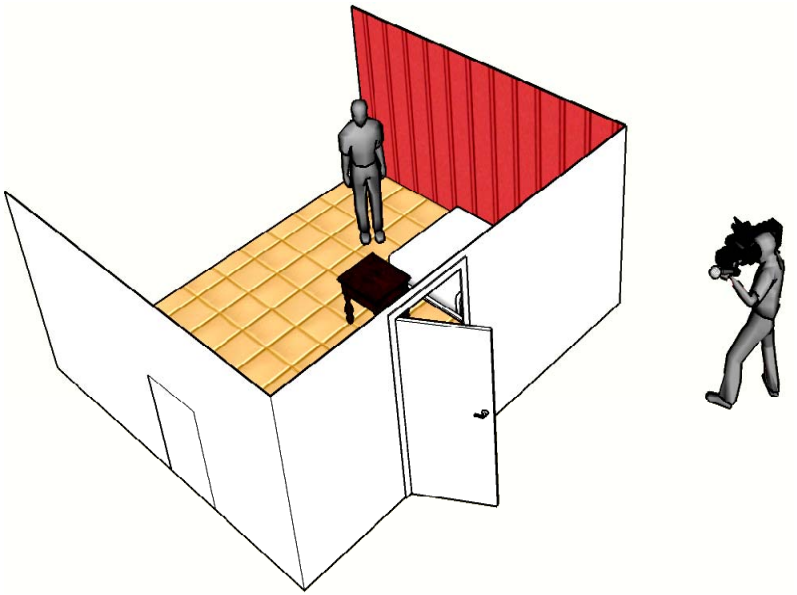
Computational Photography and Light Transport

Ramesh Raskar

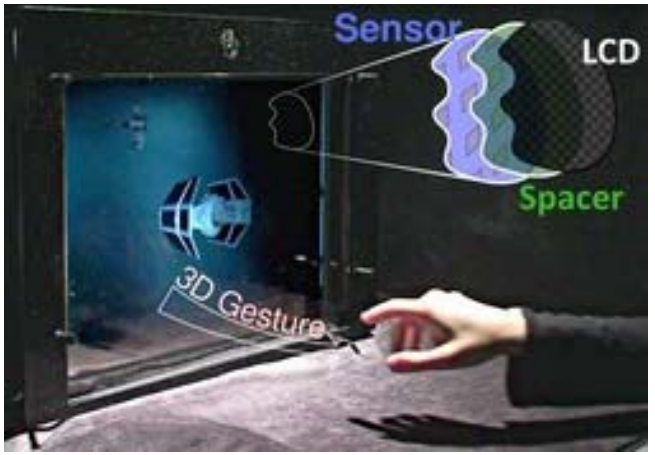
http://raskar.info

Camera Culture

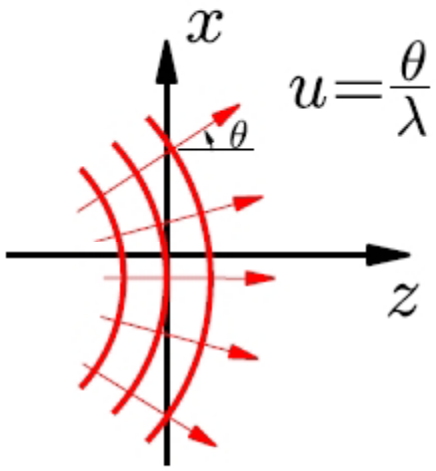
MIT Media Lab



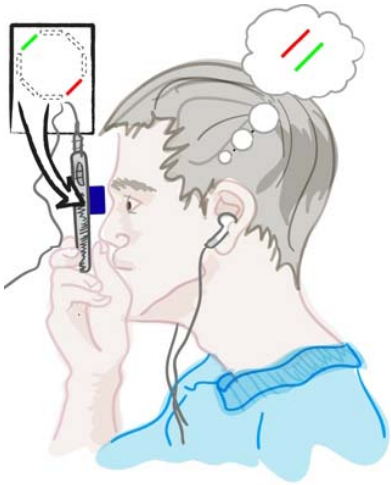
Looking around corners



LCD = Camera



Theory of Rays / Waves



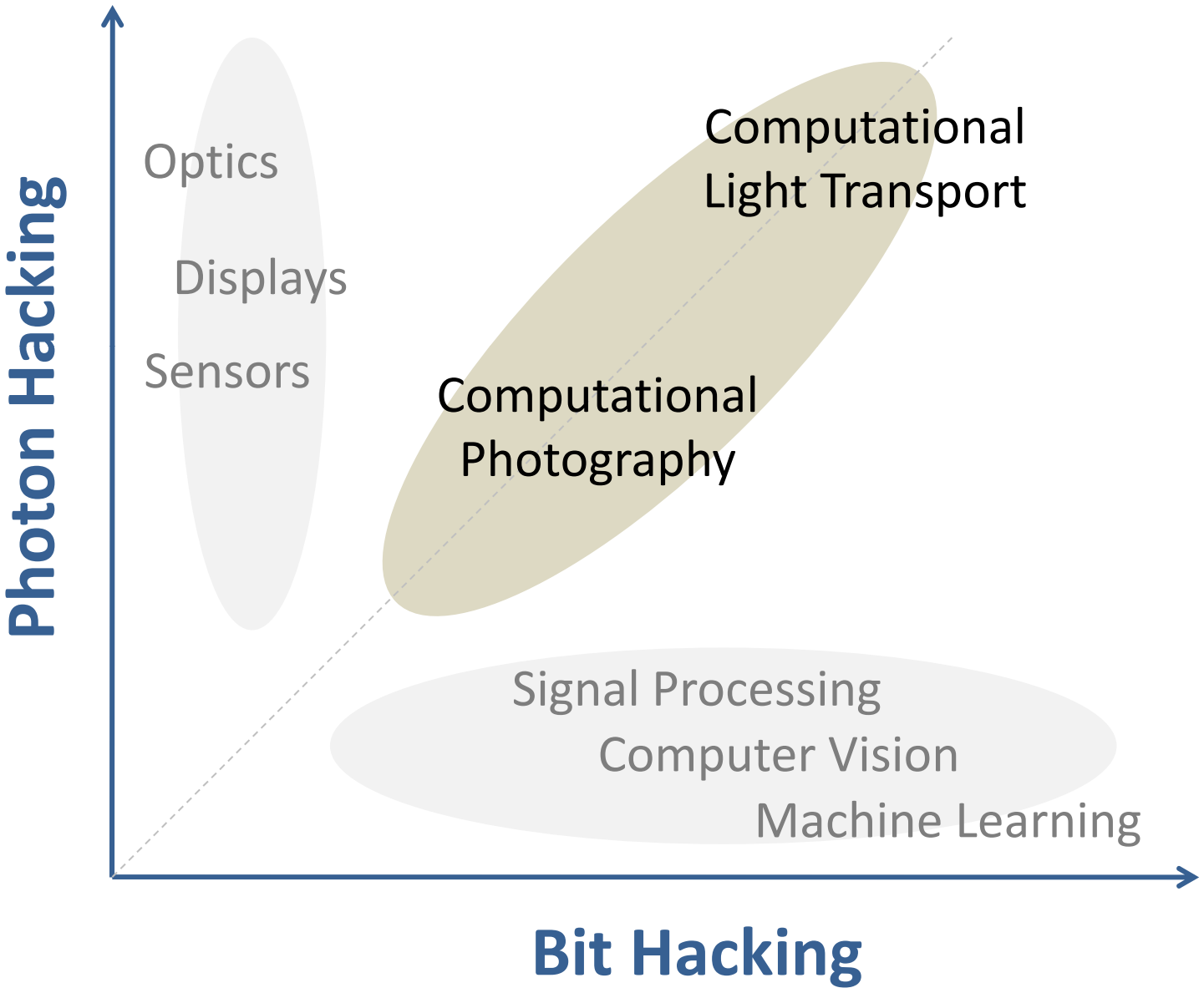
Phone = Scientific Instrument

Camera Culture
MIT Media Lab

The goal is to create an entirely
new class of imaging platforms
that have an

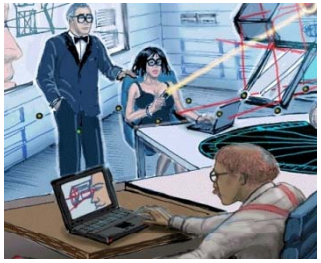
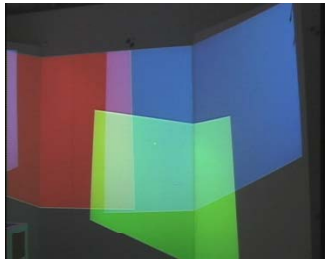
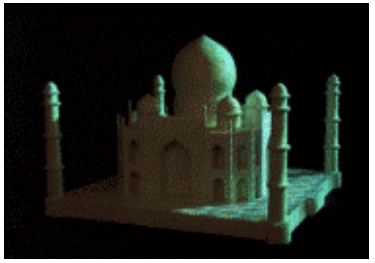
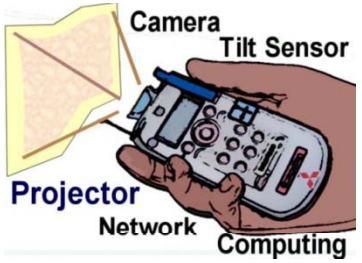
understanding of the world that
far exceeds human ability

to produce meaningful abstractions that are
well within human comprehensibility


Photon Hacking
Optics
Displays
Sensors
Computational
Light Transport
Computational
Photography
Signal Processing
Computer Vision
Machine Learning
Bit Hacking

Computational Illumination

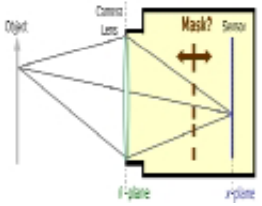
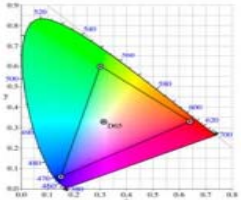
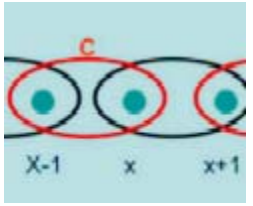
PhD + MERL 1998-2004

Office of the Future	Multi-Projector Display	Spatial Augmented Reality (SAR)	Pocket Projector	Optical Communication
3D videoconferencing	Quadric Transfer	Shader Lamps	iLamps	Location Tracking
				
Siggraph 1998	1999 Siggraph 2003	1998	2000 Siggraph 2003	Siggraph 2004

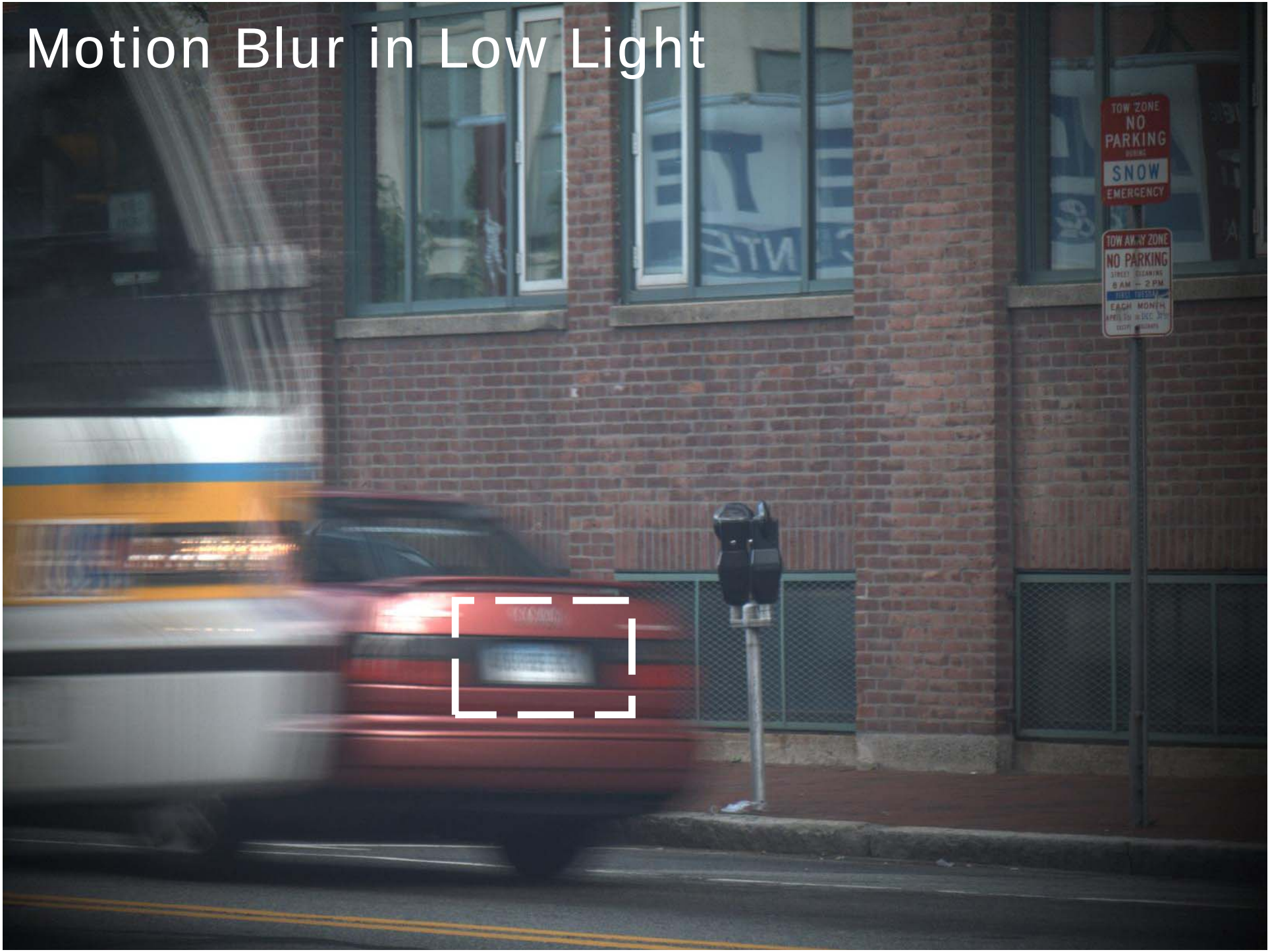
- Technology Review TR100, 2004
- Book: Spatial Augmented Reality
- Mitsubishi Electric Invention Awards (4), 2003, 2004, 2006
- Over 20 patents
- Planar and Curved Display Screen Product (6 products)

Computational Photography

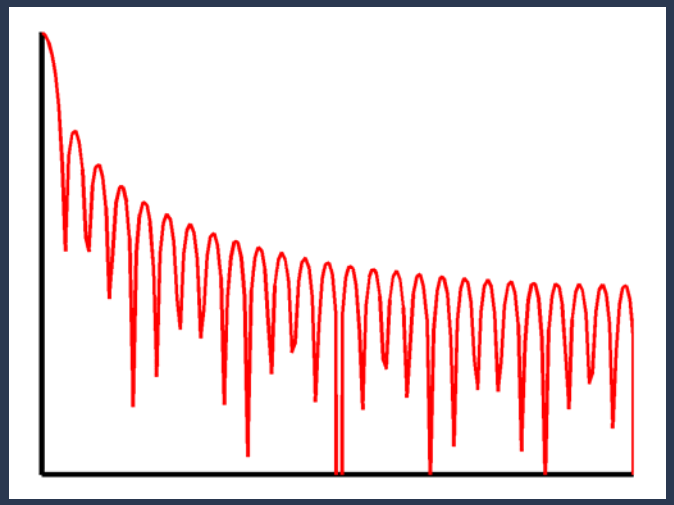
MERL 2002-2008

Coding in Time	Coding in Space (Optical Path)		Coded Illumination	Coded Wavelength	Coded Sensing
Coded Exposure for Motion Deblurring	Coded Aperture for Extended Depth of Field	Mask-based Optical Heterodyning for Light Field Capture	Multi-flash Imaging for Depth Edge Detection	Agile Spectrum Imaging	Gradient Encoding Sensor for HDR
					
Siggraph 2006	Siggraph 2007	Siggraph 2007	Siggraph 2004	EG 2007	CVPR 2006

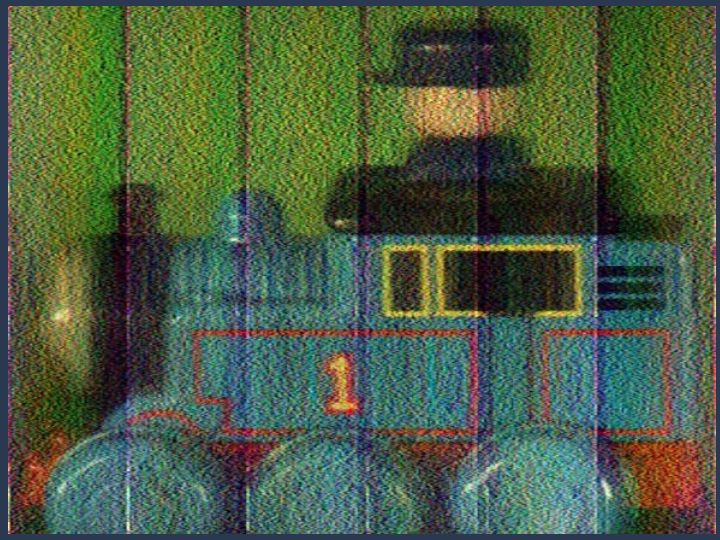
Motion Blur in Low Light



Traditional



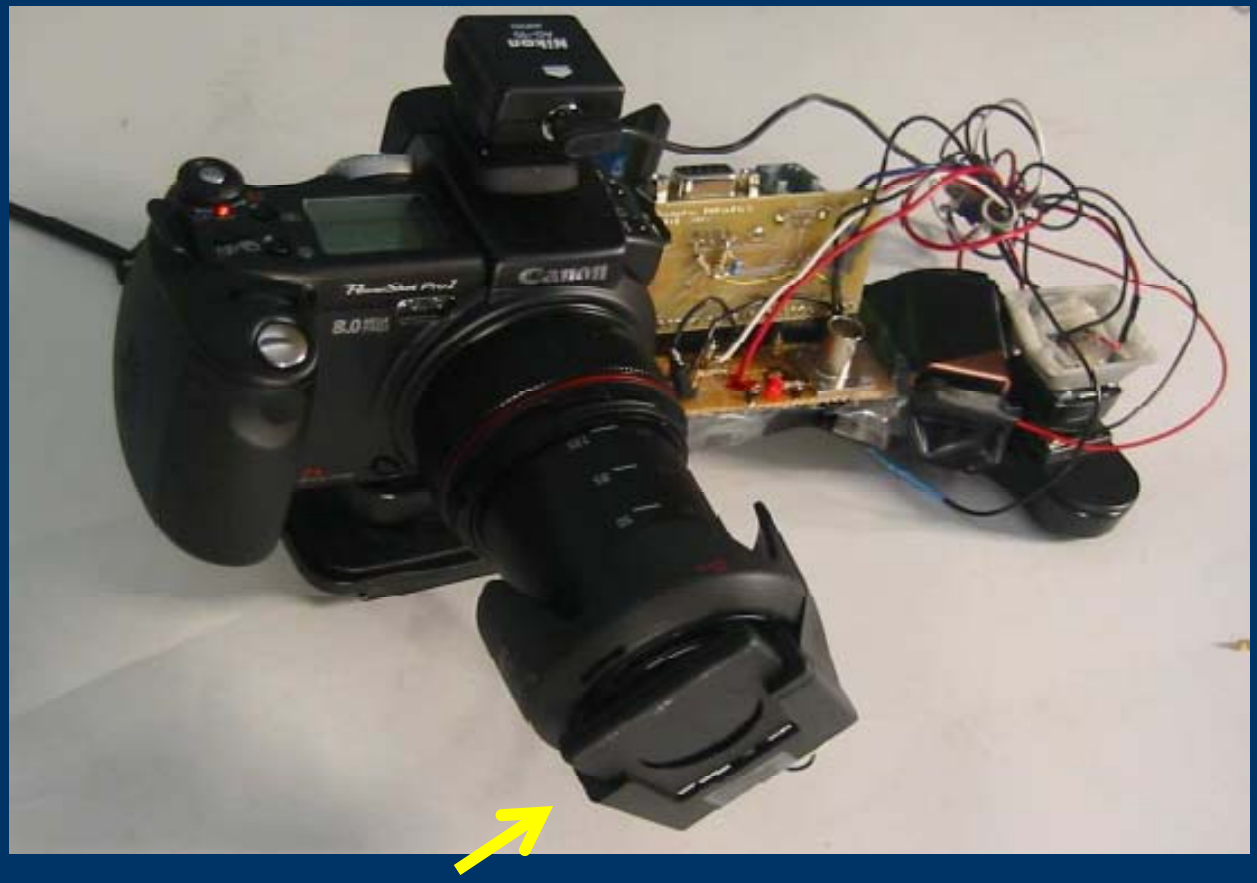
Blurred Photo



Deblurred Image

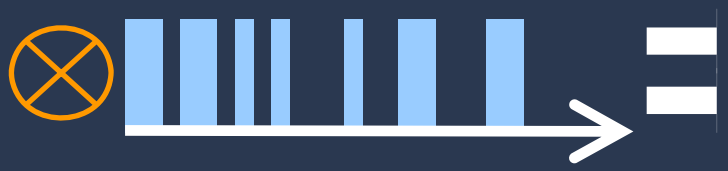
Fluttered Shutter Camera

Raskar, Agrawal, Tumblin Siggraph2006



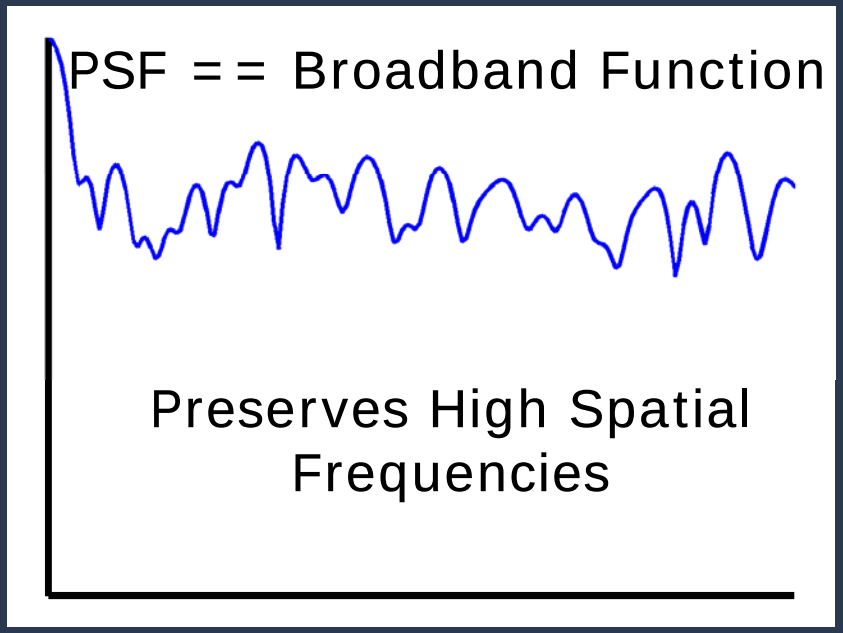
Ferroelectric shutter in front of the lens is turned opaque or transparent in a rapid binary sequence

Sharp Photo



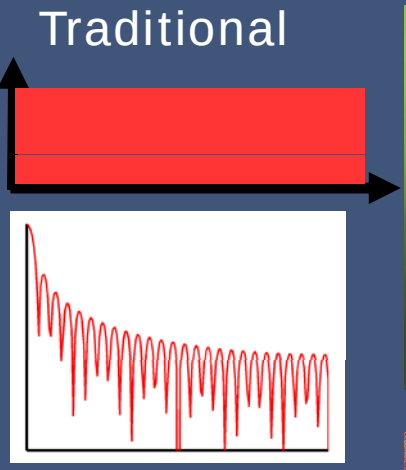
Fourier Transform

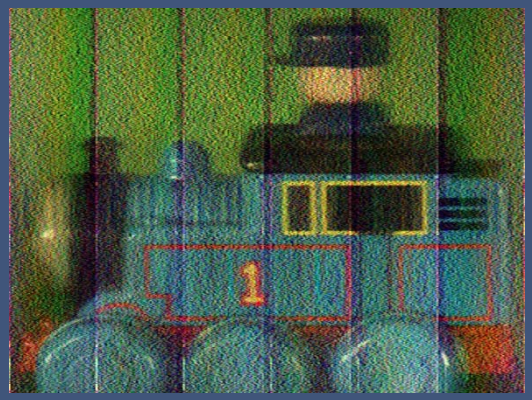
Blurred Photo



Flutter Shutter: Shutter is OPEN and CLOSED

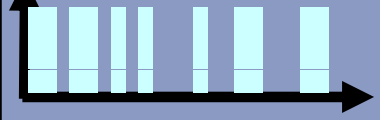
Traditional

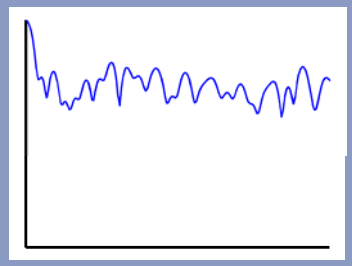




Deblurred Image

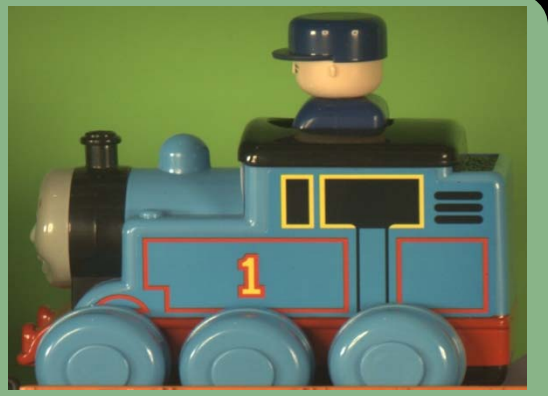
Coded Exposure



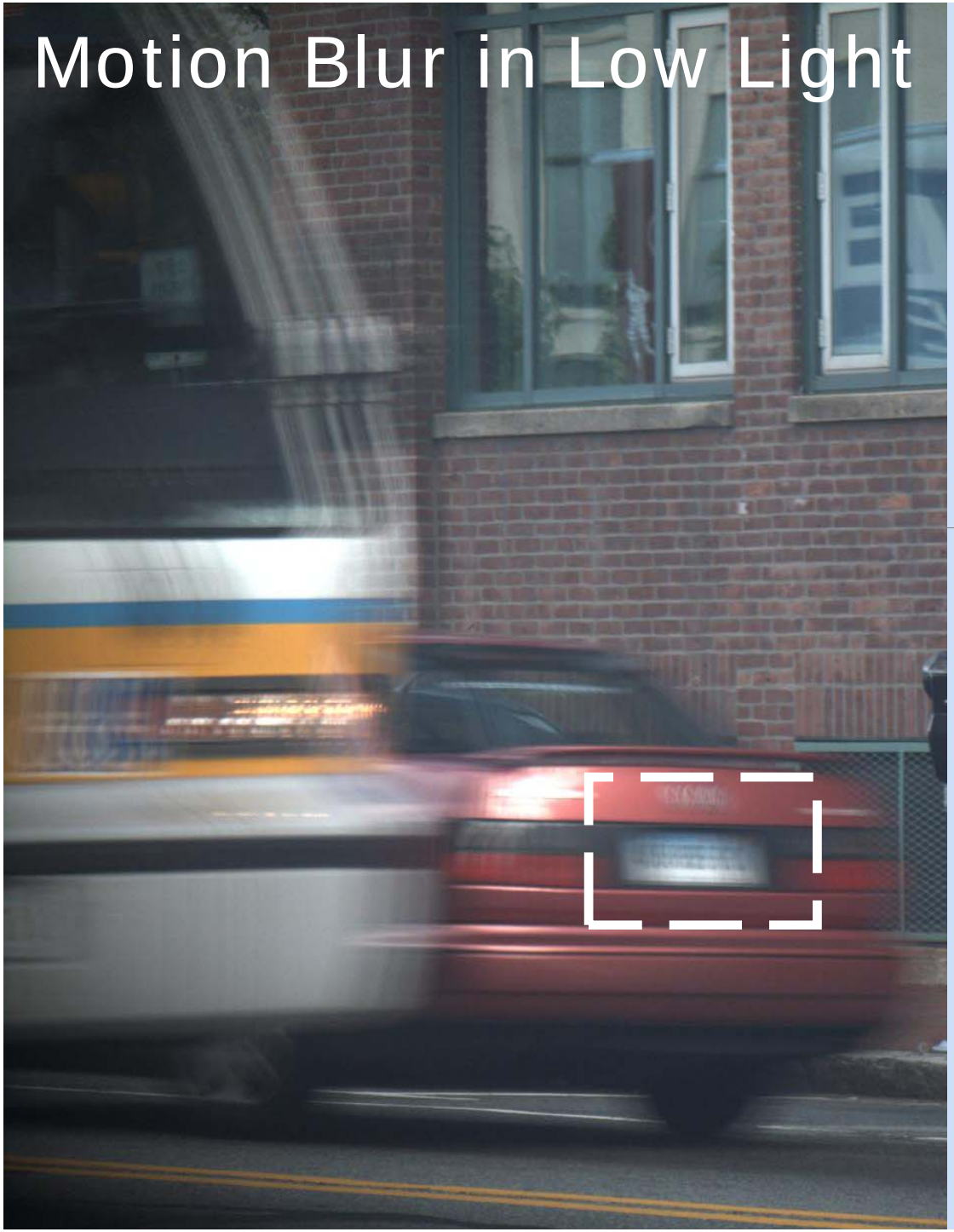


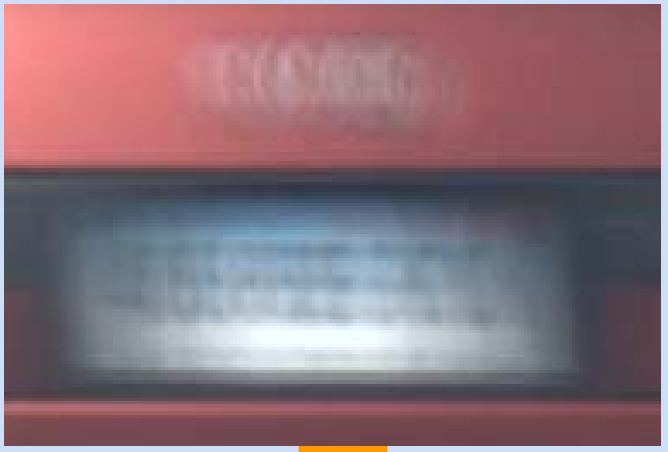
Deblurred Image

Image of Static Object



Motion Blur in Low Light





New Collaborations
Bill Freeman, EECS
David Brady, Duke U./Mosaic
Dan Schuette, Lincoln L

