Simulation technologies for image systems engineering and biology

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Wu Tsai Neurosciences Institute
Stanford Center for Cognitive and Neurobiological Imaging

QUANTITATIVE MEASUREMENTS

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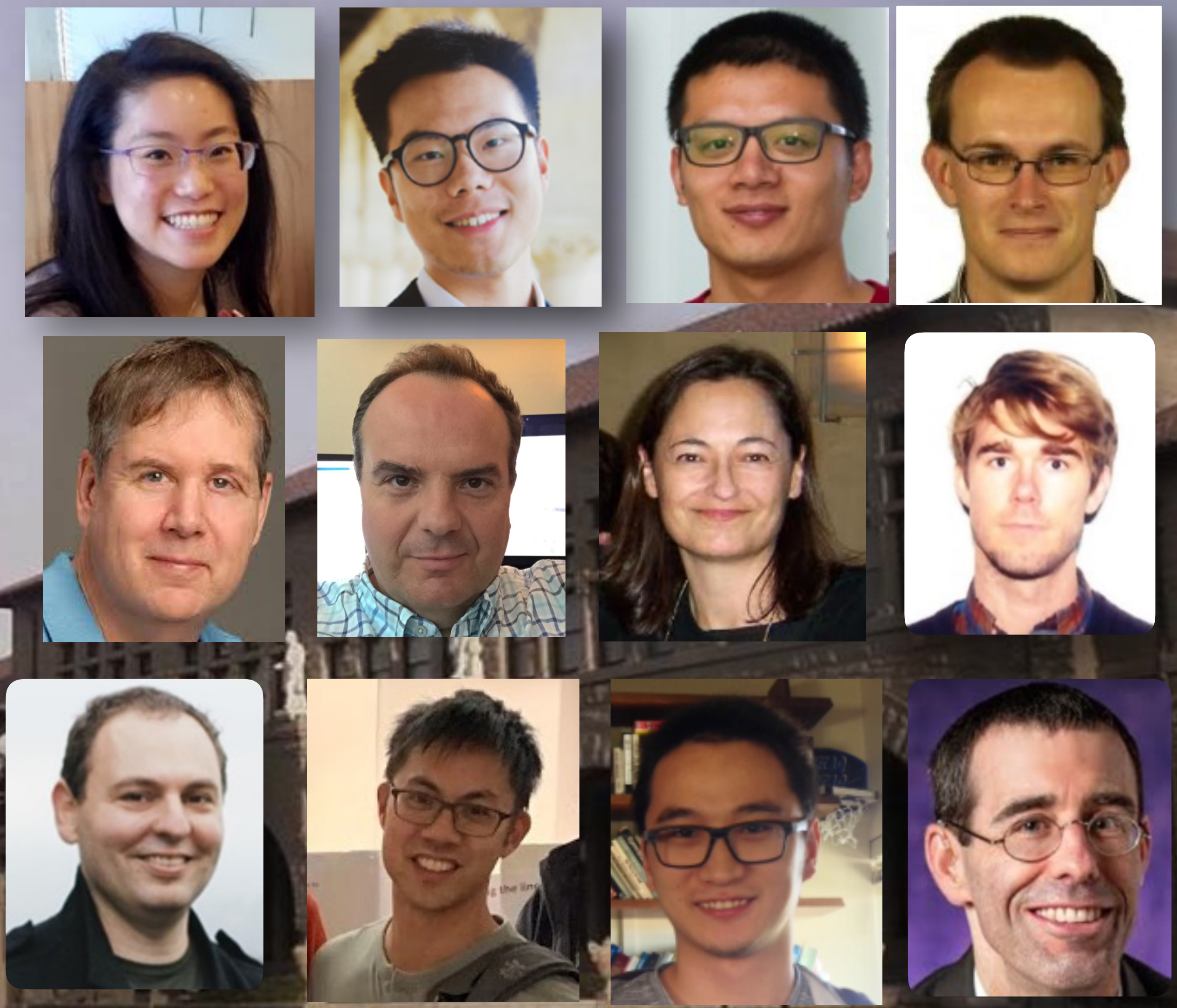
COMPUTATIONAL MODELS

∞

CHECK AND SHARE

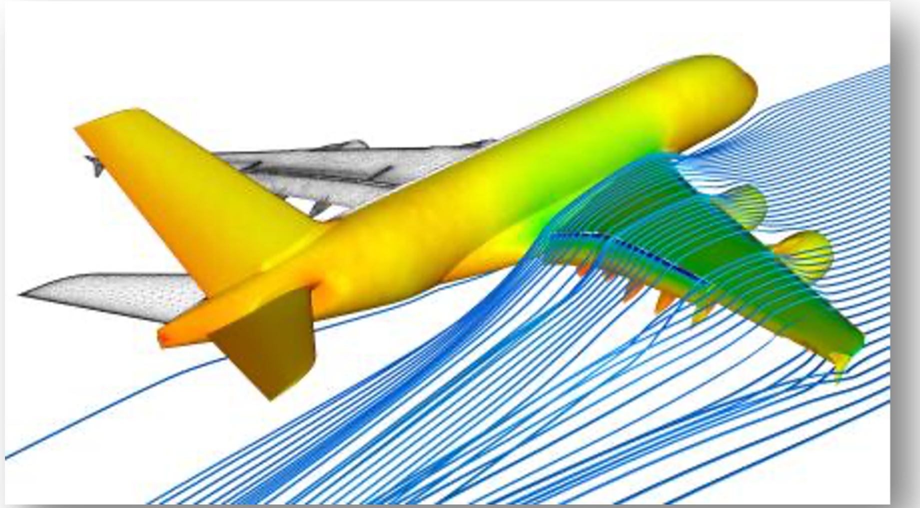


Supported by the Simons Foundation, Facebook research

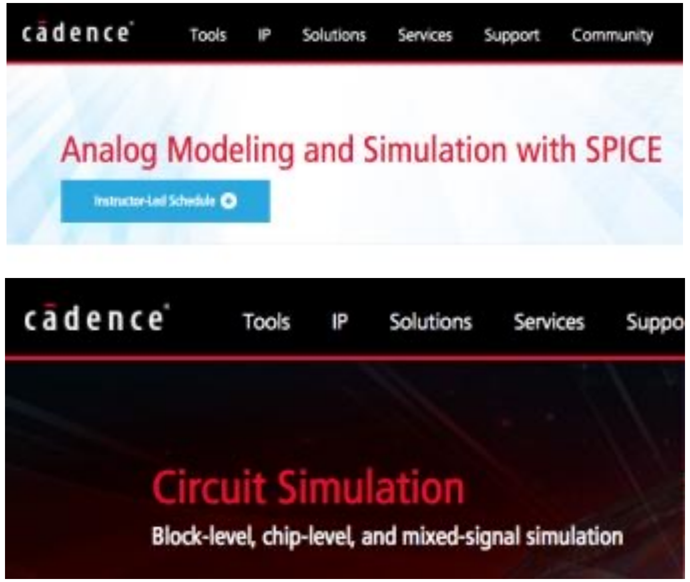
Image systems simulation

System simulation is important in many mature industries

ECU (Electronic Control Unit) Simulation for Automobiles



Numerical flow simulation on an Airbus A380



Integrated circuitry

Imaging technology is bursting with innovation

Camera Phone Image Quality
December 7, 2006

High Dynamic Range Imaging
September 10, 2009 to September 11, 2009

Mobile Visual Search
December 3, 2009

3D Imaging
January 27, 2011 to January 28, 2011

The Stanford Symposium on Biomedical Imaging
April 5, 2012 to April 6, 2012

Entertainment Technology in the Internet Age (2013)
June 18, 2013 to June 19, 2013

The Workshop on Light Field Imaging: February 12, 2015
February 12, 2015

ETIA 2015 Entertainment in the the Internet Age
June 16, 2015 9:00 am to June 17, 2015 5:15 pm

Workshop on Cinematic VR and Immersive Storytelling
May 19, 2016

Workshop on Medical VR and AR
April 5, 2018

Workshop on the Future of Medical Imaging: Sensing, Learning and Visualization
April 4, 2019 8:30 am to 6:00 pm

Dr. Joyce Farrell

Panel Discussions

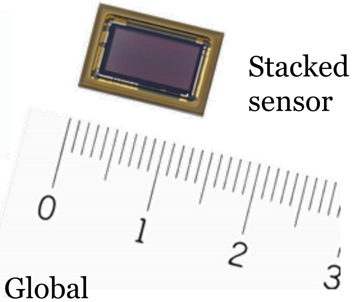
Interactive demos
Research projects, clinical applications and startup

Imaging industry innovates frequently call on informal simulations

- Informal simulations occur routinely in the imaging industry
- Software development is usually custom, in-house

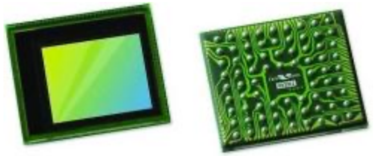


Multiple lens



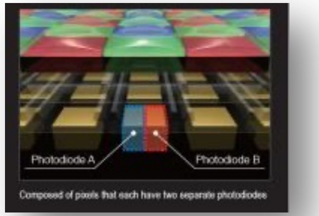
Stacked sensor

Global shutter



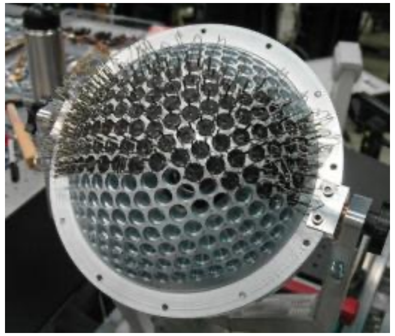
RGB-depth


Dual pixel autofocus



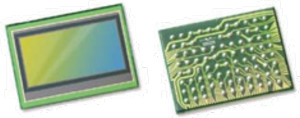
Light field

360 Surround Video



Massive resolution

RCCC automotive



We developed imaging systems simulation (ISETCam) in response to requests

Image Systems Engineering Toolbox for cameras (**ISETCam**)

- End-to-end simulation (radiance to sensor)
  - Physical units (photons to electrons)

Optics

Sensor

Display

Imaging Systems Engineering Toolbox (ISETCam)

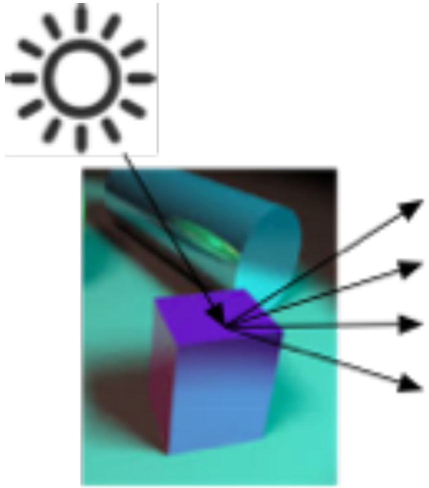
More than 500 users in
80 companies,
9 research institutes,
65 universities,
in 24 countries

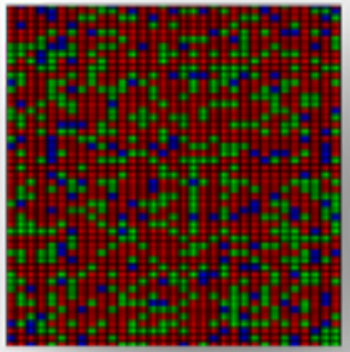
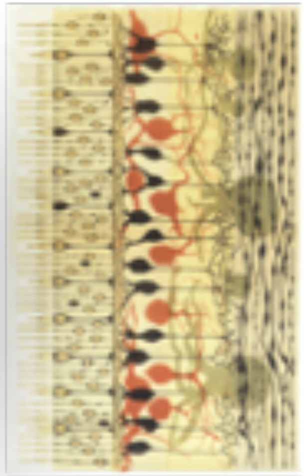
Open Sourced on GitHub
in 2018

First point

Image systems simulation software that is trusted by key stakeholders in industry and academia can speed the development of next generation image sensors, camera arrays and displays.

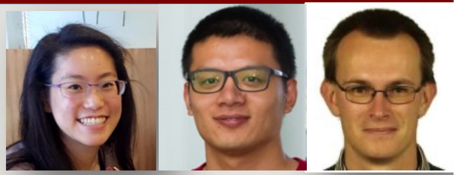
From image systems engineering for cameras to image systems for biology




- ISET3D – Modeling scenes and optics
- ISETCam (camera design)
  - Auto, Depth, Ideal, Fluorescence
- ISET3D: Human eye models (Lian)
- ISETBio: The CSF computational observer (Cottaris)

ISET3D: Modeling the input scene (spectral radiance)



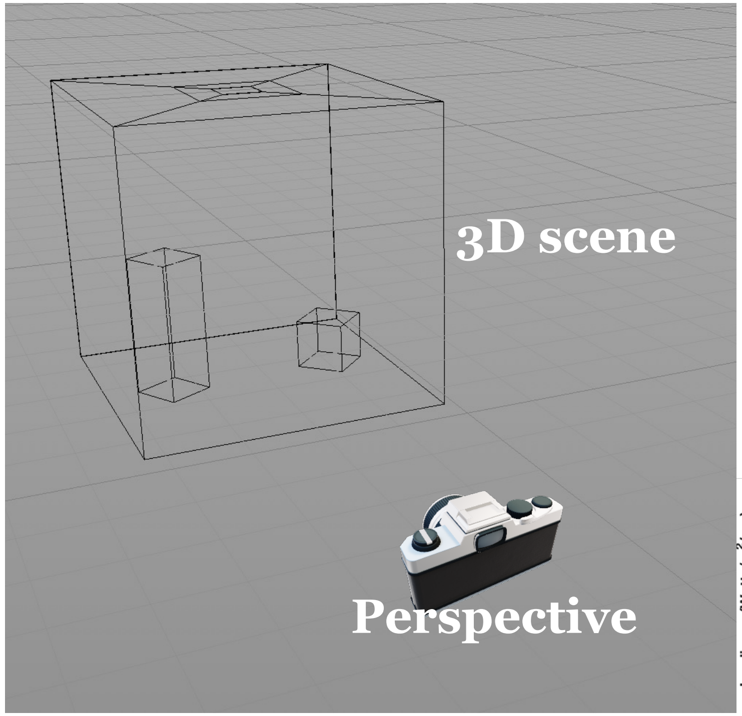
Simulated scene

- **What:** ISET3d is a toolbox that extends the range of ISETBio and ISETCam inputs from planar images to three-dimensional scenes.

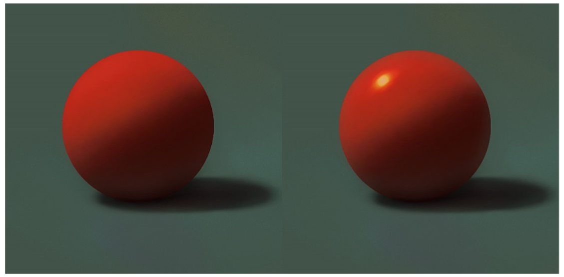
- **Why:** The extension to 3D is relevant to scientists and engineers who aim to
  - Model and understand the visual encoding of natural images and stereo vision,
  - Optimize devices, including cameras and displays, for capturing and rendering 3D scenes (such as automotive).

ISET3D in the context of ISETCam and ISETBio

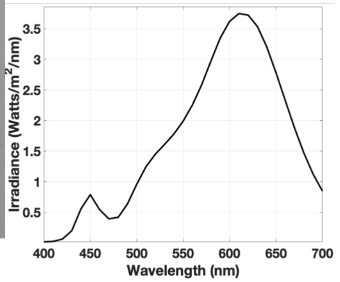
Assets and geometry
Cinema 4D



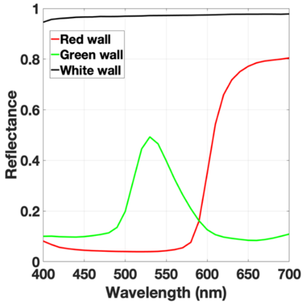
Materials and lights
(ISET3d)



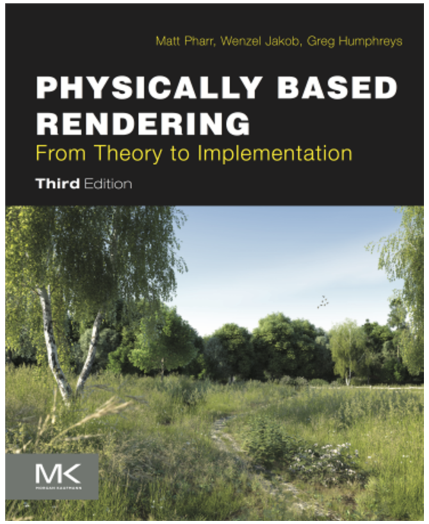
Light
spectral power

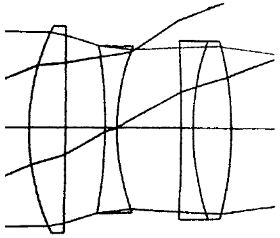


Surface
reflectances

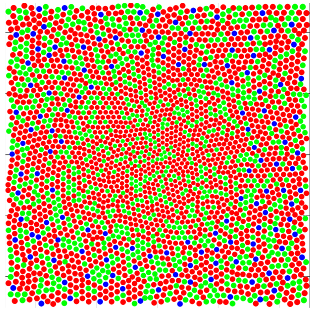


Optics and ray tracing
(PBRT)

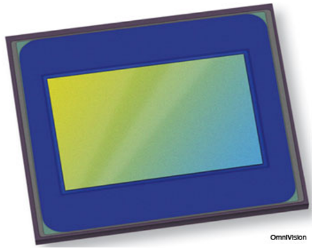




Receiver
(ISETBio or ISETCam)

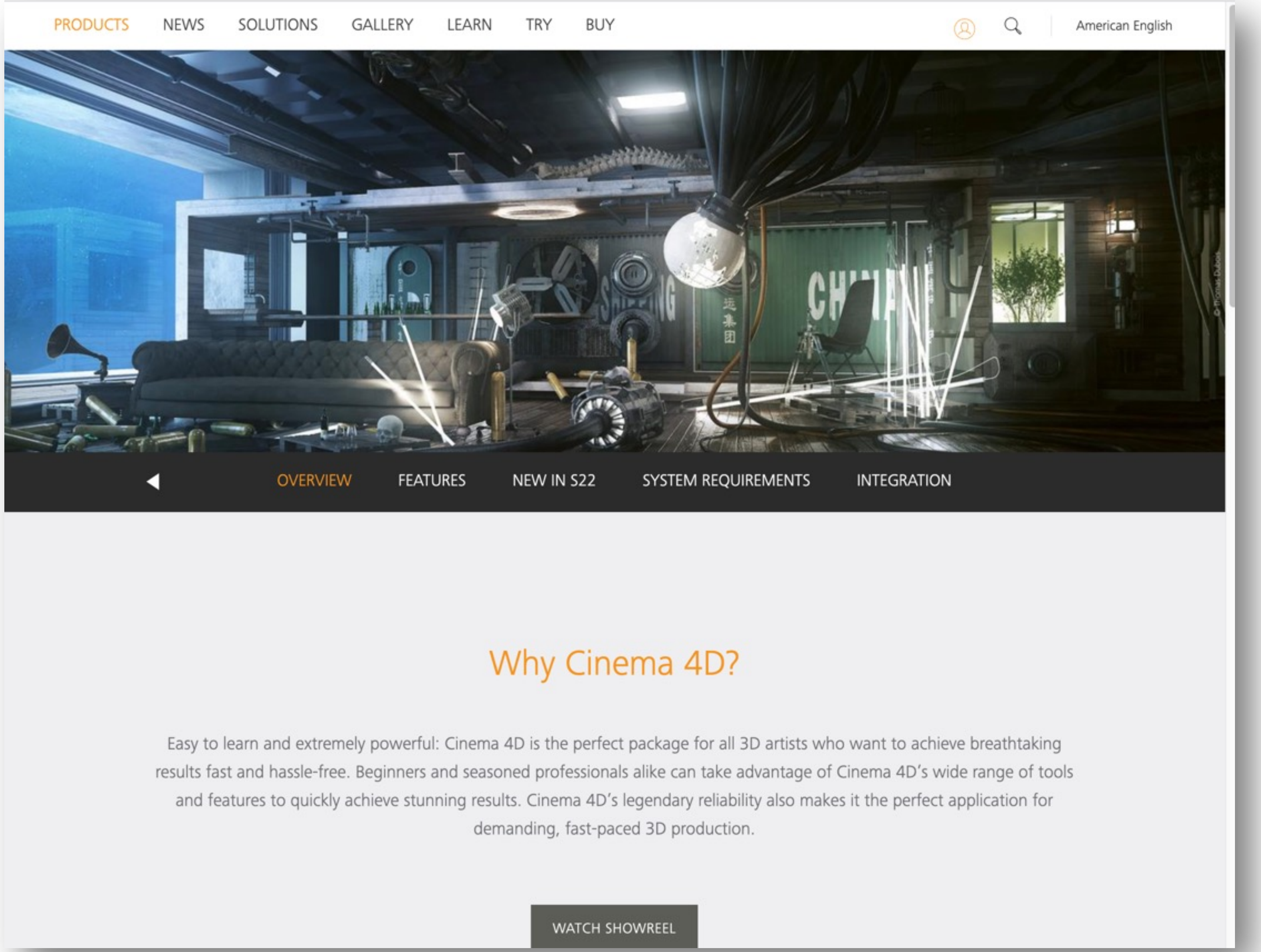


CNNs



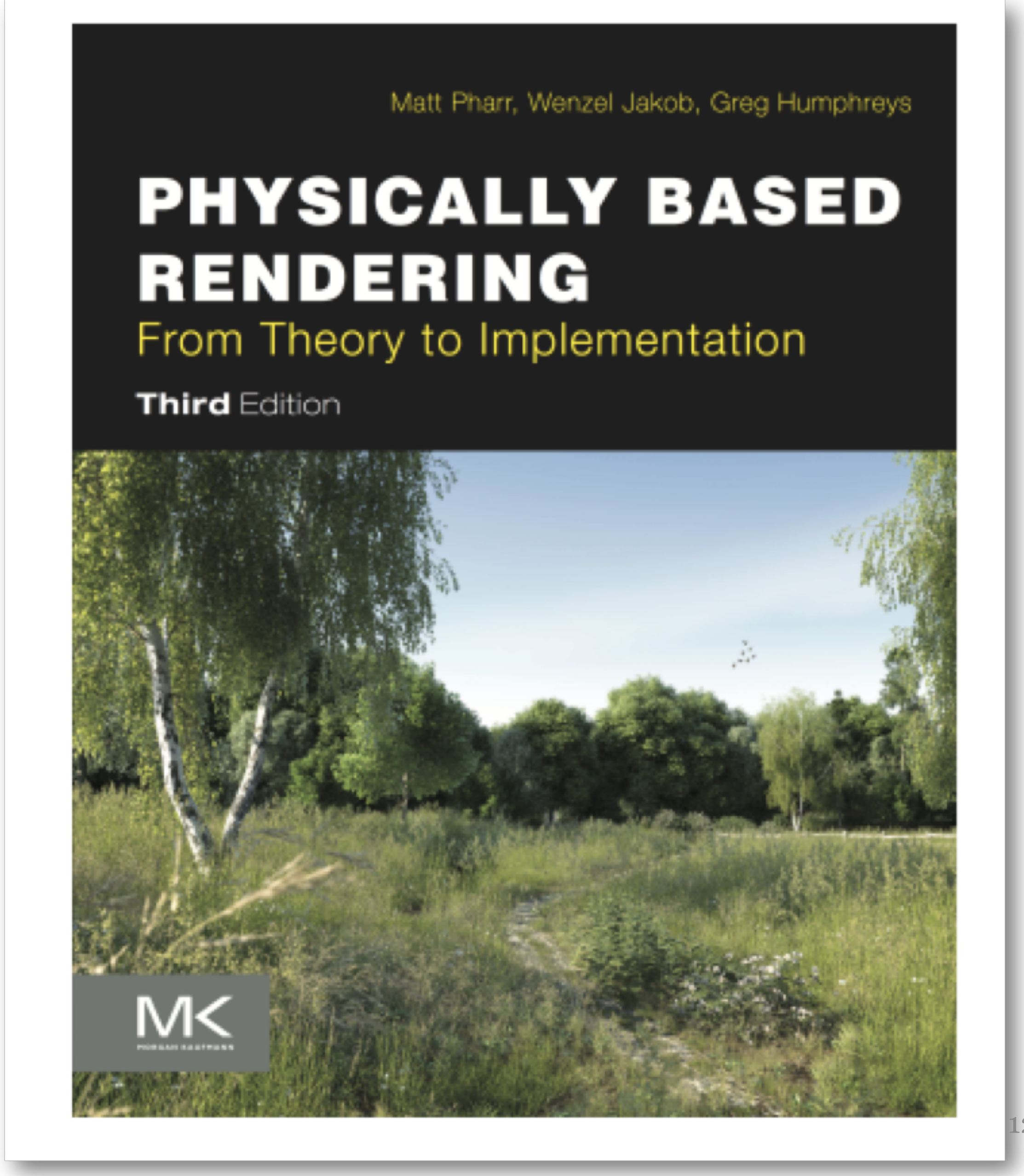
Graphics tools for representing geometry: Cinema 4D and Blender

- There are many tools for creating 3D scene geometries
- We use Cinema 4D and Blender; both integrate well with ray tracing methods
- Maxon offers **free** Cinema 4D licenses to students and teachers, and low- or no-cost "lab" licenses for schools.



