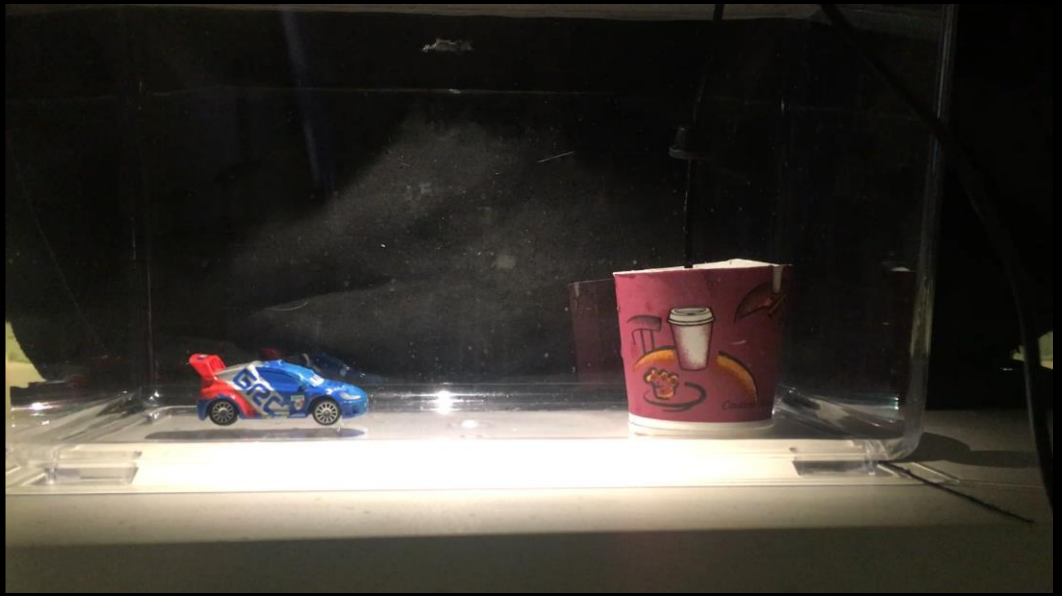
How Many Photons?



Limitations

Ignores spatial nature of scattering

- Impose priors
- Deblur



Limitations

Ignores spatial nature of scattering

Photon efficiency

- Current hardware efficiency is $\sim 1:10^6$
- Algorithm efficiency could improve

Limitations

Ignores spatial nature of scattering

Photon efficiency

Acquisition time

- New frame every $100\mu s$
- Currently use constant window of $20K$ frames → 2s
- Dynamic window based of fog estimate