Computational Photography

MERL 2002-2008

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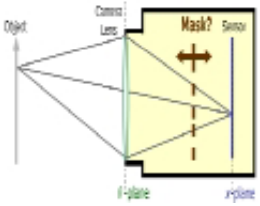
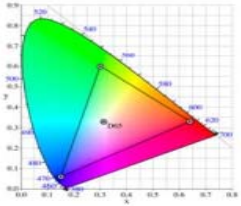
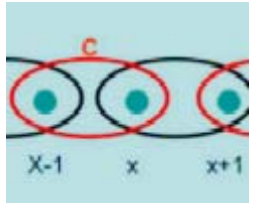
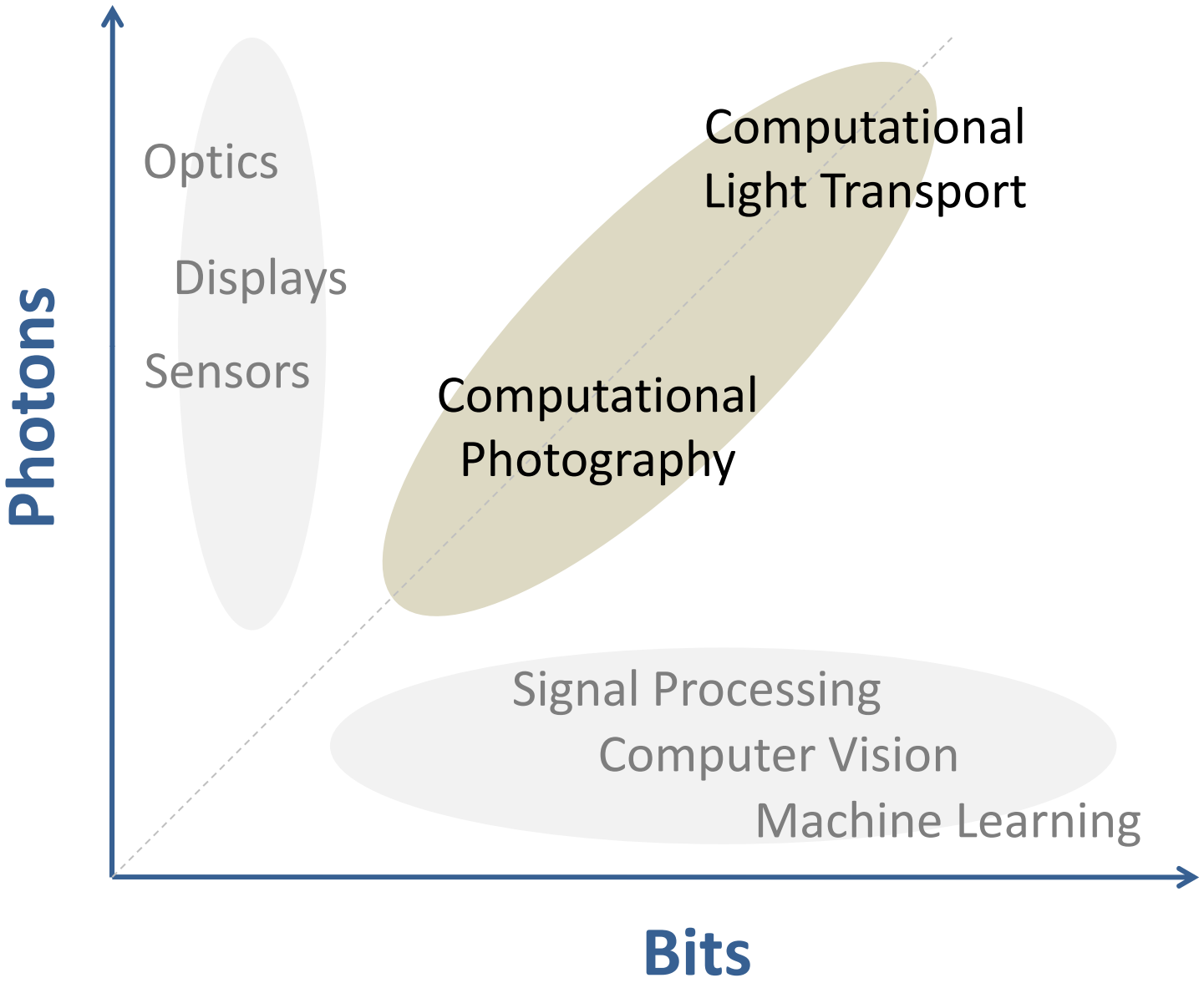
					
Siggraph 2006	Siggraph 2007	Siggraph 2007	Siggraph 2004	EG 2007	CVPR 2006

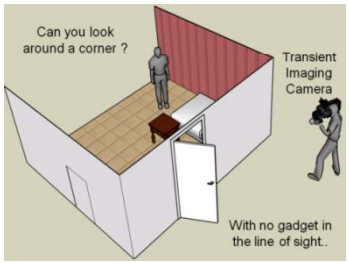
- Alfred P Sloan Research Fellowship, 2009
- Over 15 patents
- Coded Exposure and Multi-flash camera now multi-million dollar projects
- Mitsubishi Electric invention award
- Upcoming book on Computational Photography

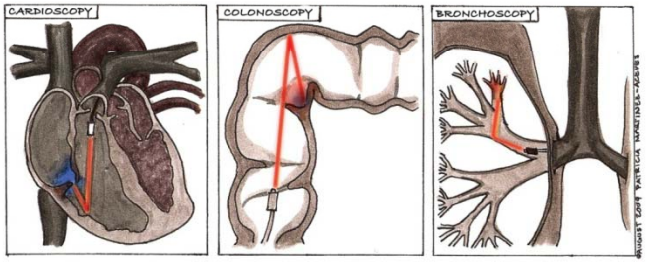

Photons
Optics
Displays
Sensors
Computational
Light Transport
Computational
Photography
Signal Processing
Computer Vision
Machine Learning
Bits

Media Lab 2008-

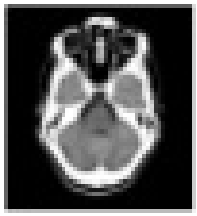
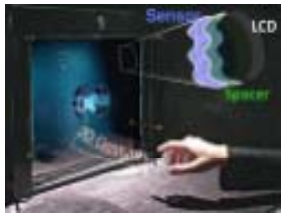
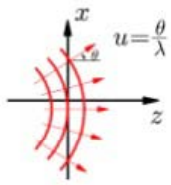
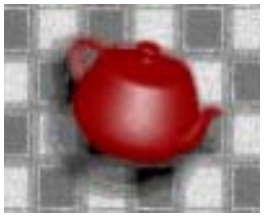
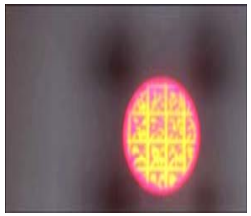
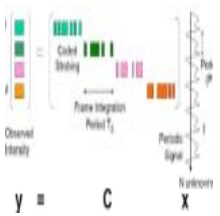
Computational Light Transport

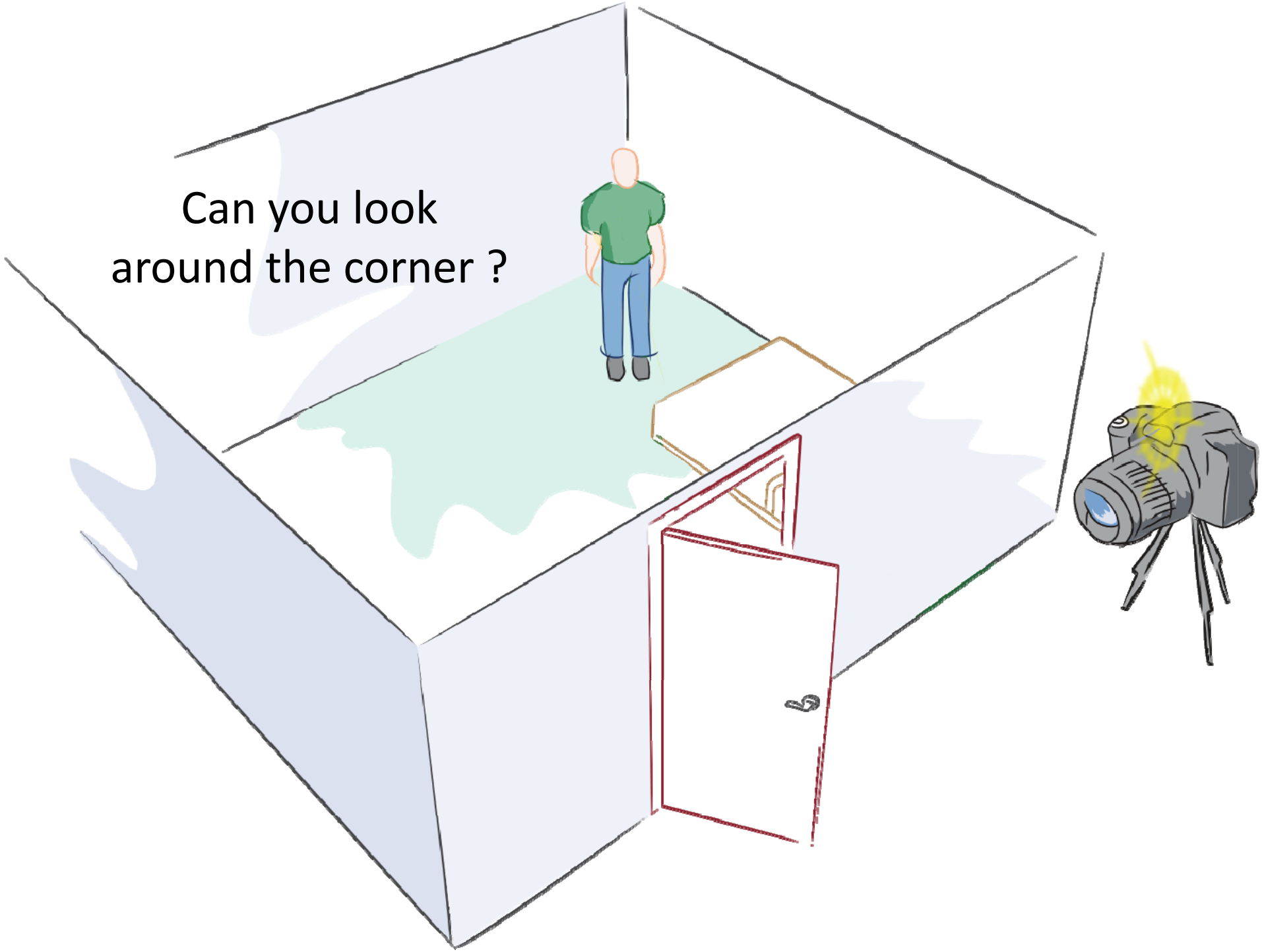
1. Time resolved

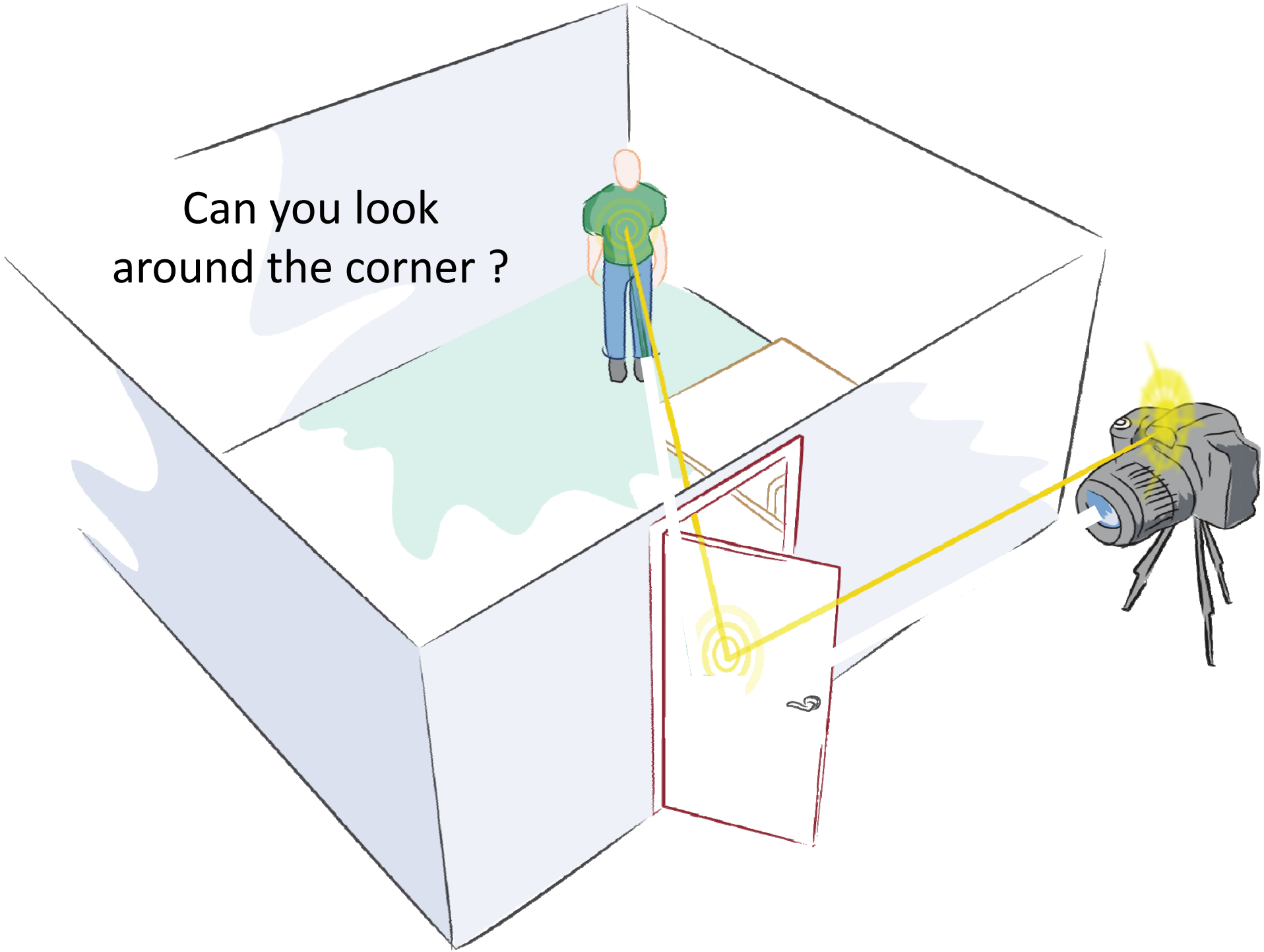




2. Angle resolved

Descattering Analysis	Spatial Heterodyning	Augmented Light Field	Rank-constraint of 3D Displays	Computational Probes	Wavefront Sensing	Compressive Sensing
CAT-Scan without moving parts	BiDi Screen	Geometric + Wave optics	Glasses Free 3D	Bokode	NETRA	Sparsity Analysis
						
2009 -	2007-	2008-	2009 -	2008 -	2010	2009 -


Can you look
around the corner ?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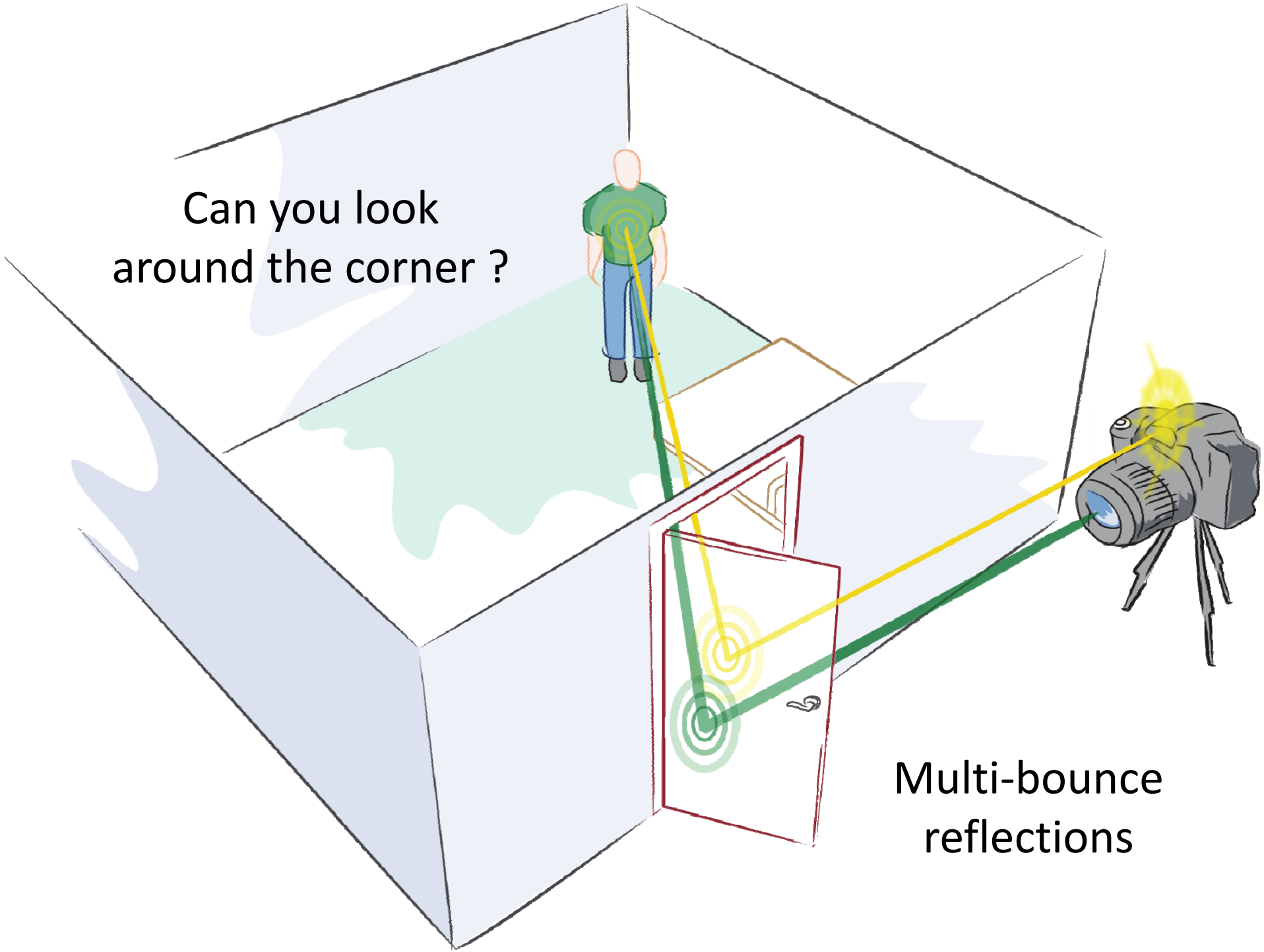
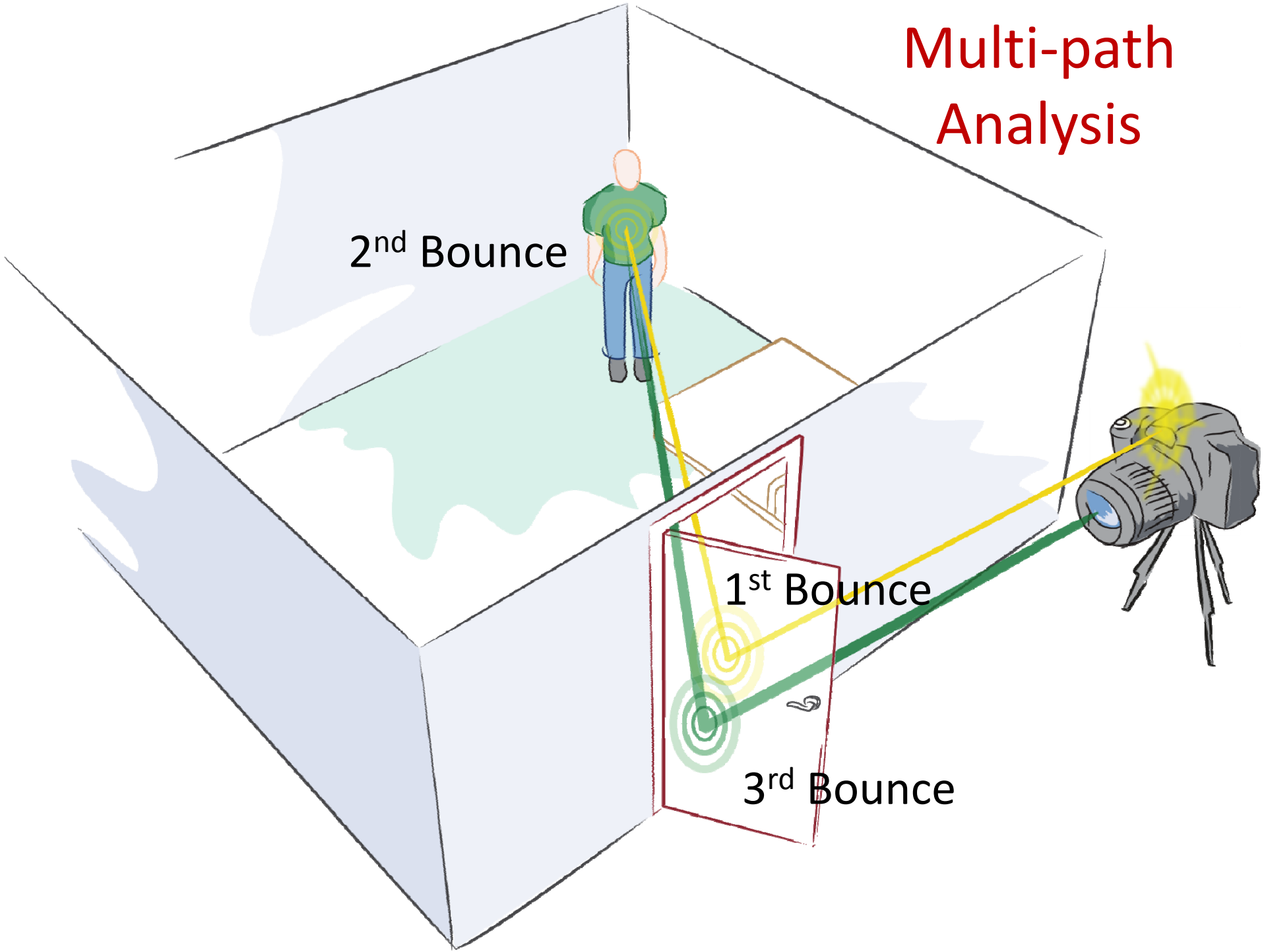

Can you look
around the corner ?
Multi-bounce
reflections

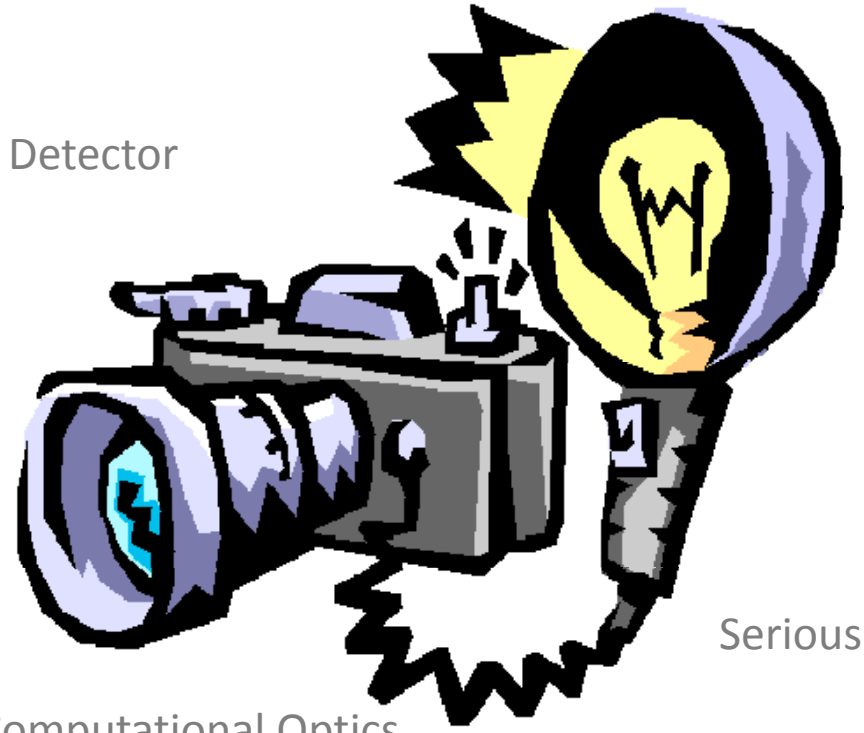
Multi-path Analysis



Femto-Photography

FemtoFlash

UltraFast Detector



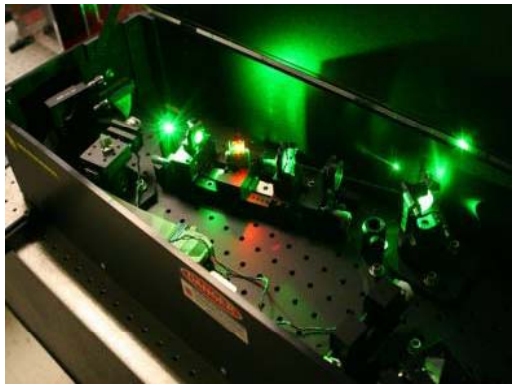
Serious Sync

Computational Optics

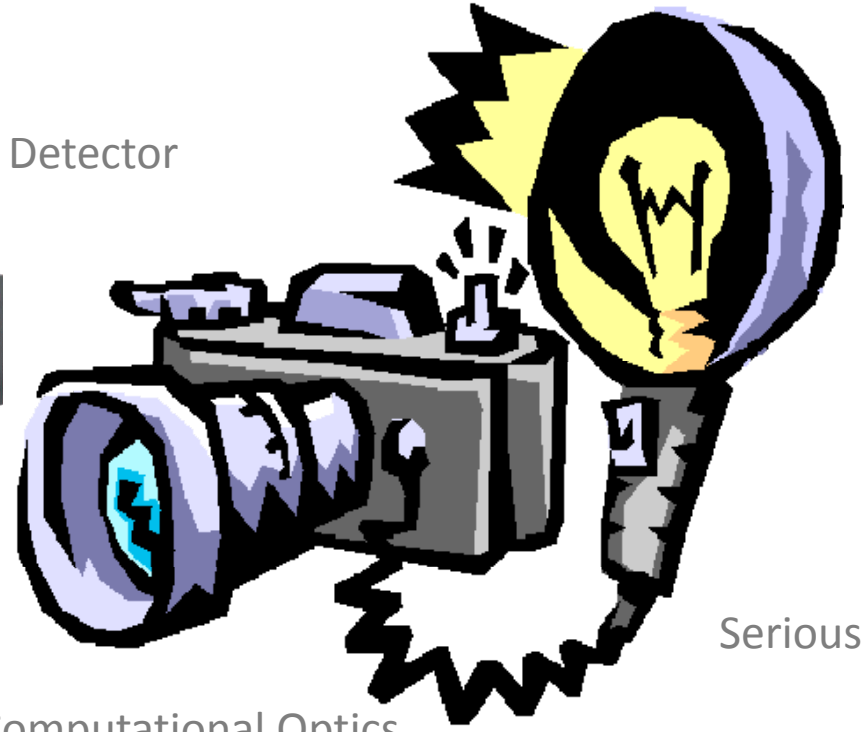
- Darpa Young Faculty Award, 2010
- Lincoln Labs, Campus Collaboration Award, 2010
- Kirmani, Hutchinson, Davis, Raskar, ICCV'2009, Marr Prize Honorable Mention
- Pandharkar, Velten, Bardagjy, Bawendi, Raskar, CVPR 2011