Quantitative computer graphics is necessary component for materials and lights

- Progress in computer graphics enables us to create synthetic and yet highly realistic input data.
- We want simulations with meaningful units; quantitative computer graphics
- Open-source and well documented!

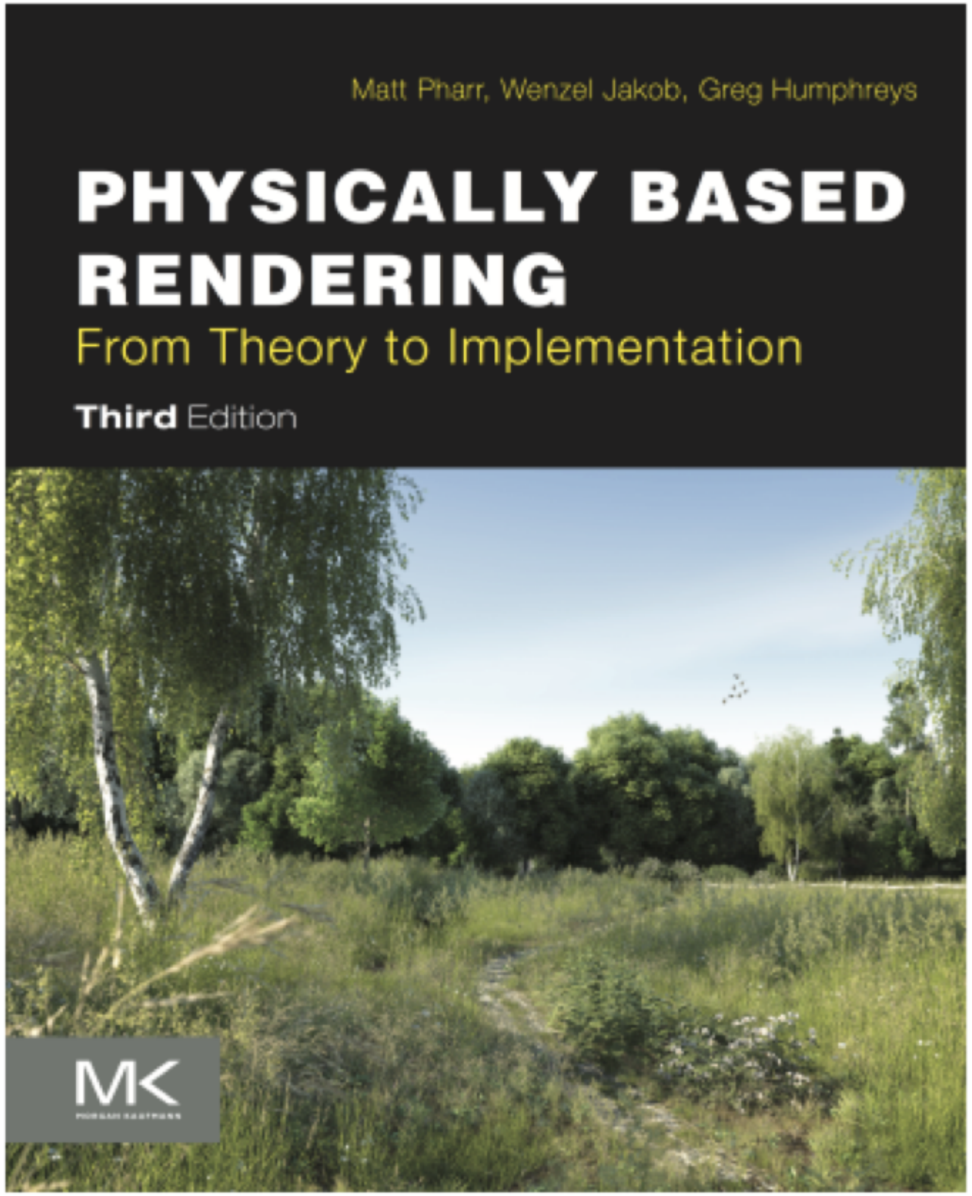


Quantitative computer graphics is necessary component for materials and lights

PBRT uses ray tracing from the sensor, through multi-element optics, into the scene spectral radiance. It includes accurate physics and the option to specify physical units

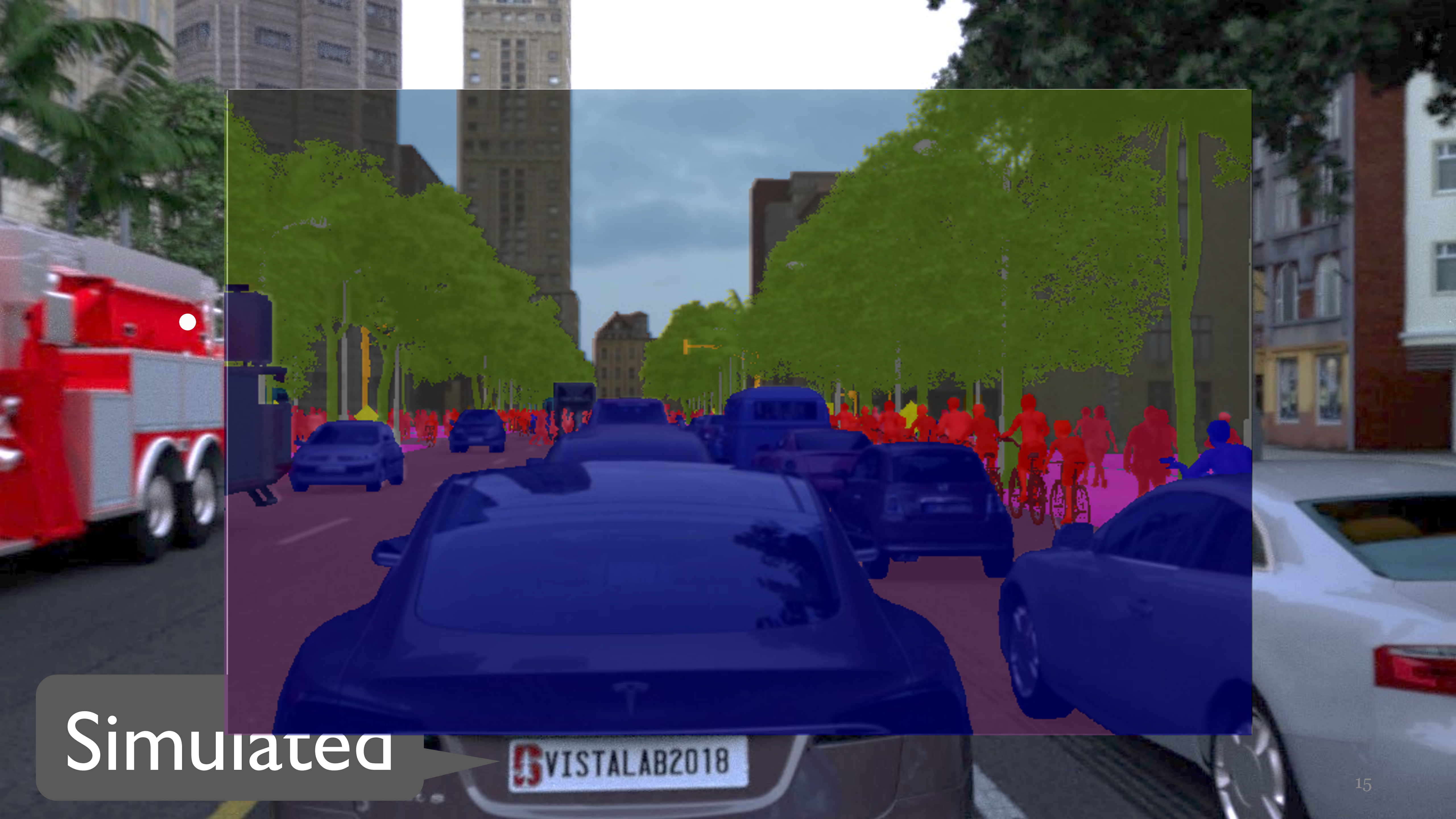
We added methods to model and comp;ute

- Diffraction
- Human eye
- Aspherical lenses
- Microlens arrays
- Linear models of texture maps to control surface spectral reflectance
- Fluorescence (Medical imaging)
- Participating media (Underwater)
- Computational imaging (CNN, Ideal observer)



Asset curation

Set Pivot Point to Move object freely


Simulated
VISTALAB2018

Rasterization is excellent for many purposes, but not physically accurate

- No physical quantities (e.g., spectral radiance, irradiance)
- Pinhole, not real optics
- Bag of tricks for visual appeal

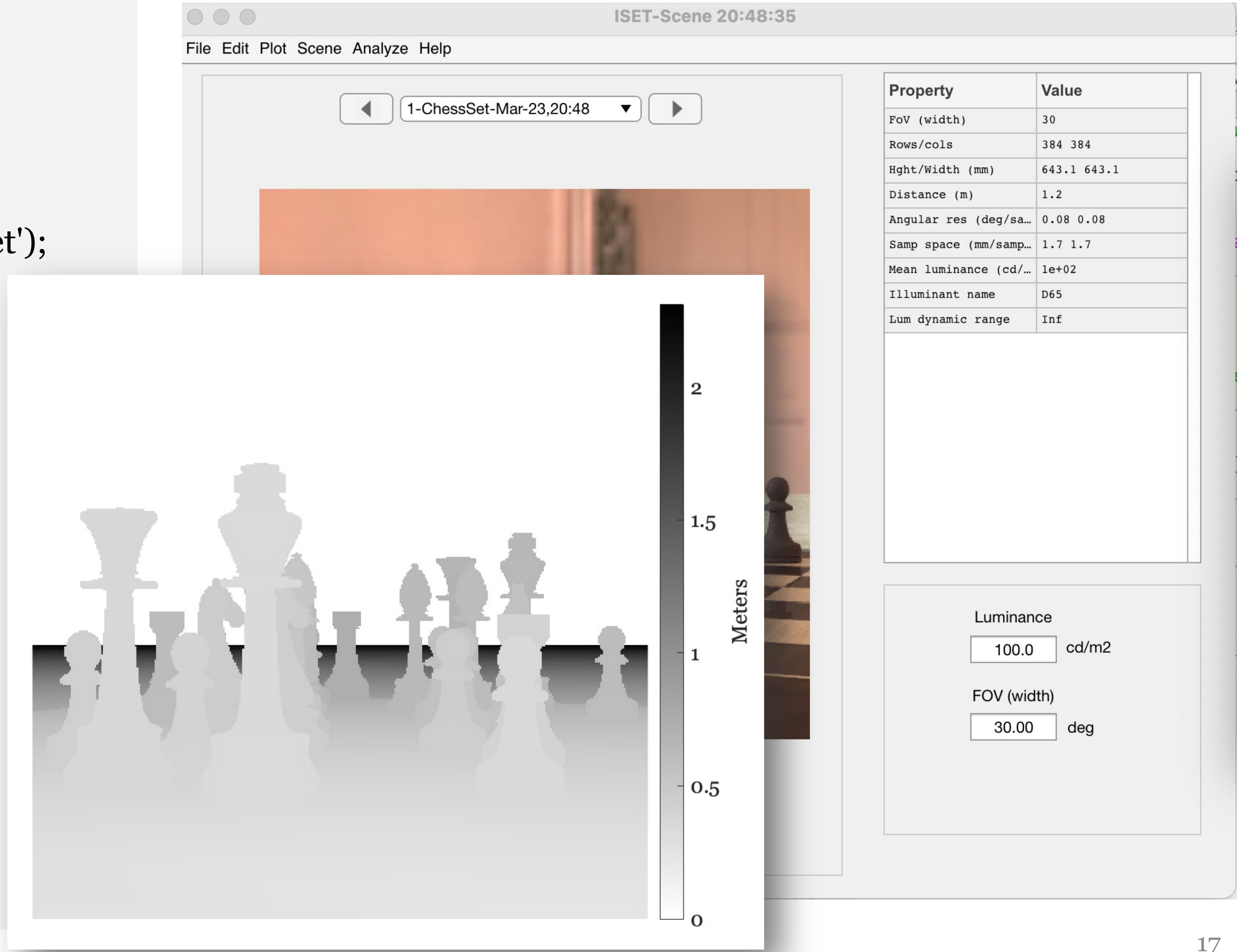
High quality rasterization – hand-edited (800 x 421) (Unity)

- Attempts to be physically accurate
- Incorporate lens and microlens models
- Produces complex visual effects

Ray traced – (712 x 395) (PBRT)

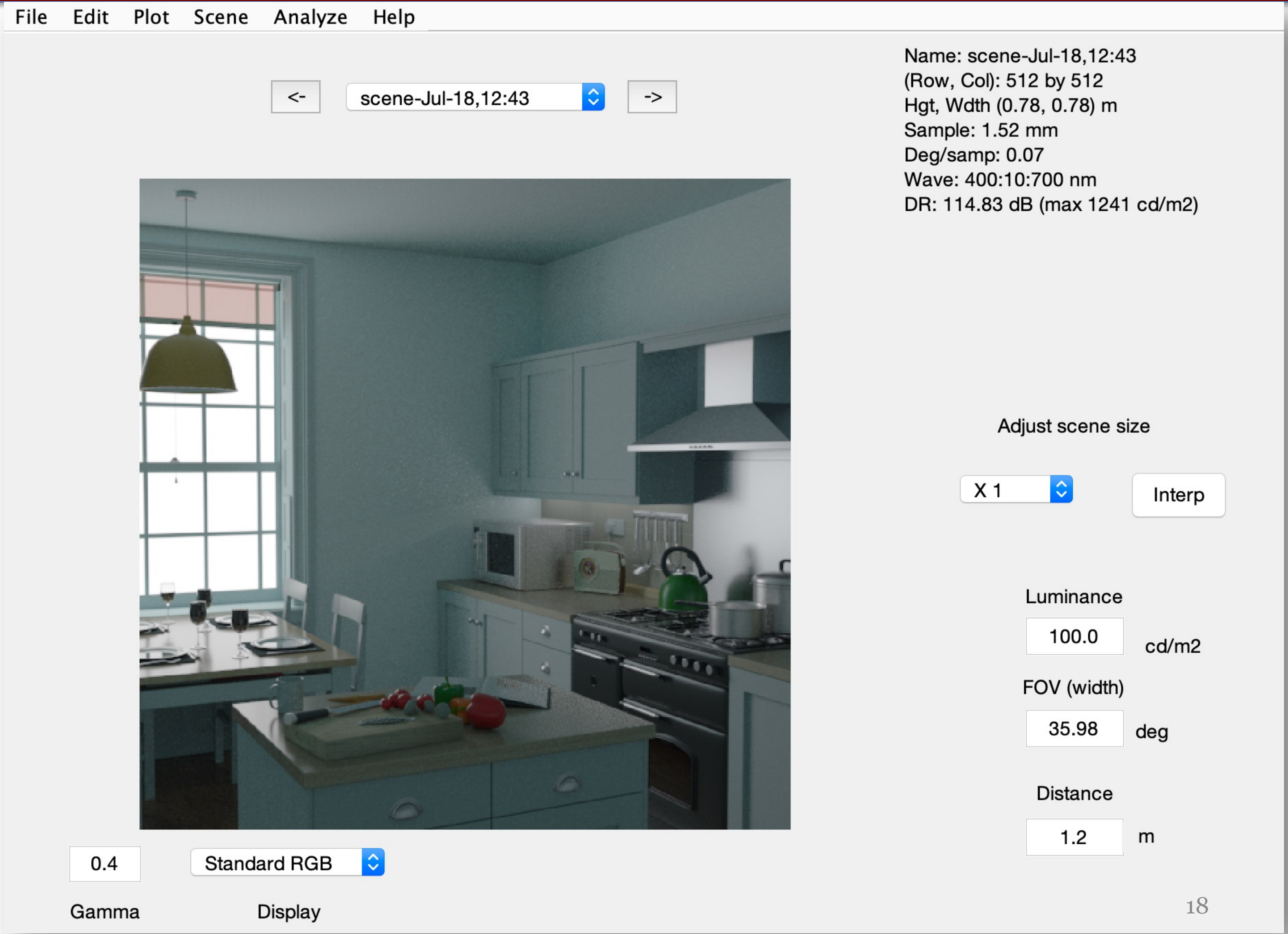
Software principles: Clarity over speed

```
% Start ISET and check docker
ieInit;
if ~piDockerExists, piDockerConfig; end

% Read a recipe for rendering a scene
thisR = piRecipeDefault('scene name','ChessSet');

% Set render parameters
thisR.set('film resolution',[384 384]);
thisR.set('rays per pixel',96);
thisR.set('n bounces',2);

% Write and Render
piWrite(thisR);
[scene, result] = piRender(thisR);

%  Show the radiance and depth map
sceneWindow(scene);
scenePlot(scene,'depth map');
```



ISET3D: Scenes can be quite complex and realistic

- We have more than 25 high quality scenes like these
- The geometry, reflectance, lighting and textures can be edited (ask me)
- This collection will grow and already includes HDR, inter-reflections, many types objects, materials, textures, shadows, occlusions



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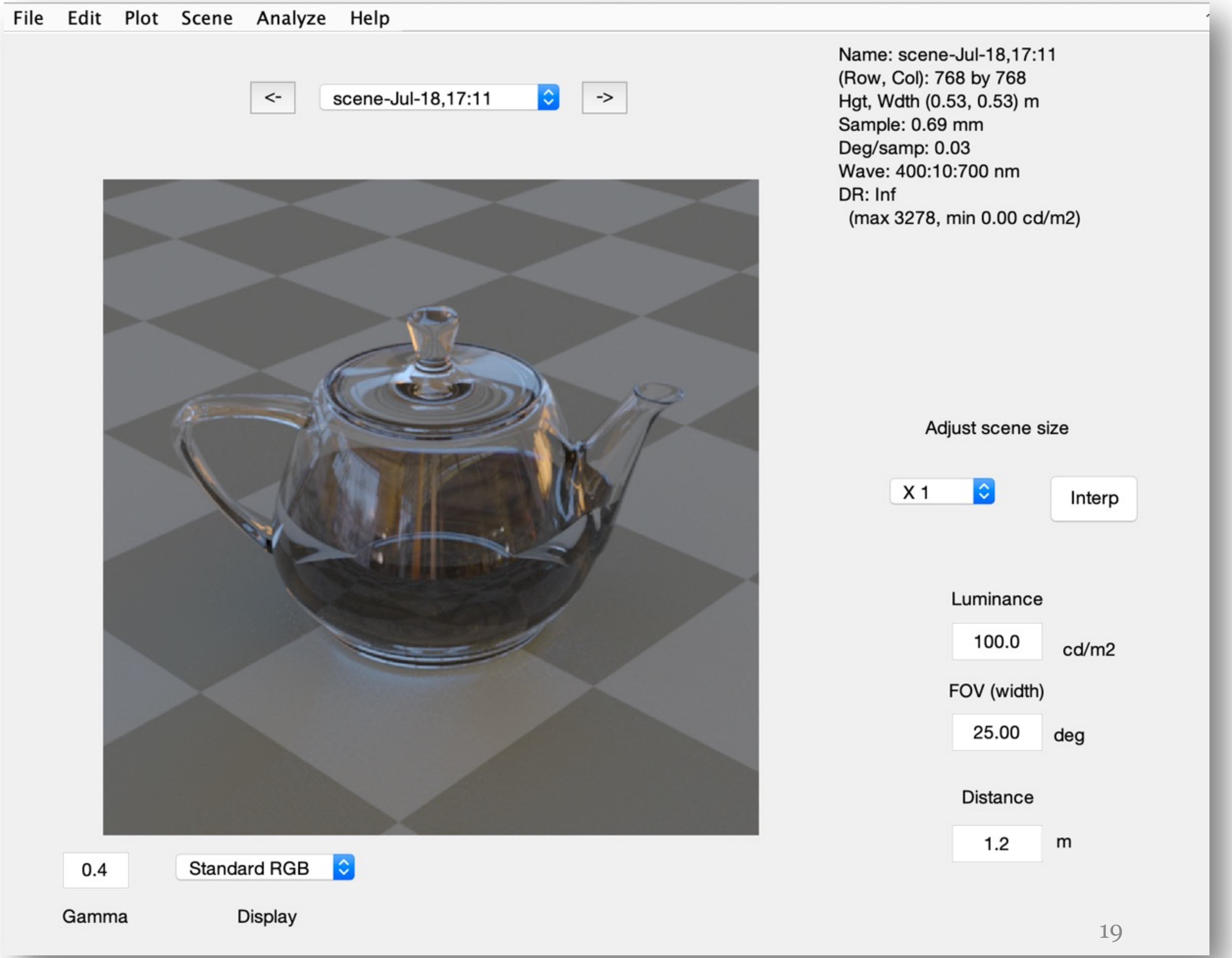