Limitations

Ignores spatial nature of scattering

Photon efficiency

Acquisition time

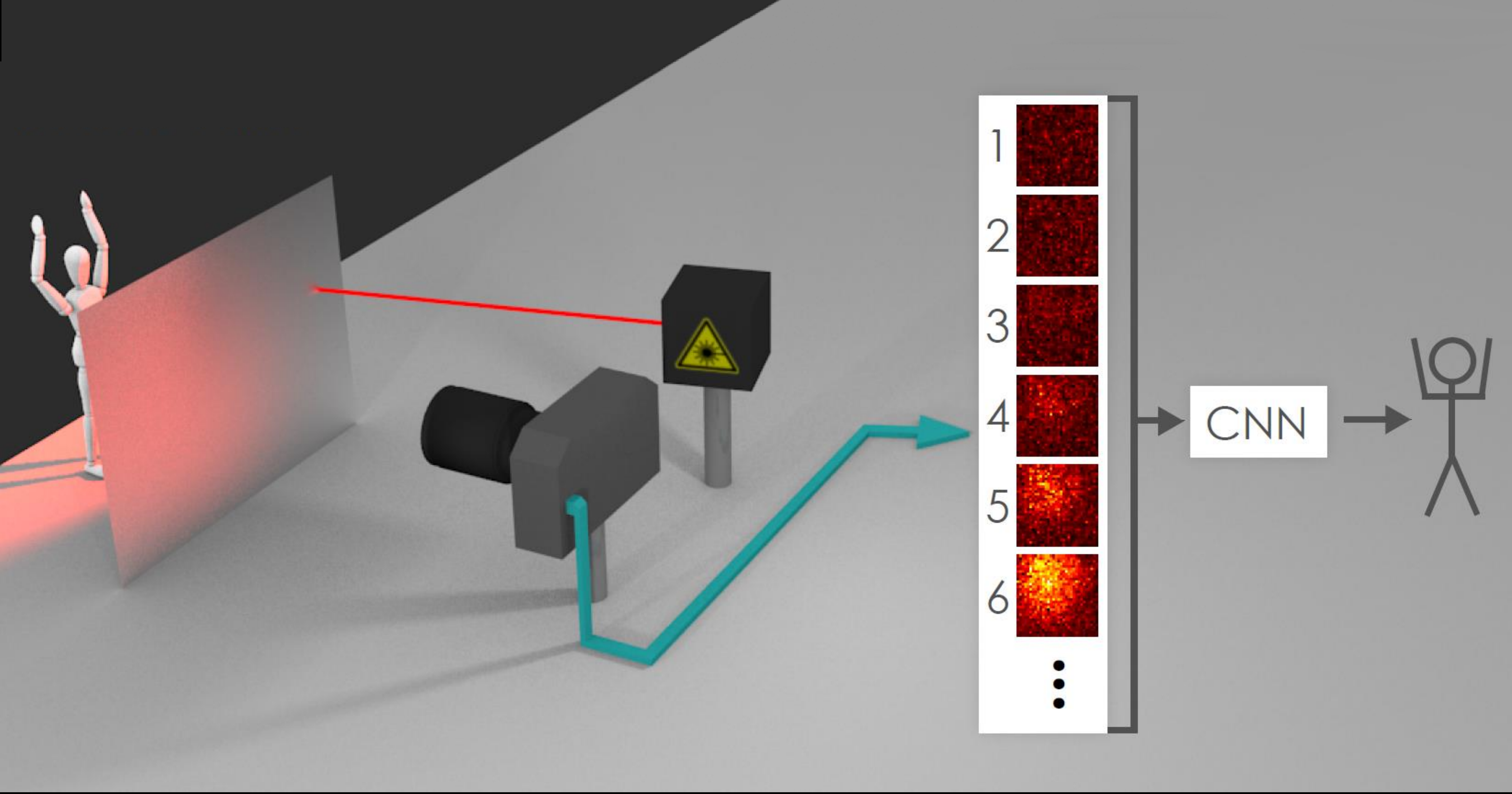
Scale

- Optical thickness is unitless
- Larger scenes → relaxed requirement for time resolution
- More dependency on spatial scattering?

Object Classification through Scattering Media with Deep Learning

Guy Satat, Matthew Tancik, Otkrist Gupta, Barmak Heshmat, Ramesh Raskar

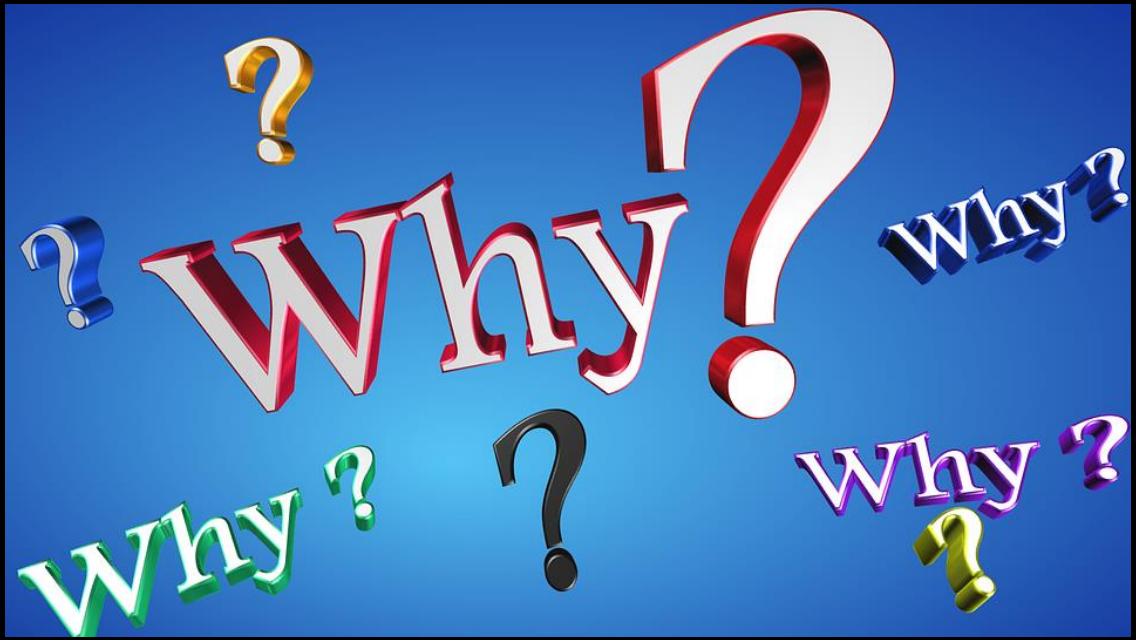
Optics Express (2017)