Femto-Photography (Transient Imaging)

FemtoFlash



UltraFast Detector



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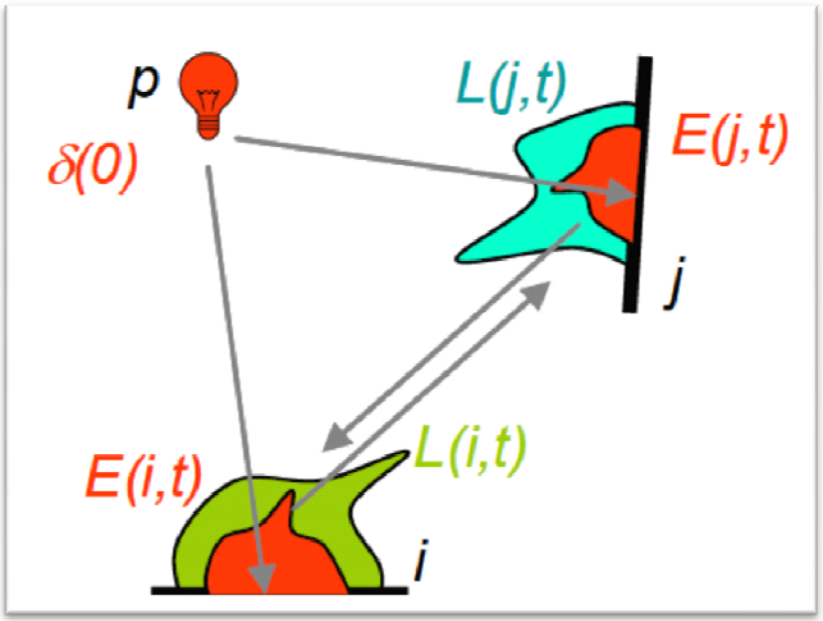
Steady State 4D

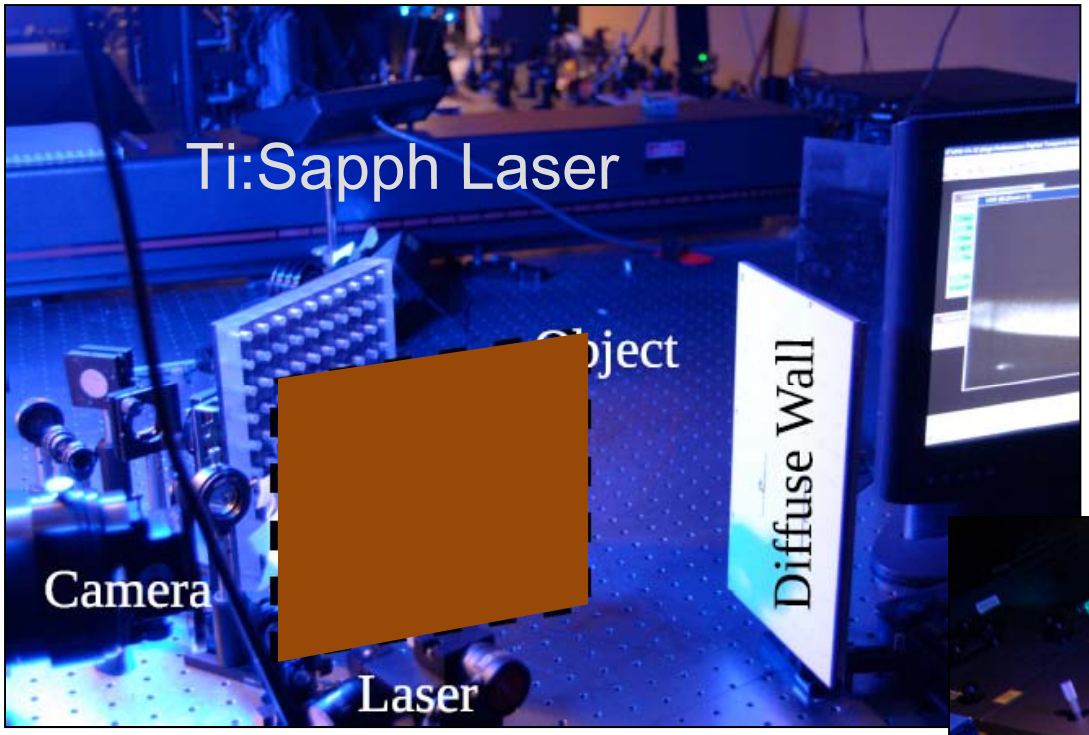
$$L[i] = E[i] + \sum_j \rho(i,j) L[j]$$

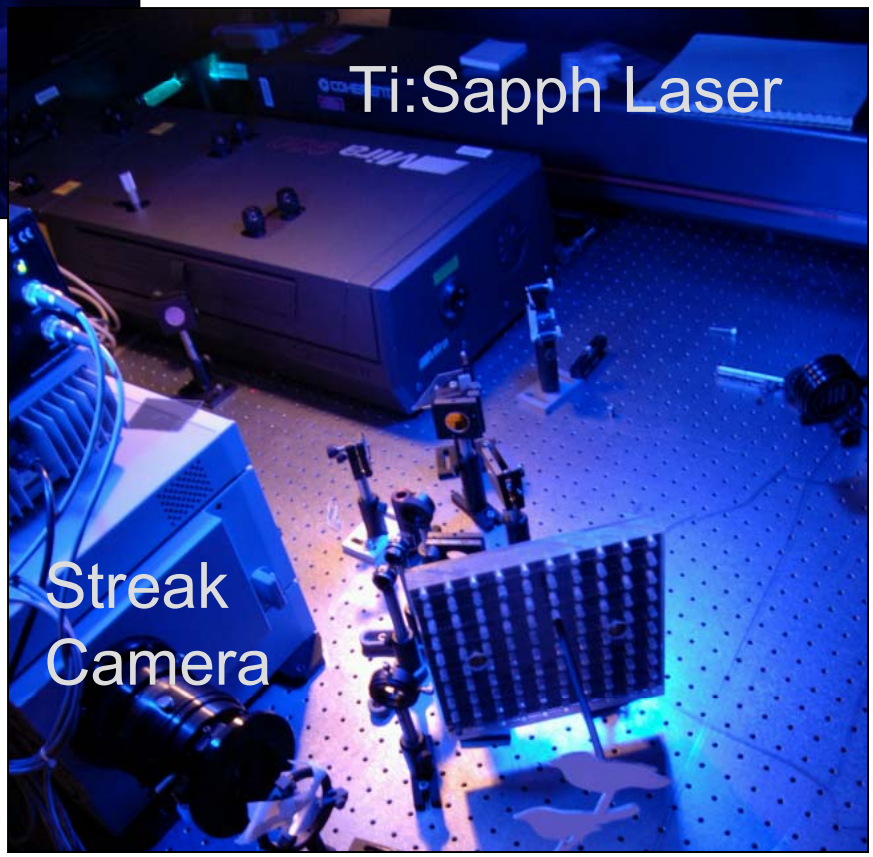
$$L = E + \rho L$$



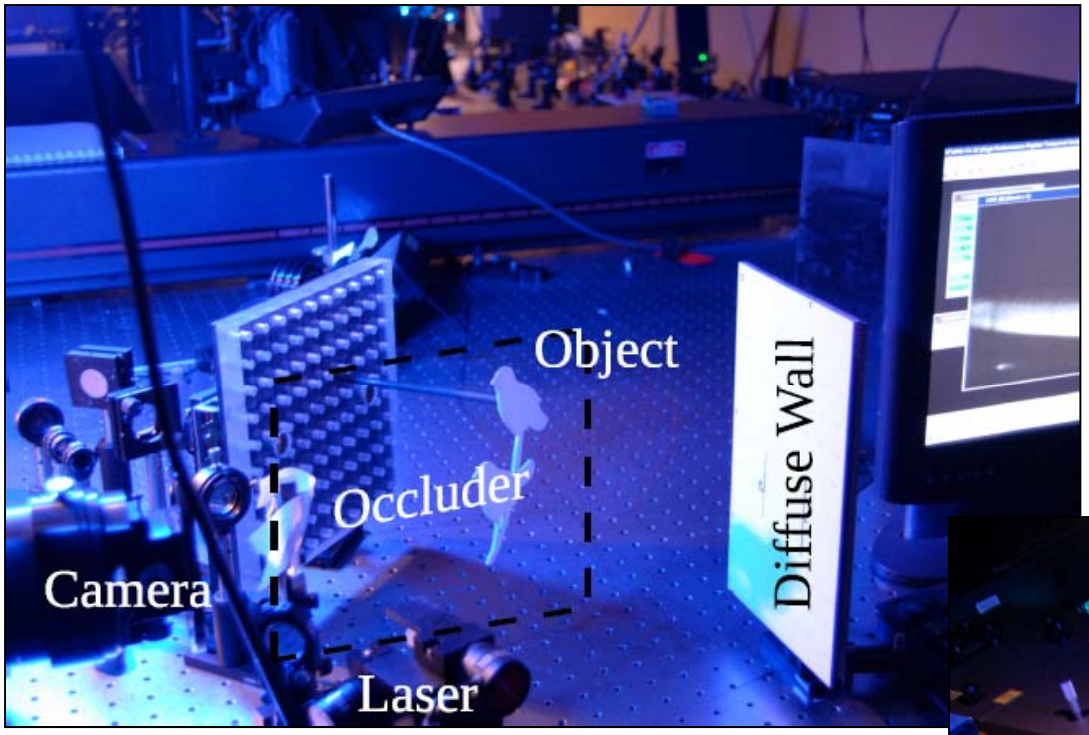
Impulse Response, 5D

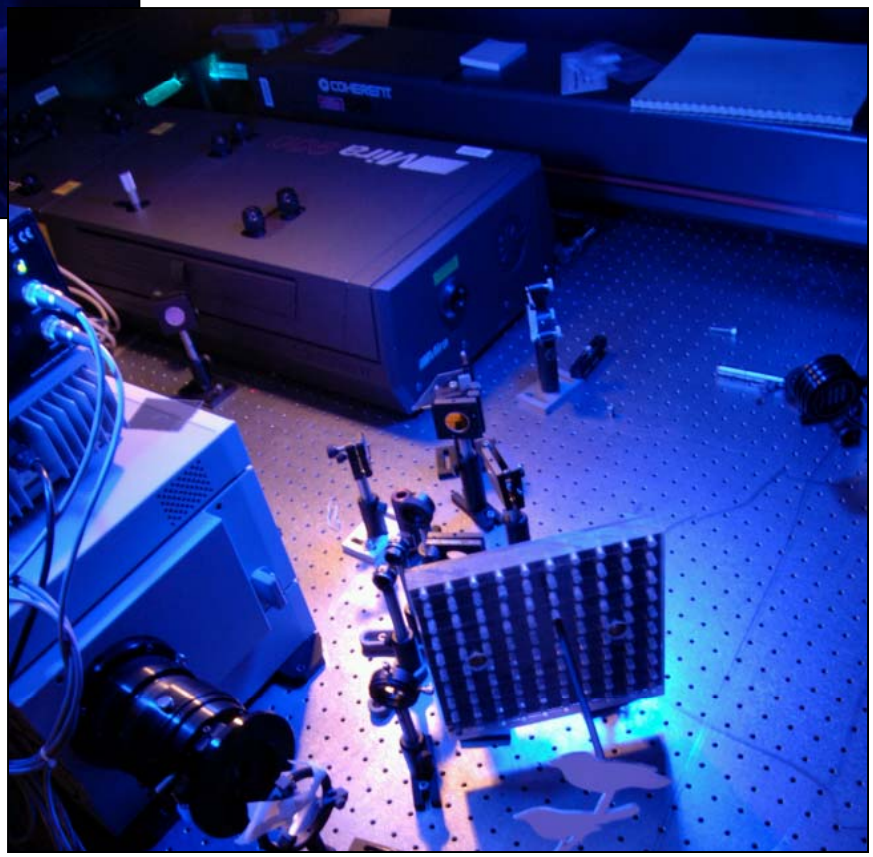
$$L[i,t] = E[i,t] + \sum_j \rho(i,j) L[j, t - d_{ij}]$$