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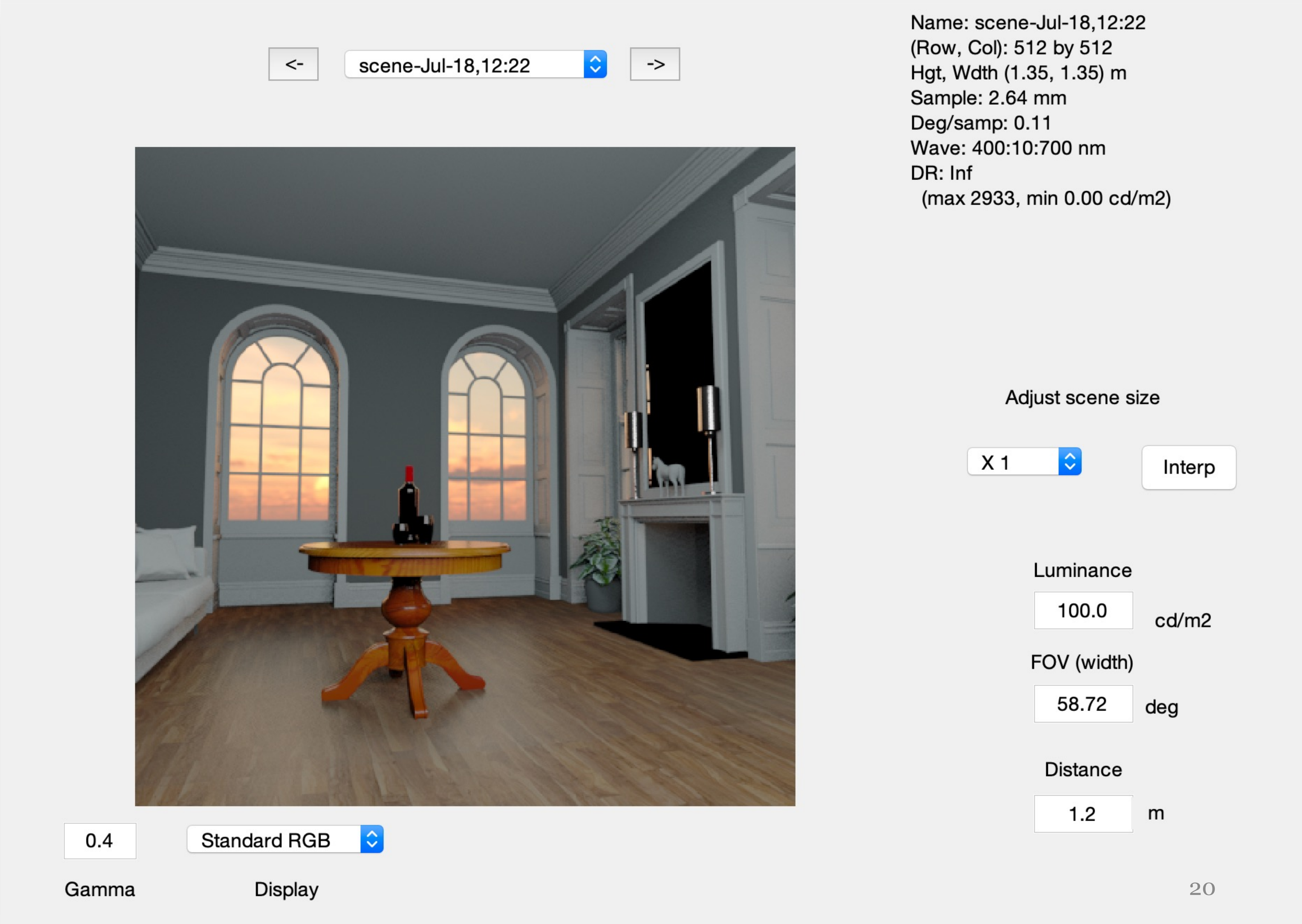
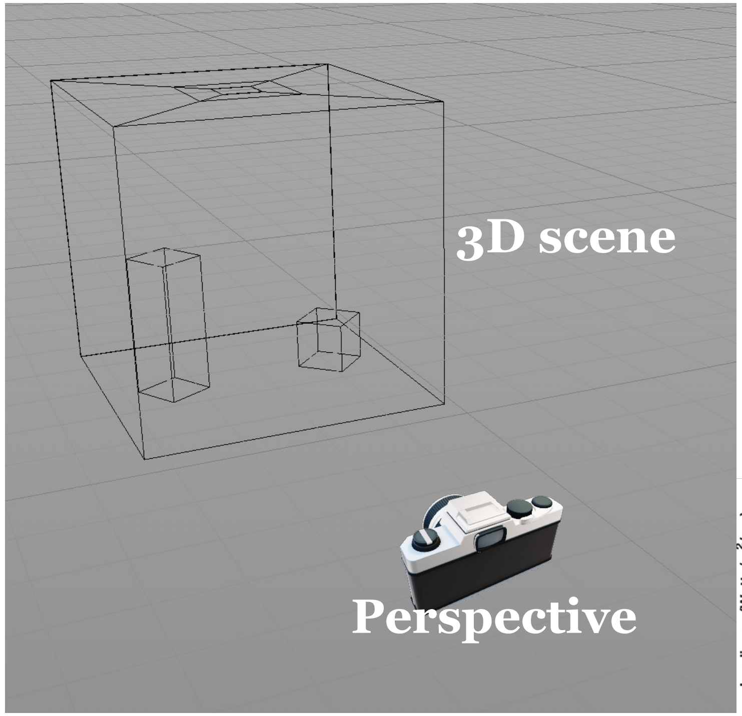
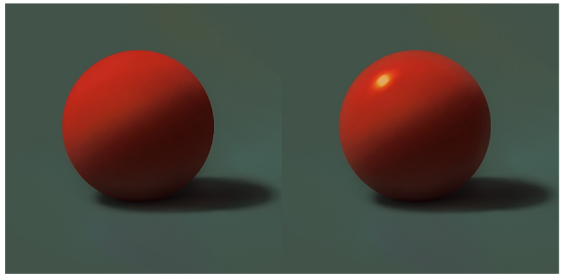


ISET3D - ISETCam applications

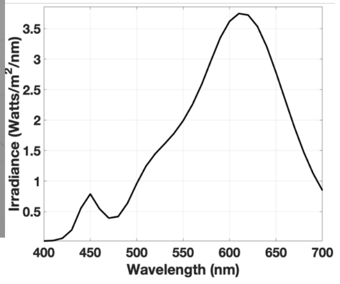
Assets and geometry Cinema 4D



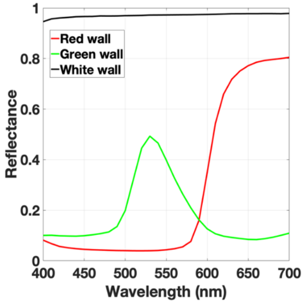
Materials and lights (ISET3d)



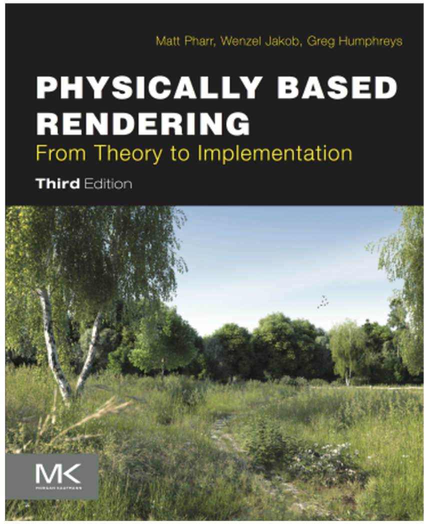
Light
spectral power

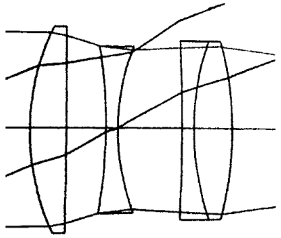


Surface
reflectances

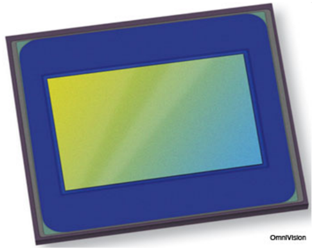


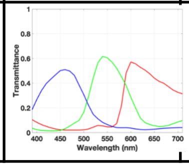
Optics and ray tracing (PBRT)





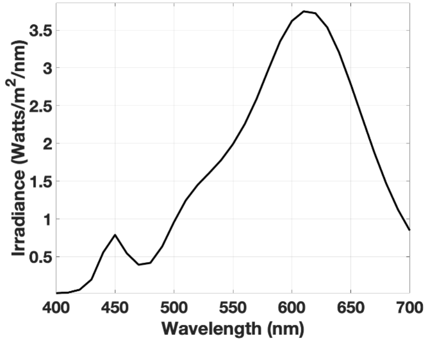
Sensor modeling (ISETCam)



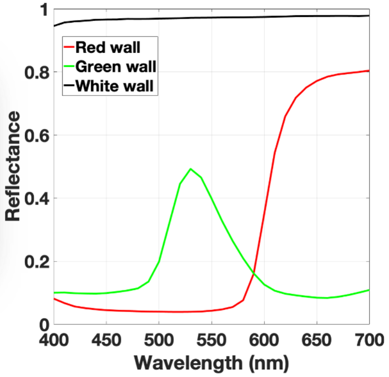
Properties	Parameters	Values (units)
Geometric	Pixel size	[1.4, 1.4] (um)
	Fill factor	100 (%)
Electronics	Well capacity	6000 (# e-)
	Voltage swing	0.4591 (volts)
	Conversion gain	7.65 x 10^{-5} (Volts/e-)
	Analog gain	1
	Analog offset	0.0287
	Quantization method	10 bits
Noise sources @ Analog gain = 1	DSNU	0
	PRNU	0.7 (%)
	Dark voltage	0
	Read noise	5 (mV)
Color filters		

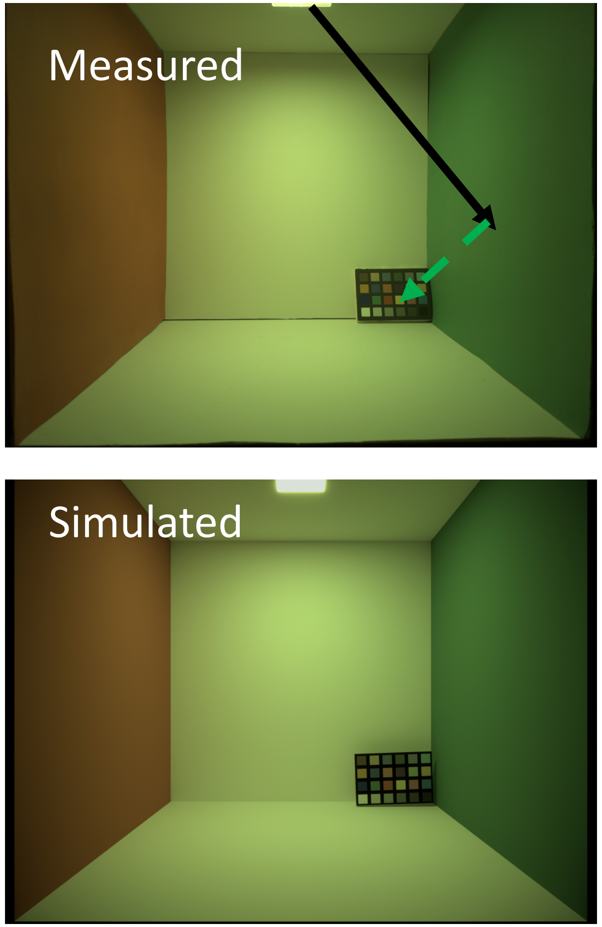
Quantitative validation of 3D scene and camera models

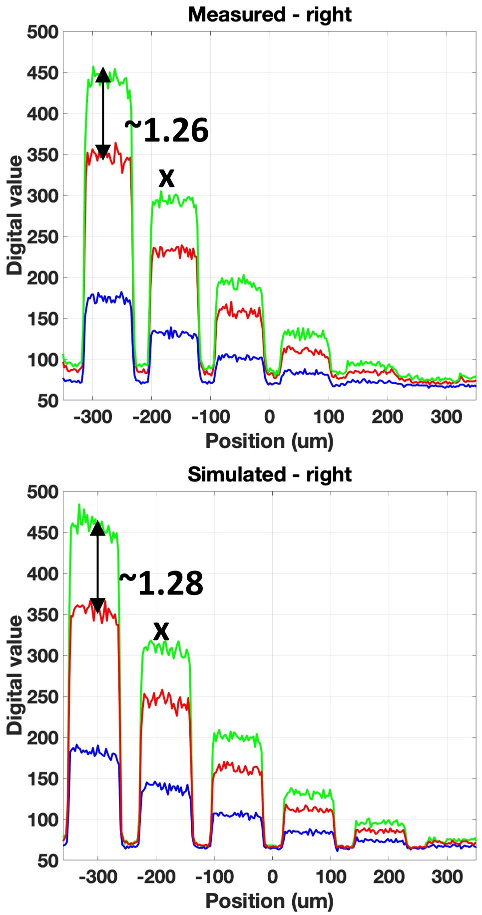
Illuminant SPD

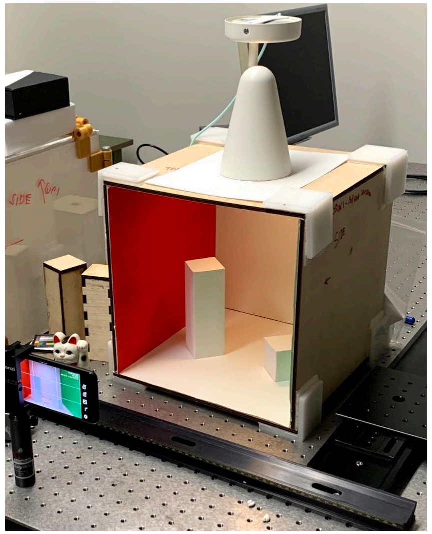


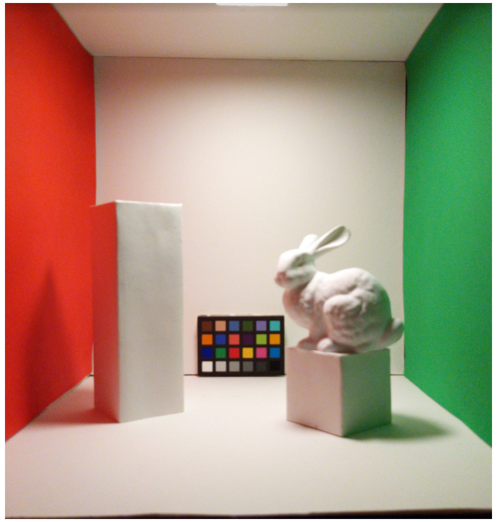
Surface spectral reflectance











ISETAuto applications

A system for generating complex physically accurate sensor images for automotive applications

Zhenyi Liu[1,2], Minghao Shen[2], Jiaqi Zhang[3], Shuangting Liu[3], Henryk Blasinski[1], Trisha Lian[1], Brian Wandell[1]
1. Stanford University, 2. Jilin University, 3. Beihang University

Abstract

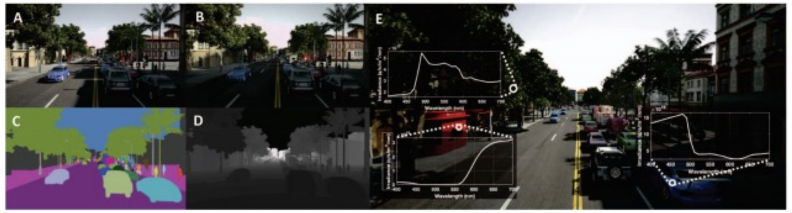
We describe an open-source simulator that creates sensor irradiance and sensor images of typical automotive scenes in urban settings. The purpose of the system is to support camera design and testing for automotive applications. The user can specify scene parameters (e.g., scene type, road type, traffic density, time of day)

distributions that enable us to model the impact of wavelength-dependent components, including the optics and sensors (Blasinski et al. 2018).

This paper describes an open-source and freely distributed toolbox to synthesize scene spectral radiances and sensor data for neural network automotive applications. The software includes procedural methods to generate a large number and variety of scenes

Soft Prototyping Camera Designs for Car Detection Based on a Convolutional Neural Network

Zhenyi Liu[1,2], Trisha Lian[1], Joyce Farrell[1], and Brian Wandell[1]
[1]Stanford University, USA, [2]Jilin University, China
{zhenyiliu, tlian, jefarrel, wandell}@stanford.edu



Neural Network Generalization: The Impact of Camera Parameters

ZHENYI LIU[1,2], TRISHA LIAN[2], JOYCE FARRELL[2], AND BRIAN A. WANDELL[2]
[1]State Key Laboratory of Automotive Simulation and Control, Jilin University, Changchun 13000, China
[2]Department of Electrical Engineering, Stanford University, Stanford, CA 94305, USA
Corresponding author: Zhenyi Liu (zhenyiliu27@gmail.com)

This work was supported by the Jilin University.

ABSTRACT We quantify the generalization of a convolutional neural network (CNN) trained to identify cars. First, we perform a series of experiments to train the network using one image dataset - either synthetic or from a camera - and then test on a different image dataset. We show that generalization between

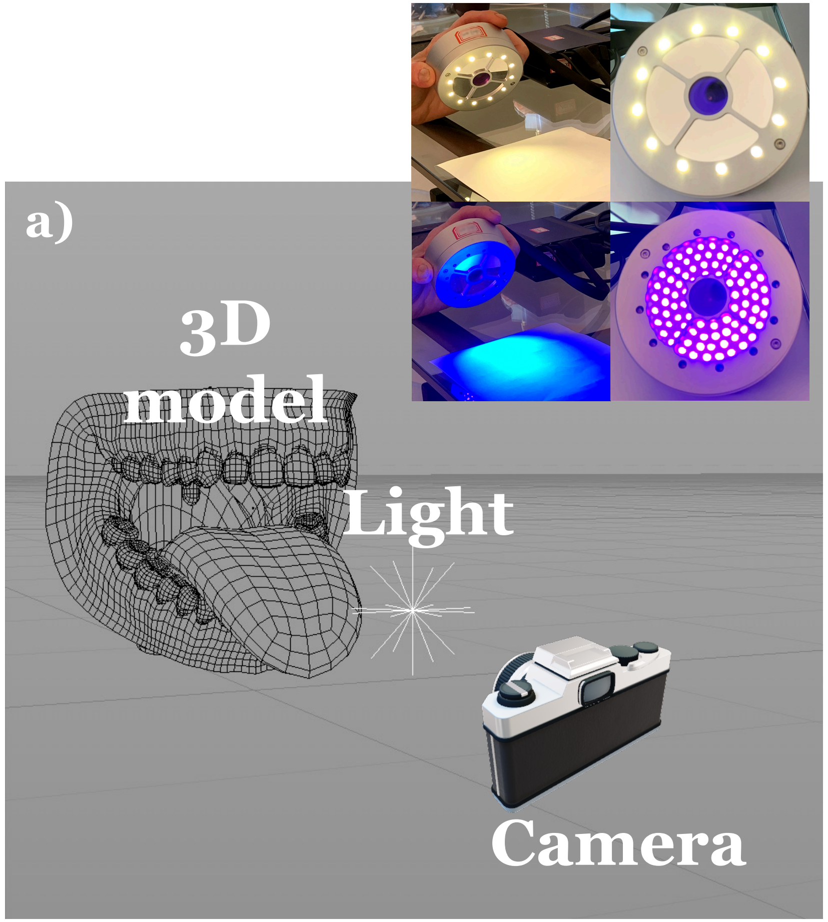
ISETAuto: Detecting vehicles with depth and radiance information

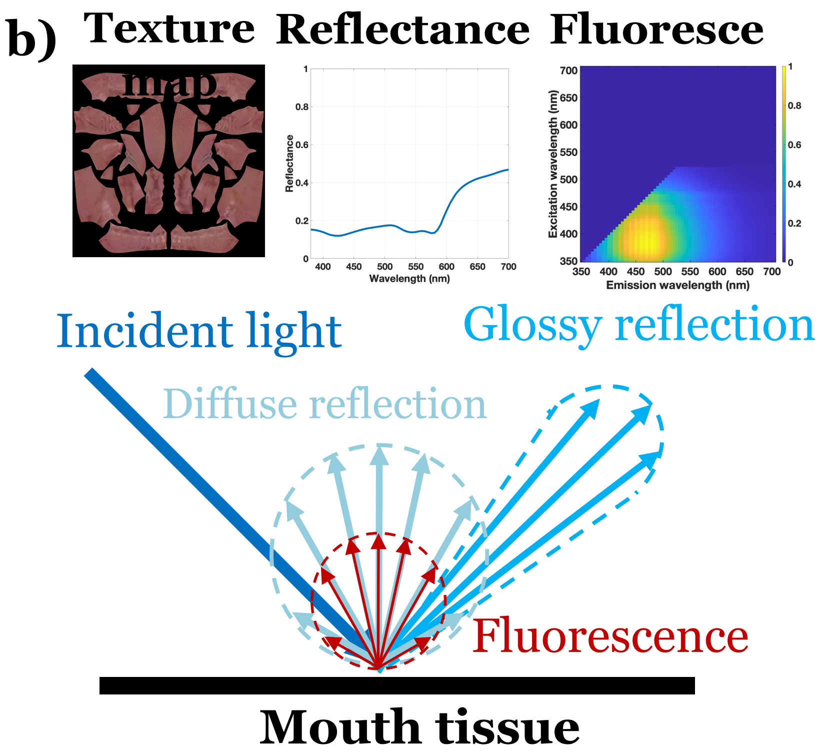
ZHENYI LIU[1], JOYCE FARRELL[2] AND BRIAN WANDELL[2]
[1]State Key Laboratory of Automotive Simulation and Control, Jilin University (e-mail: zhenyiliu27@gmail.com)
[2]Stanford University (e-mail: jefarrel, wandell@stanford.edu)
Corresponding author: Zhenyi Liu (e-mail: zhenyiliu27@gmail.com)

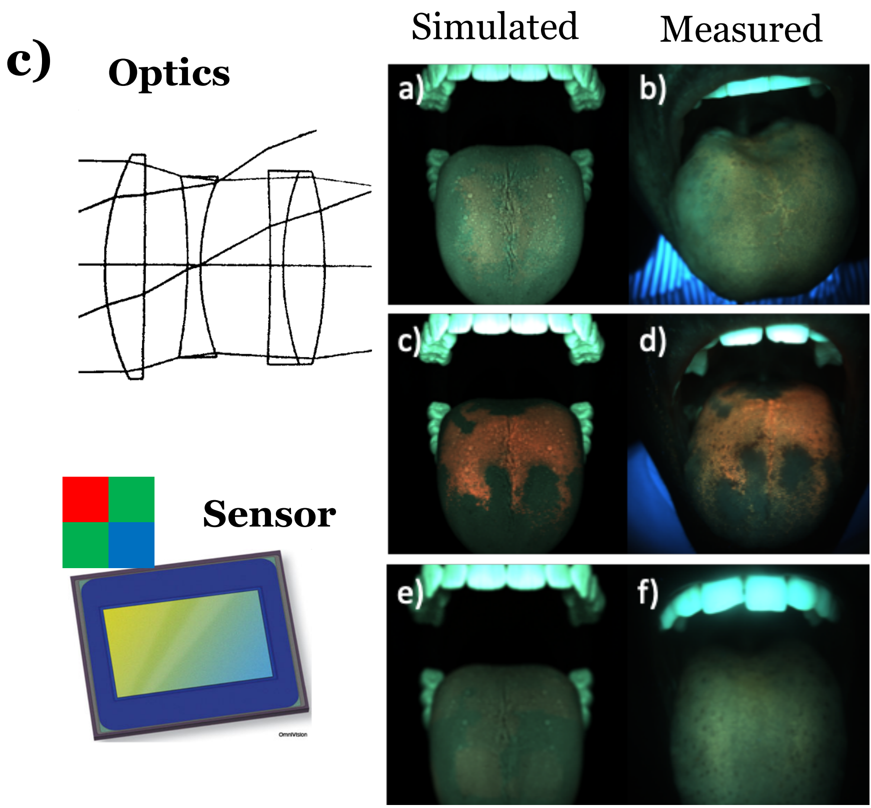
Supported by Jilin University. We thank Boyd Fowler at Omnivision and Sergio Goma at Qualcomm for drawing our attention to prior work on RGB-D sensor technology.