1
2
3
4
5
6
CNN

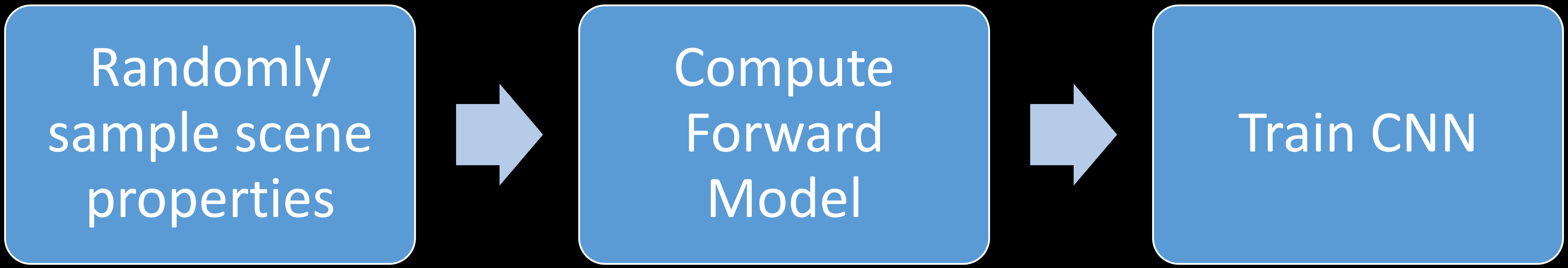
We Have to Calibrate

Why Deep Learning?

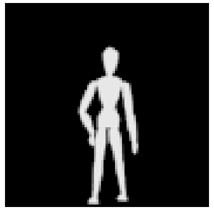
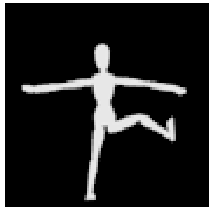
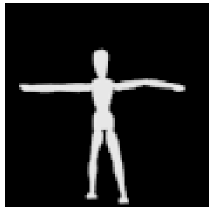
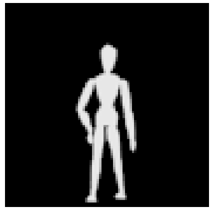
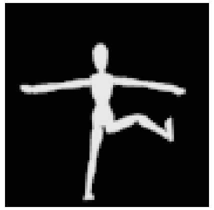
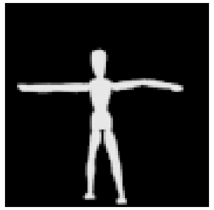
Can learn invariants