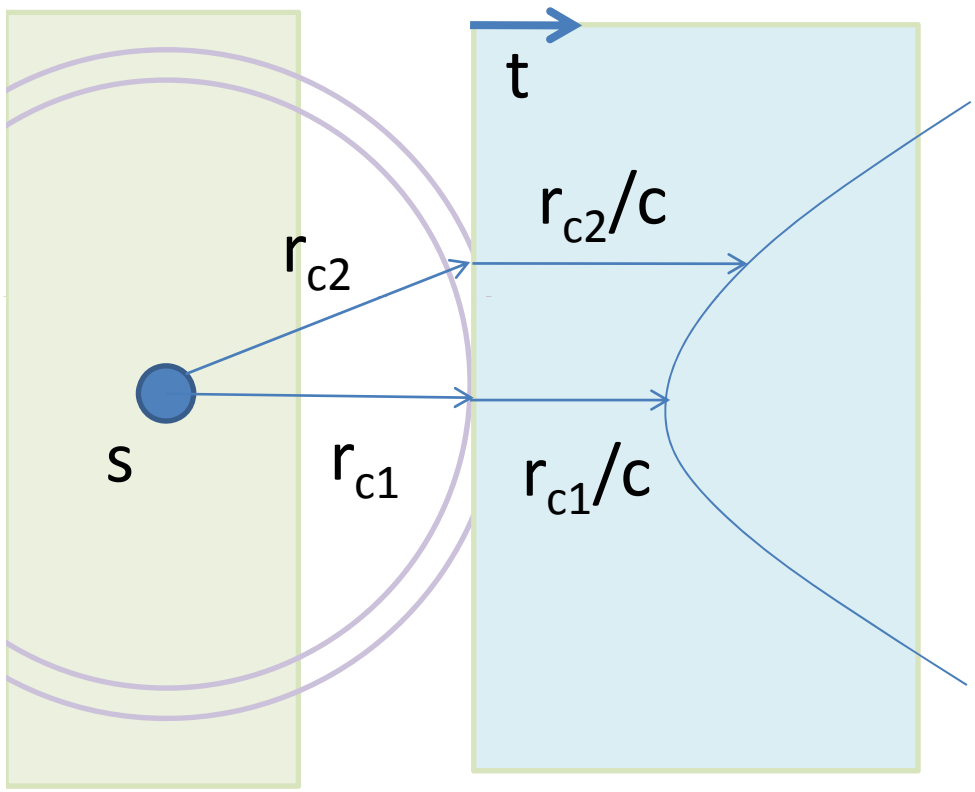


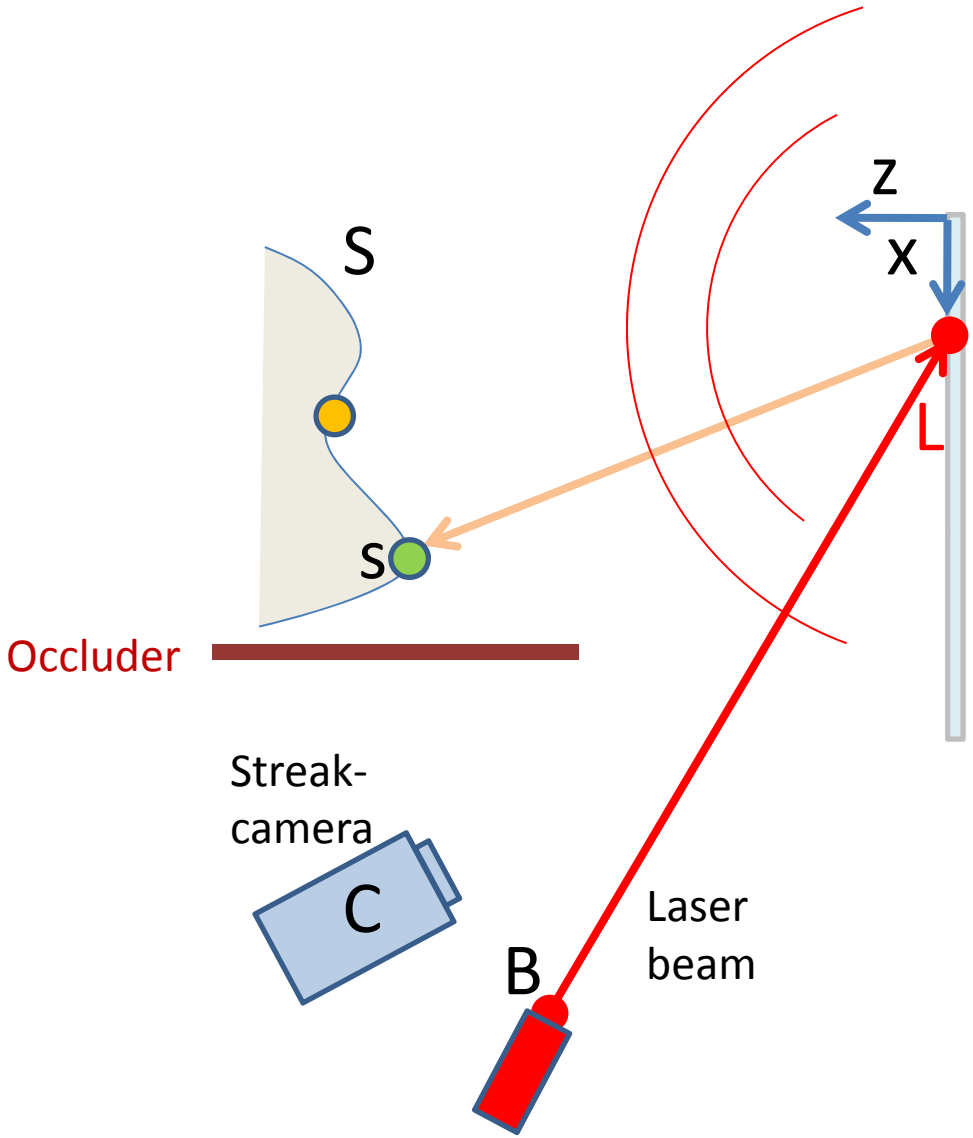
With M Bawendi, MIT Chemistry



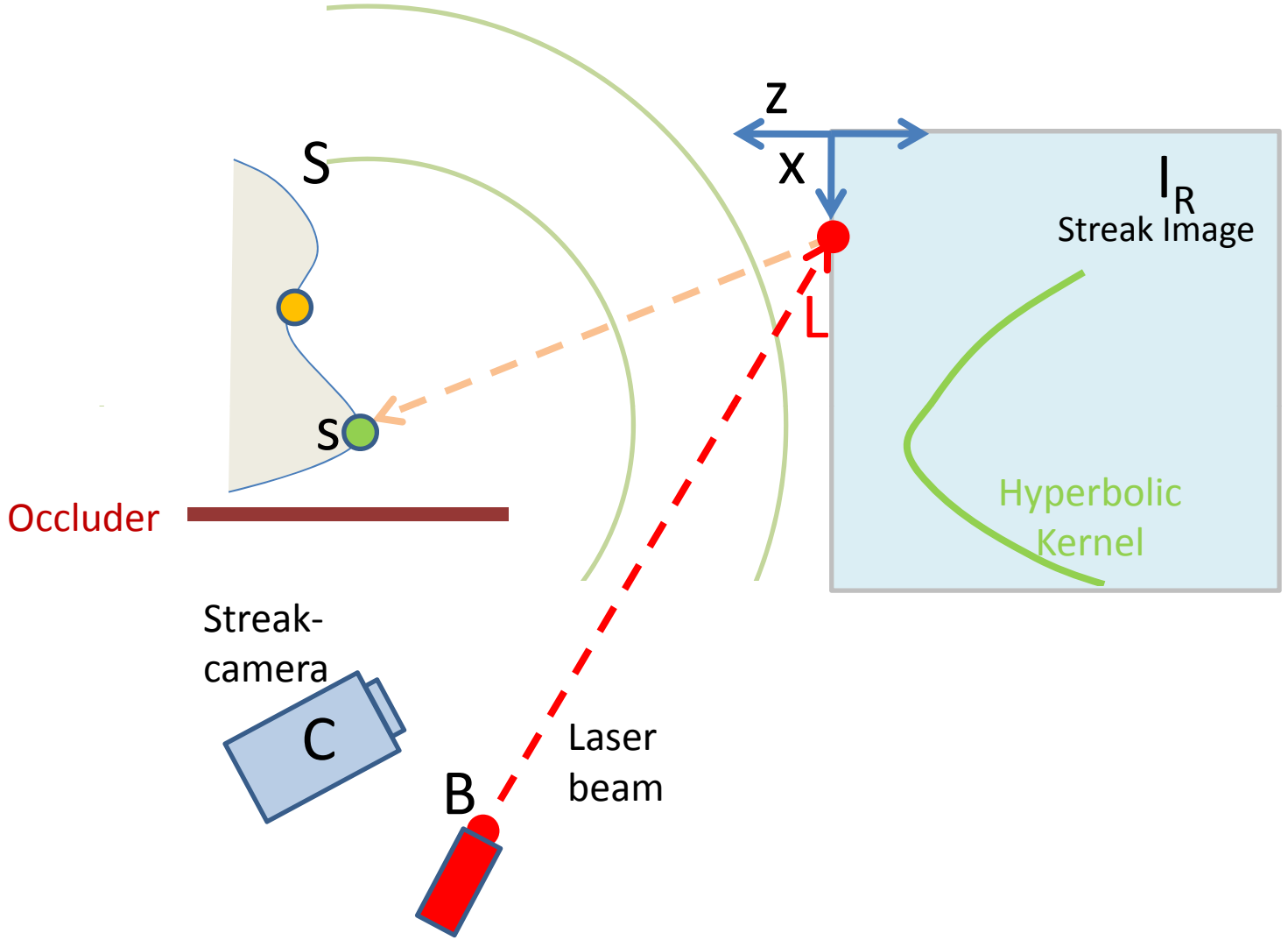


With M Bawendi, MIT Chemistry

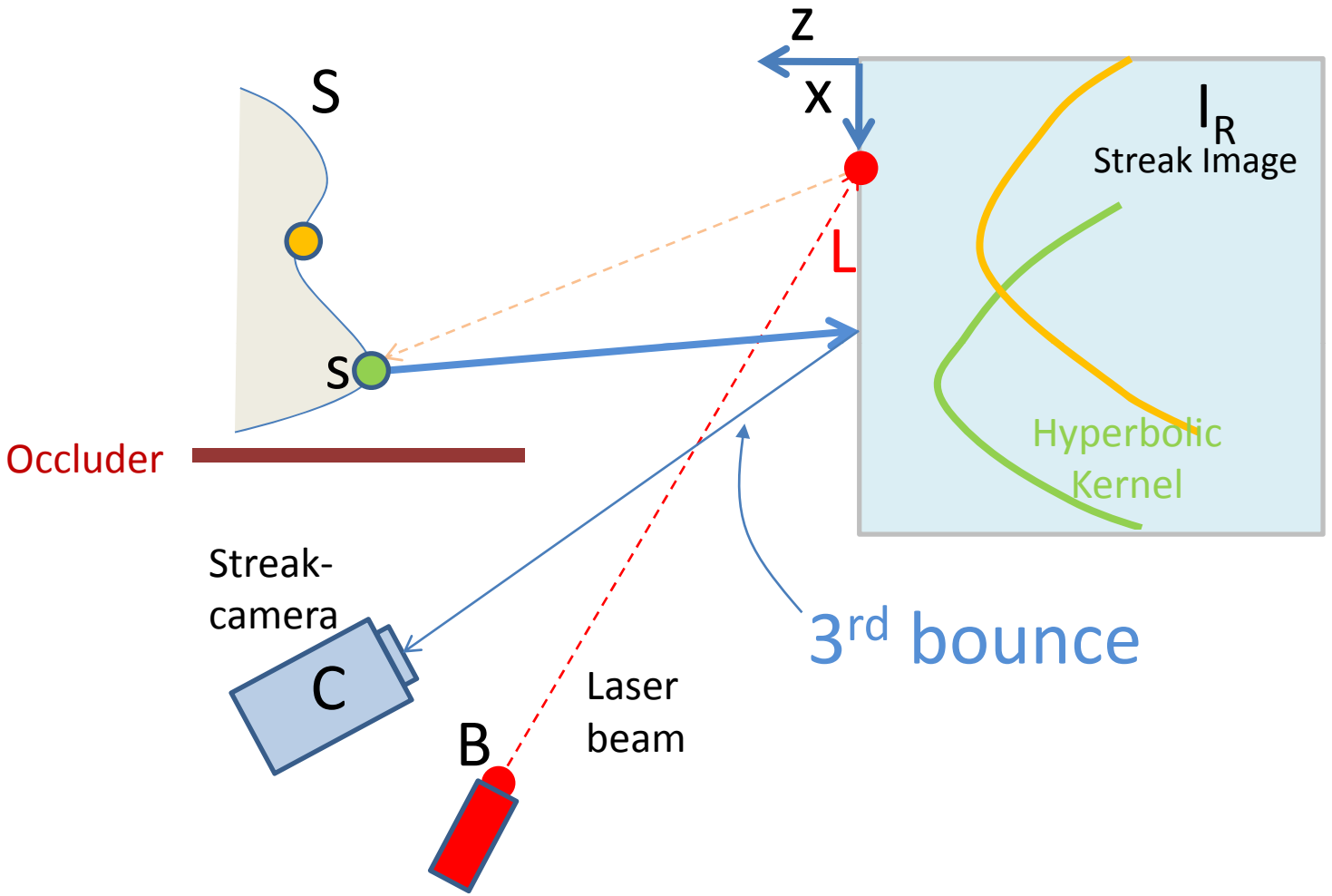

t
r_{c2}/c
r_{c2}
s
r_{c1}
r_{c1}/c



Echoes of Light



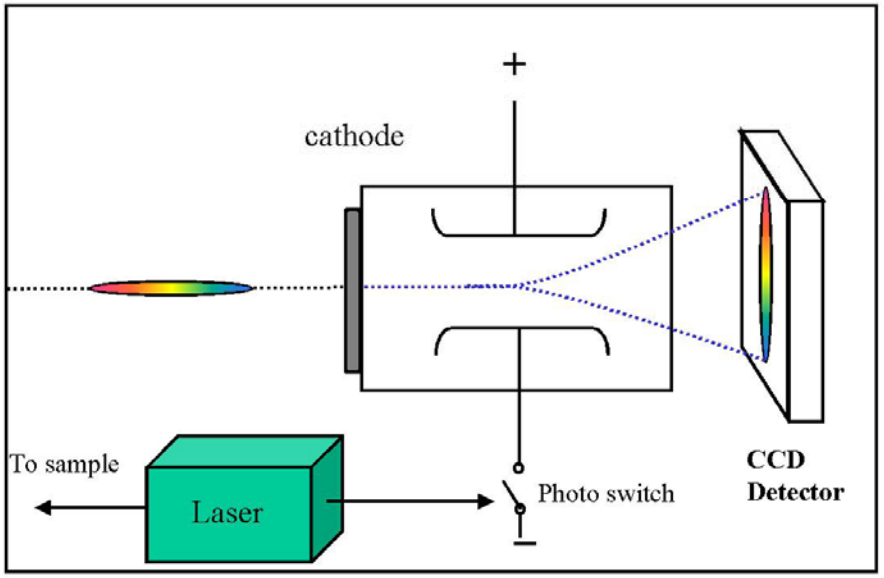
Echoes of Light

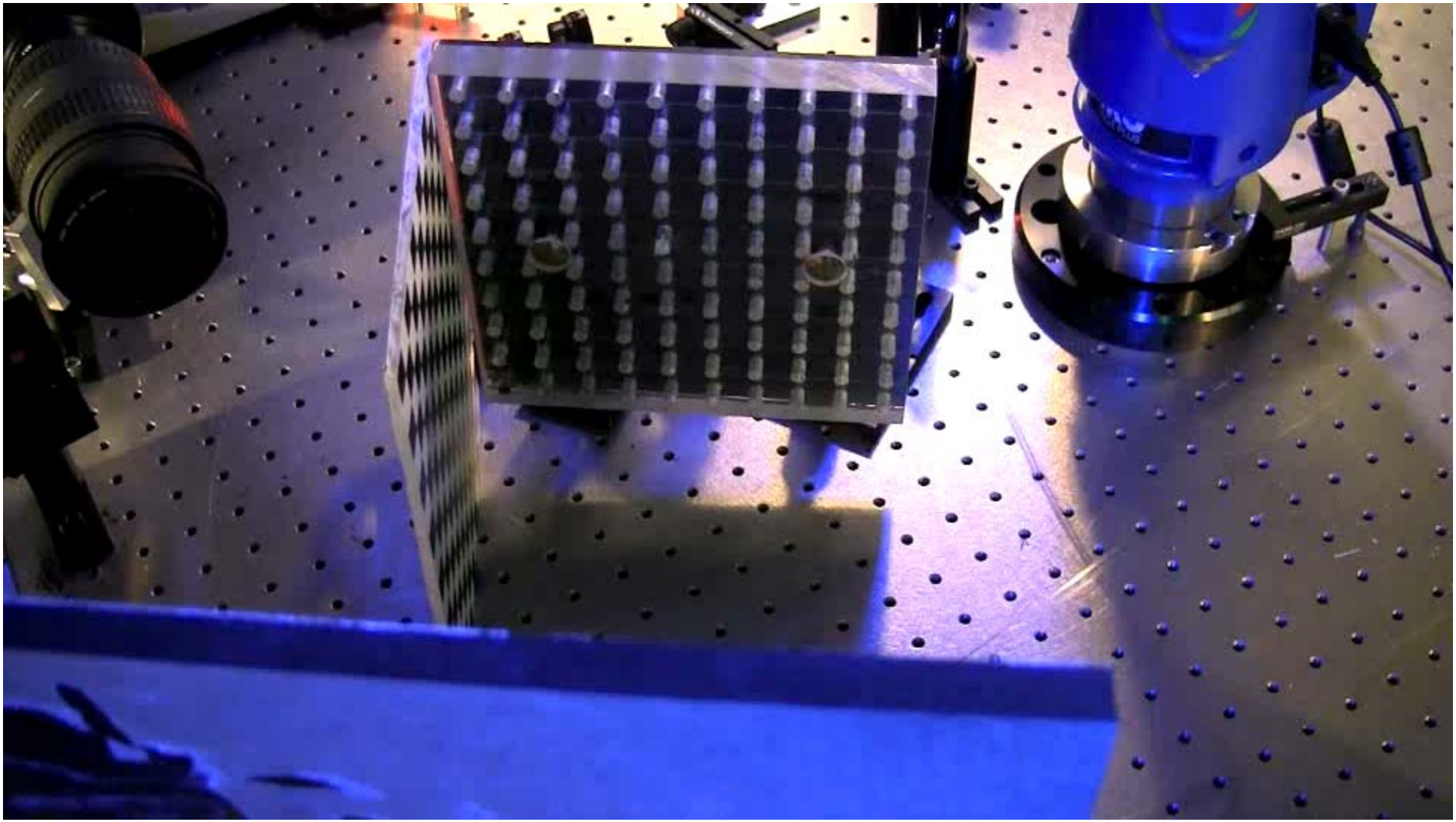


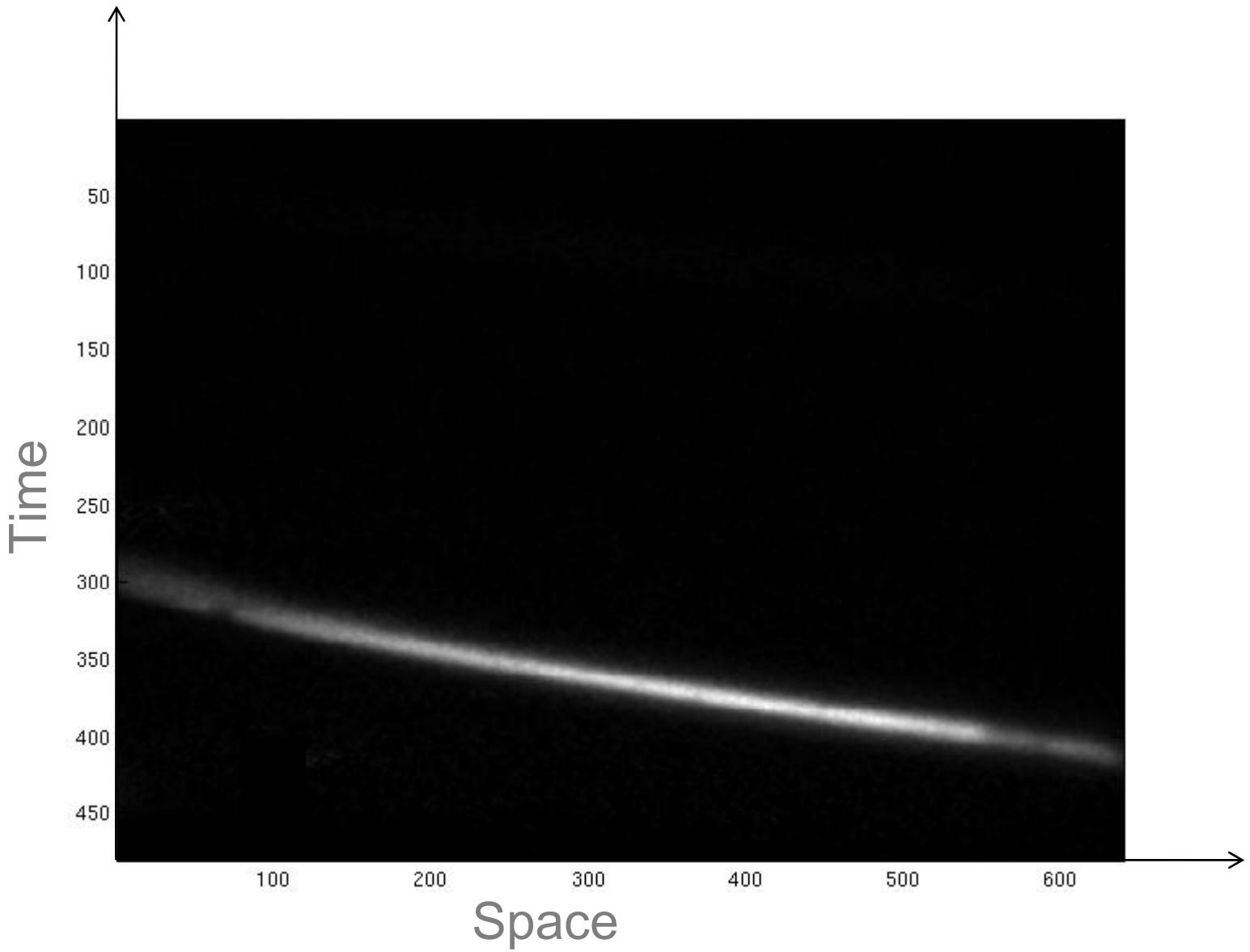
Echoes of Light

Trillion FPS

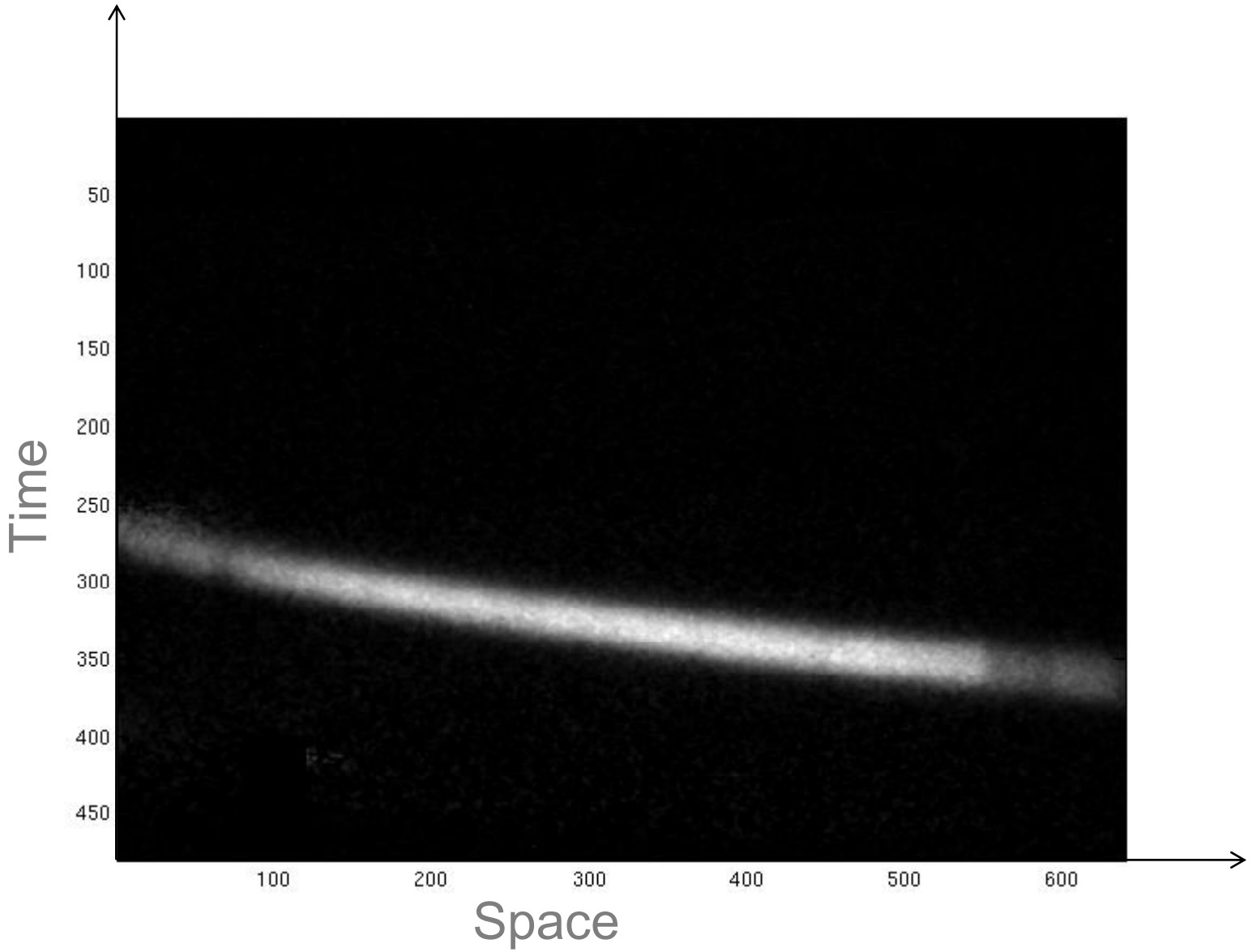
ToF Streak Camera = Inverse of CRO



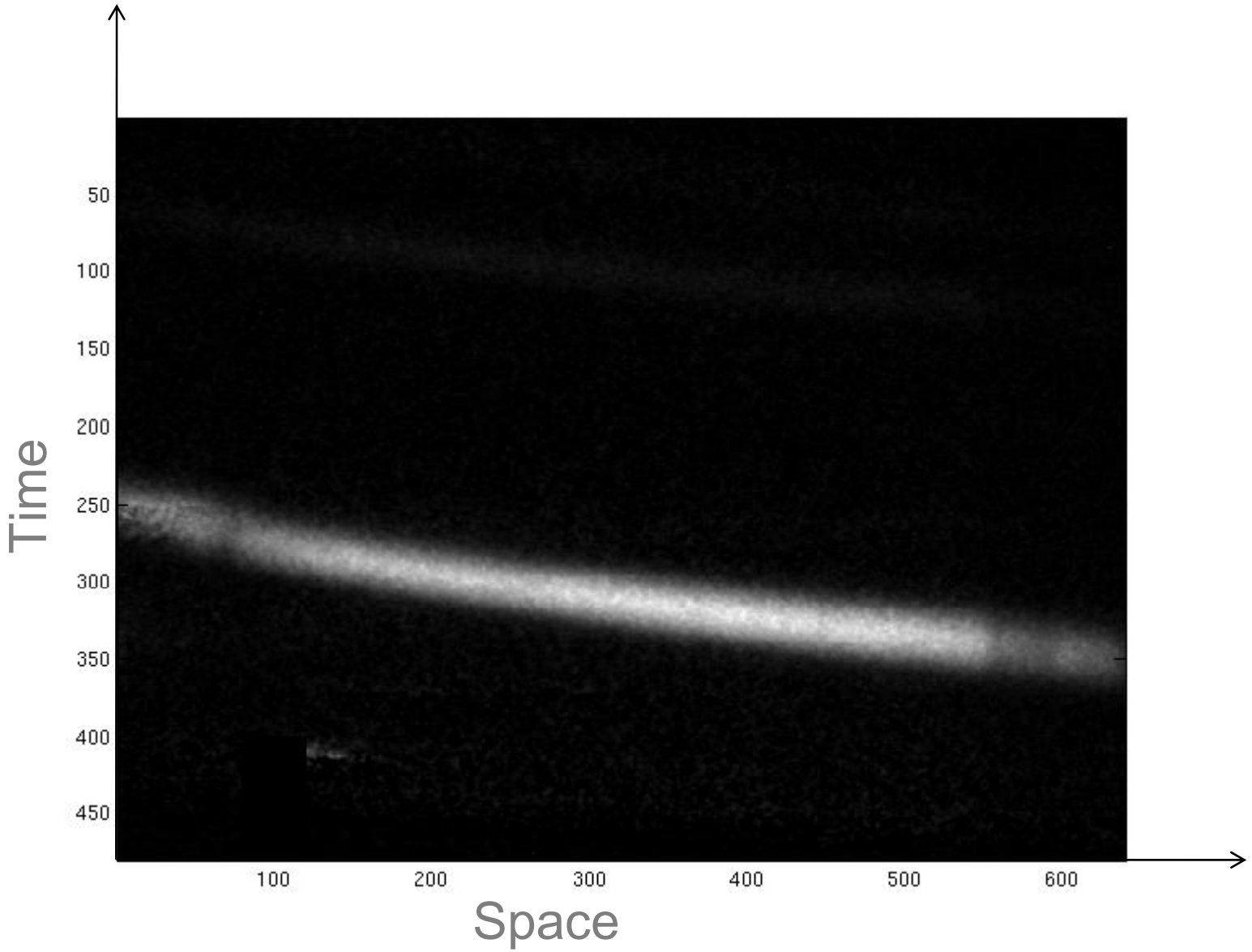




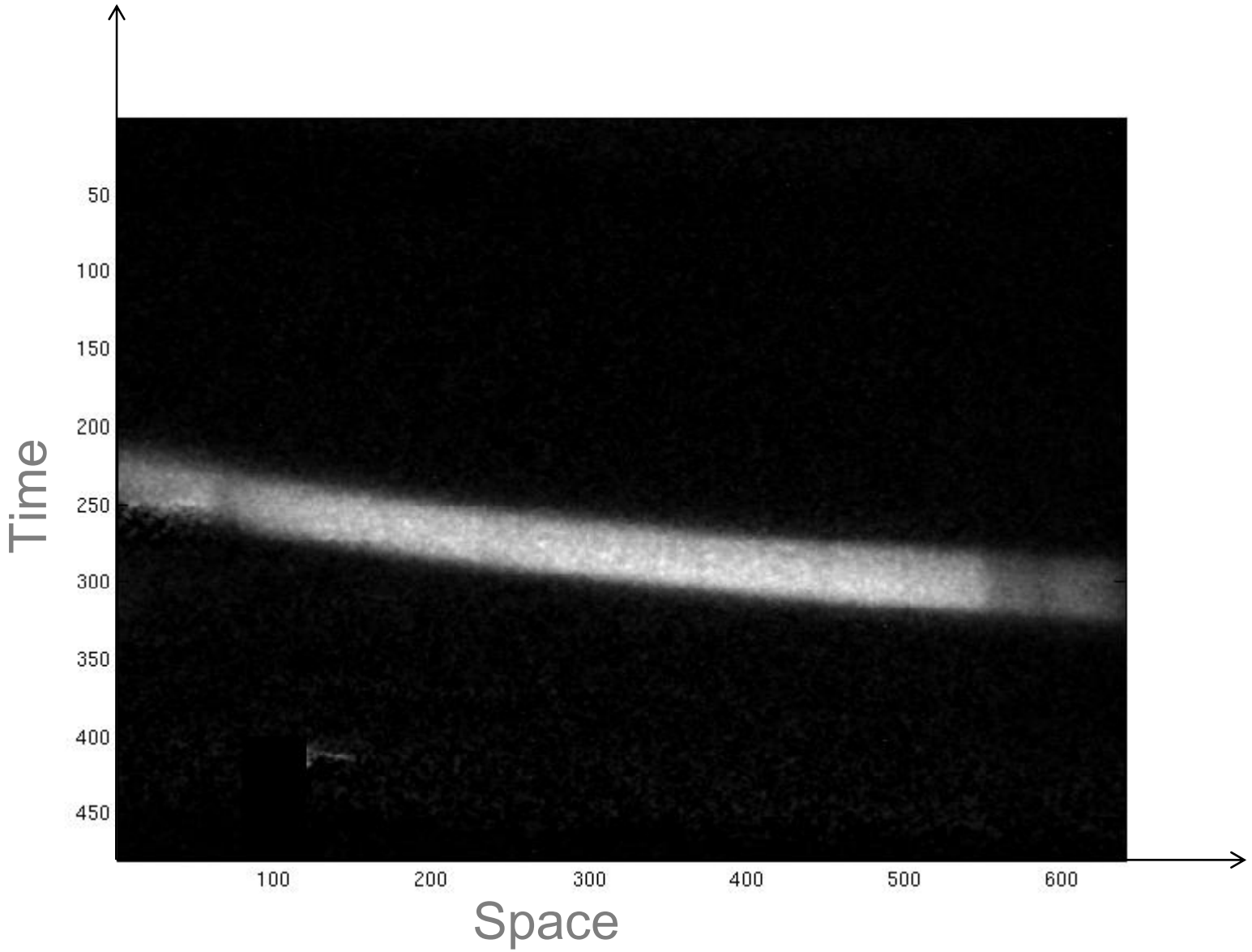
Third Bounce (First bounce not shown)



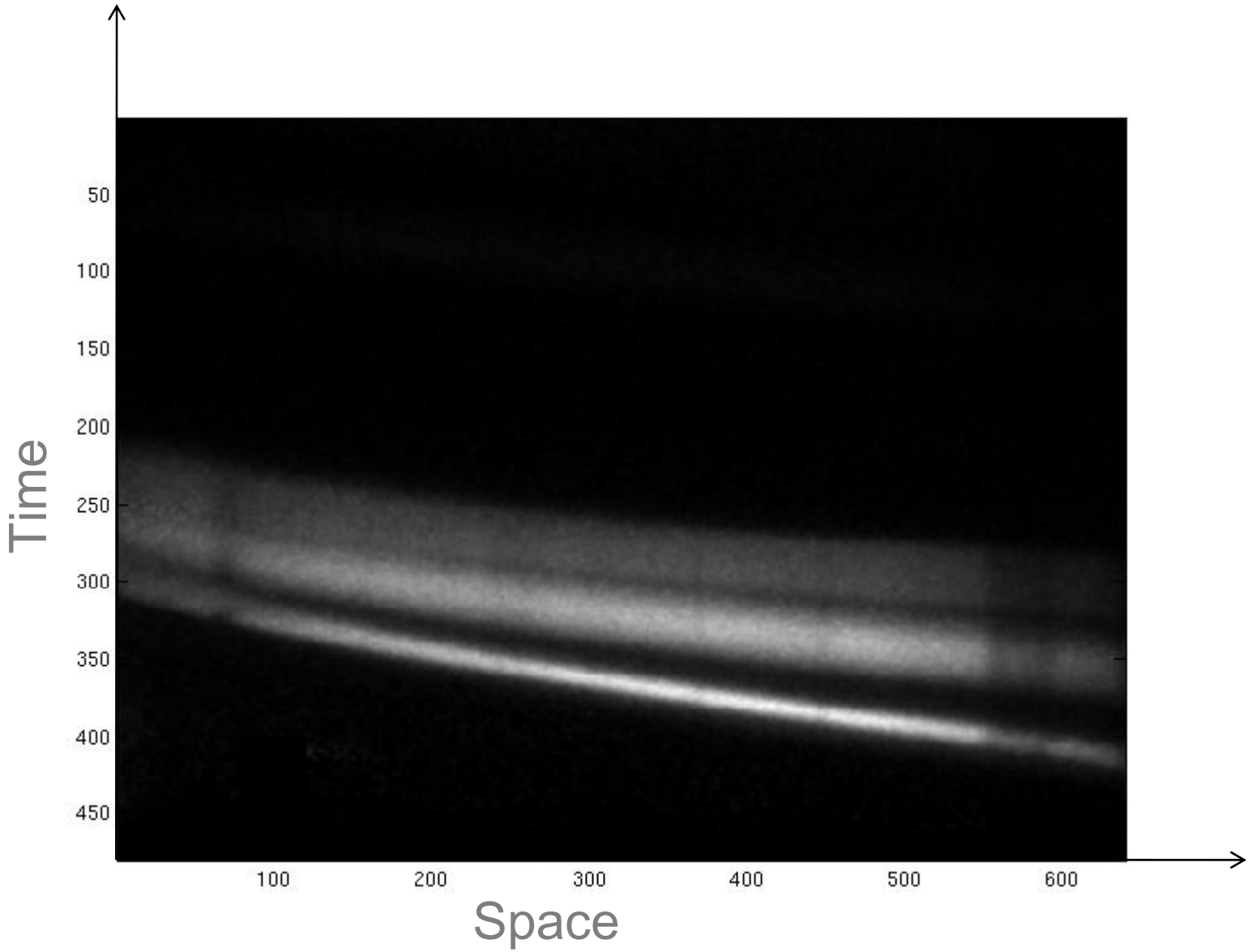
Third Bounce (First bounce not shown)



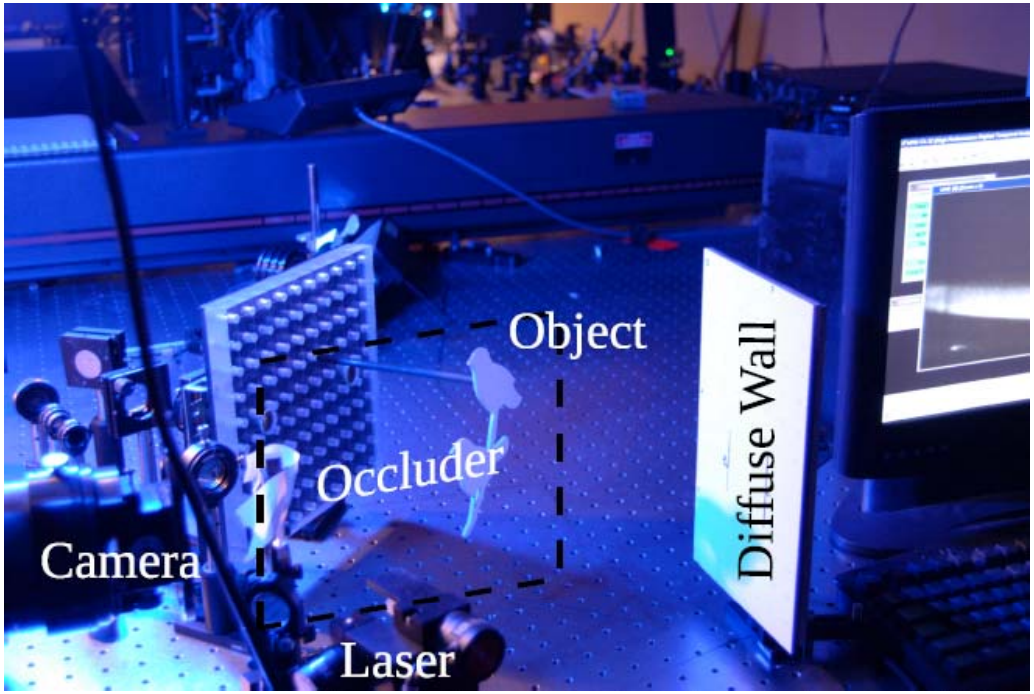
Third Bounce (First bounce not shown)

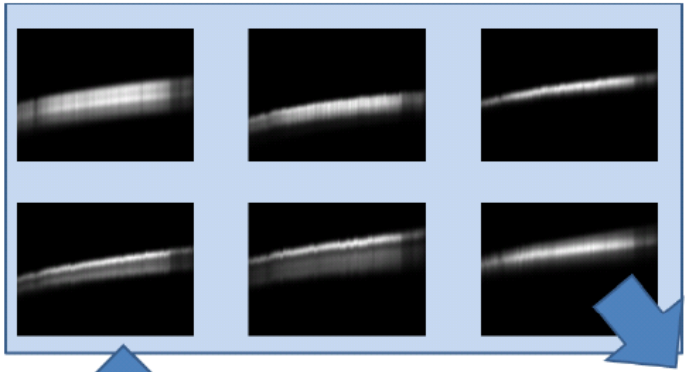


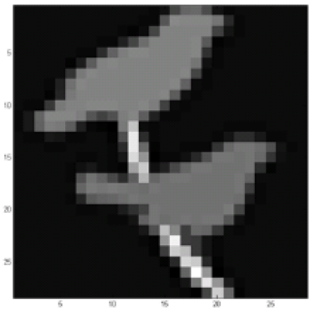
Third Bounce (First bounce not shown)