ABSTRACT Autonomous driving applications use two types of sensor systems to detect vehicles - depth sensing LiDAR and radiance sensing cameras. We compare the performance (average precision) of a ResNet for vehicle detection in complex, daytime, driving scenes when the input is a depth map [D = d(x,y)], a

Medical applications: Fluorescence







Second point

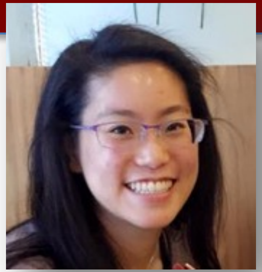
Image systems simulation software involves skills that are beyond the capabilities of most academic labs and many commercial ventures (particularly startups).

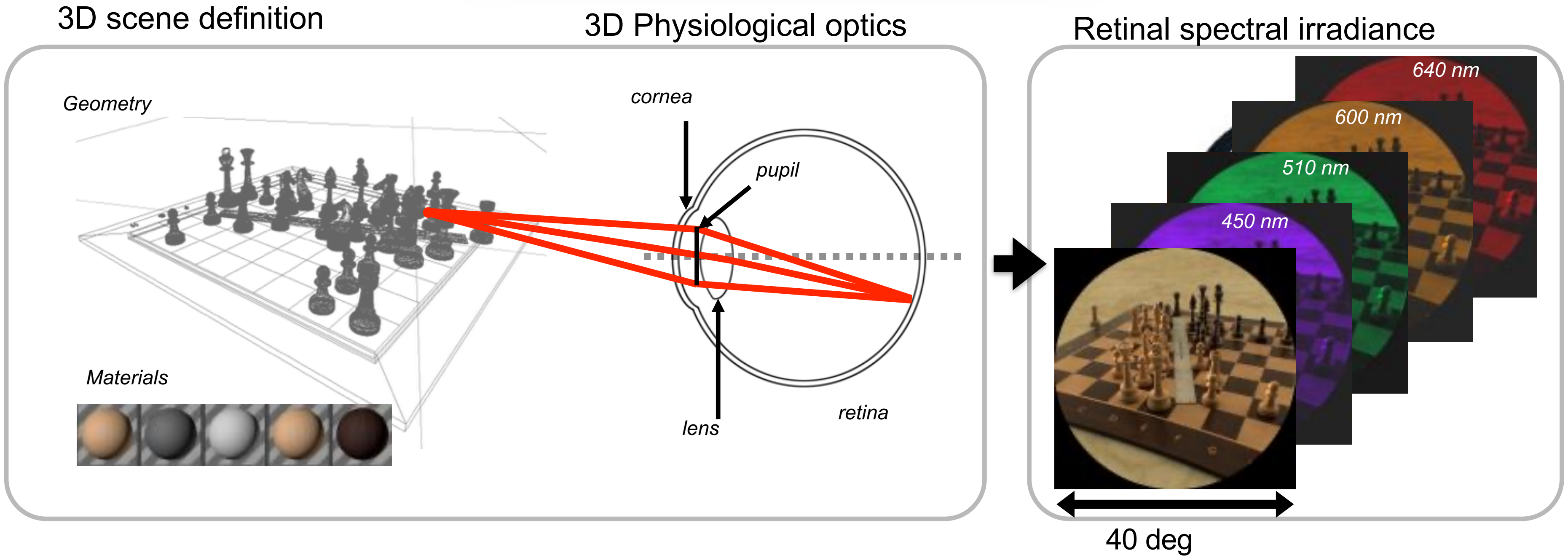
To speed progress, we might build and share consensus (validated) tools

ISET3D extension to incorporate human optics


OPEN ACCESS
Article | October 2019
Ray tracing 3D spectral scenes through human optics models
Trisha Lian; Kevin J. MacKenzie; David H. Brainard; Nicolas P. Cottaris; Brian A. Wandell
+ Author Affiliations
Journal of Vision October 2019, Vol.19, 23. doi:https://doi.org/10.1167/19.12.23

Gullstrand/LeGrand
Navarro, 1999
Arizona



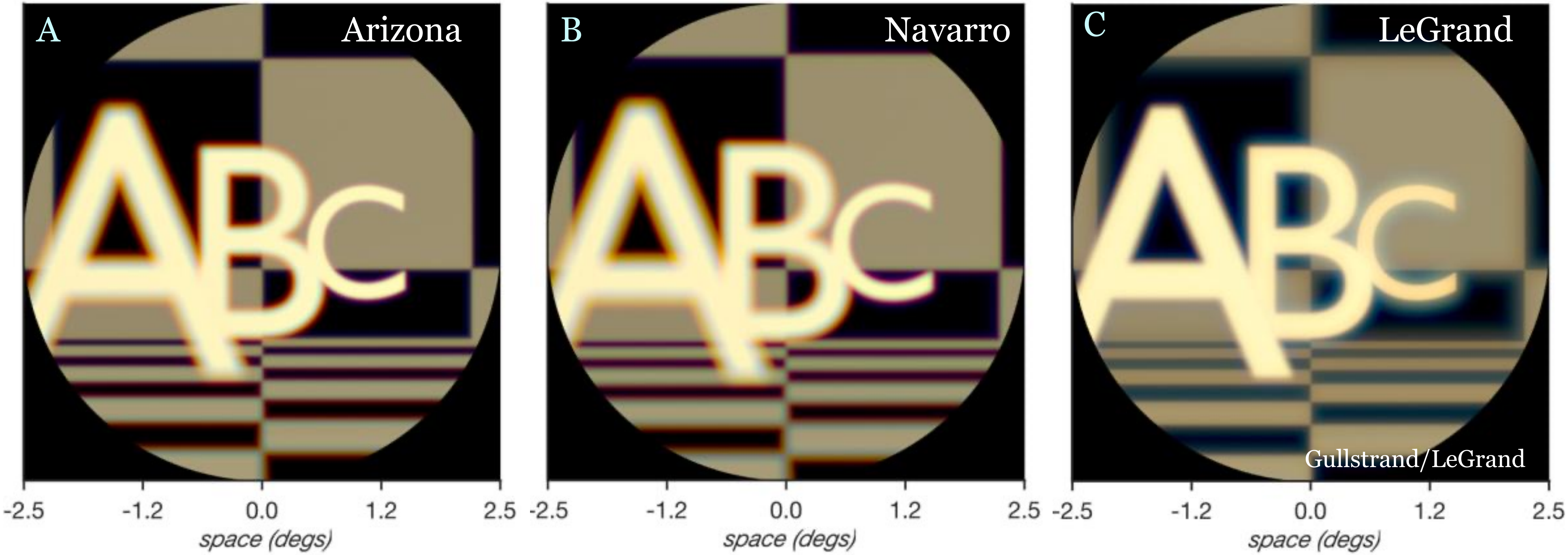


Use computer graphics and ray-tracing to model how spectral, 3D scenes are transformed by human optics to the retinal irradiance.

Comparison of eye models

The code flexibility accommodates the major human eye models
(Lian et al. 2019, Journal of Vision).

Remember: these images represent underlying spectral irradiance

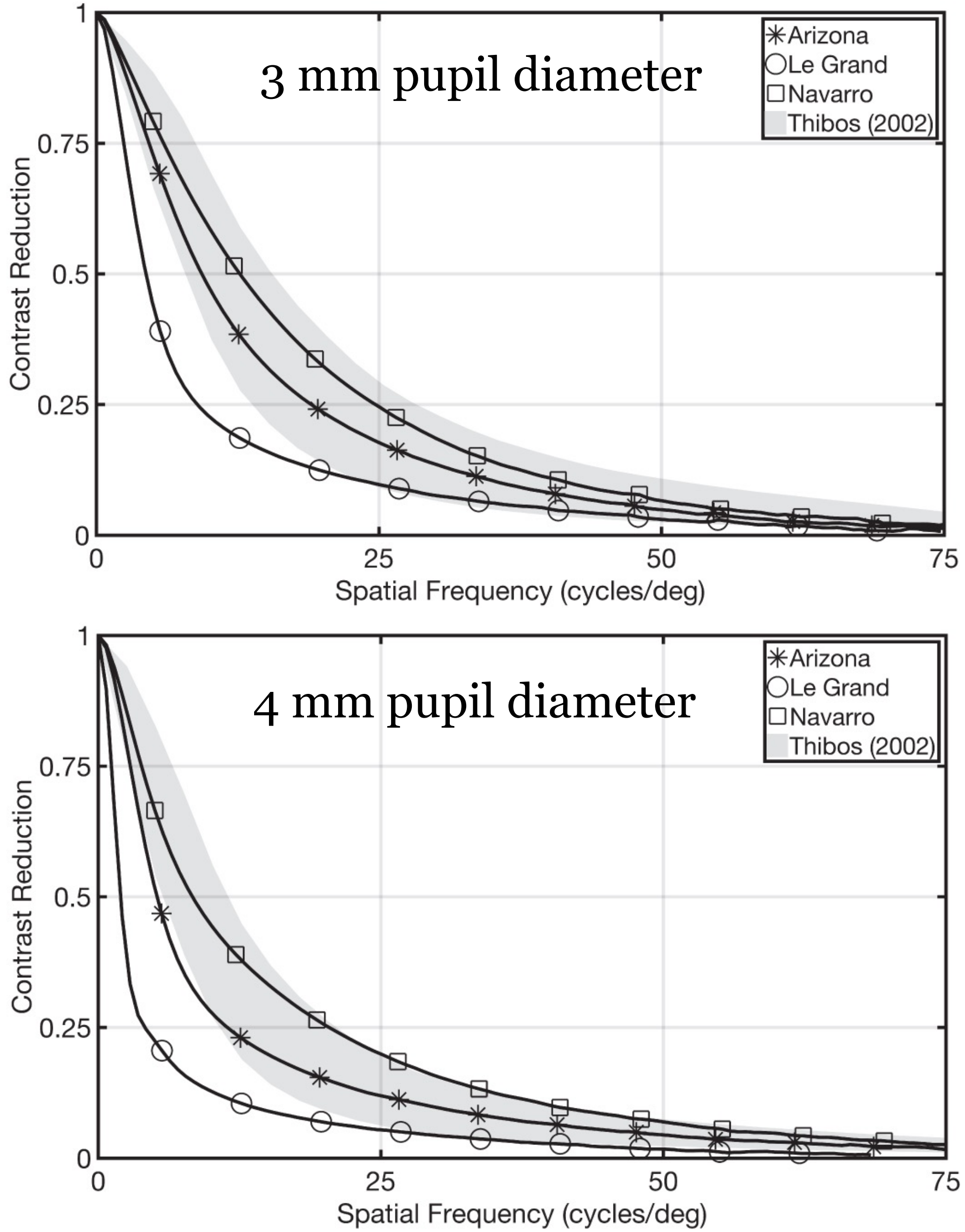


Eye model comparisons

- In which we learned that there are quantitative differences

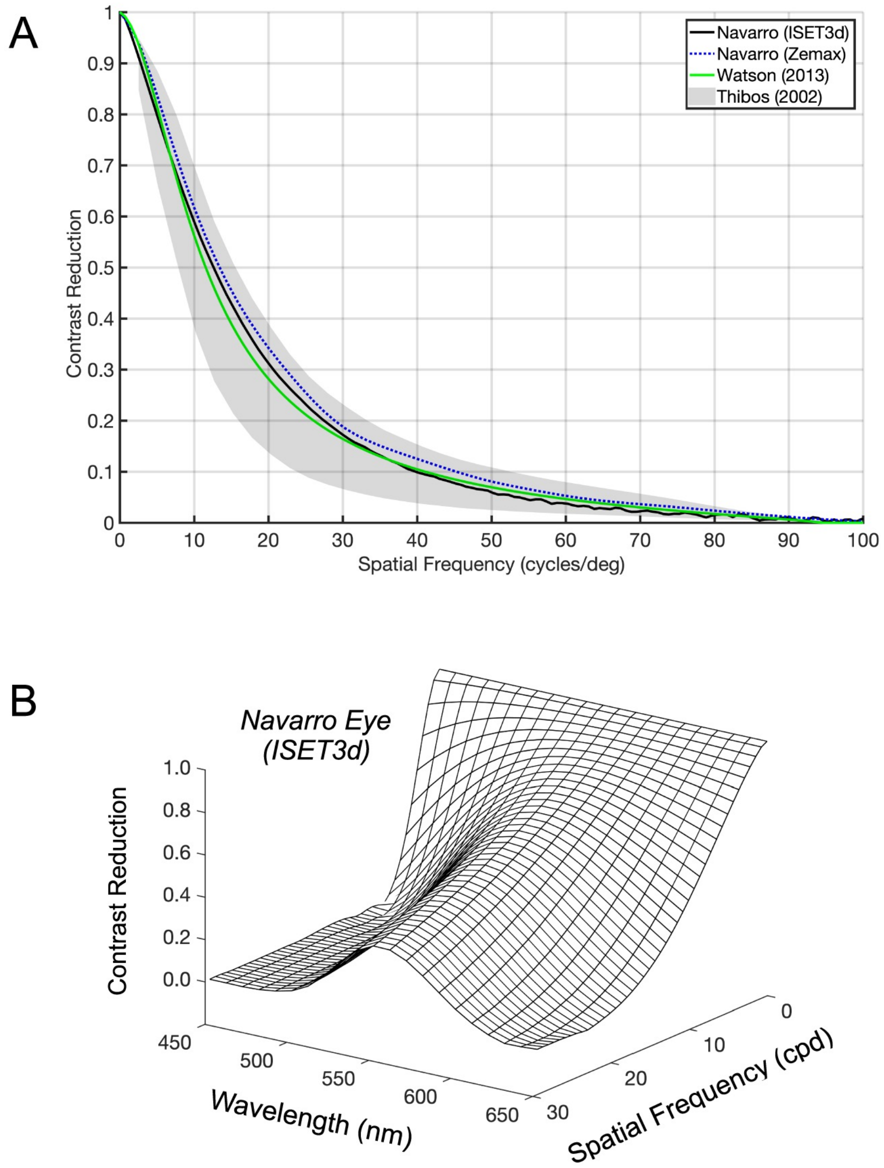
- The LeGrand eye extension of Gullstrand – is out of compliance with modern measurements

- We can also compare with different eye parameters



Numerical validation of the ray tracing (PBRT) methods

- We tested whether the PBRT implementation was the same as Zemax calculated
- And we compared with L. Thibos' data from a large number of eyes – which is the basis of the Watson summary as well
- We can calculate as a function of wavelength, too



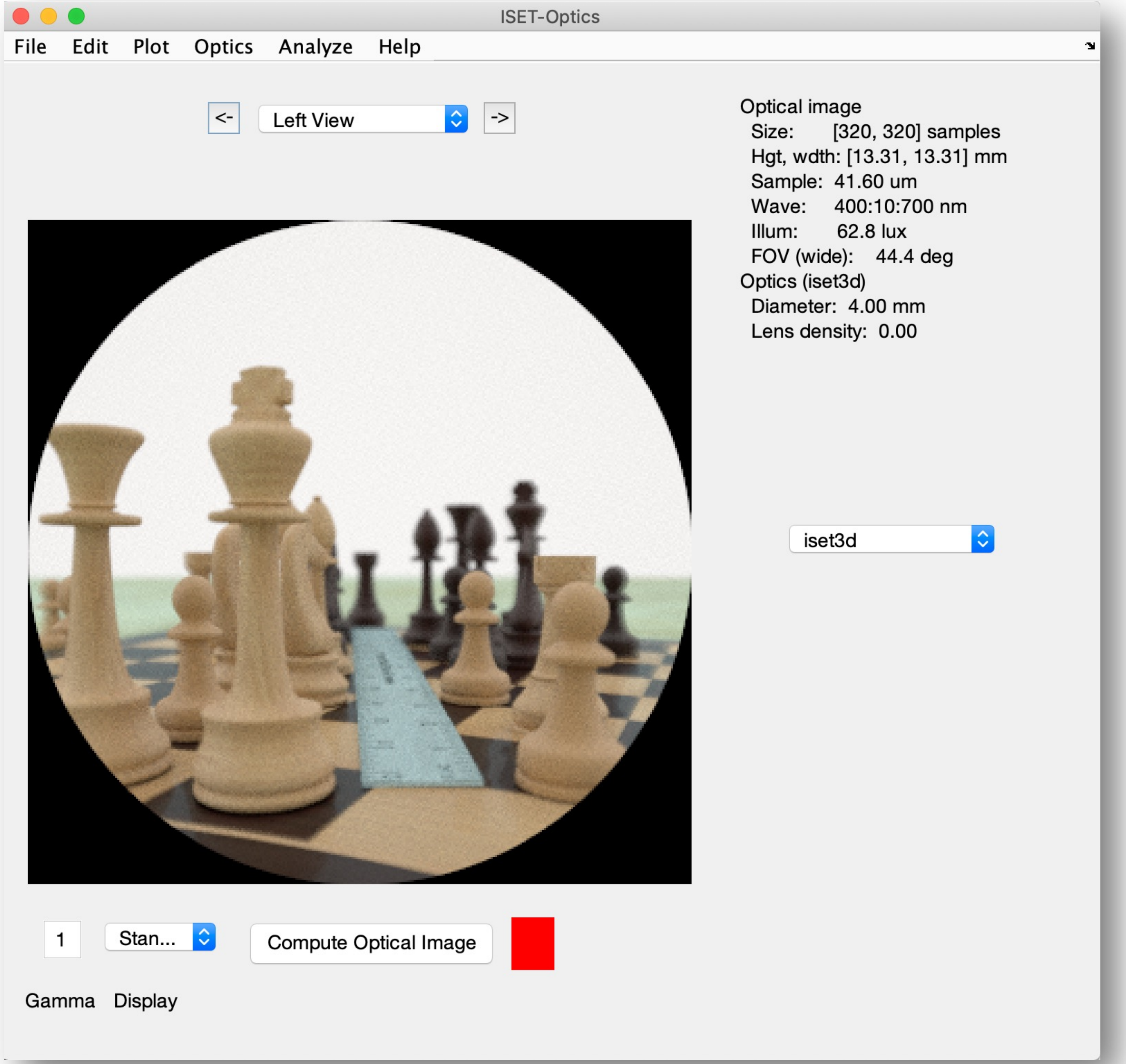
ISET3d: Making a stereo pair

Left eye

This is the position
of the left eye

from = thisEye.get('from')