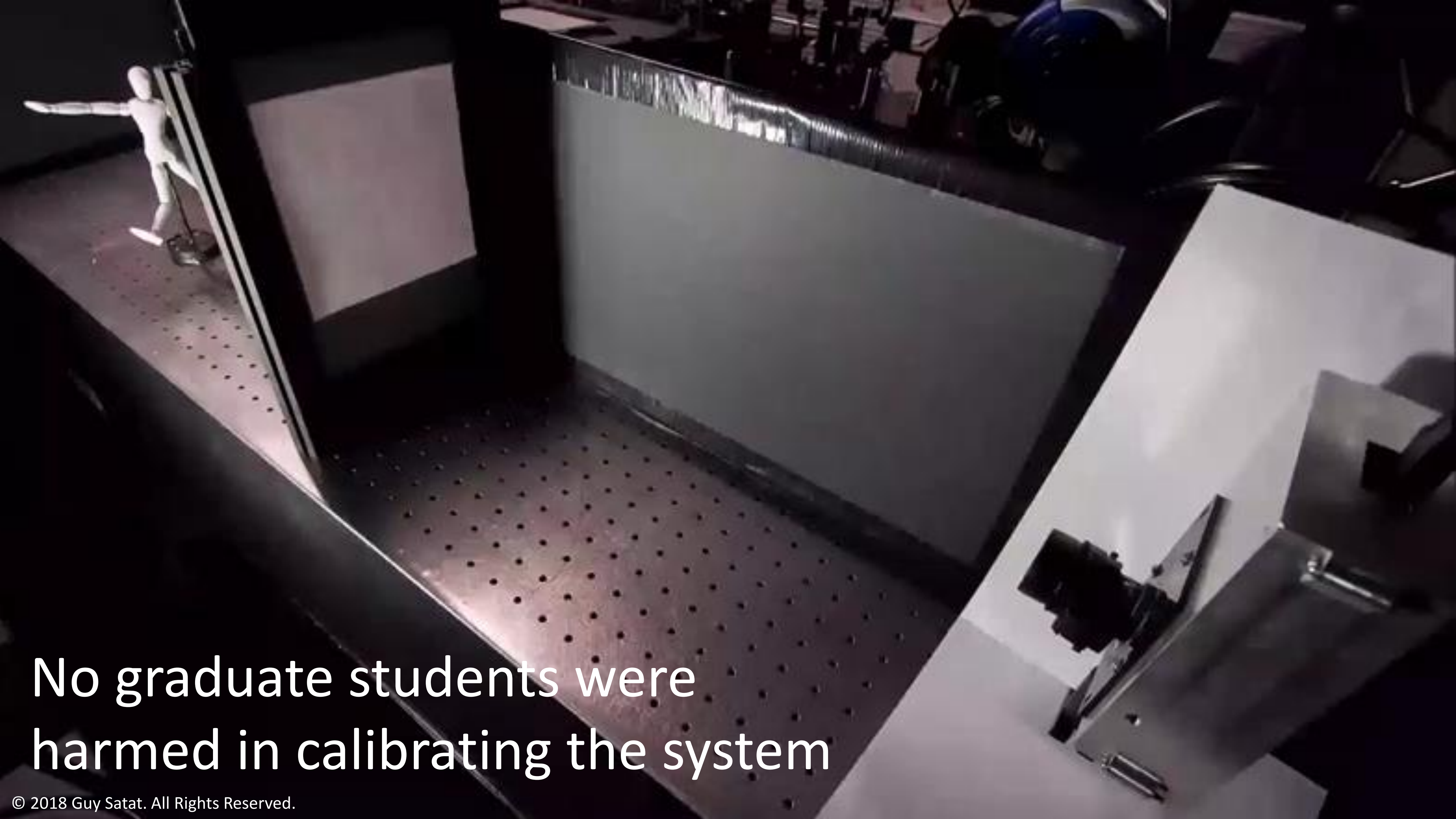


Learning Invariant to Calibration Parameters



Train on Synthetic Data
Test on Lab Measurement

			
	0.9	0.0	0.1
	0.3	0.7	0.0
	0.1	0.2	0.7



No graduate students were harmed in calibrating the system

Summary

media.mit.edu/~guysatat
guysatat@mit.edu

- Variety of weather conditions
- Imaging through fog ~ Imaging through scattering
  - Wide range of fog conditions:
    - Dense, dynamic, heterogeneous
    - Calibration free
  - No raster scan
- Probabilistic Computational Imaging
- Data Driven Computational Imaging