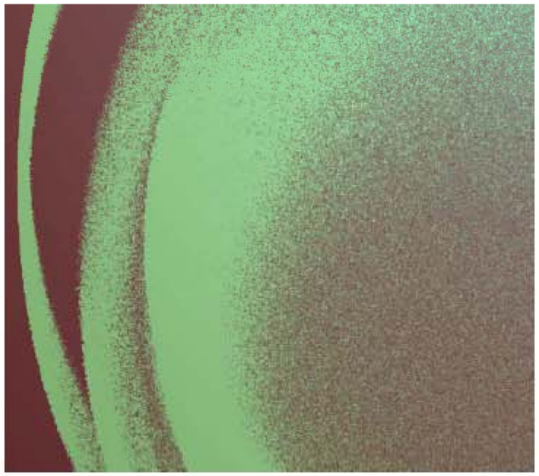


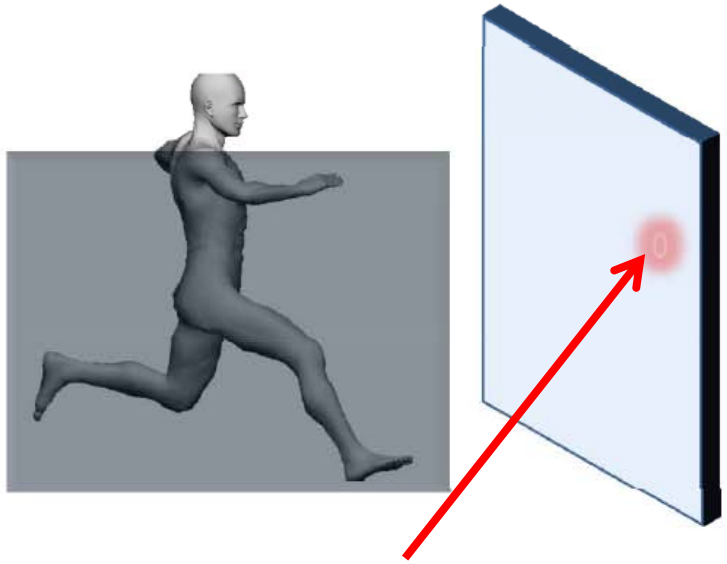
Third Bounce (First bounce not shown)


Object
Occluder
Camera
Laser
Diffuse Wall



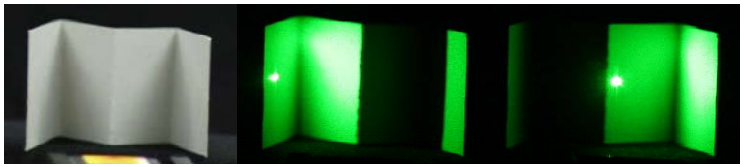






Forward	Reconstruction	Invertibility	Analysis
Modified Fresnel Approximation	Backpropagation + Carving	Scene Priors, L1 reconstruction via COSaMP	Resolution and dimensions

Inverting Light Transport

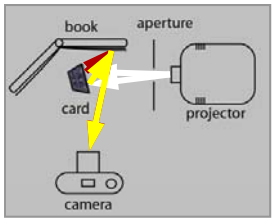


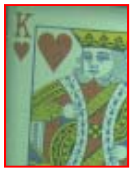
Multiple Scattering

[Seitz , Kutulakos, Matsushita 2005]

Direct/Global

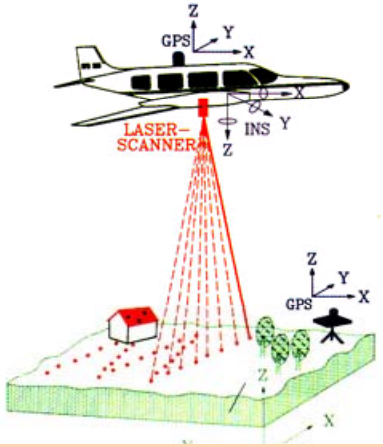
[Nayar, Raskar et al 2006]





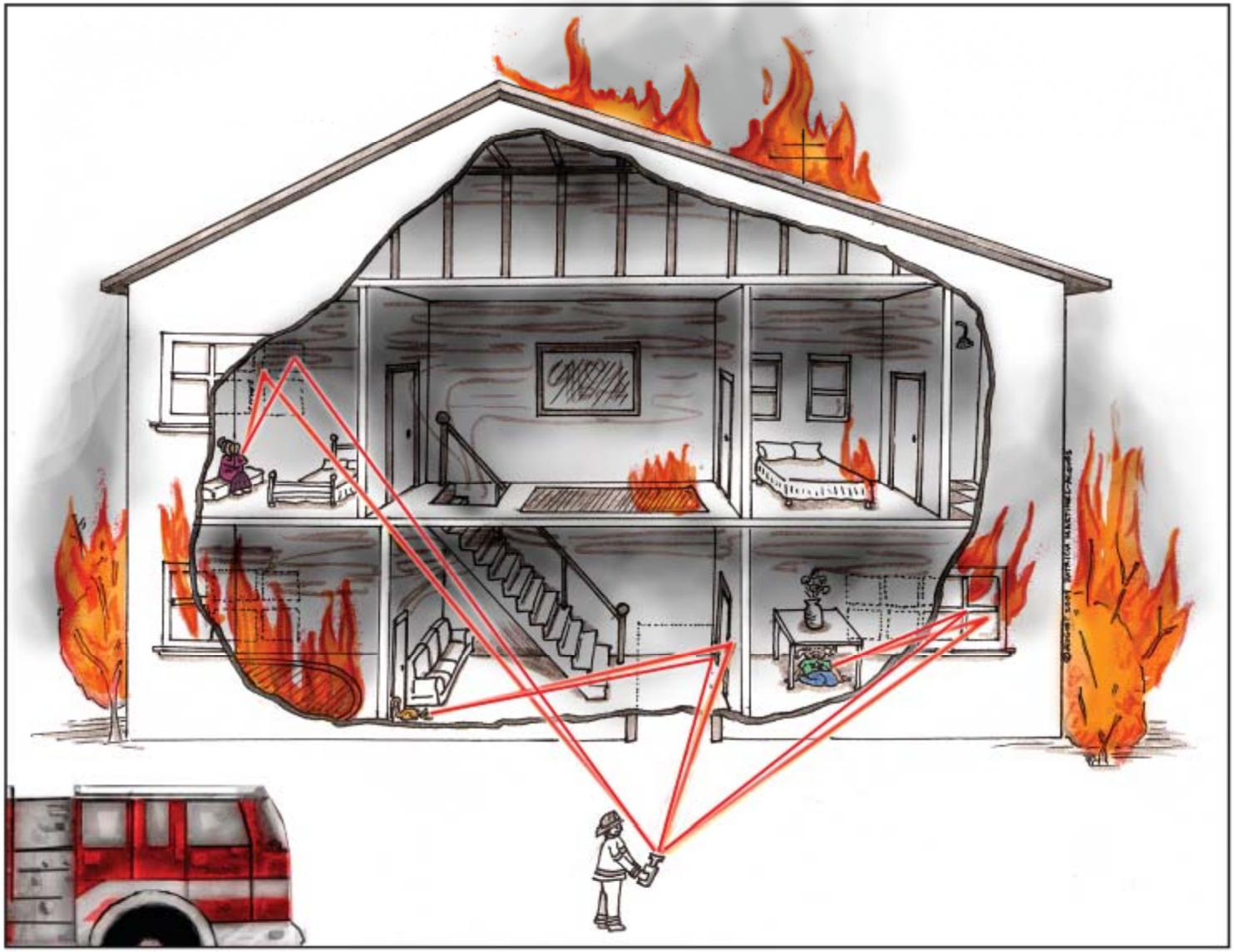
Dual Photography

[Sen et al 2005]

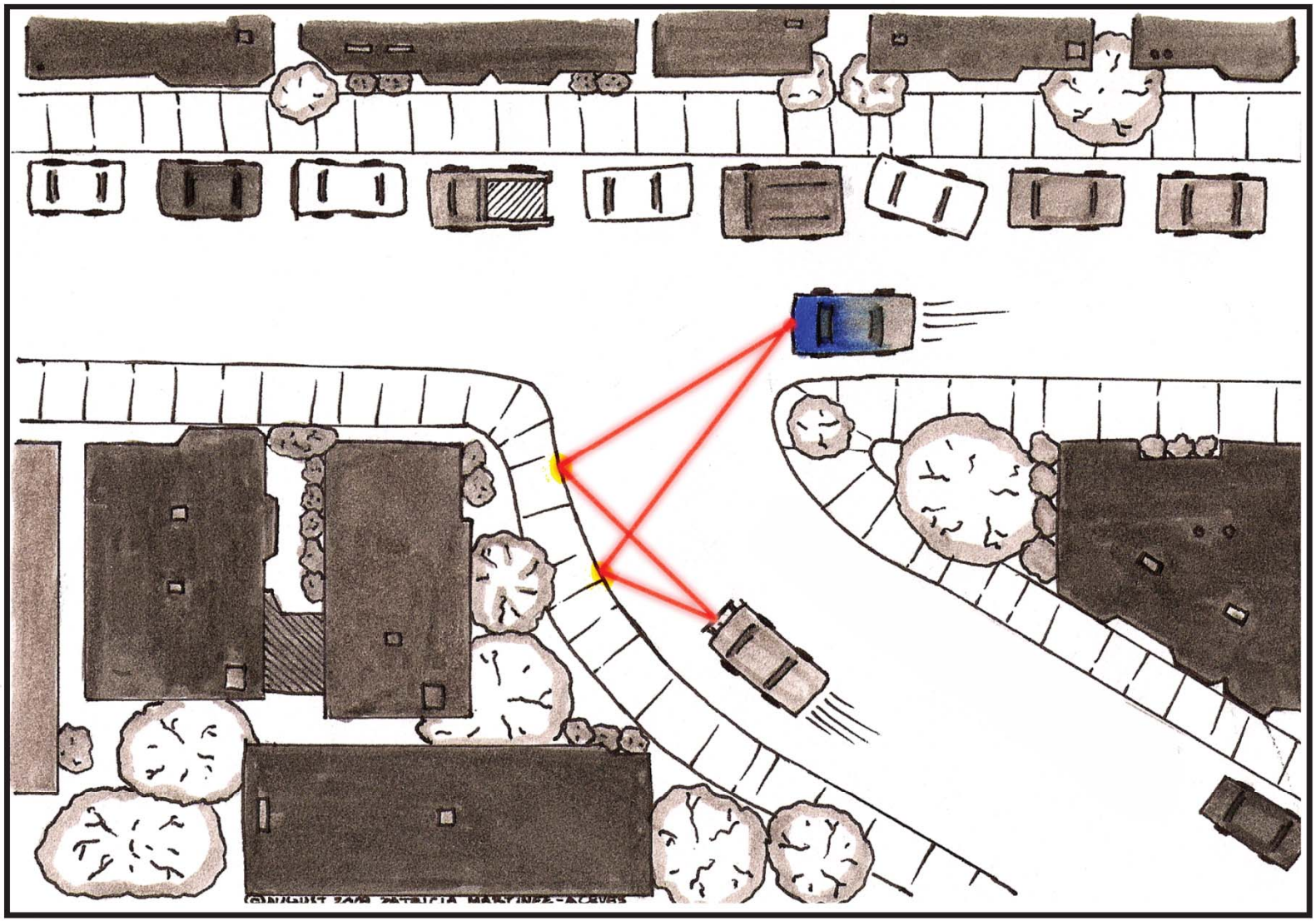


LIDAR

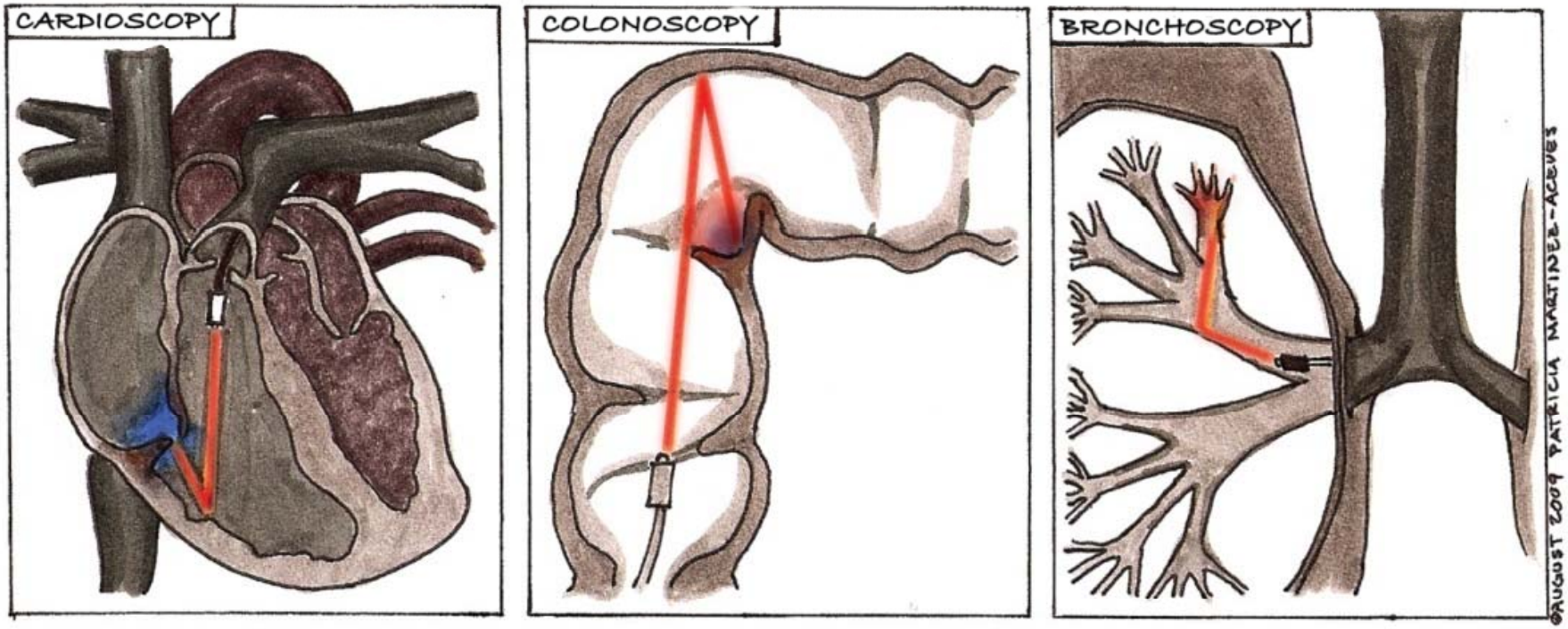
Rescue and Planning



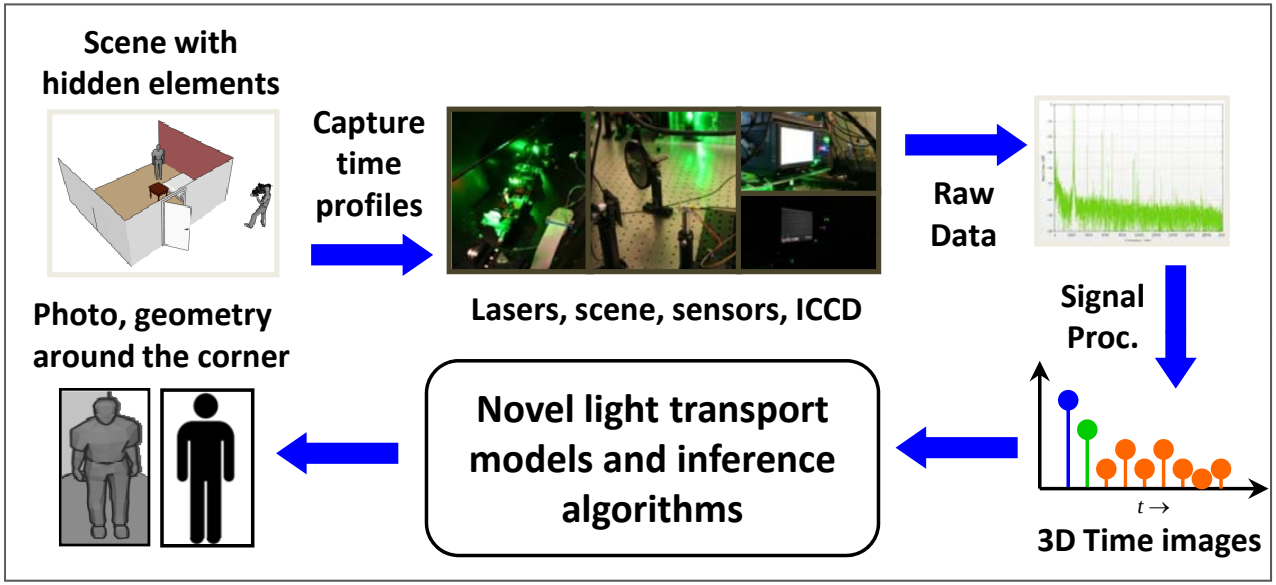
Robot, Car Path Planning



Endoscopy


CARDIOSCOPY
COLONOSCOPY
BRONCHOSCOPY
©AUGUST 2009 PATRICIA MARTINEZ-ACEVES

Time Resolved Multi-path Imaging: Plans

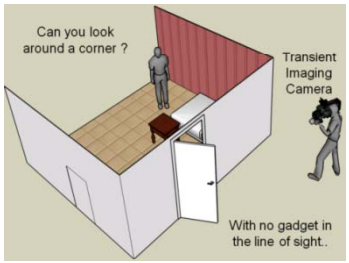


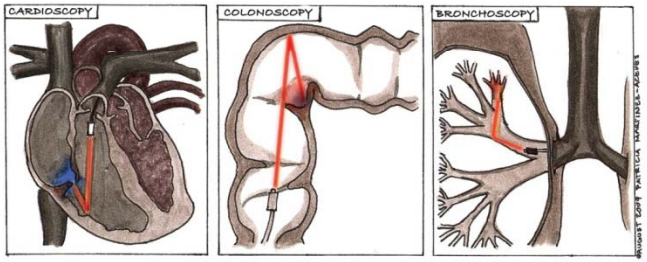
Scenes: NLoS, Motion, BRDF in single shot, Volumetric (tissue)
Scale: Endscopes, table-top, room-sized, outdoors, underwater
Inversion: Sparsity, Rank, Bounded Approx, Scene Priors, Transforms
SignalProc: Compressive, SNR, Bandwidth, Noise models
Capture: Coding in space/time/wavelgth, Solid state, non-linear optics
Spectrum: Radar, Sonar/Ultrasound

MIT 2008-

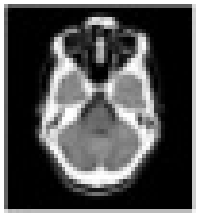
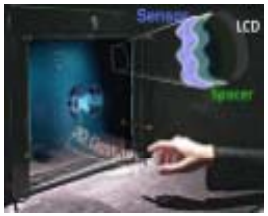
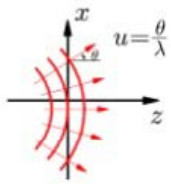
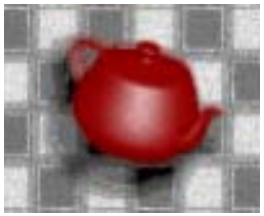
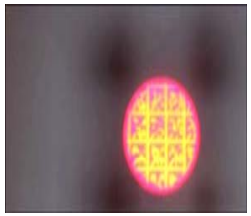
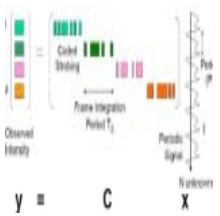
Computational Light Transport

1. Time resolved

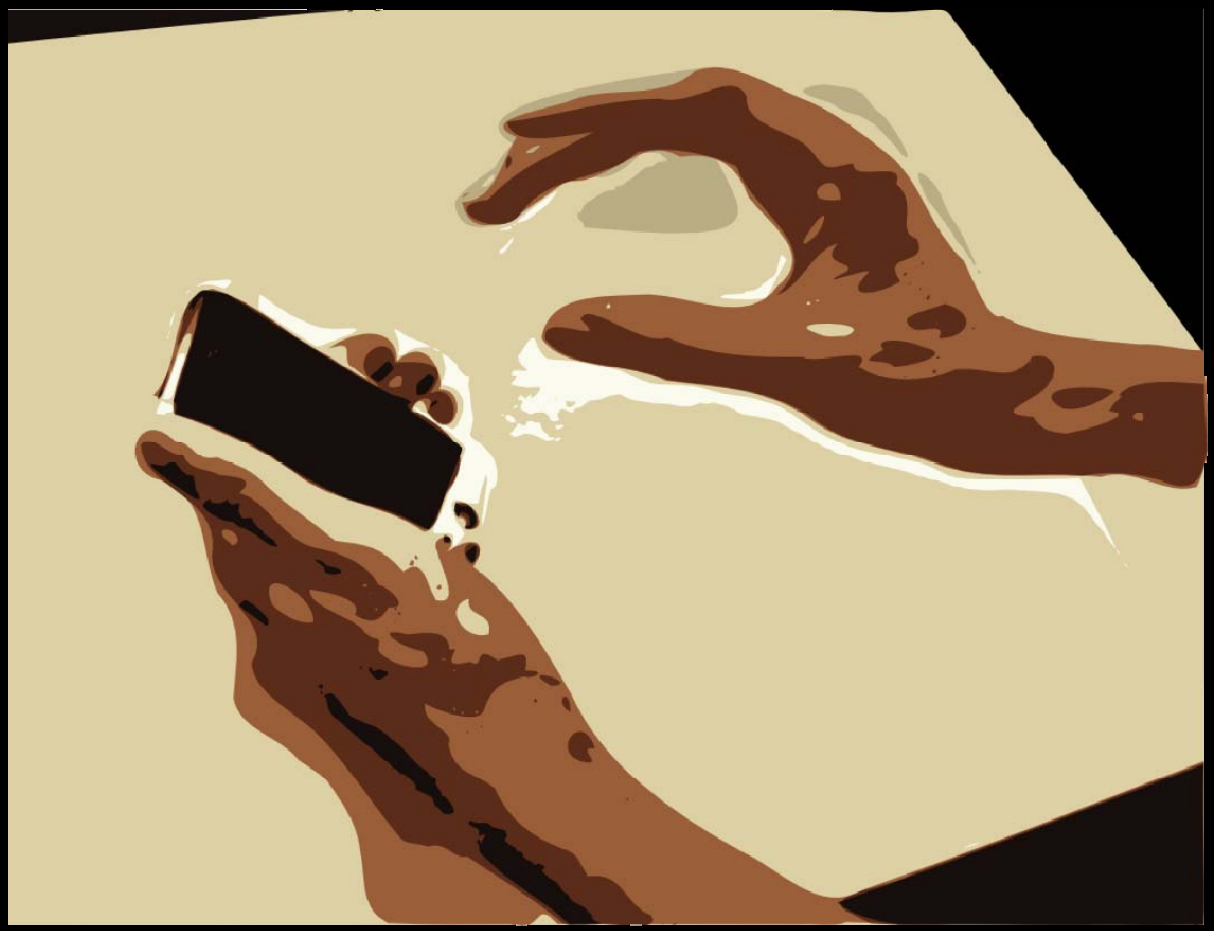




2. Angle resolved

Descattering Analysis	Spatial Heterodyning	Augmented Light Field	Rank-constraint of 3D Displays	Computational Probes	Wavefront Sensing	Compressive Sensing
CAT-Scan without moving parts	BiDi Screen	Geometric + Wave optics	Glasses Free 3D Dual Layer LCD	Bokode	NETRA	Sparsity Analysis
						
2009 -	2008-	2008-	2009 -	2008 -	2010	2009 -

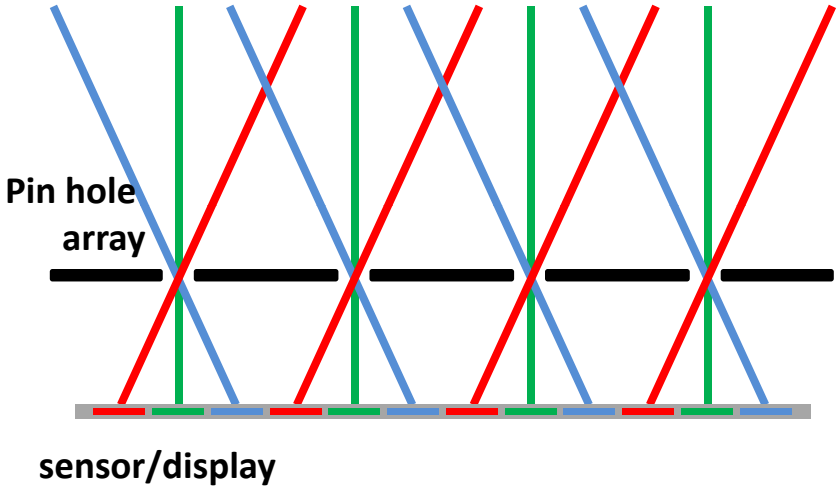
LCD = a big flat camera?