It is the 'from' parameter in
the recipe



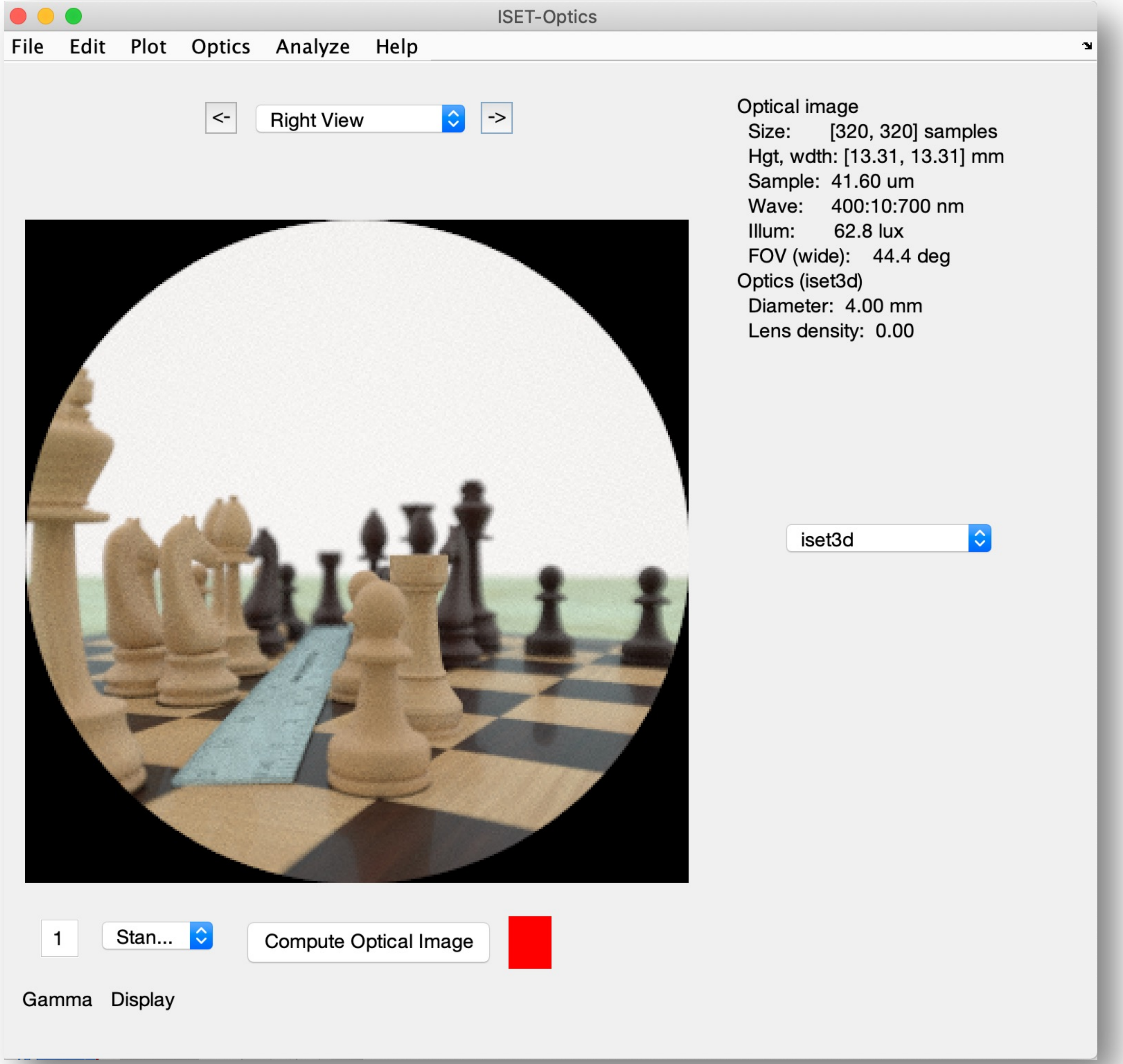
ISET3d: Making a stereo pair

Right eye

Move the camera position
by 6 cm to the right

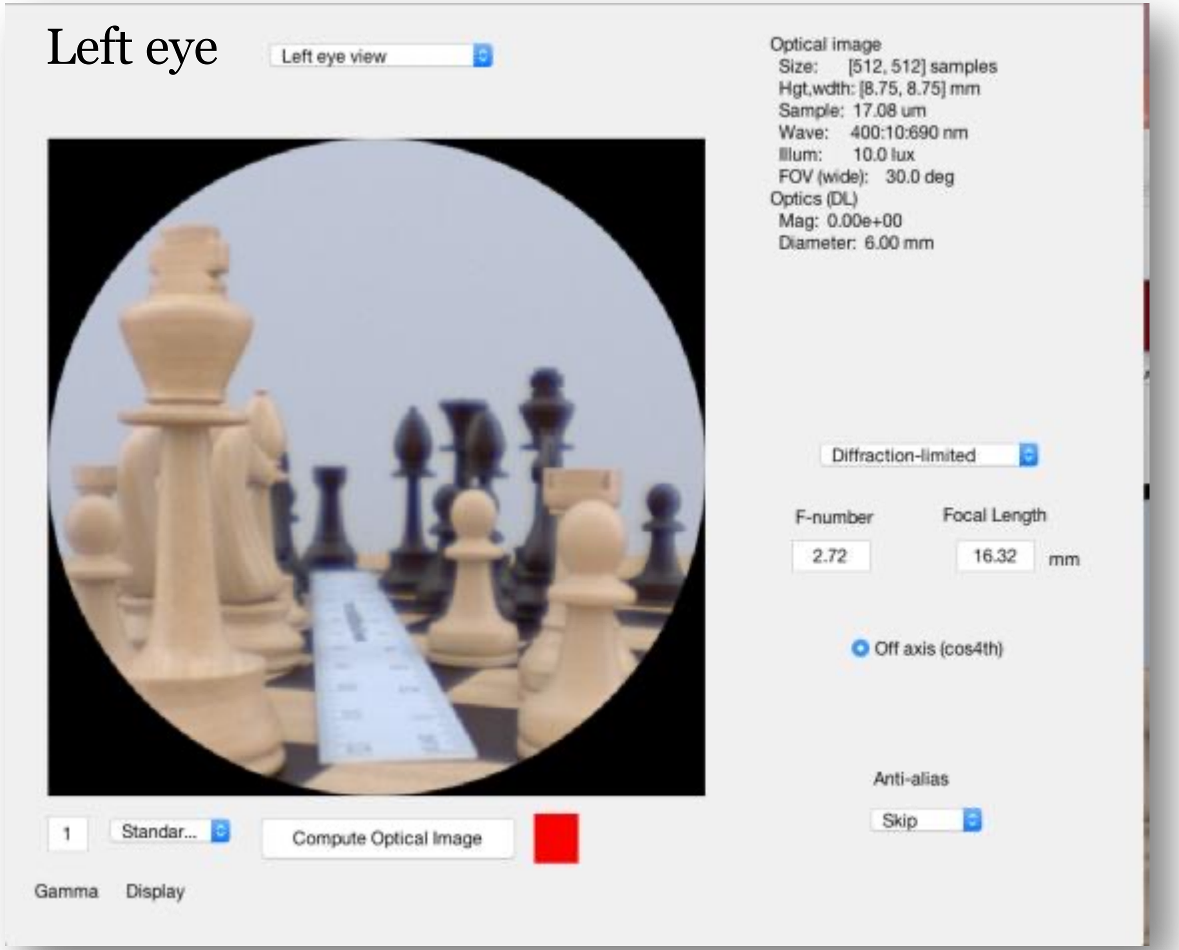
newFrom = from + (0.060, 0, 0)

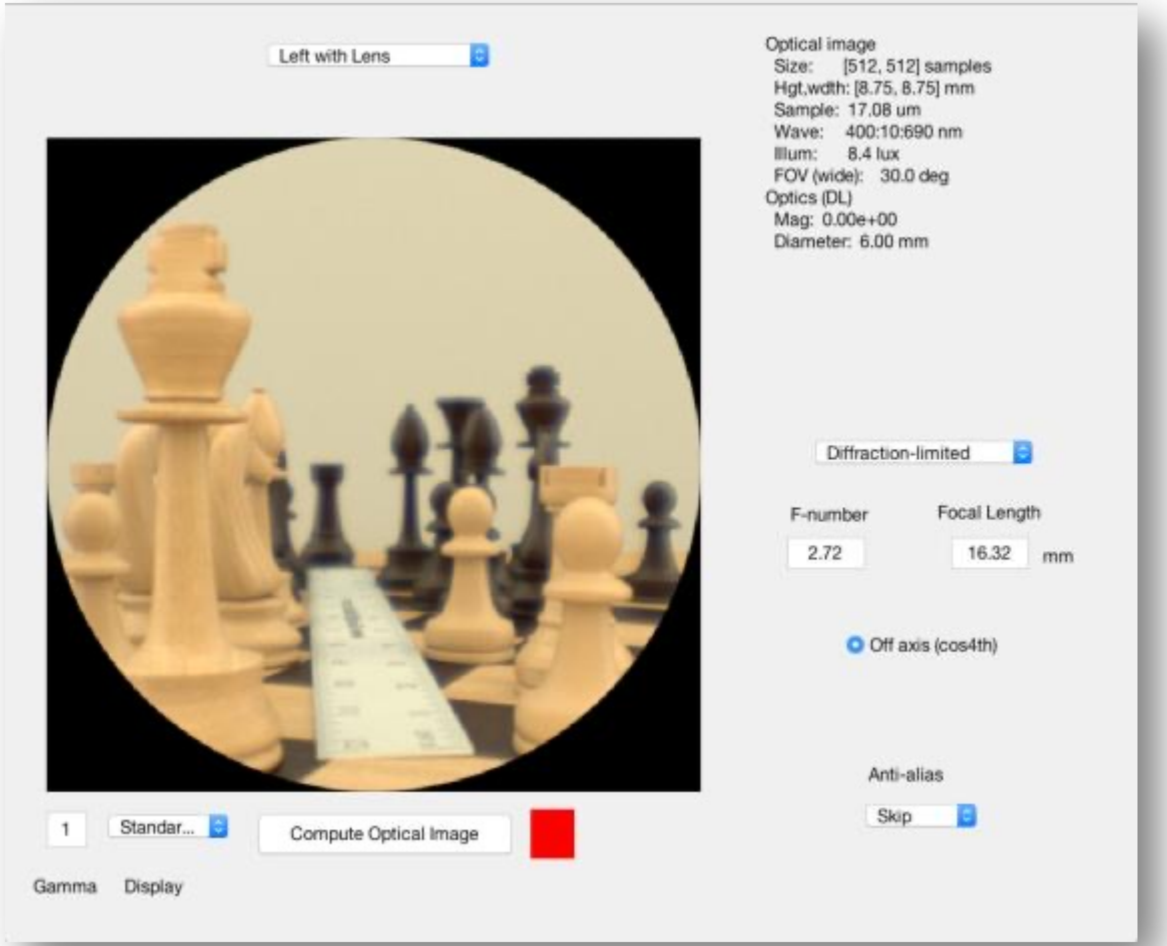
thisEye.set('from',newFrom)
oiRight = thisEye.render;



Natural images - Image formation (optics) models and quantitative graphics

Inert pigments (e.g., lens transmission) are included and controlled



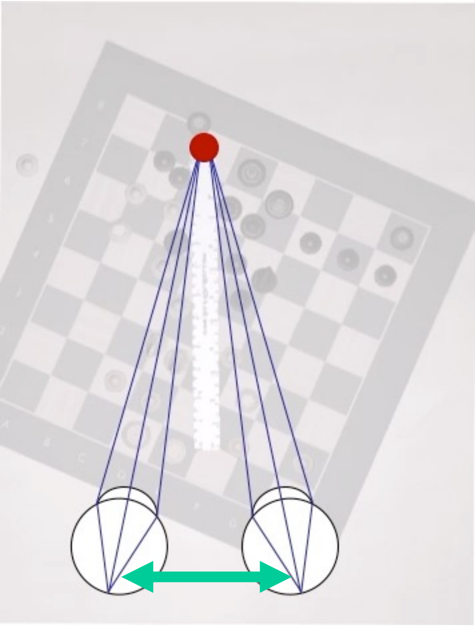


Remember: these images represent underlying spectral irradiance

Vergence and Accommodation

Where the eye (or eyes) is looking is controlled

thisEye.set('to',loc)



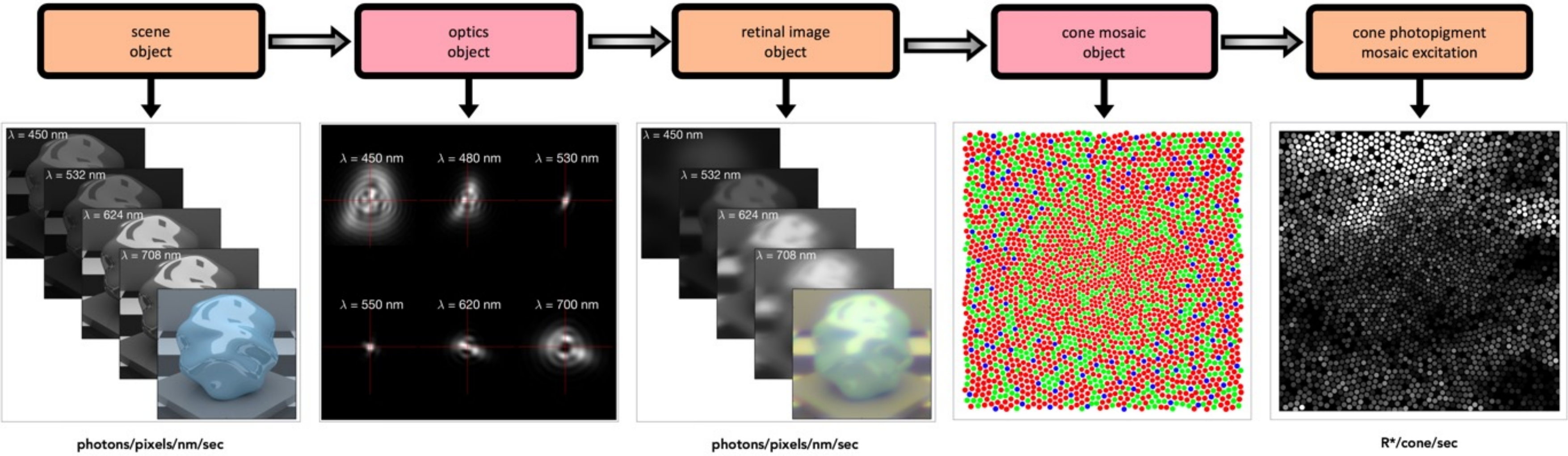
64 mm

1.66 D (Left)

1.66 dpt (Right)

Remember: these images represent underlying spectral irradiance

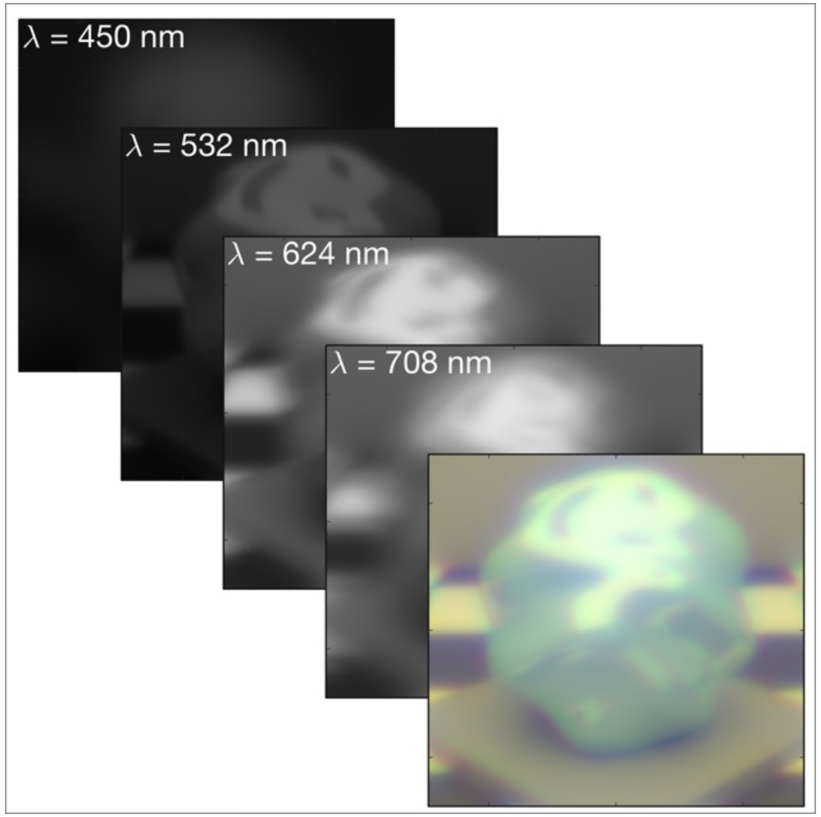
Image System Engineering Tools for Biology (ISETBio)

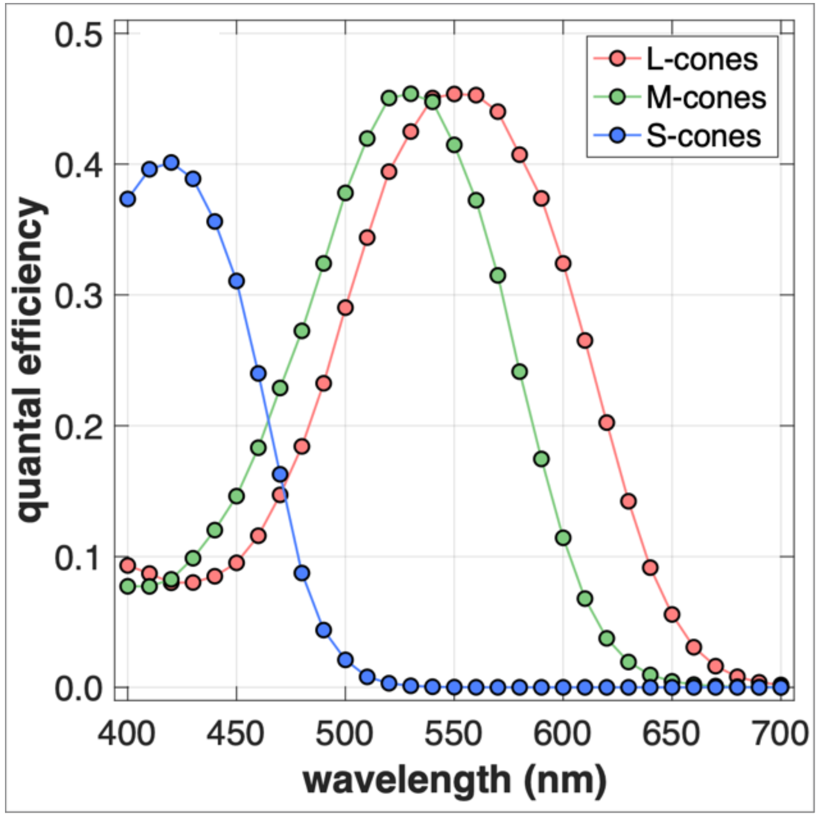


- ISETBio is a set of computational tools to model how light from a scene is encoded and processed by visual circuitry.
- One goal is to make the results of 200 years of quantitative vision research easily available for computation.
- ISETBio can be used to clarify the impact of different elements of the eye and neural processing on visual perception and performance.