Angular Information

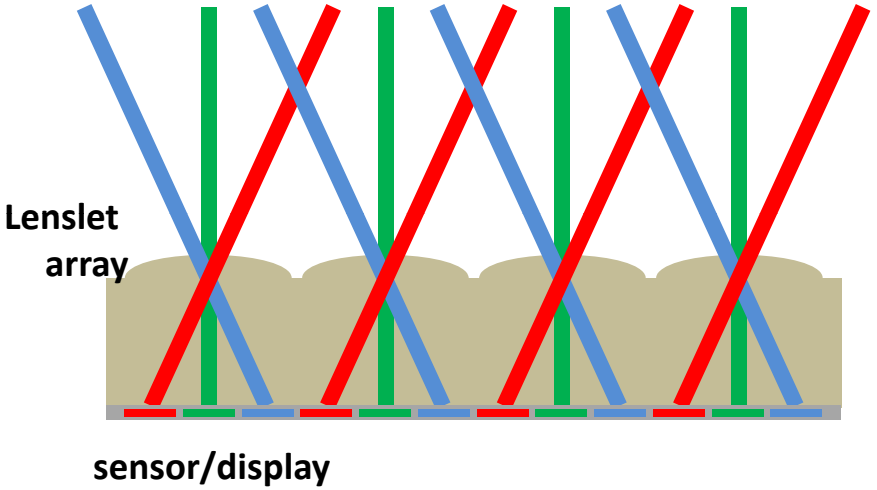
1903

Parallax Barrier = dim displays



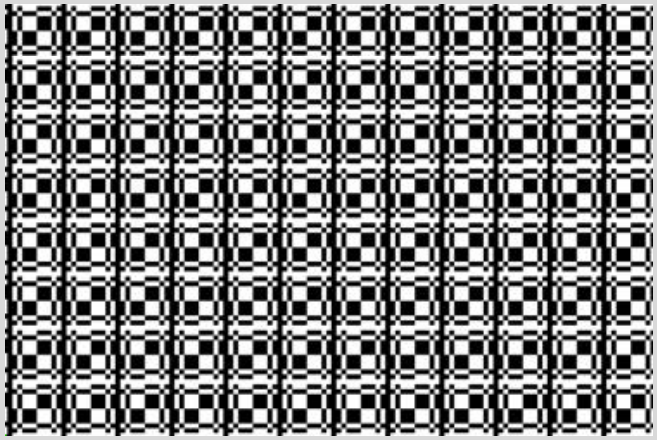
1908

Lenslets = fixed low
space/angle resolution

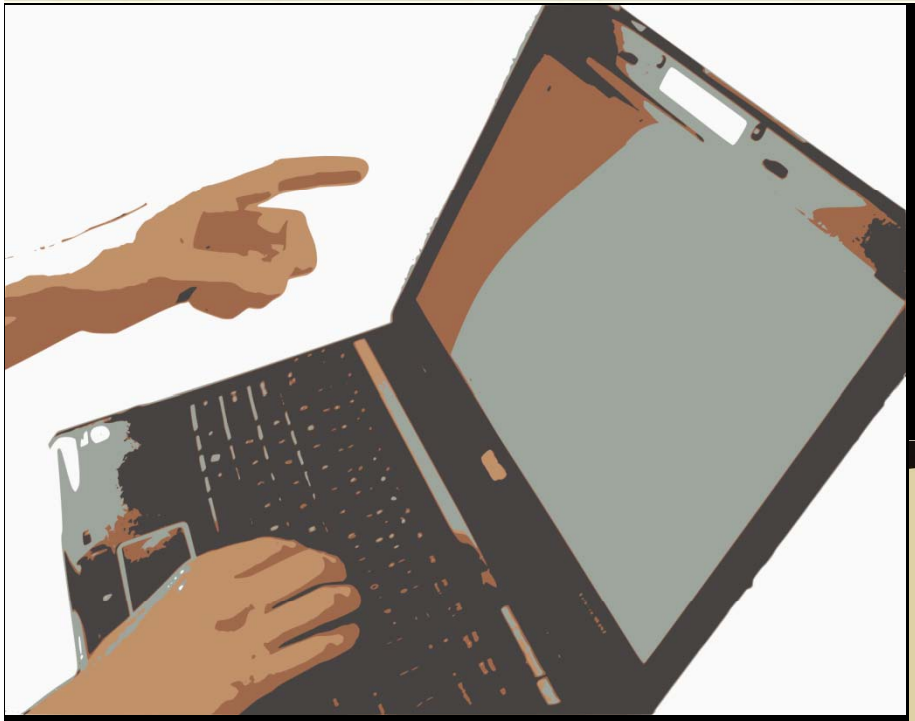


New Solution:

Spatial Heterodyning
using a patterned mask

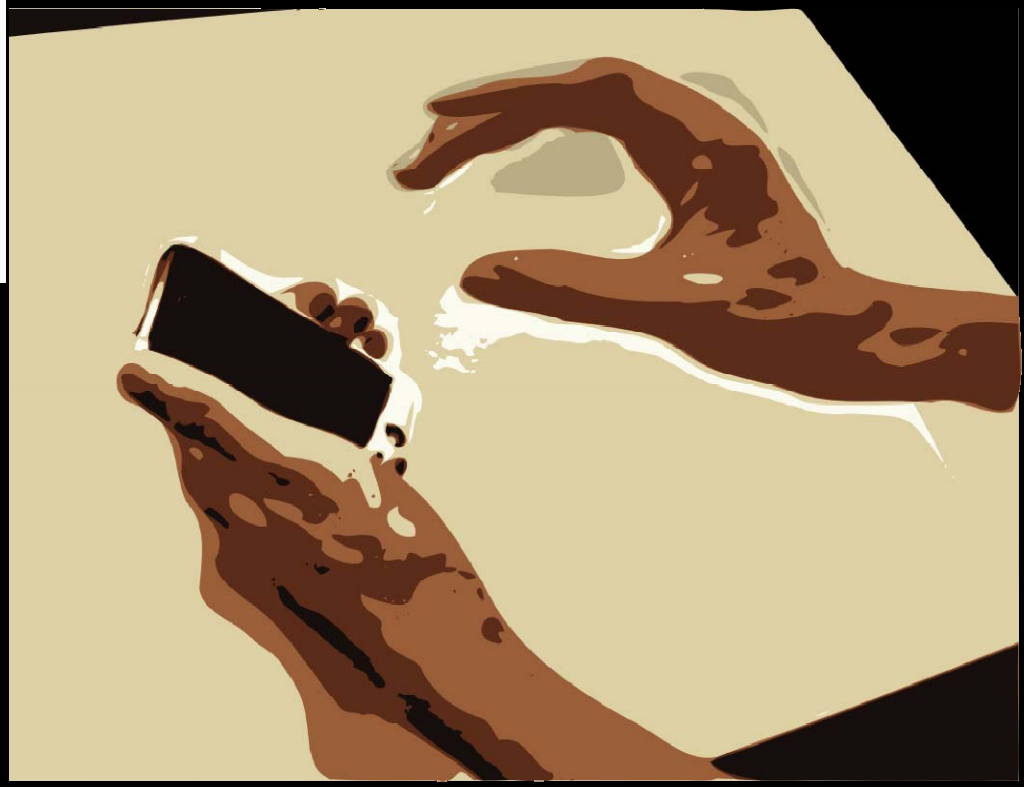


Beyond Multi-touch: Thin LCD for touch+hover

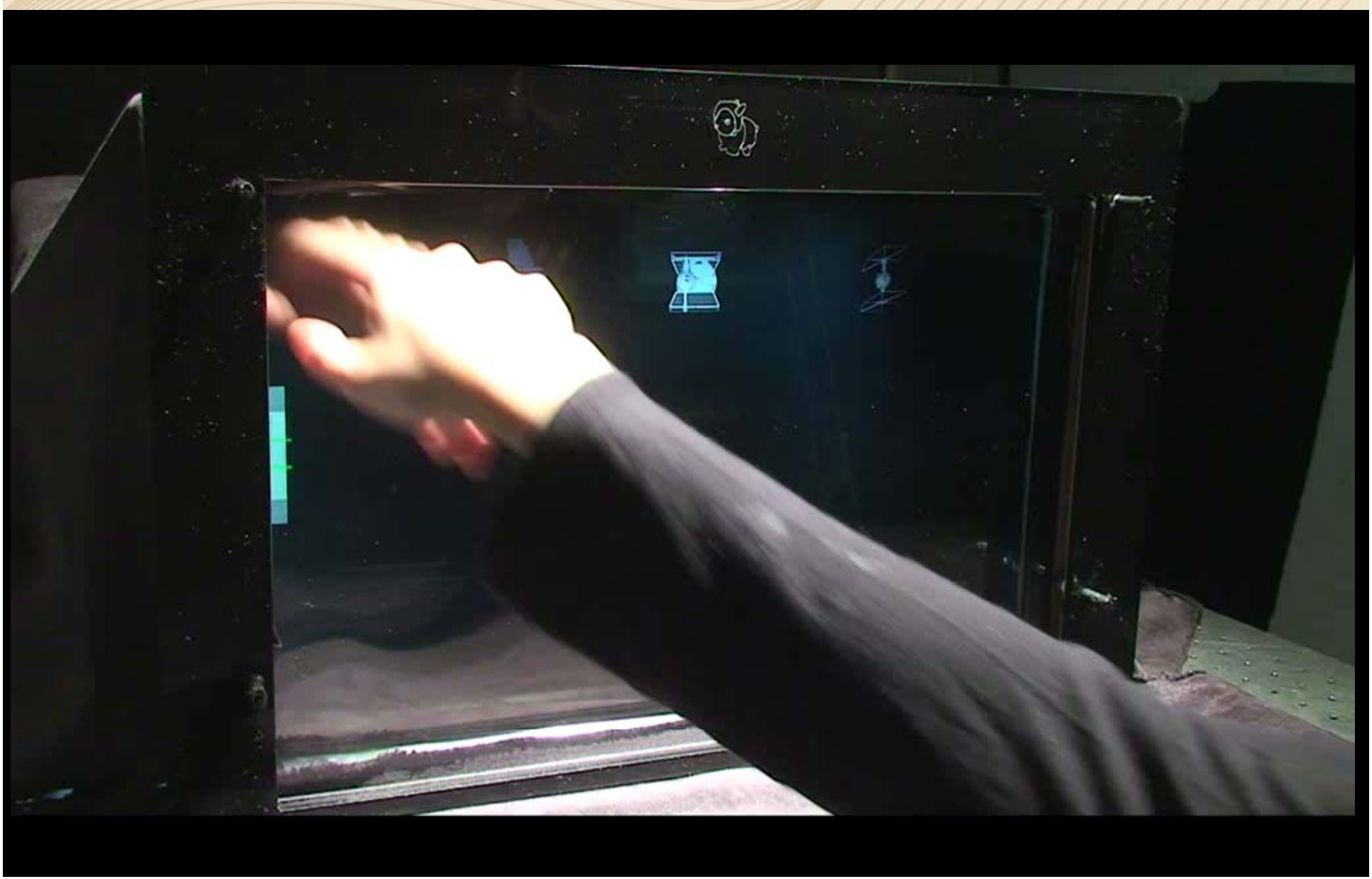


Laptops

Mobile



BiDi Screen: Multi-touch + Hover 3D interface

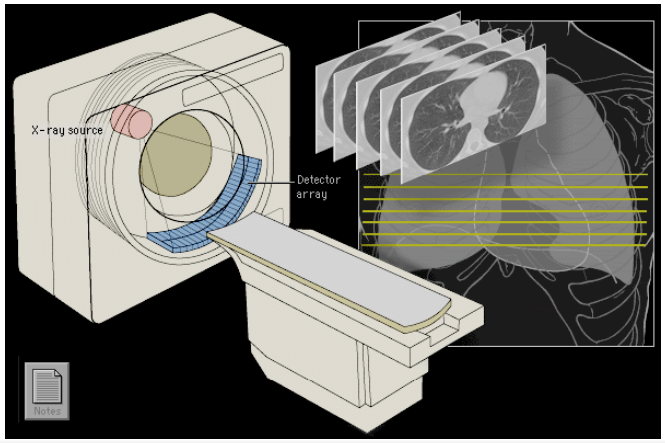


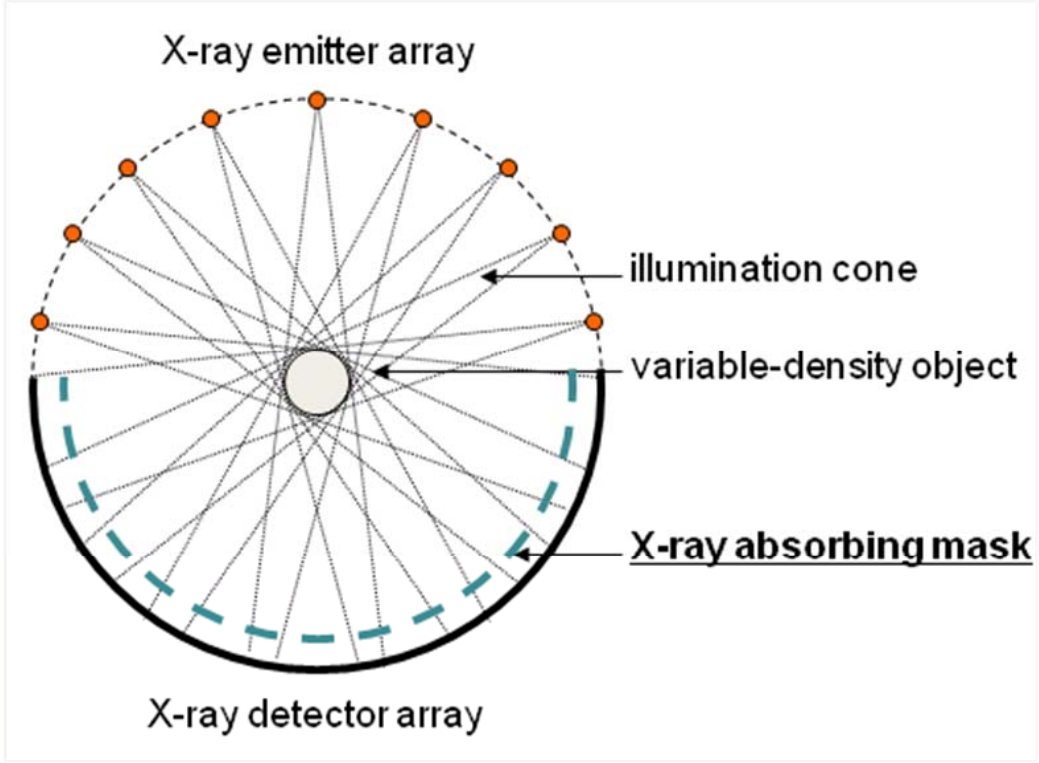
Sensing Depth from Array of Virtual Cameras in thin LCD

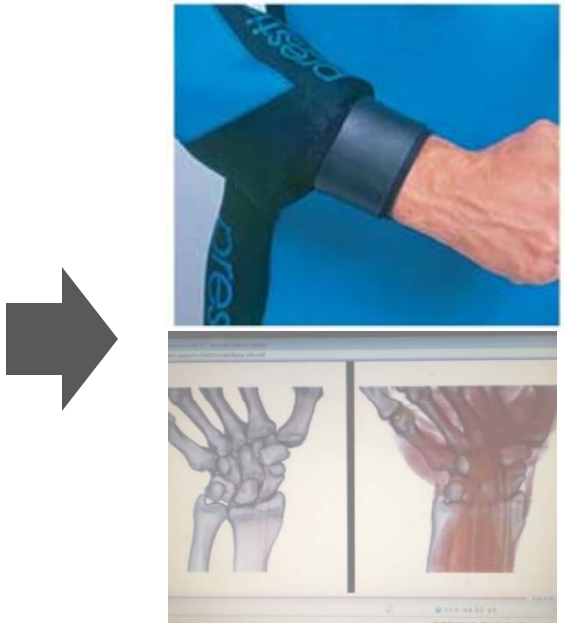
Hirsch, Holtzman, Lanman, Raskar, SiggraphAsia 2009

Funding : Samsung SAIT

CAT Scan without moving parts

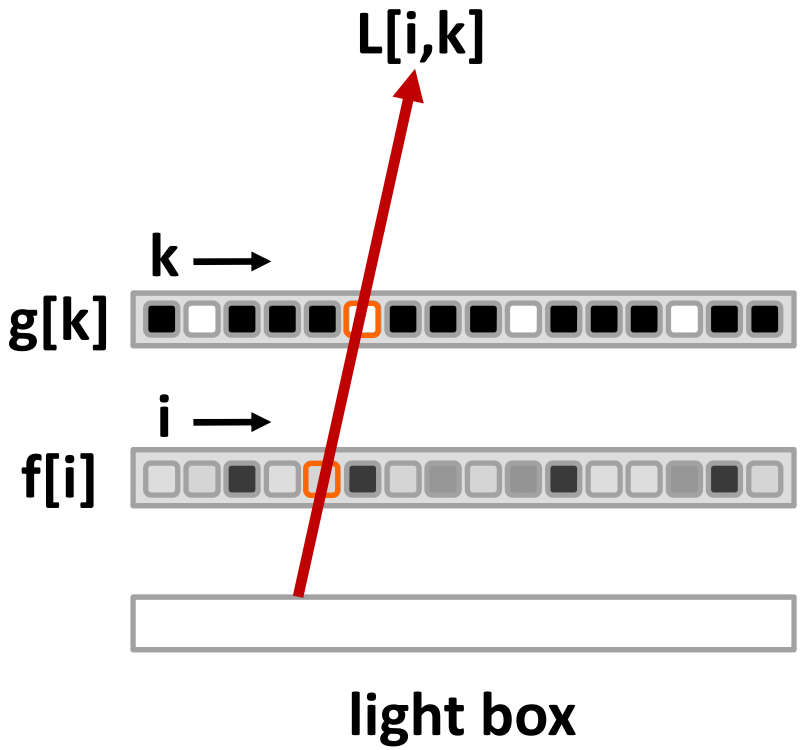


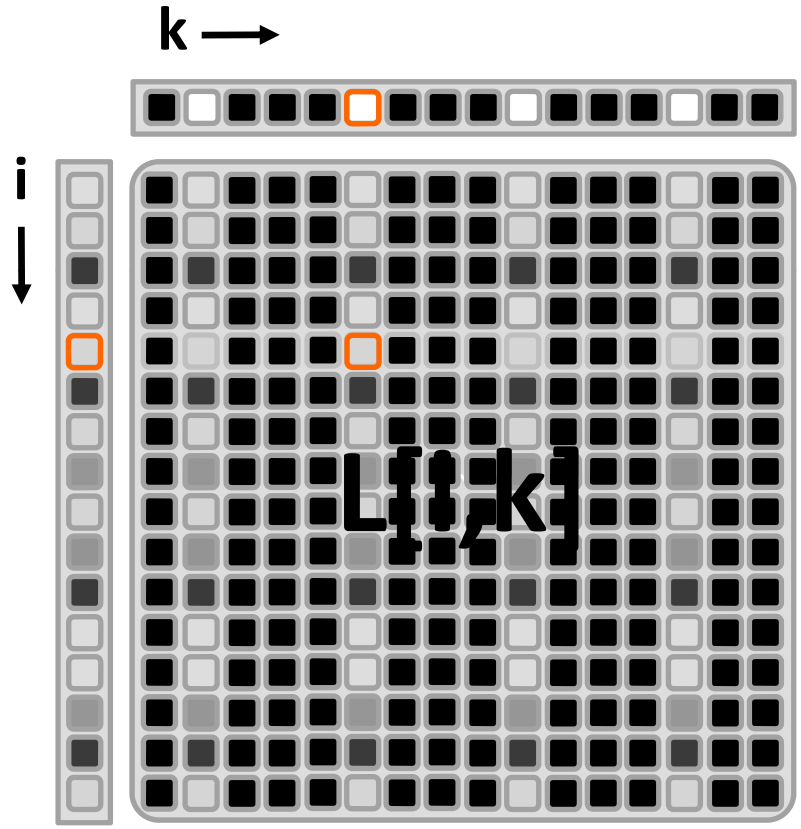




With , Berthold Horn, EECS,
Dick Lanza, Nuclear Engg.

Rank Analysis of 3D Pbarriers Displays

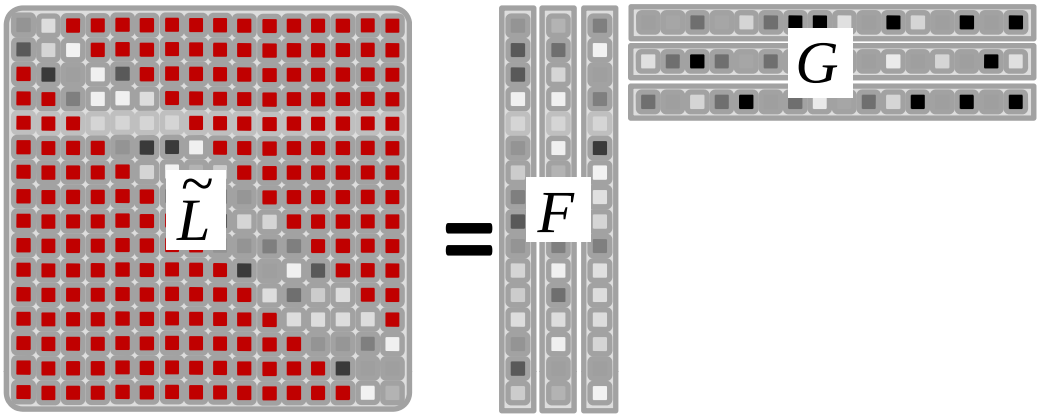




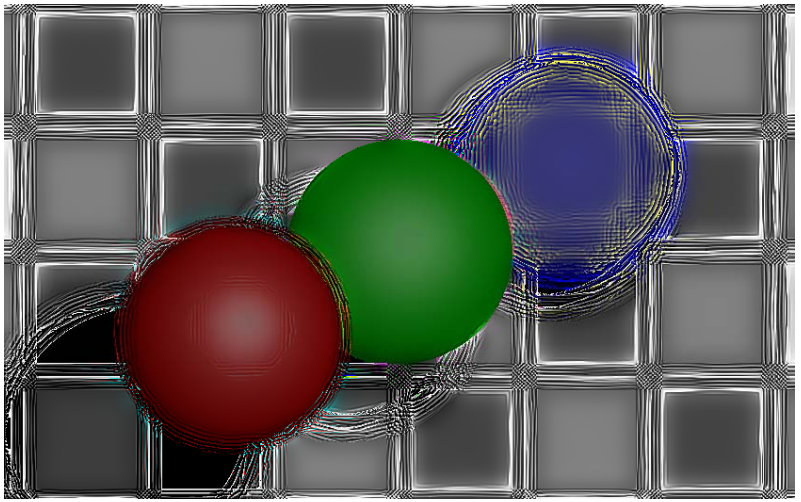
$$L[i,k] = f[i] \cdot g[k]$$

$$L = f \otimes g$$

Glasses Free 3D using High Rank Displays



$$\arg\min_{F,G} \frac{1}{2}\left\|L - FG\right\|_W^2, \text{ for } F, G \geq 0$$



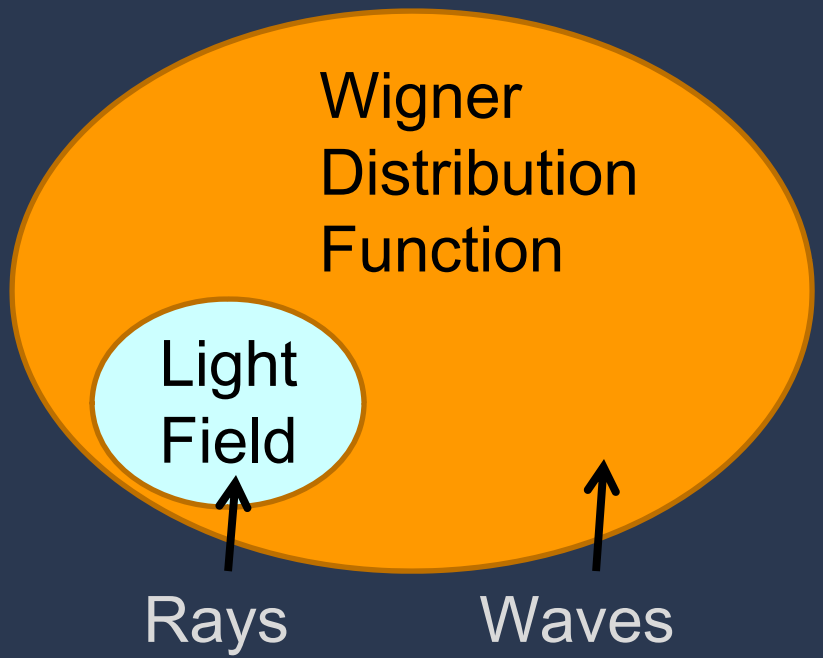
Content-Adaptive Parallax Barriers

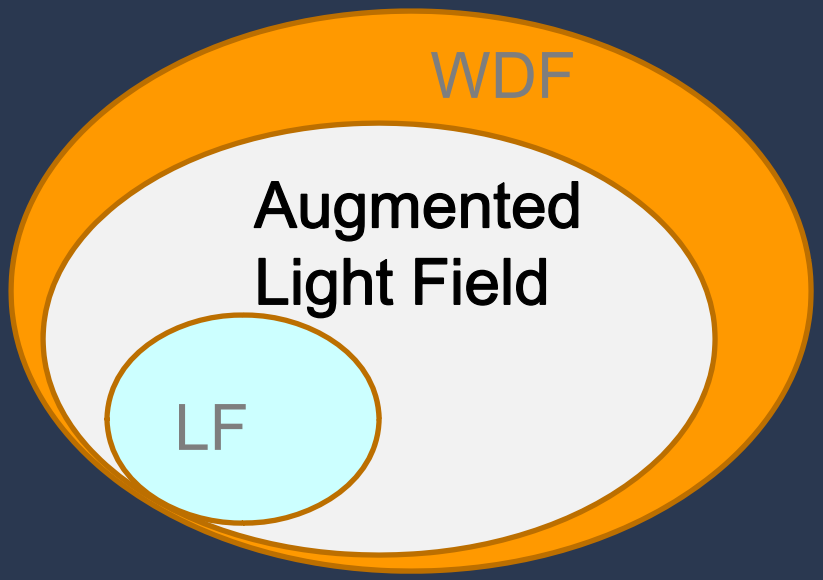
All dual layer display = *rank-1 constraint*

Light field display is a *matrix approximation problem*

Exploit *content-adaptive parallax barriers*

Light Rays vs Waves





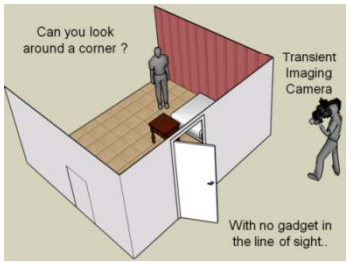
Augmented Light Field

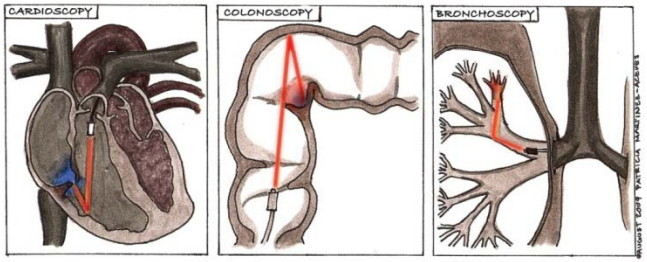
Supports diffraction/interference
Radiance = Positive/Negative

MIT 2008-

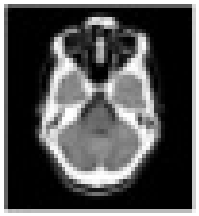
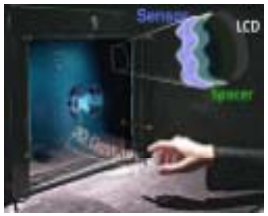
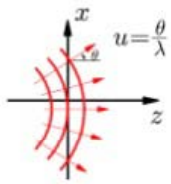
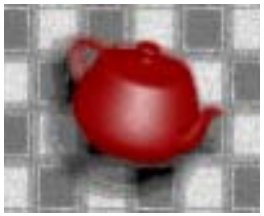
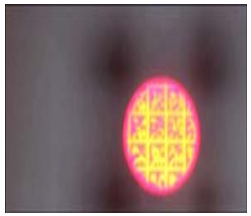
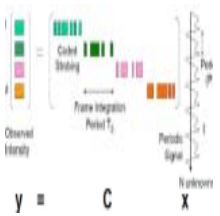
Computational Light Transport

1. Time resolved



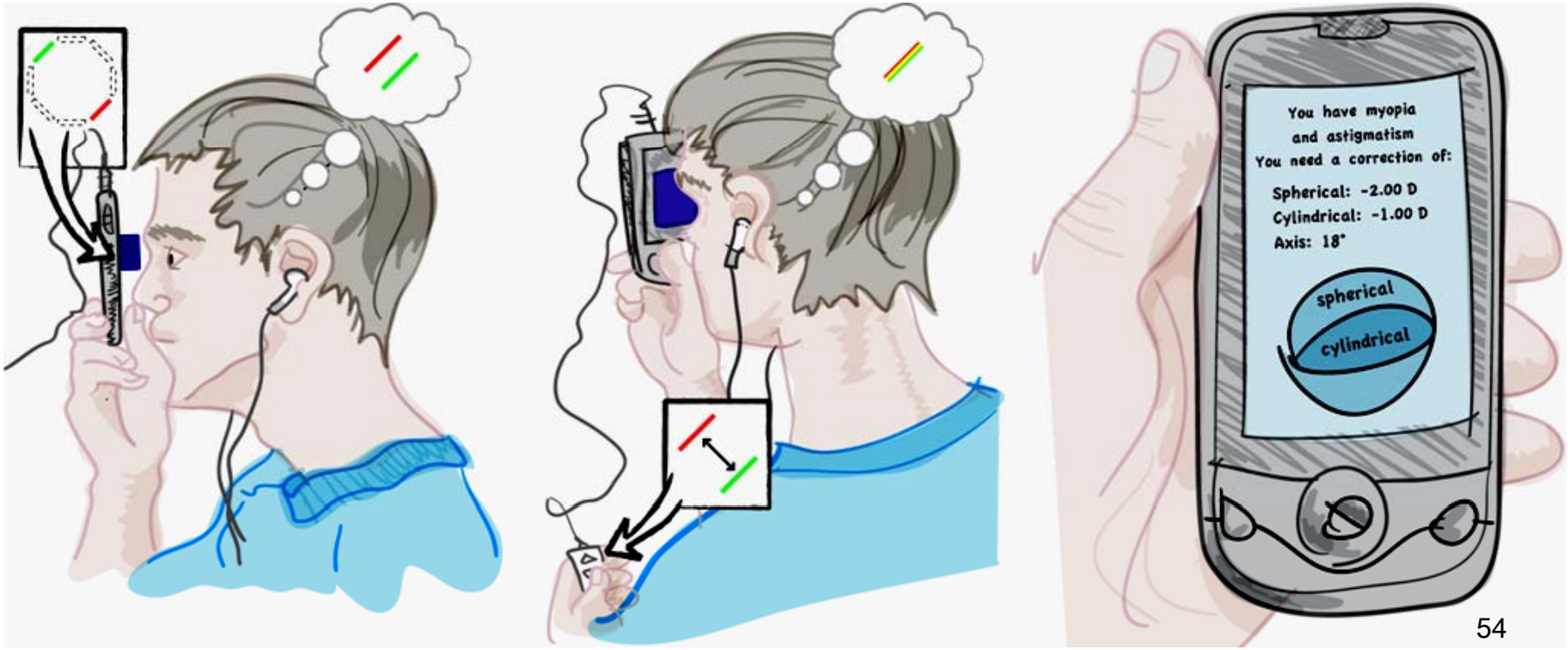


2. Angle resolved

Descattering Analysis	Spatial Heterodyning	Augmented Light Field	Rank-constraint of 3D Displays	Computational Probes	Wavefront Sensing	Compressive Sensing
CAT-Scan without moving parts	BiDi Screen	Geometric + Wave optics	Glasses Free 3D Dual Layer LCD	Bokode	NETRA	Sparsity Analysis
						