ISETBio components – retinal image and cone isomerizations

retinal image object → cone mosaic object



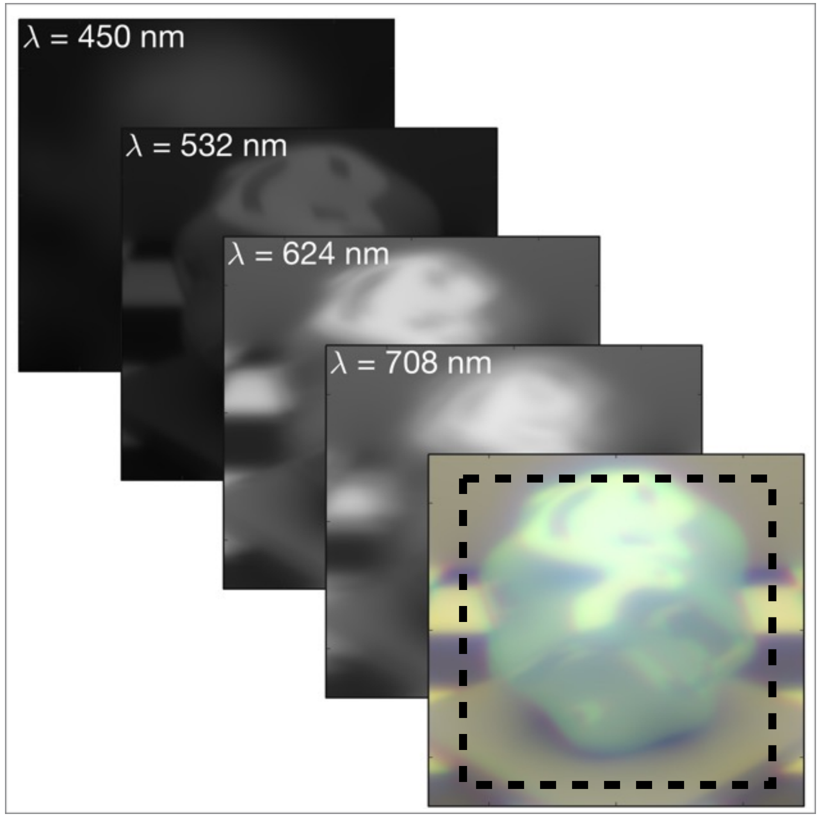


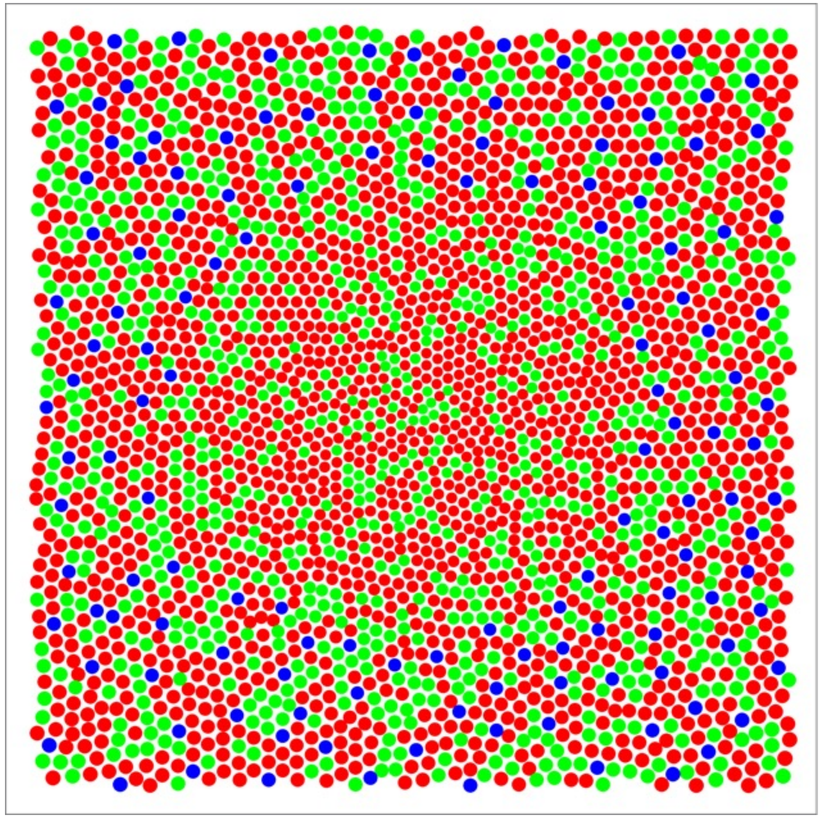
photons/pixels/nm/sec

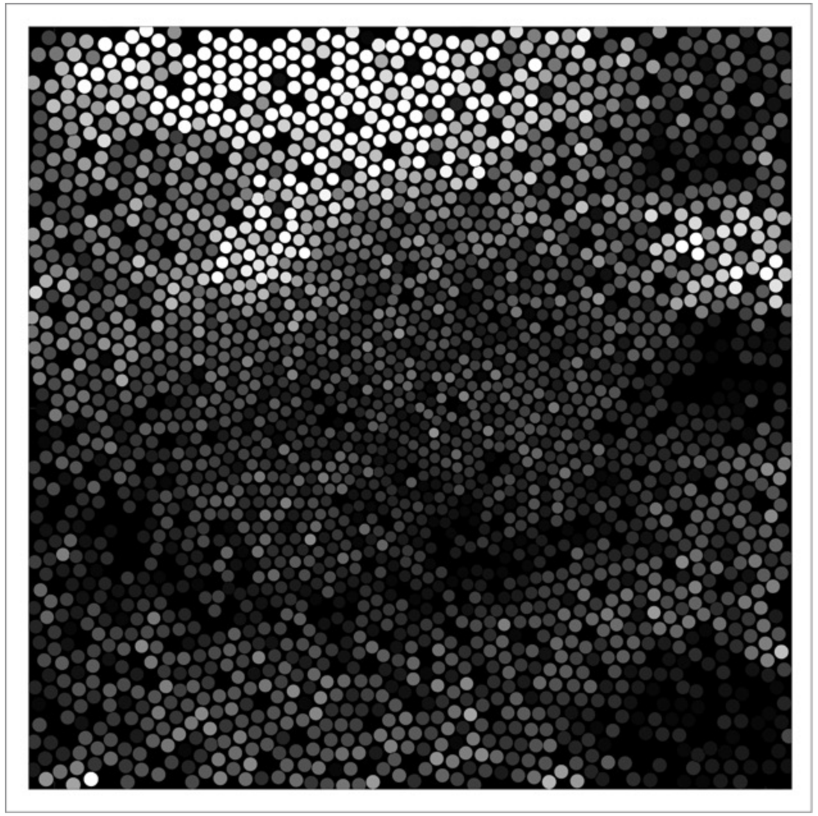
Courtesy Nicolas Cottaris

ISETBio components – retinal image and cone isomerizations

retinal image object → cone mosaic object → cone photopigment mosaic excitation





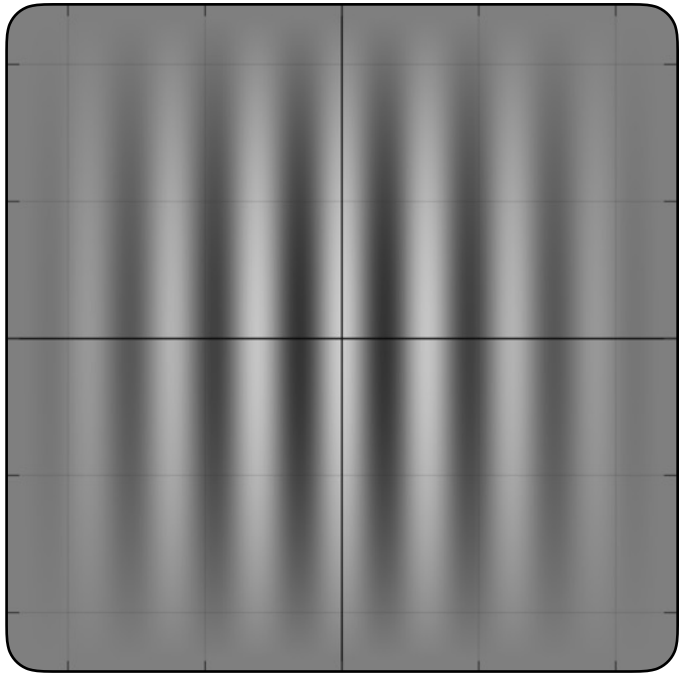


photons/pixels/nm/sec

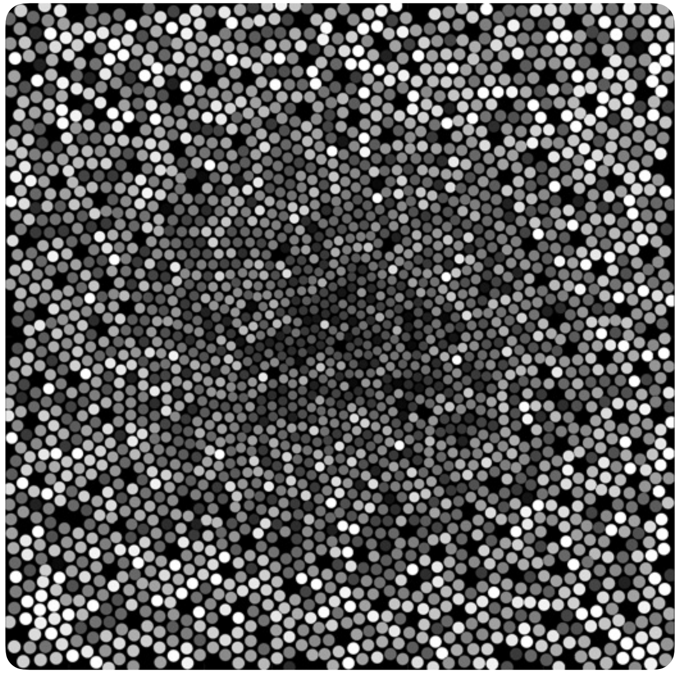
R*/cone/sec

Example: cone mosaic isomeraizations to gratings at different contrasts

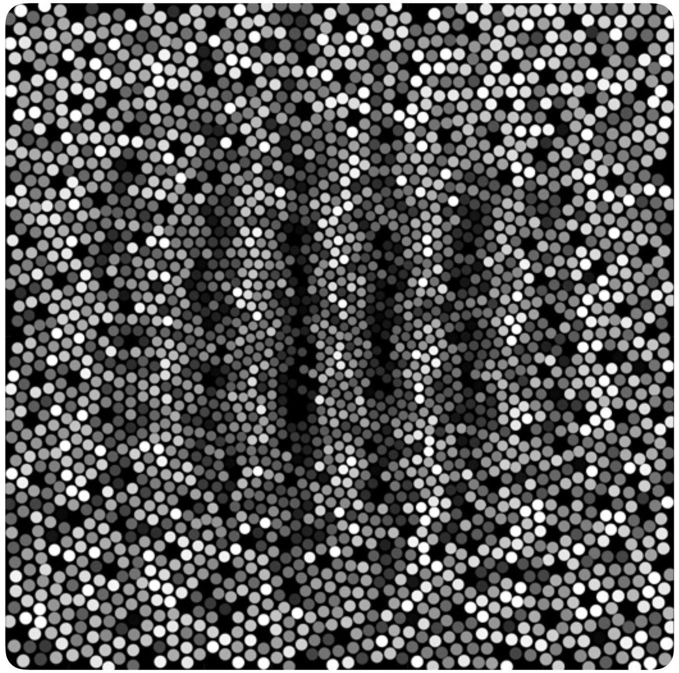
scene (c, sf)



c = 0



c = 100%, sf = 16 c/deg

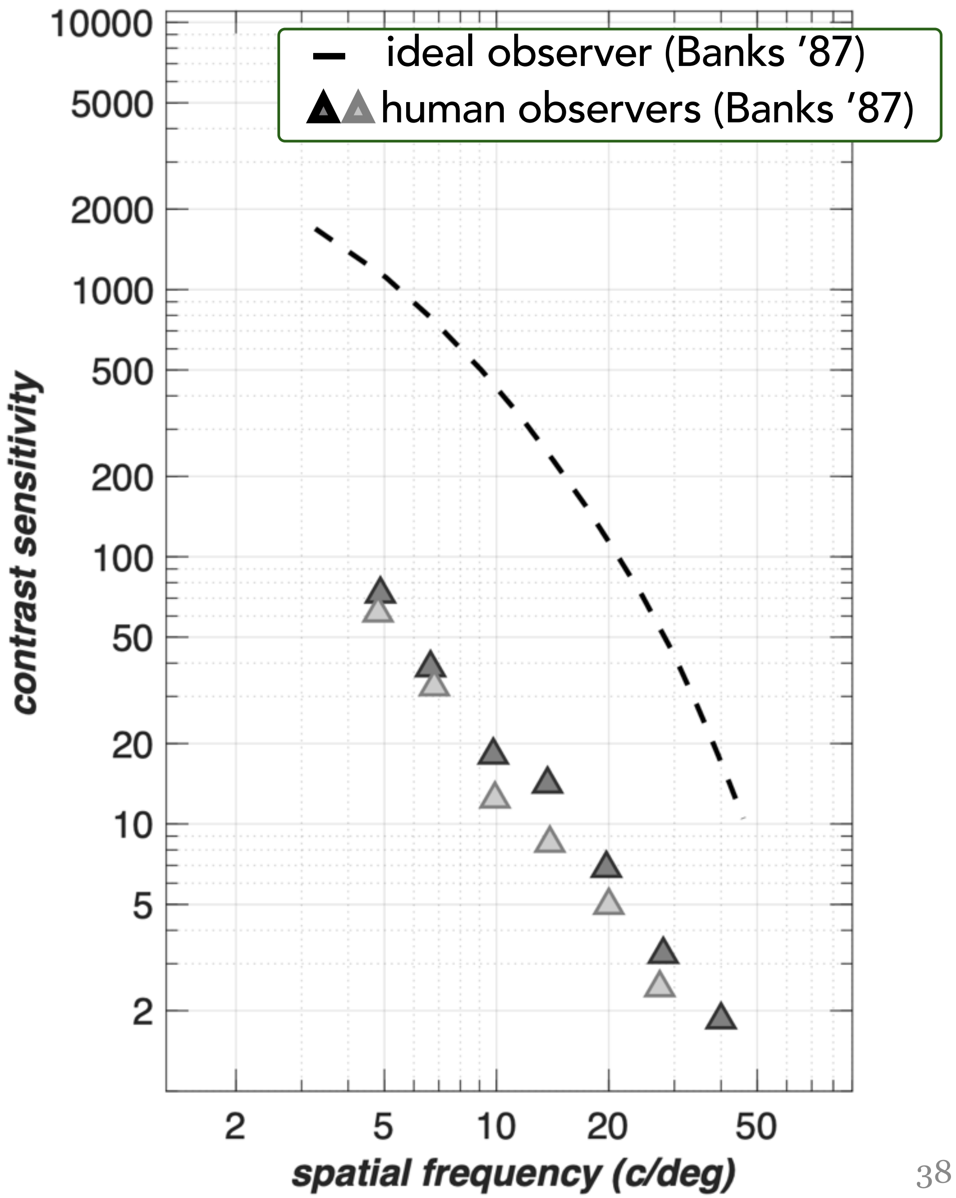


Courtesy Nicolas Cottaris

Ideal observer accounts for shape of CSF rolloff at increasing SF

- The original work from Banks et al. (1987) compared the high frequency roll-off predicted using an ideal observer and measured with a few real observers

- The predictions were based on formulae and various simplifying assumptions about the mosaic

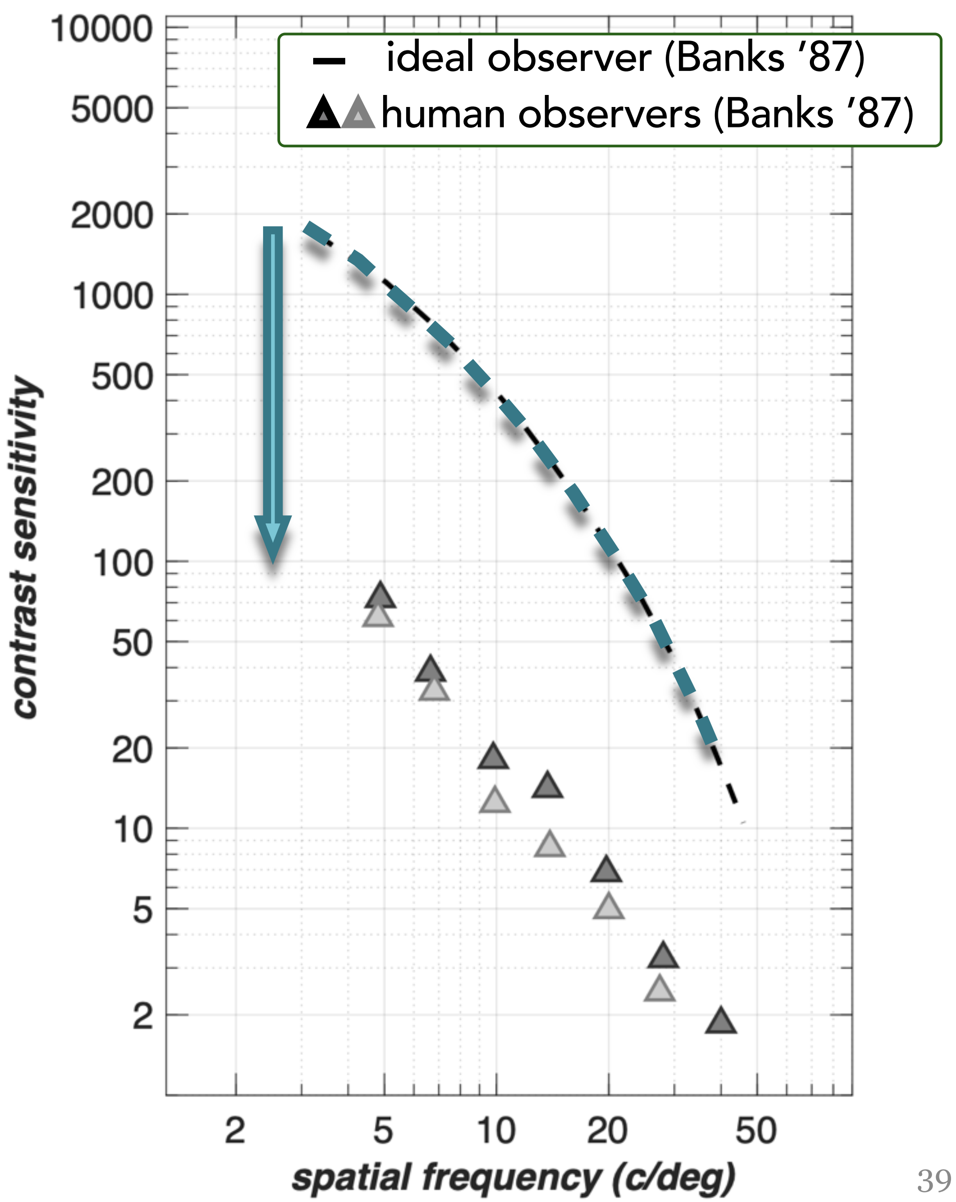


Ideal observer accounts for shape of CSF roll-off at increasing SF

- The original work from Banks et al. (1987) compared the high frequency roll-off predicted using an ideal observer and measured with a few real observers

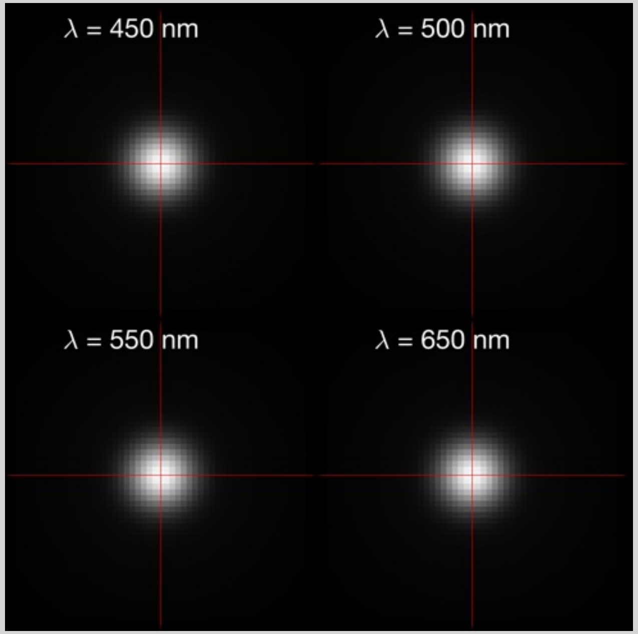
- The predictions were based on formulae and various simplifying assumptions about the mosaic

- The shapes were in good alignment



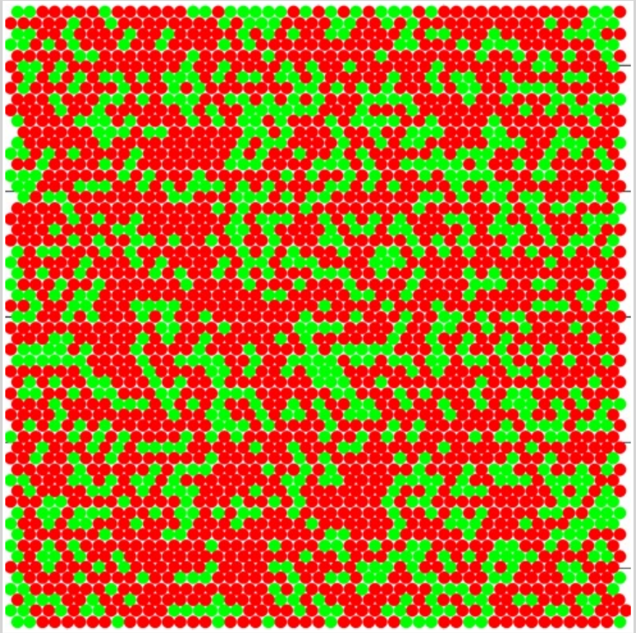
ISETBio validation: reproduce earlier ideal observer calculation

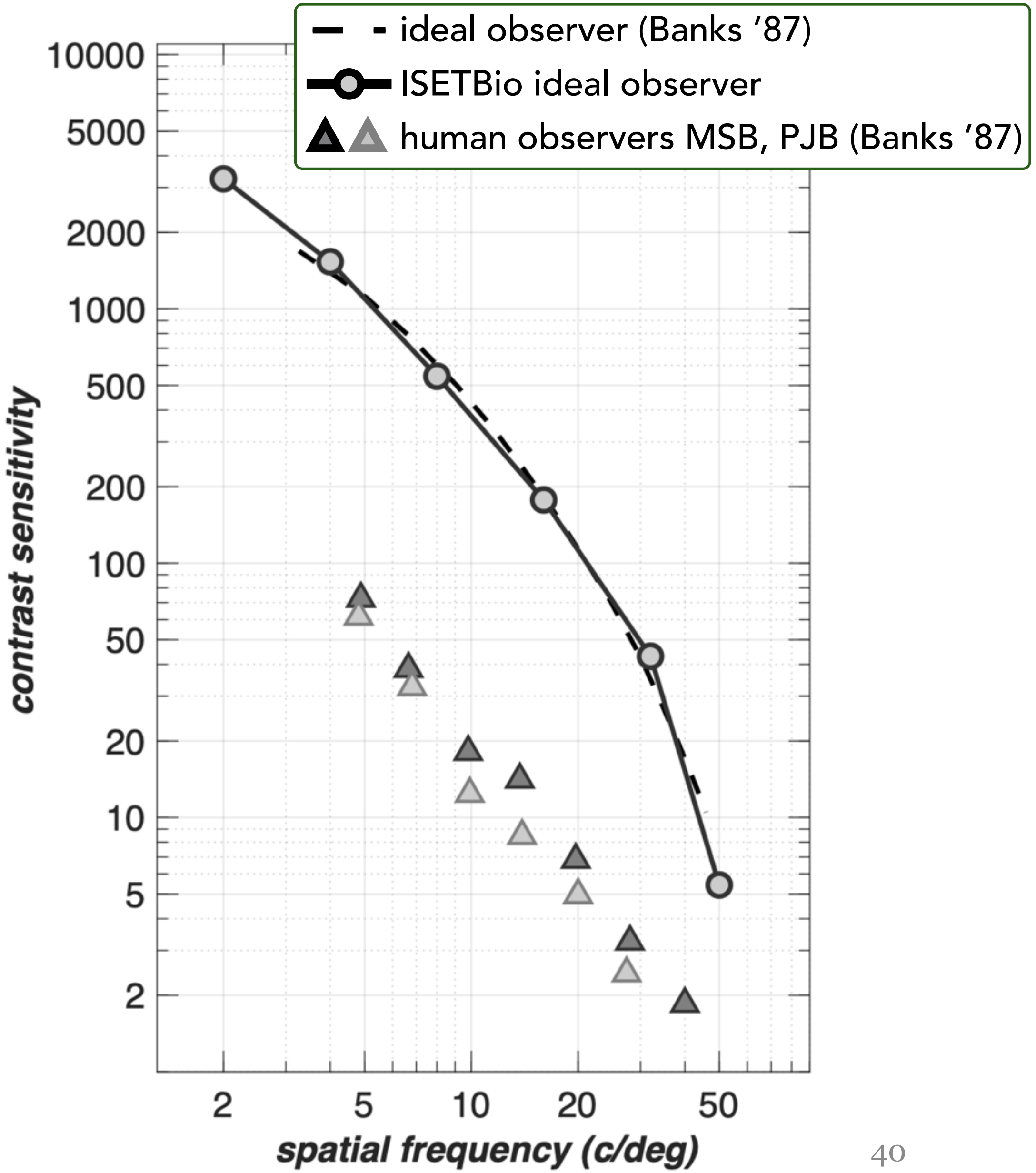
line spread function - based optics



(based on Campbell & Gubisch '66)

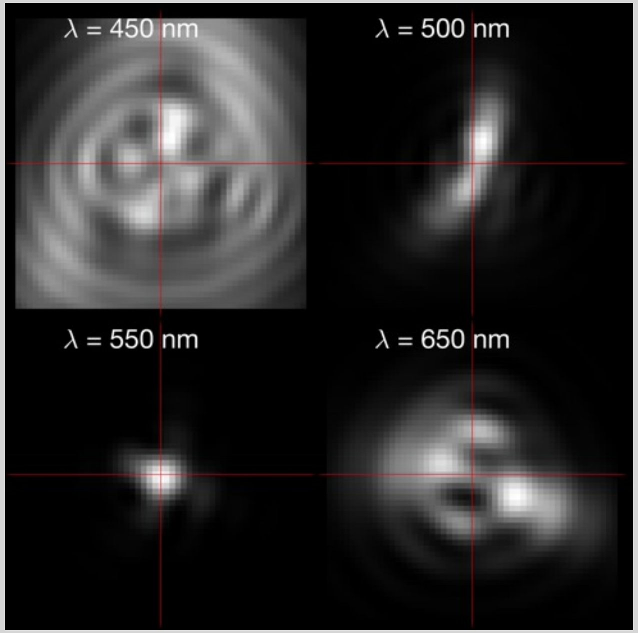
constant cone density mosaics





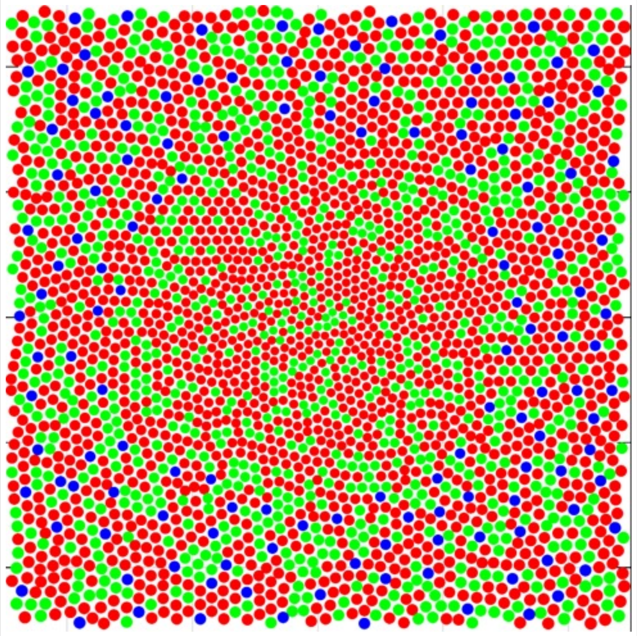
Accounting for absolute sensitivity: modern estimates of optics/mosaic