2009 -	2008-	2008-	2009 -	2008 -	2010	2009 -

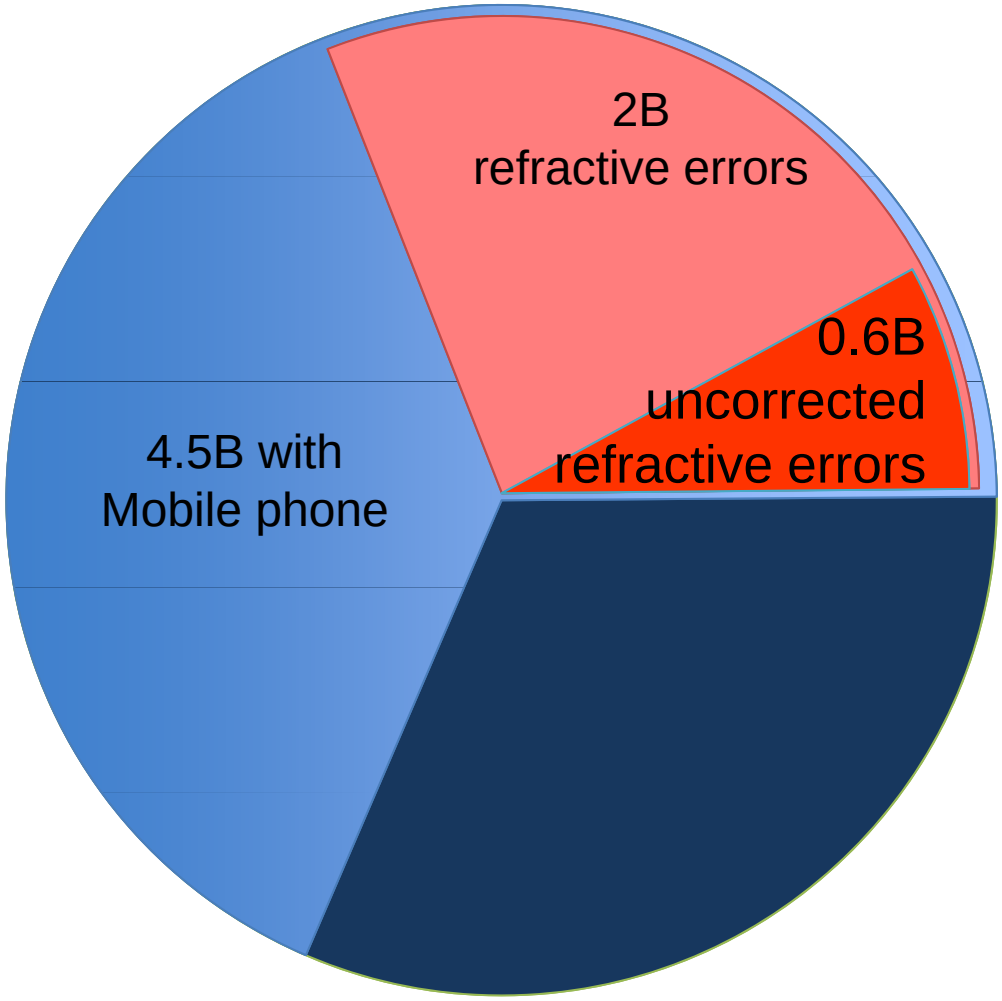
NETRA:
Interactive Display for Estimating Refractive Errors and Focal Range

Vitor Pamplona Ankit Mohan Manuel Oliveira **Ramesh Raskar**



NETRA:
Near **E**ye **T**ool for **R**efractive **A**ssessment

Vitor Pamplona Ankit Mohan Manuel Oliveira Ramesh Raskar



6.5 Billion people

NETRA at
LVP Eye Institute

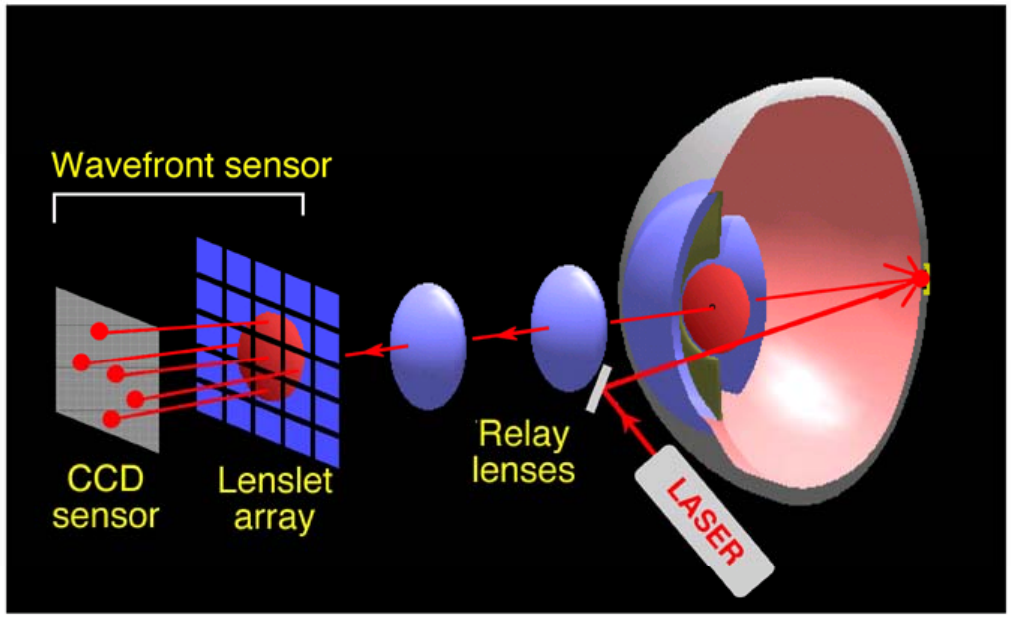
Needs expert, Moving parts, Shining lasers

	Retino scope w/ Lenses	Auto-refracto-meter	Chart with Lenses	In-Focus: Focometer	Optiopia	Solo-health: EyeSite	NETRA
Technology	Shining Light plus lenses	Fundus Camera		Moving lenses + target	Moving lenses + target	Reading chart on monitor	Cellphone + eyepiece
Cost to buy	$2,000*	~$10,000	~$100	~$495	~$200	--	$30
Cost per test	~$36	~$36	~$5	--	--	--	~$1
Data capture	No	Comp.	No	No	No	Comp.	Phone
Mobility	<500g	>10Kg	2kg	1kg	<5kg	>10Kg	<100g
Speed	Fast	Fast	Medium	Medium	--	Fast	Fast
Scalability	No	No	No	Yes	Probably	No	Yes
Accuracy	0.15	0.15	0.5	0.75	--	--	<0.5
Self evaluation	No	No	Yes	Yes	Yes	Yes	Yes
Electricity Req	No	Yes	No	No	--	Yes	No
Astigmatism	Yes	Yes	Yes/No	No	--	Yes	Yes
Network	No	Yes	No	No	No	Yes	Yes
Training	High	High	High	Medium	Medium	Low	Low

* Phoropter-based: $5,000.00

Shack-Hartmann Wavefront Sensor

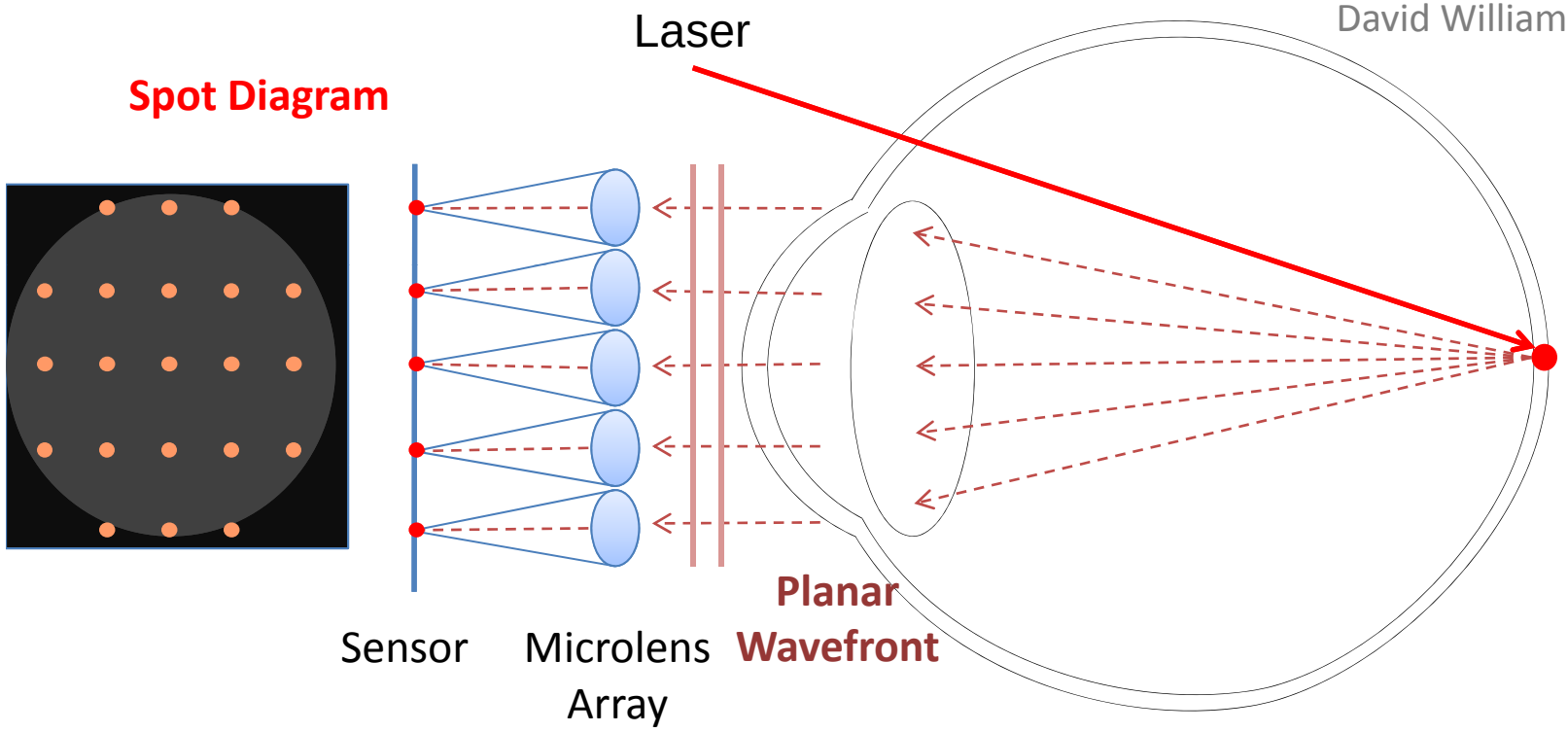
Wavefront aberrometer



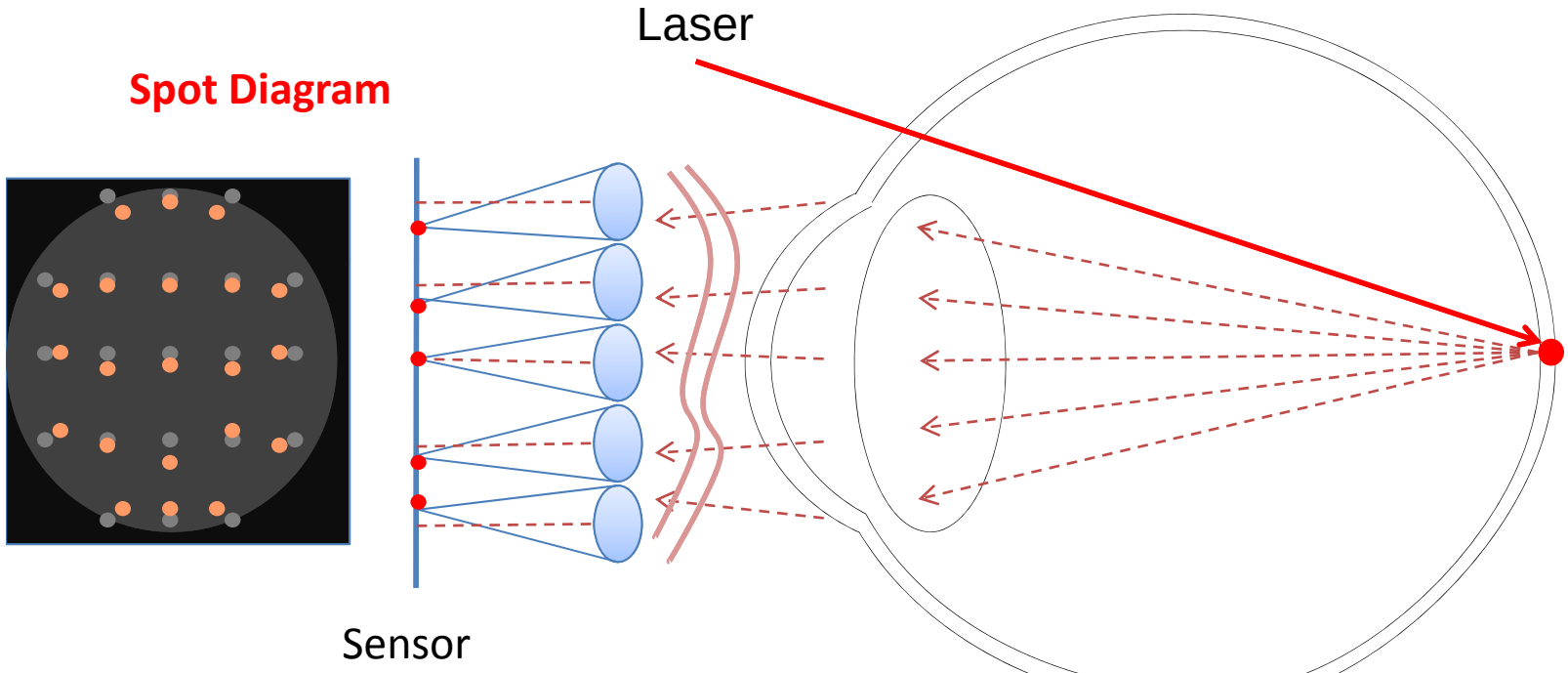
Expensive; Bulky, Requires trained professionals

Shack-Hartmann Wavefront Sensor

Shack & Platt 1971
Liang et al 1994
David Williams et al, Rochester



Shack-Hartmann Wavefront Sensor



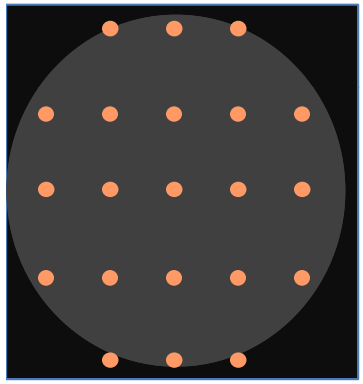
Displacement =
Local Slope
of the Wavefront