Wavefront aberration - based optics

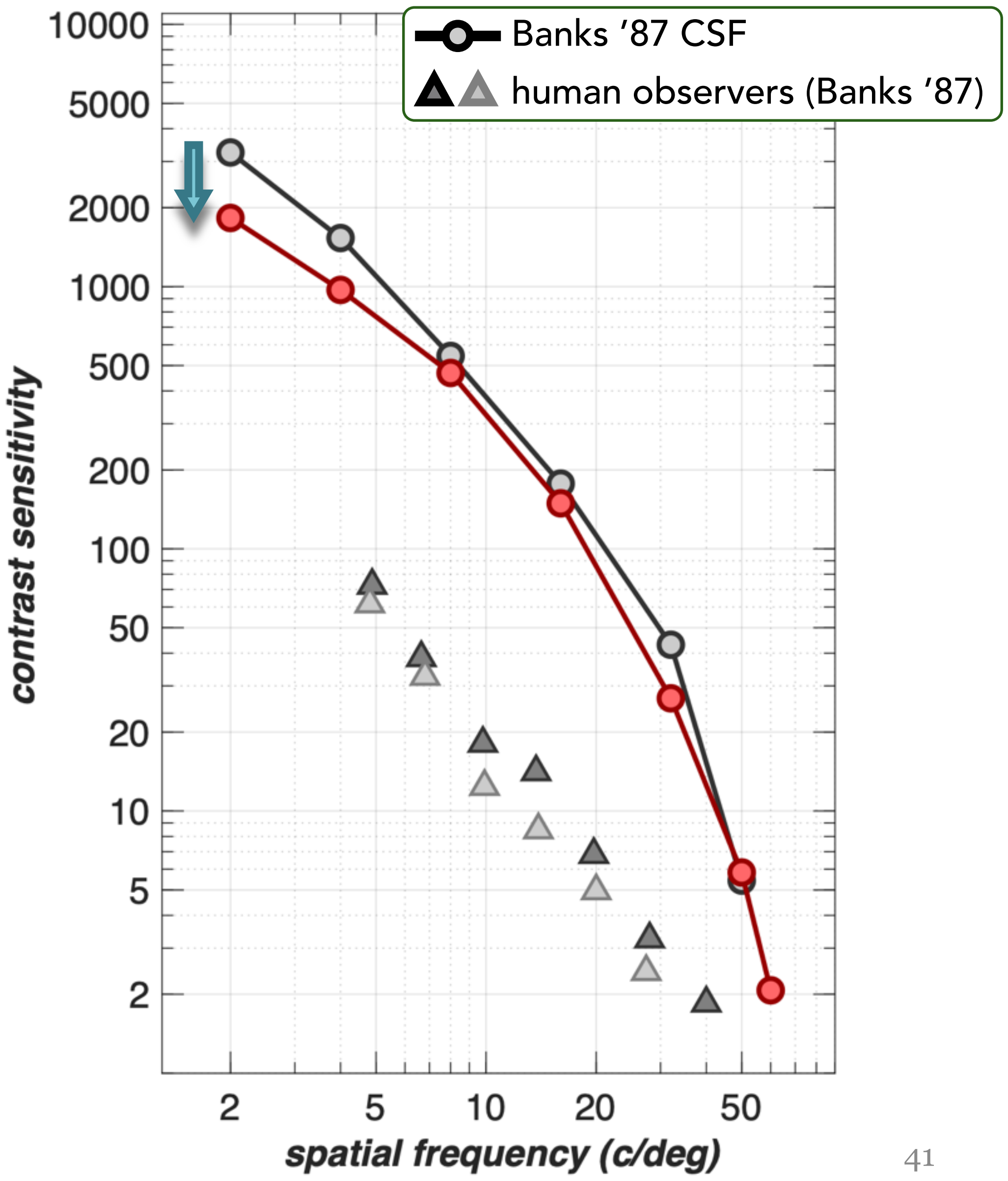


(from Thibos et al. ’92)

Eccentricity-dependent density mosaics

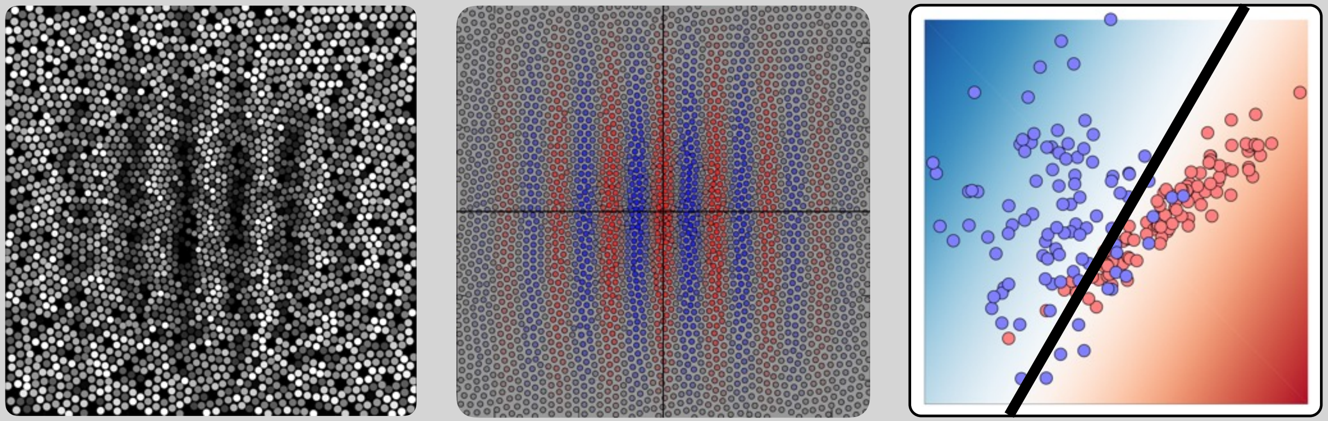


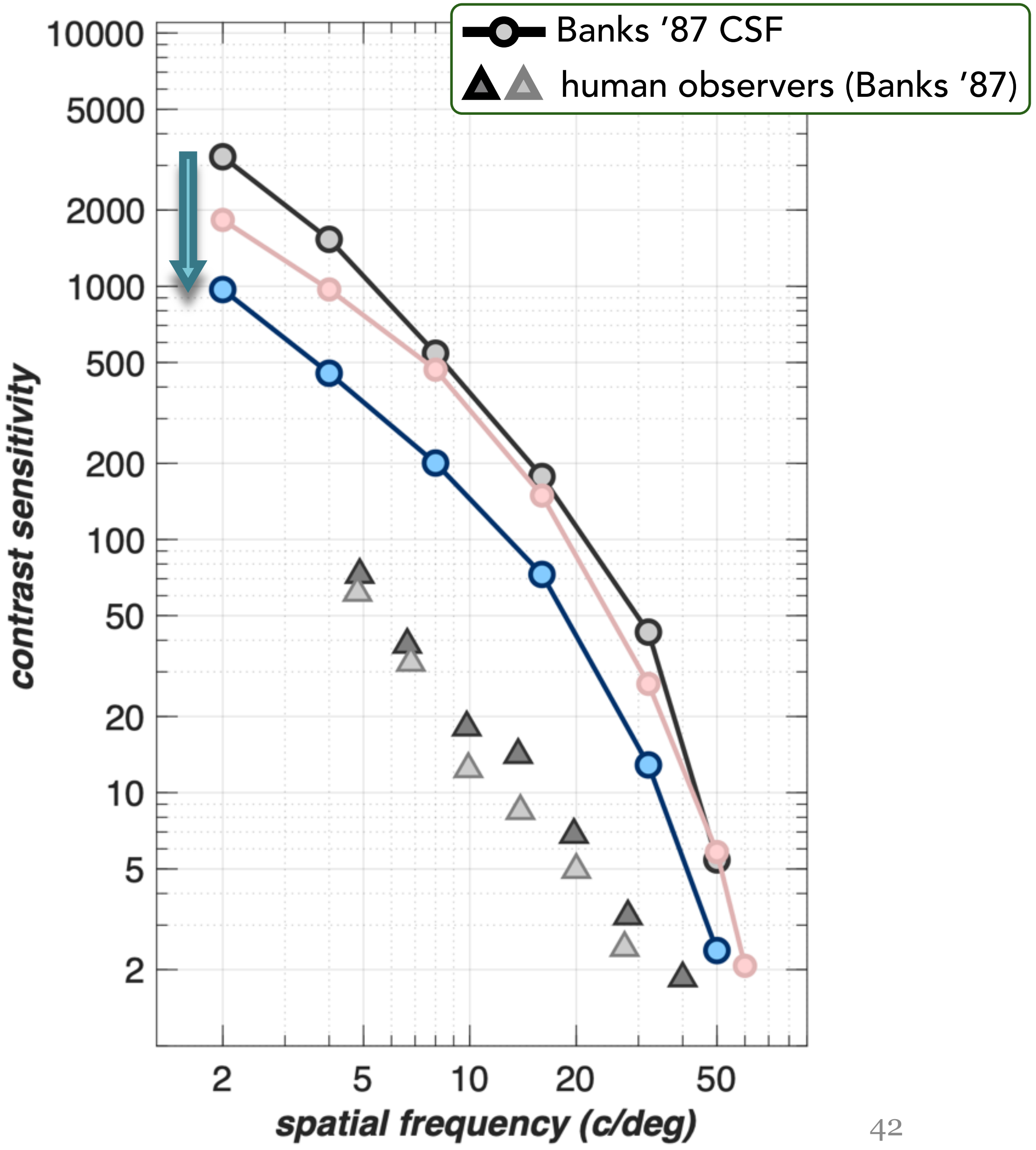
(based on Curcio et al. ’90)



Accounting for absolute sensitivity: partially learned classifier

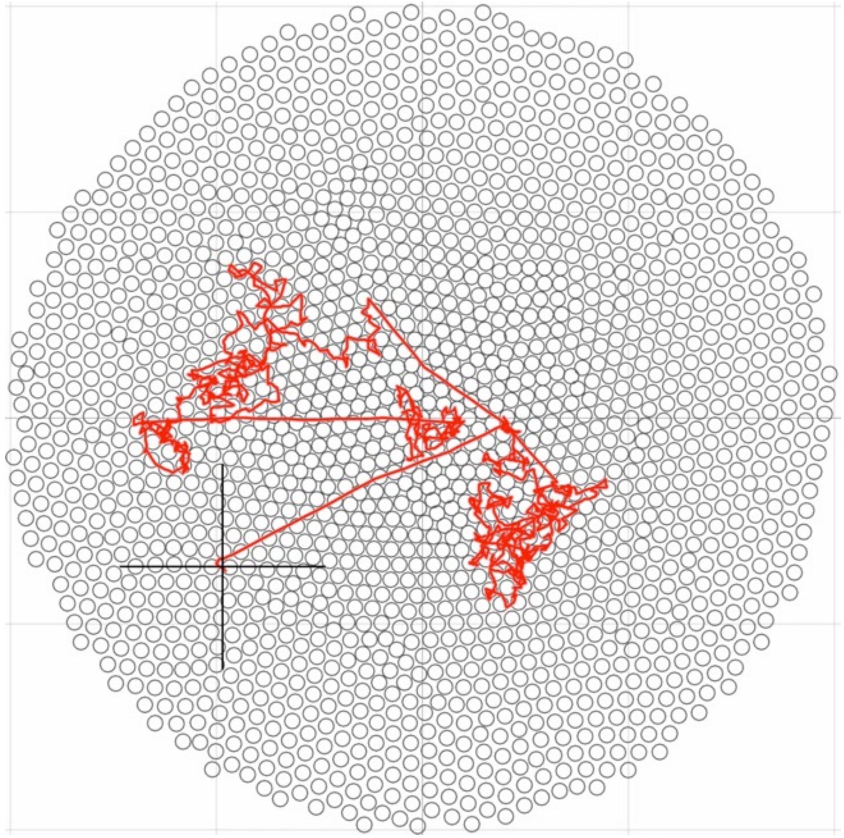
Computational observer

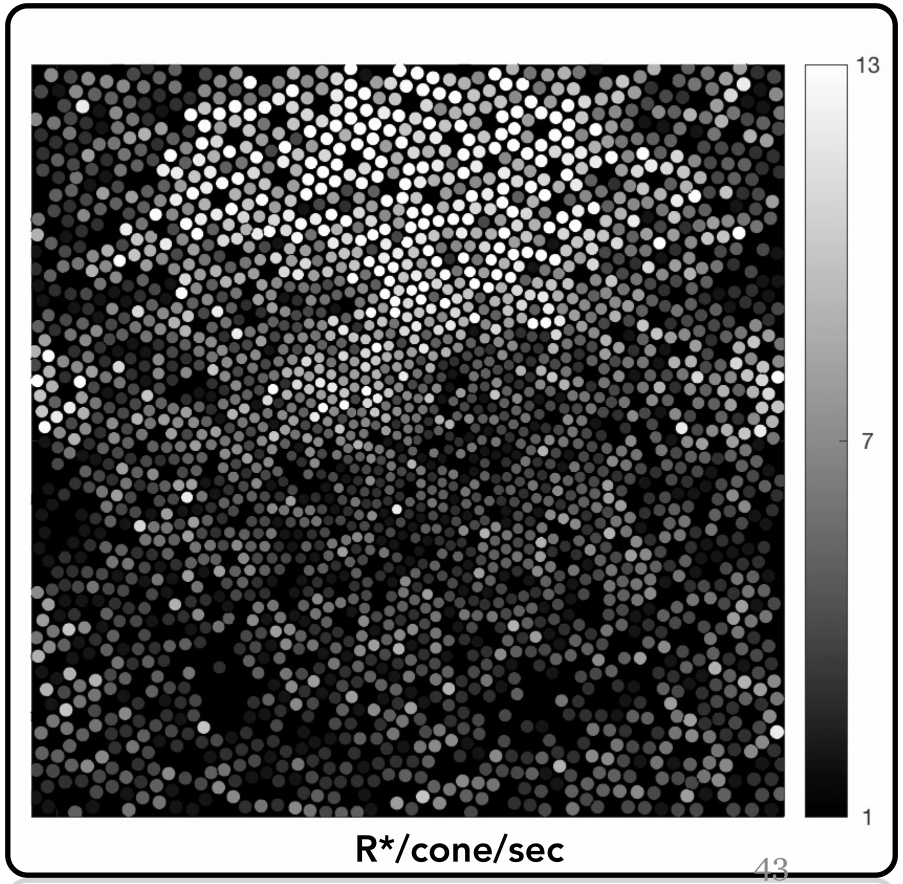




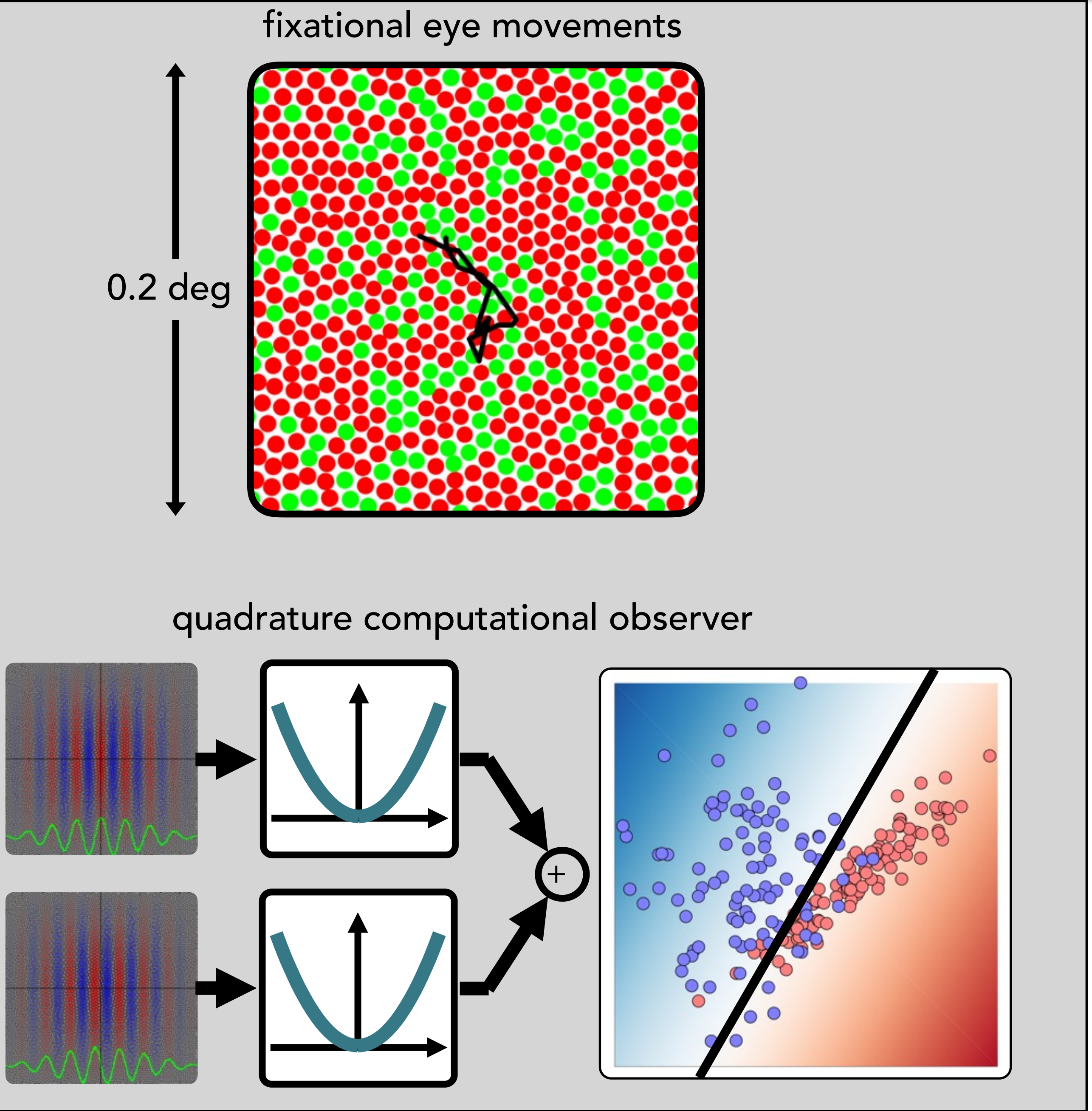
Accounting for absolute sensitivity: fixational drift

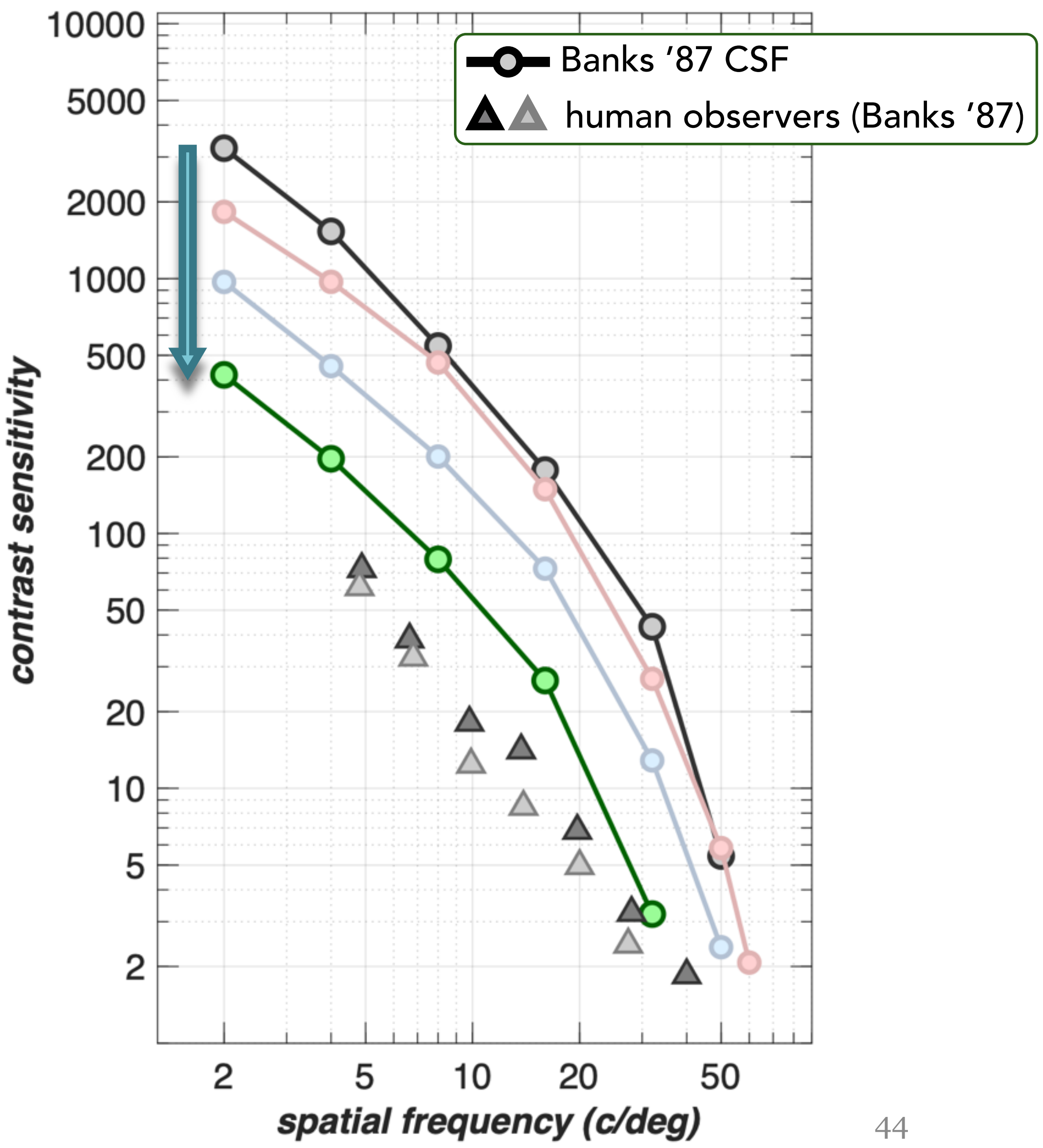
cone photopigment excitation → fixational eye movement object → cone photopigment excitation sequence





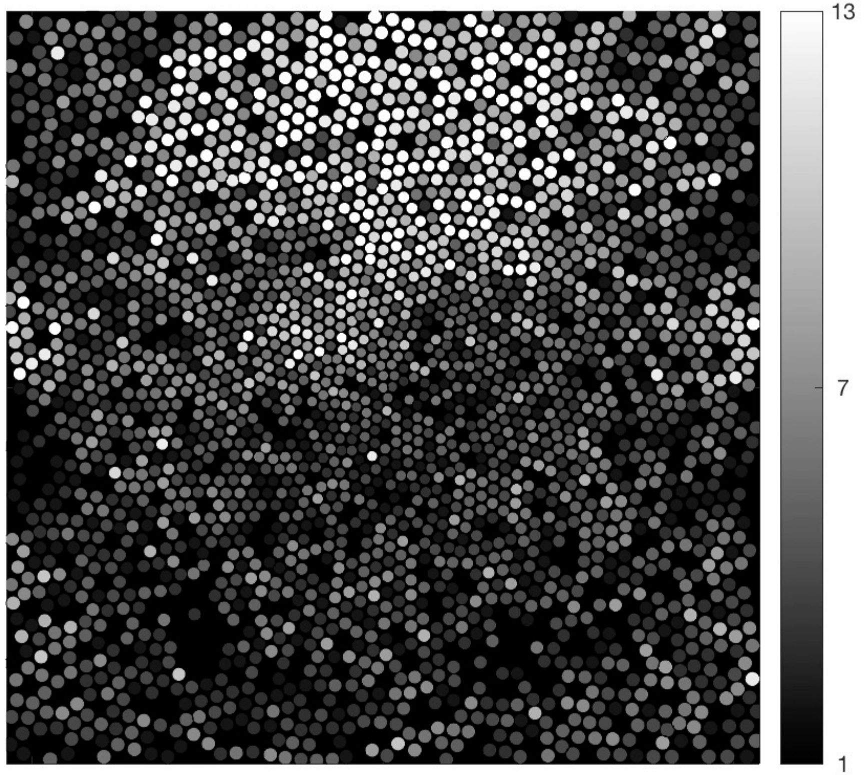
Energy computations (quadrature filters) reduce the impact of fixational drift