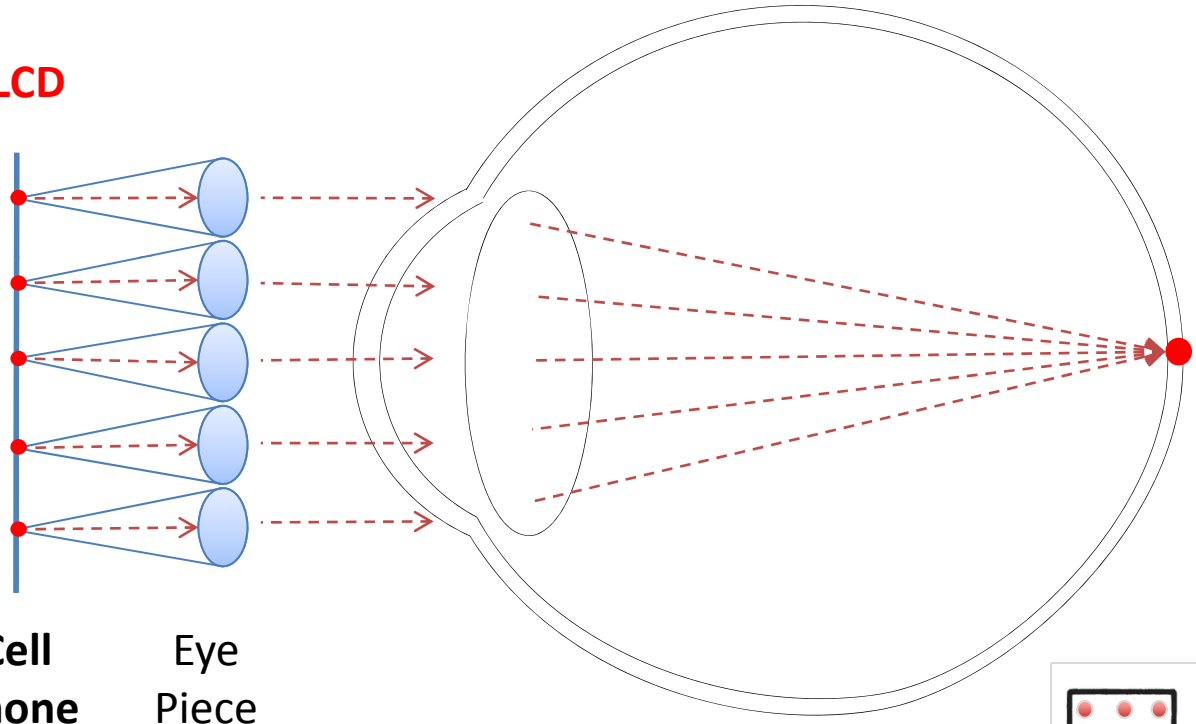
Shack-Hartmann ~ Lightfields

Oh, Raskar, Barbastathis 2009: Augmented Light Field

NETRA = **Inverse** of Shack-Hartmann

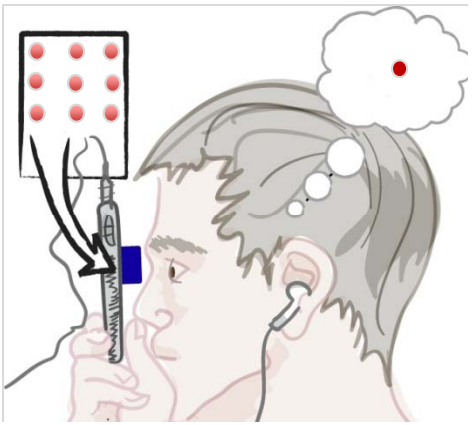
Spot Diagram on LCD





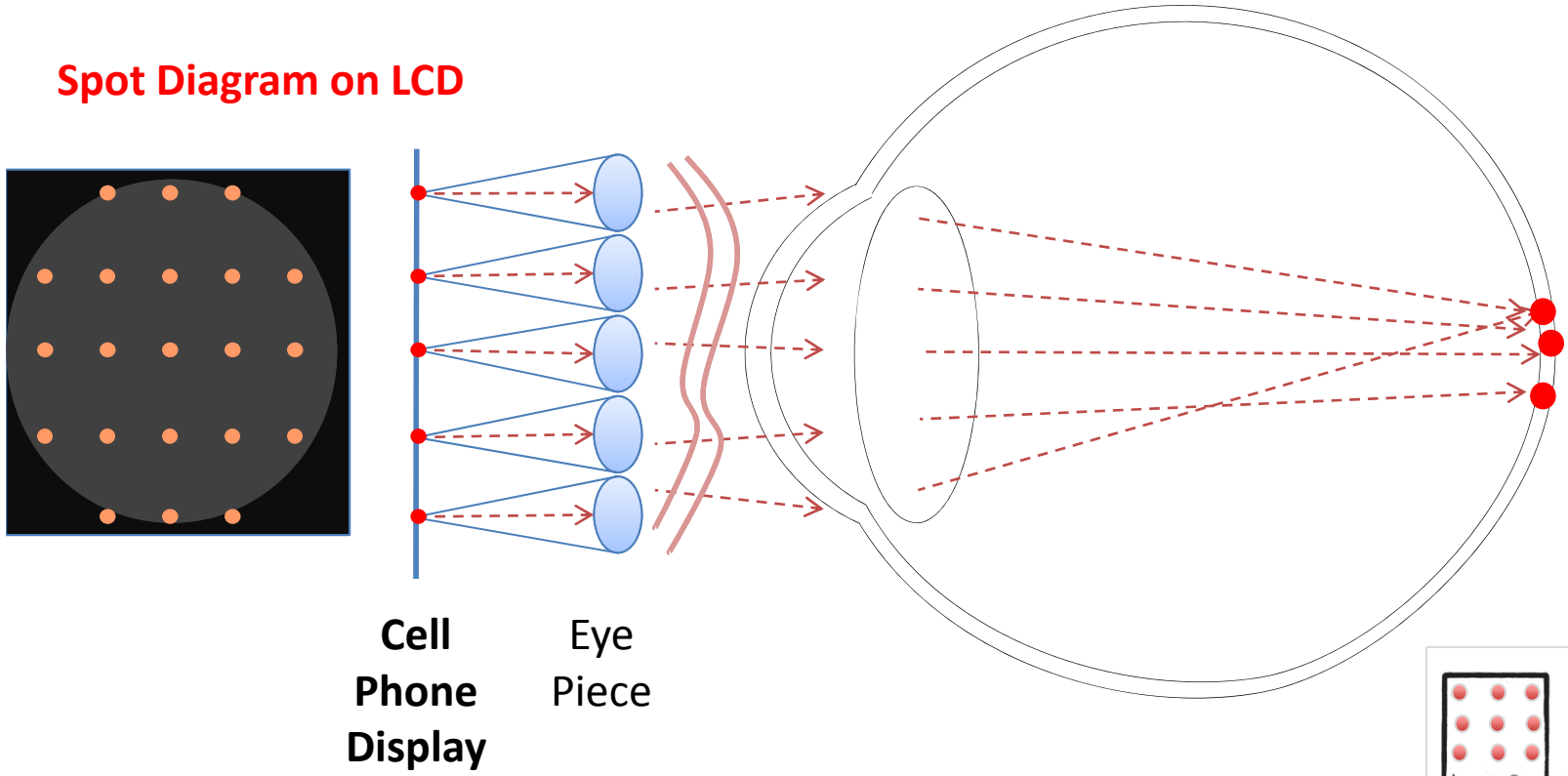
Cell Phone Display

Eye Piece



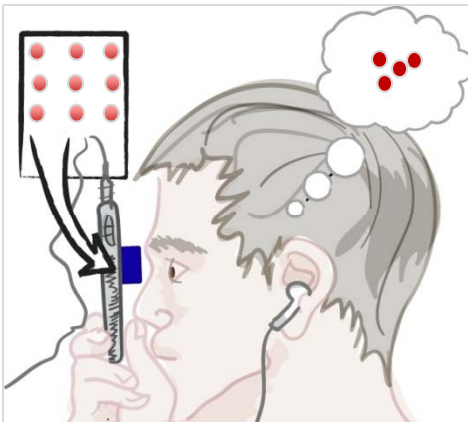
NETRA = **Inverse** of Shack-Hartmann

Spot Diagram on LCD



Cell Phone Display

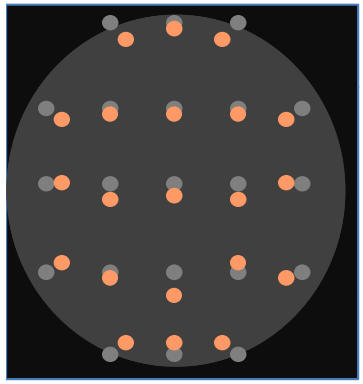
Eye Piece

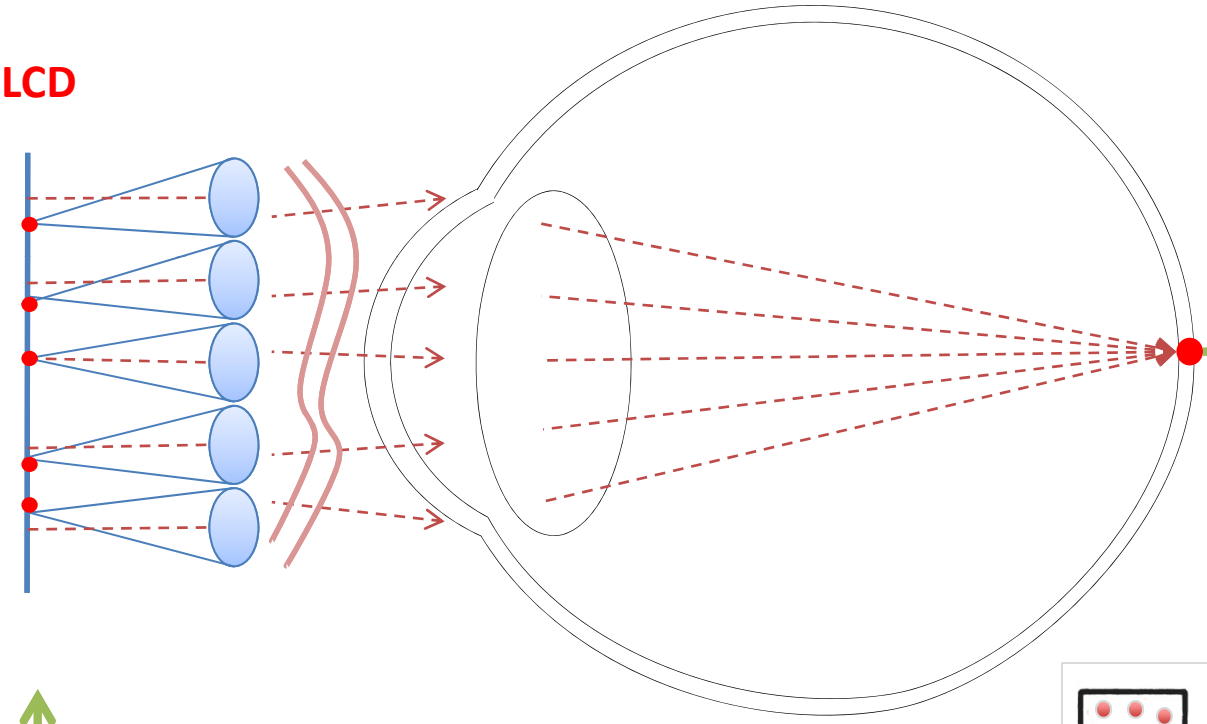


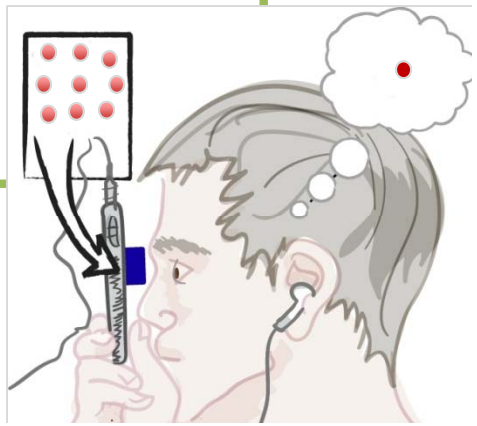
Inverse of Shack-Hartmann

User interactively creates the Spot Diagram

Spot Diagram on LCD





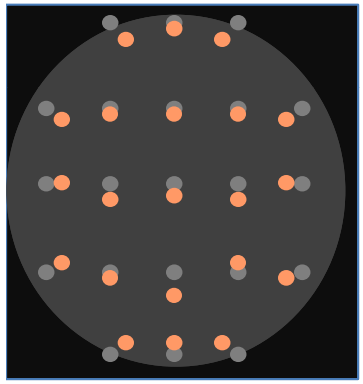


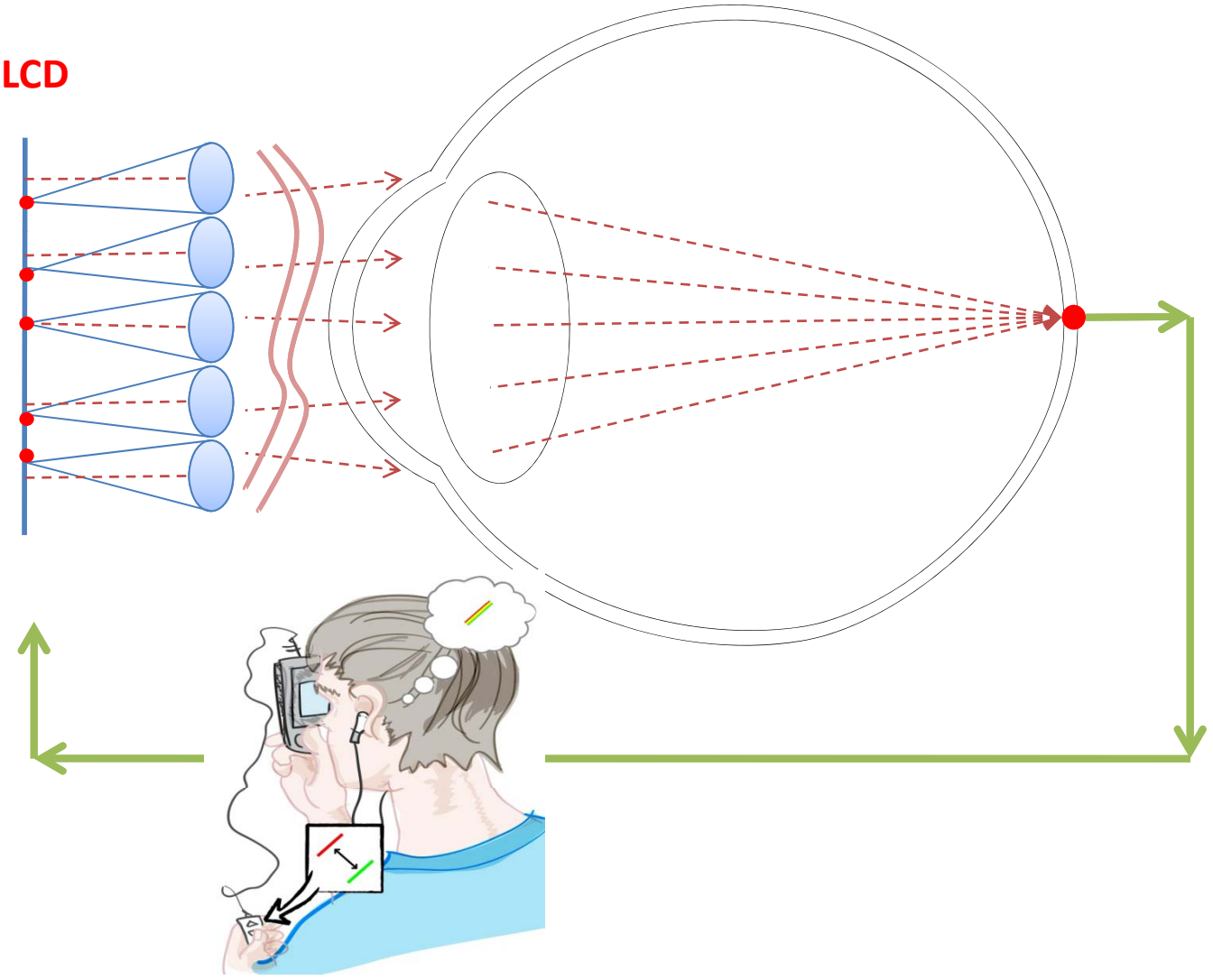
Displace 25 points with smart UI

Inverse of Shack-Hartmann

User interactively creates the Spot Diagram

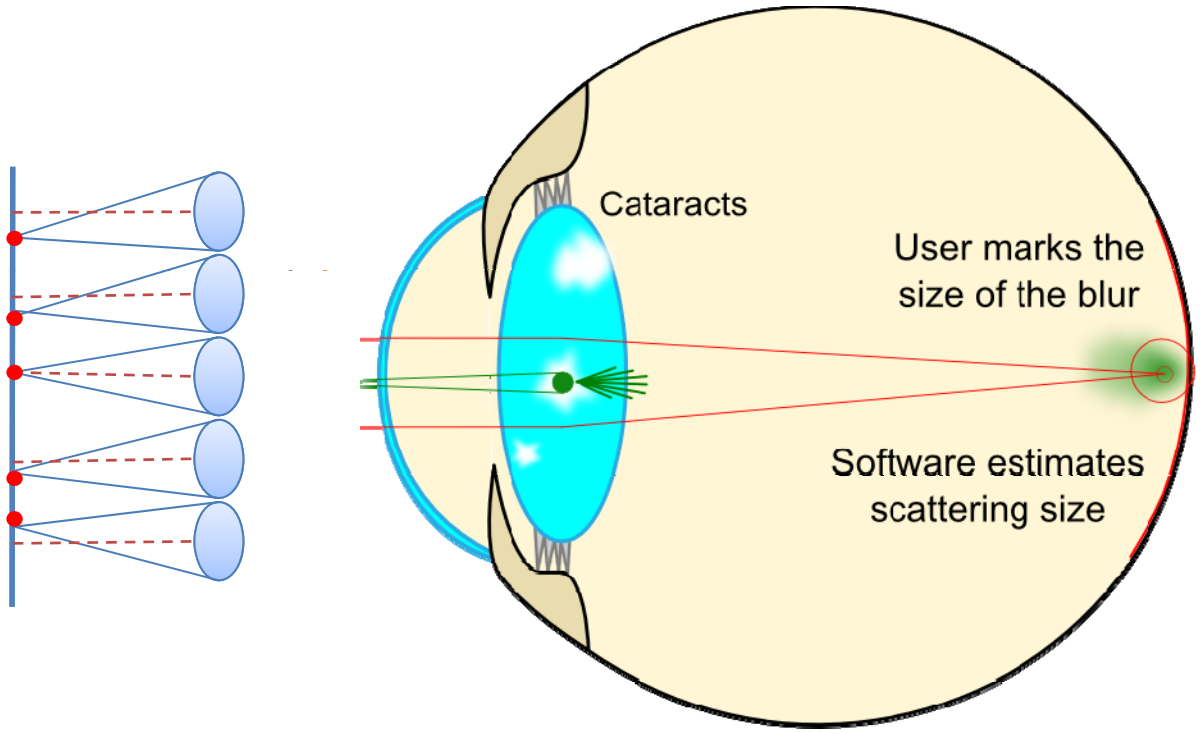
Spot Diagram on LCD





Displace 25 points but **3 parameters**

Cataract screening using inverse Shack-Hartmann



Under review 2011

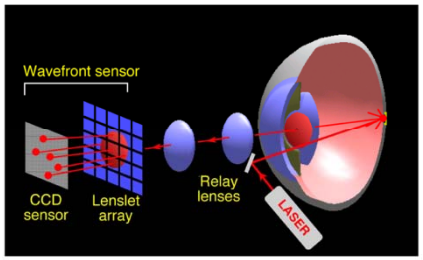
Limitations

- Ability to align lines
  - Children
  - Retinal conditions
  - Accomodation cues

- Resolution is a function of the display DPI
  - Samsung Behold II – 160 DPI – 0.35D
  - Google Nexus One – 250 DPI – 0.2D
  - Apple iPhone 4G – 326 DPI – 0.14D

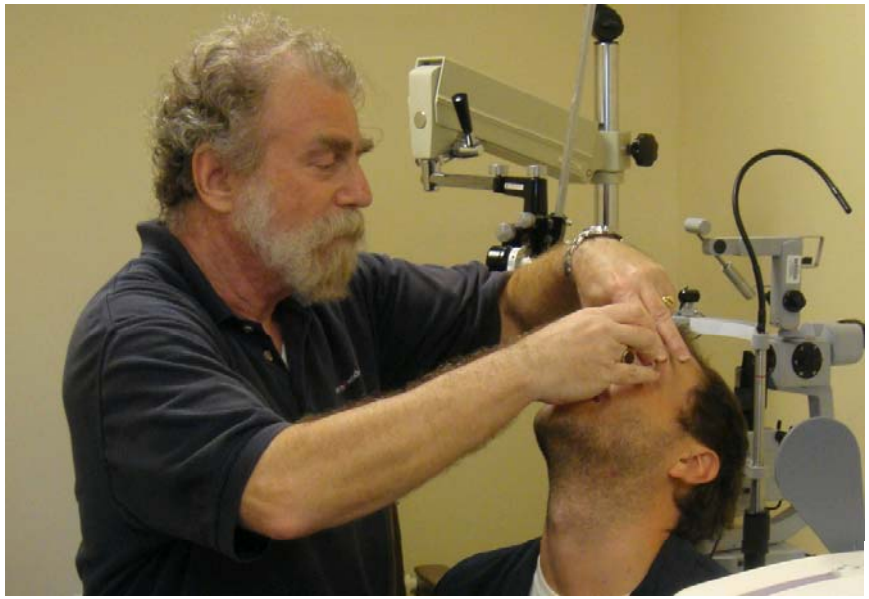
NETRA: Refraction + Cataract Tests

- Inverse of Shack-Hartmann wavefront aberrometer
  - High-resolution displays and user interaction
  - No lasers, moving parts
  - Trials in progress
  - Hardware app store



- Parameters
  - Myopia, Hyperopia, Astigmatism
  - Cataract, Lazy eye

- Impact in Developing Countries
  - 600 Million without corrective glasses
  - $1 cost, easy to deploy, free s/w, see **EyeNetra.com**



THE NEW ENGLAND COLLEGE OF OPTOMETRY
visus per mentem
18 94

D'AMBROSIO Eye Care INC.

Tufts Medical Center

LVPEI
So that all may see
L V Prasad Eye Institute

Clinical Testing Partners


NETRA in a dozen+ countries

Awards

- MIT IDEAS (#2 award)
- Deshpande Ignition Grant
- MIT 100K (dev finalist)
- Google + (L Page)
- Vodafone Foundation (finalist)

Selection

- NASA/USAID Innovators
- Worldbank Social Health Inventions
- International Space Station evaluation

Validation

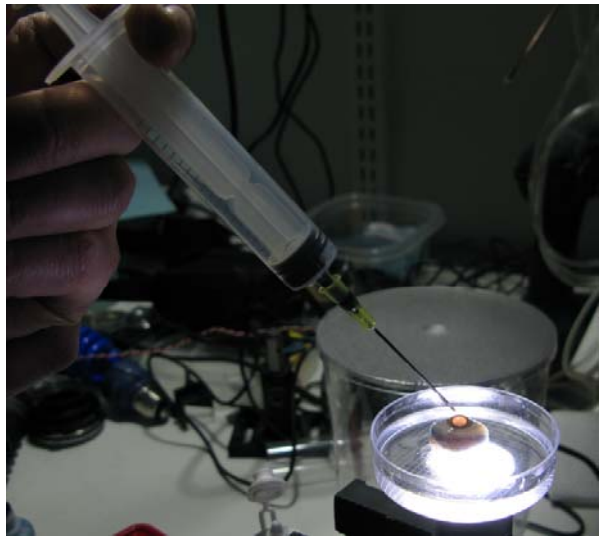
- 0.09 D : objective precision
- ~ 0.5 D: subjective trials
- 0.3 D: IRB approved wet-studies (Prelim data)

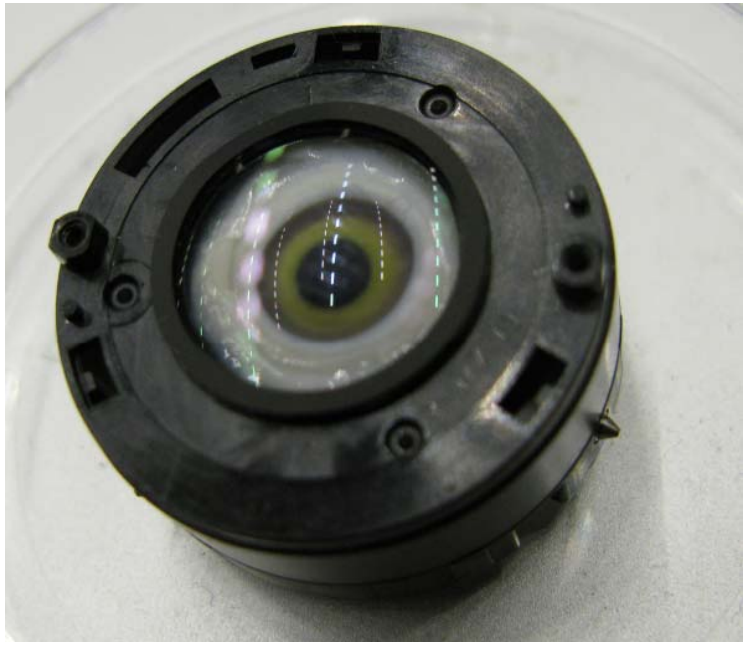
Papers

- SIGGRAPH
- Frontiers in Optics
- Am Academy of Optometry (AAO)

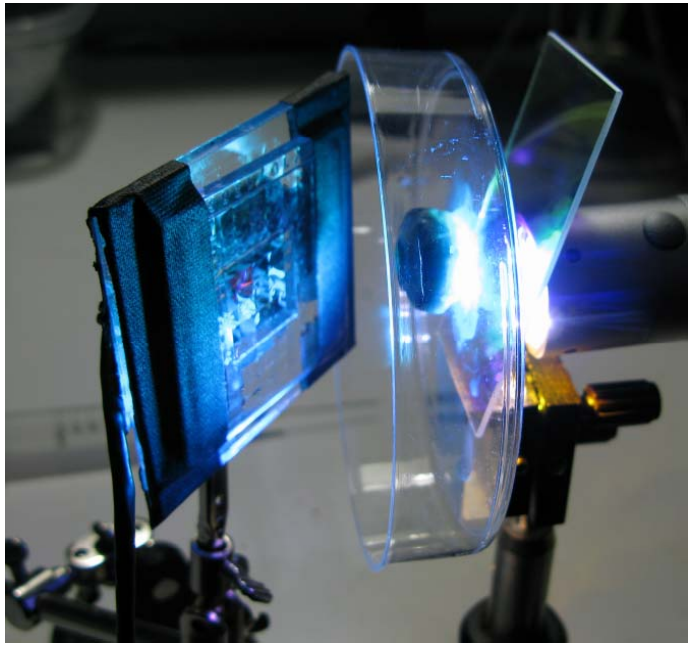
Chicken Eye

Inducing Cataract





‘Lens’



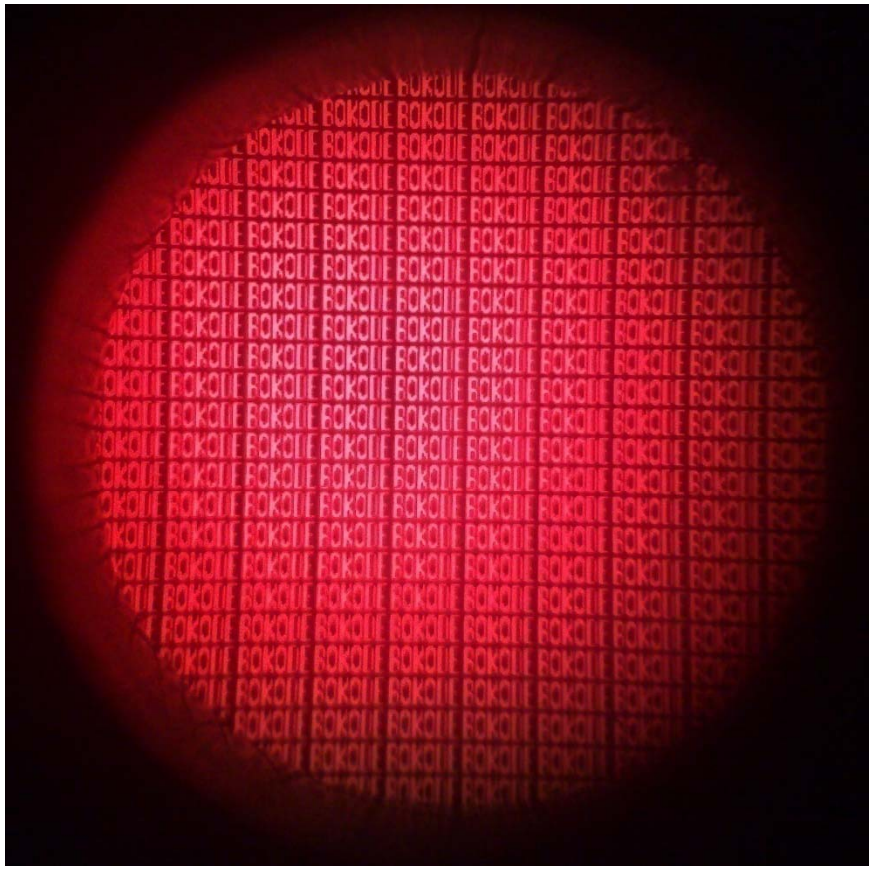
Imaging CCD

Optics: Bokodes = Human Eye
Bokode Capture = Retinal Imaging

cell-phone camera

close to the Bokode

(10,000+ bytes of data)



Like a Retinal Image


Eye = Mirror of Health
Yoon Lab, U of Rochester

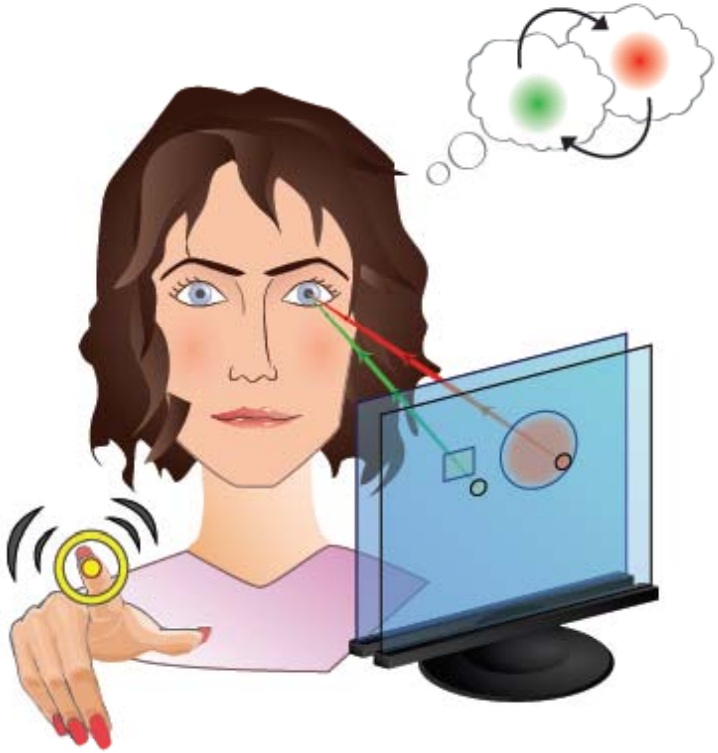
Slit Lamp Exam

Retinal Scan

Ocular Manifestation: Leading Indicator?

Traditional

User Driven



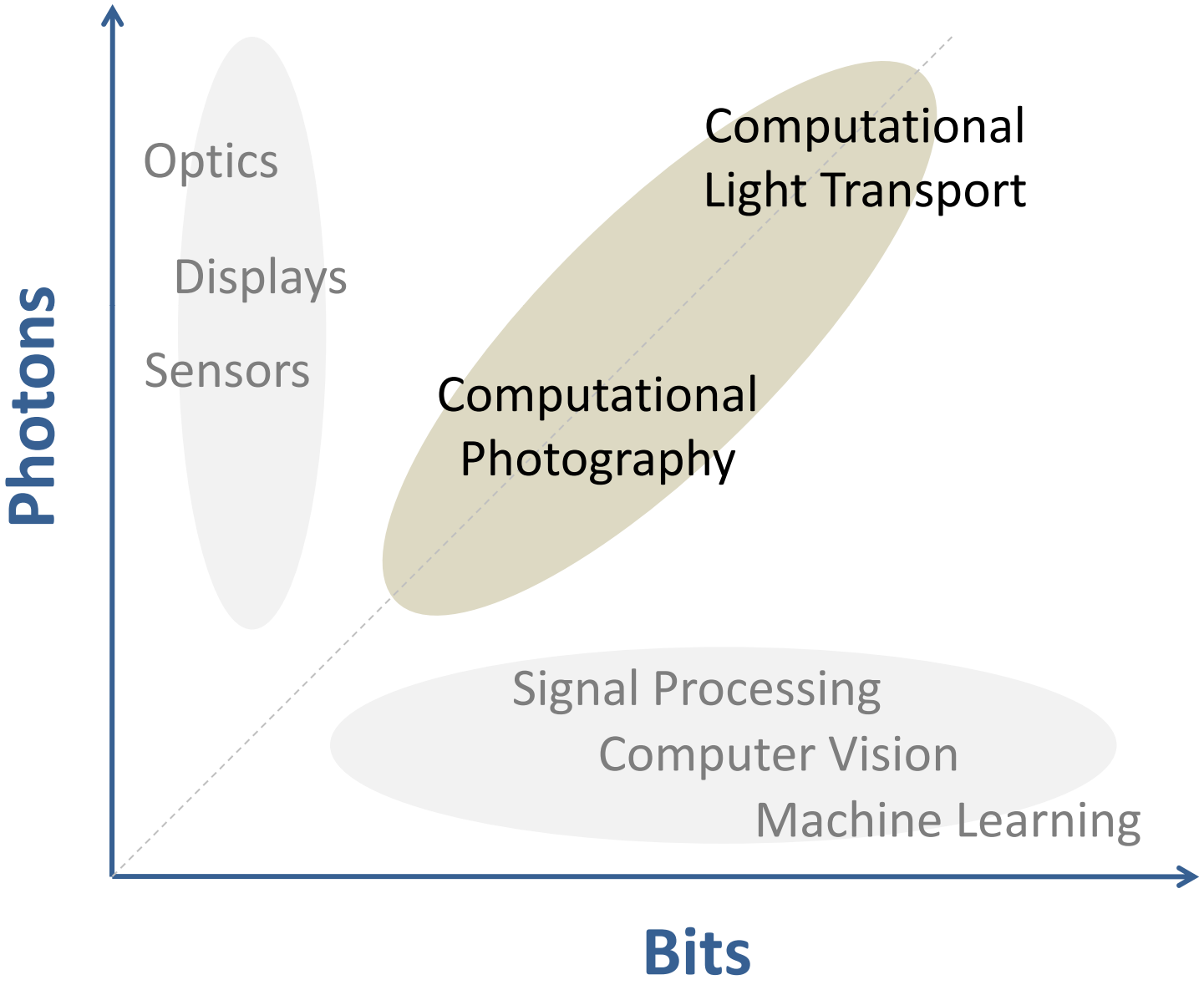
Mass-use Devices -> Scientific Instruments

Current and Former Members

- Post-docs
  - Ankit Mohan
  - Andreas Velten
  - Douglas Lanman
  - Yunhee Kim
- RAs
  - Andy Bardagjy
  - Kevin Chiu
  - Matthew Hirsch (w Holtzman)
  - Roarke Horstmeyer
  - Otkrist Gupta
  - Ahmed Kirmani
  - Jaewon Kim
  - Nikhil Naik
  - Rohit Pandharkar
- MEng
  - Tyler Hutchison
  - Sharmeen Browarek
  - Dennis Miaw
- Visitors
  - Vitor Pamplona
  - Abhijit Bendale
  - Erick Passos
  - Behzad Sajjadi
  - Gordon Wetzstein
  - Matthias Hullin

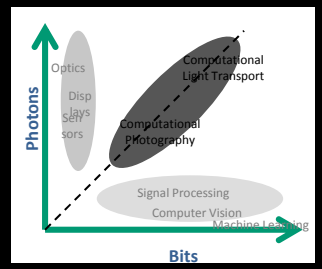
- Daniel Saakes
- Grace Woo
- Tom Cuypers
- Manuel Oliviera
- Shinsaku Hiura
- Yasuhiro Mukaigawa

Codesigning Optical and Digital Processing

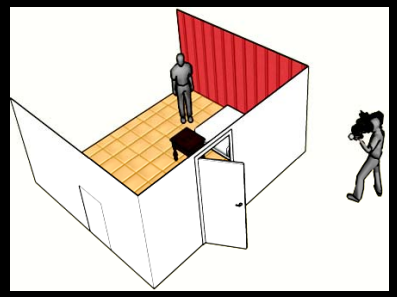


Computational Light Transport

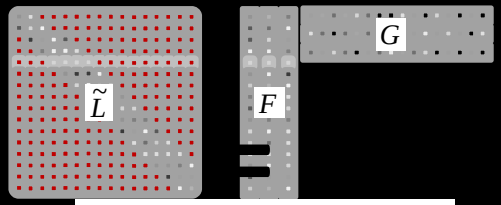
- Super-human visual abilities
- Empirical, Multi-directional rather than one narrow field
- Fusion of dissimilar



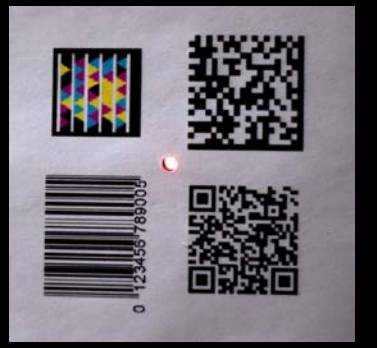
- New Fields
  - Femto-photography
  - Dream Augmentation, Image IP



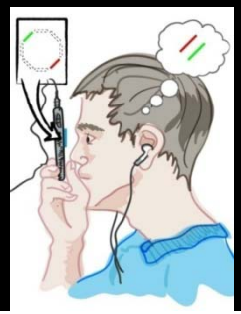
- New Insights
  - Challenge the status quo
  - BiDi Screen, CAT-scan, Augmented LF
  - Sparsity, rank, priors



$$\arg\min_{F,G} \frac{1}{2}\|L - FG\|_W^2, \text{ for } F, G \geq 0$$



- New Purpose
  - Disruptive mass-use tech for social impact
  - Netra, Cataract, Retinal scans
  - $1M -> $1



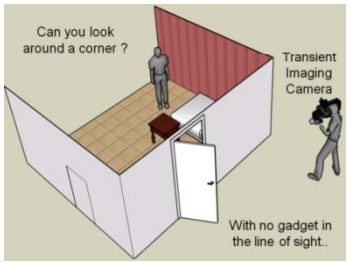
Cameras, Displays, Medical Tools, Future Devices

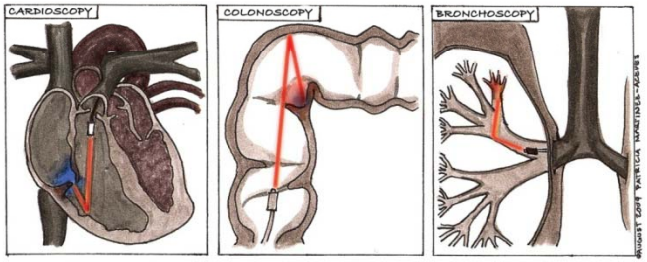
- Theory, Modeling, Optical+Mathematical insight

Media Lab 2008-

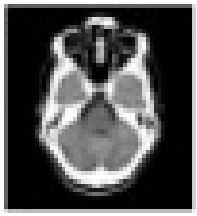
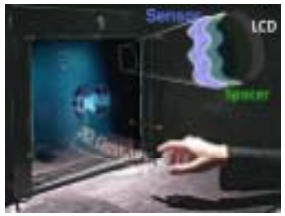
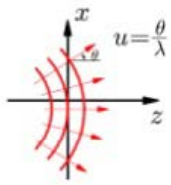
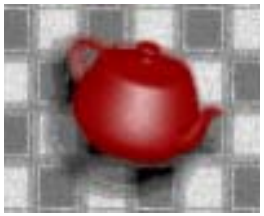
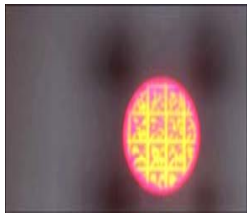
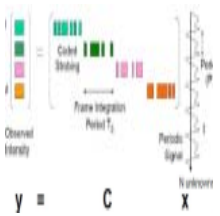
Computational Light Transport

1. Time resolved





2. Angle resolved

Descattering Analysis	Spatial Heterodyning	Augmented Light Field	Rank-constraint of 3D Displays	Computational Probes	Wavefront Sensing	Compressive Sensing
CAT-Scan without moving parts	BiDi Screen	Geometric + Wave optics	Glasses Free 3D	Bokode	NETRA	Sparsity Analysis
						
2009 -	2007-	2008-	2009 -	2008 -	2010	2009 -