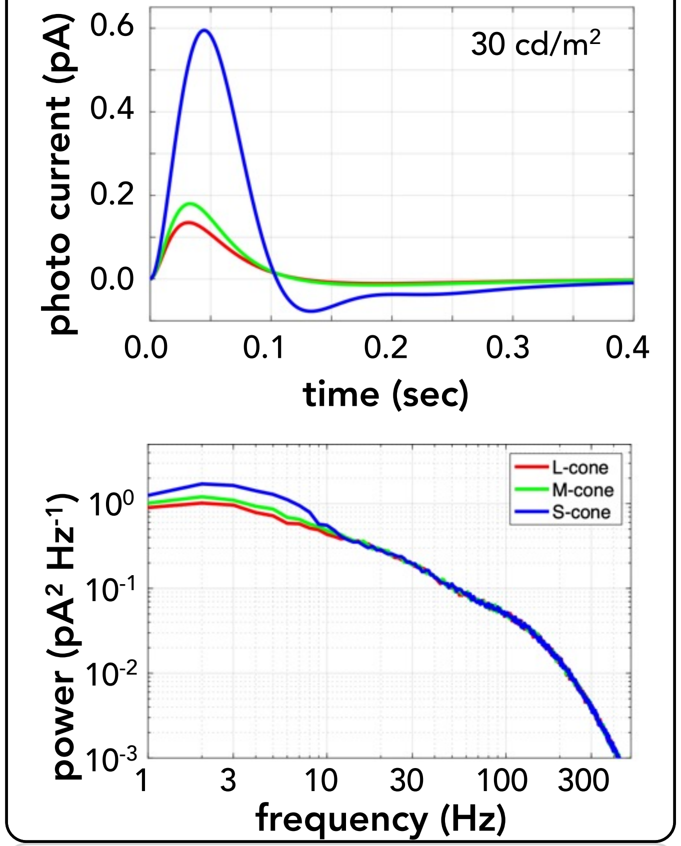


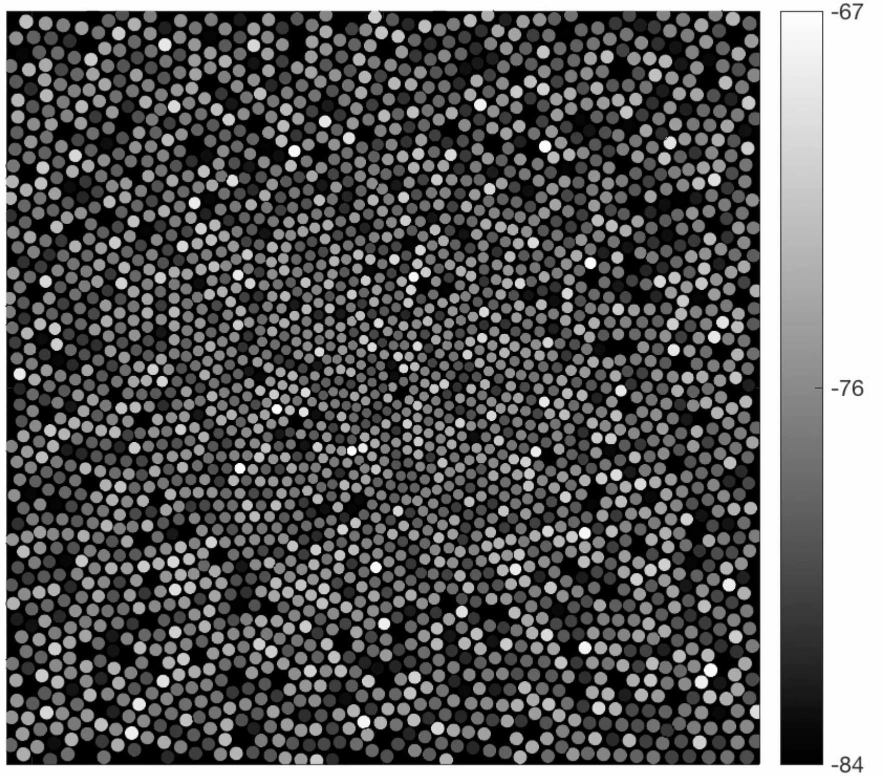
Time: Photocurrent transduction

cone photopigment excitation sequence → outer segment object → cone outer-segment photocurrent response



R*/cone/sec





pAmps

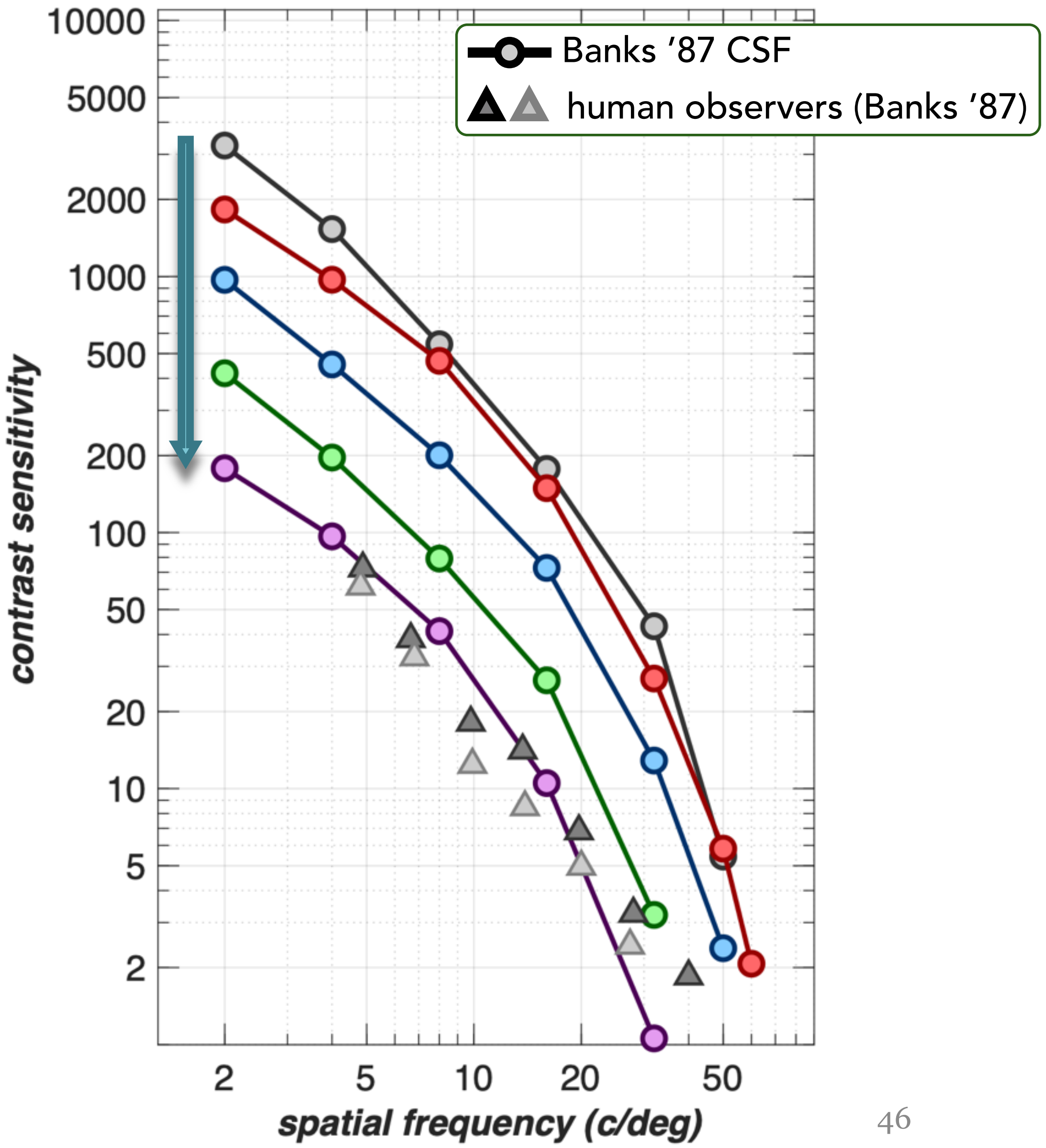
Accounting for absolute sensitivity: photocurrent transduction

1. **Updated optics & cone mosaic** modeling has a minor impact relative to the Banks '87 estimate (factor of 1.7 at 2 c/deg),

2. **Computational observers**, which learn visual tasks by observing neural responses, result in a significant sensitivity drop across the entire spatial frequency range (accumulated factor of 2-3).

3. Inclusion of **fixational eye movements**, requires non-linear computational observers, and further reduces sensitivity across the entire spatial frequency range (accumulated factor: 7-10).

4. Inclusion of **photocurrent encoding** further reduces sensitivity approaching psychophysical limits (accumulated factor:18-30).



Third point

Modeling the the visual pathways can be helpful in understanding how the complex array of biological factors combine to limit performance

Fourth point

Visual system simulation might be best understood in the broader context of image systems simulation – the visual system is a key element of many imaging systems

Simulation technologies for image systems engineering

Brian A. Wandell
Stanford Center for Image Systems Engineering
Department of Psychology

The number and type of imaging systems has grown enormously over the last several decades; these systems are an essential component in mobile communication, medicine, automotive and drone applications. Imaging systems are also increasingly used with deep learning systems that require large amounts of training data. For these reasons software prototyping has become an essential tool for the design, evaluation and training of modern image systems. I will describe three closely related open-source and freely available image systems engineering toolboxes, ISETCam, ISETBio, and ISET3d that are designed to support design and evaluation of image systems. The presentation will include several examples of how we model the three-dimensional scene spectral radiance, retinal encoding (physiological optics and cone sampling), and image systems hardware (multi-element lenses, image sensors). We are working with the goal of building image systems simulation infrastructure that can speed the development of new systems as academia and industry rise to meet many new opportunities.

Related publications

ISETAuto: Detecting vehicles with depth and radiance information (2021). Zhenyi Liu, Joyece Farrell, Brian Wandell, **IEEE Access** **10.1109/ACCESS.2021.3063692**

A system for generating complex physically accurate sensor images for automotive applications (2019). Zhenyi Liu, Minghao Shen, Jiaqi Zhang, Shuangting Liu, Henryk Blasinski, Trisha Lian, Brian Wandell. **IS&T Electronic Imaging Conference,** San Francisco.

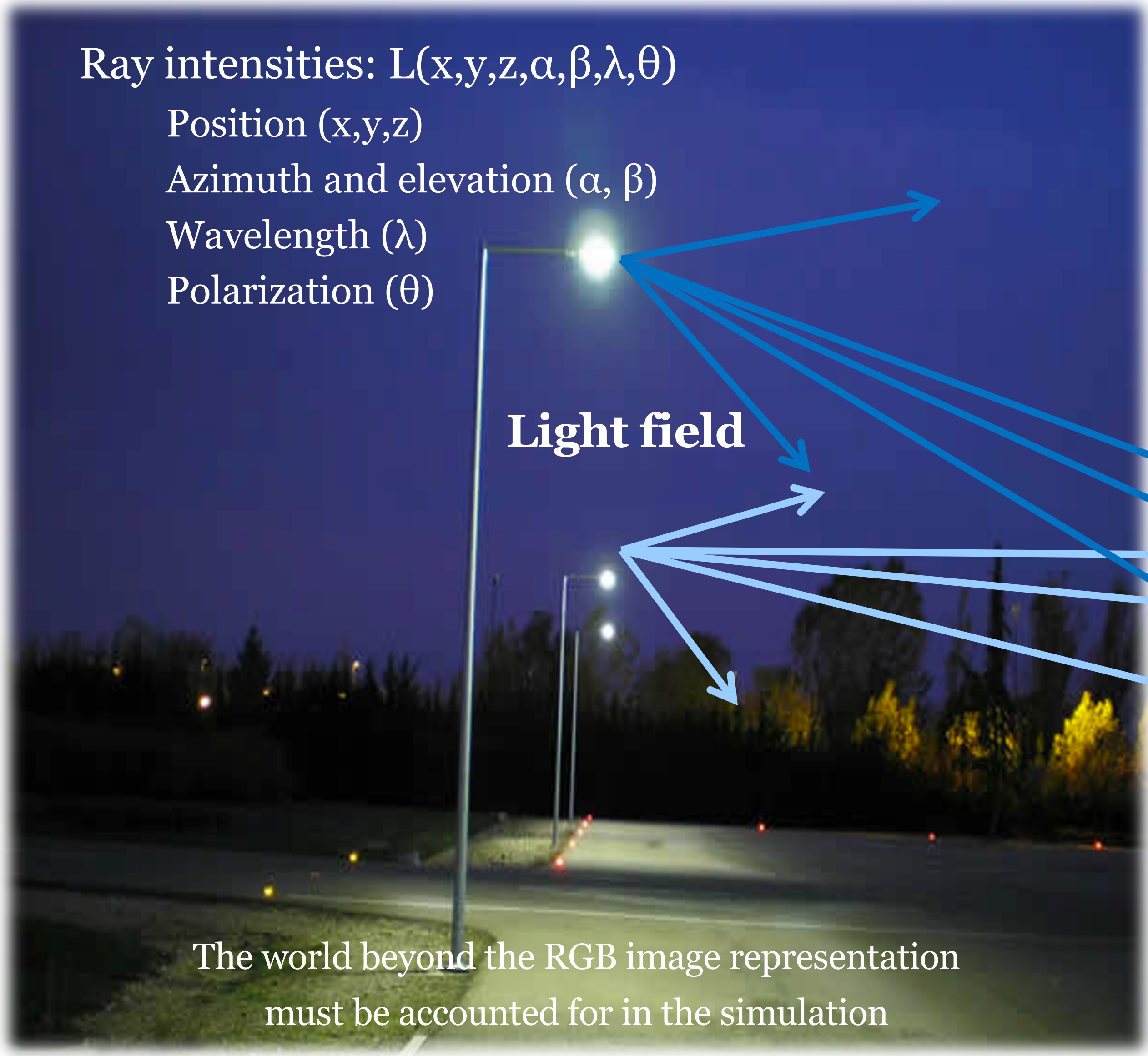
Ray tracing 3D spectral scenes through human optics models (2019). Trish Lian, Kevin McKenzie, David Brainard, Nicolas Cottaris, Brian Wandell. **Journal of Vision** October 2019, Vol.19, 23. doi:https://doi.org/10.1167/19.12.23

A computational observer model of spatial contrast sensitivity: Effects of photocurrent encoding, fixational eye movements and inference engine (2020). Nicolas P. Cottaris, Brian A. Wandell, Fred Rieke, David H. Brainard **Journal of Vision** doi:https://doi.org/10.1167/jov.20.7.17

See the wiki pages of the repositories at: https://github.com/ISET

3D scene spectral radiance in the world and at the eye

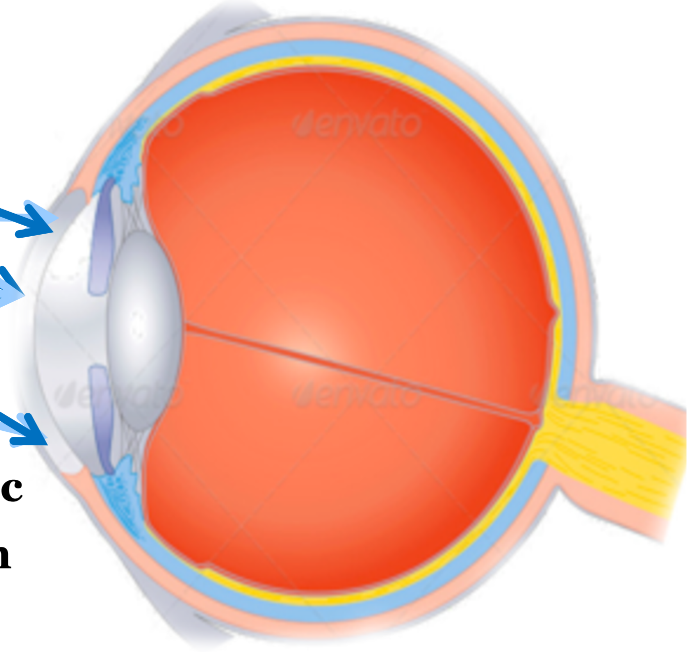
Gershun (1936)



Adelson and Bergen (1991)

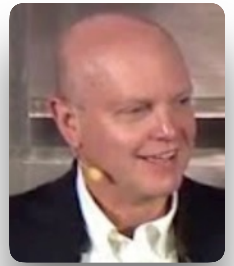
Ray intensities: L(u,v,α,β,λ)

- Position (u,v)
- Azimuth and elevation (α, β)
- Wavelength (λ)

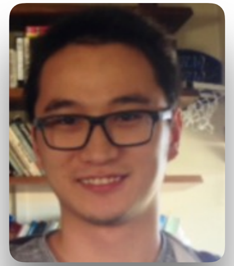


Plenoptic function

ISETBio Team and Funding


Brian Wandell


Trisha Lian


Haomio Jiang

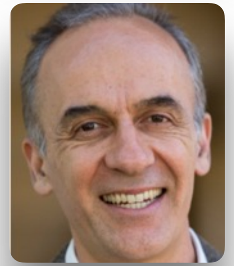

James Golden


David Brainard


Nicolas Cottaris


Xiaomao Ding

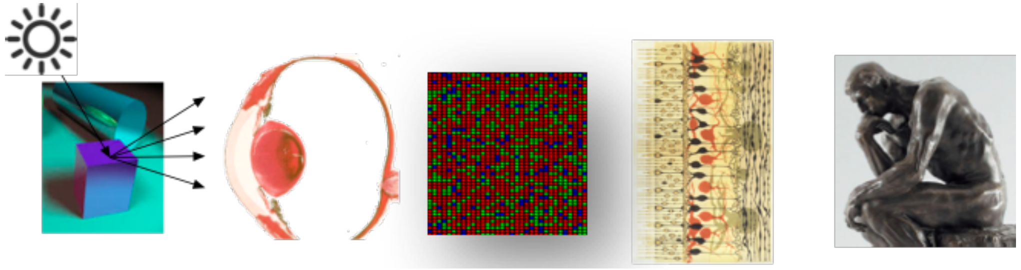

Lingqi Zhang


E.J. Chichilnisky


Fred Rieke


Joyce Farrell


Jon Winawer



facebook research

SIMONS FOUNDATION

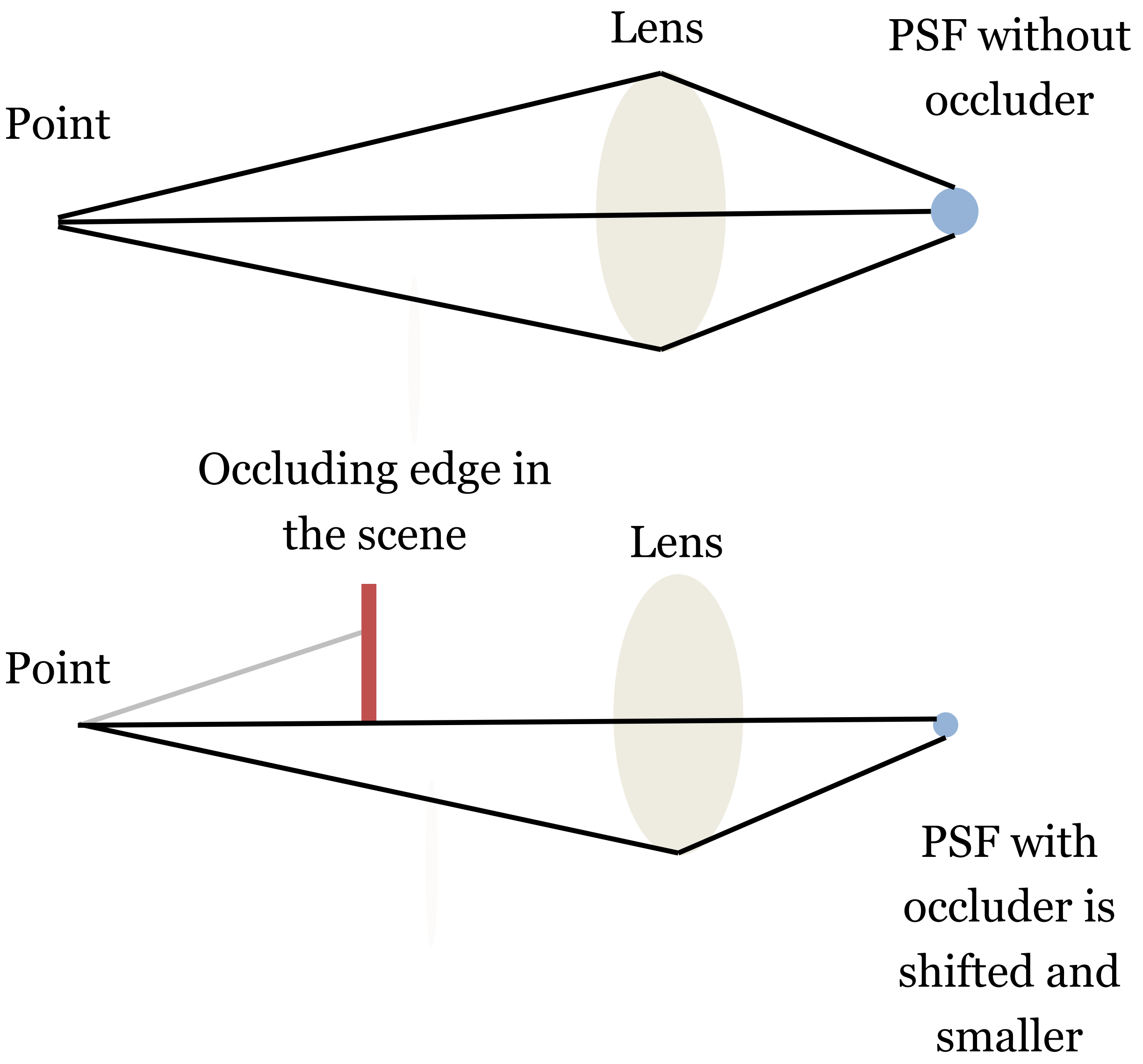
NIH National Eye Institute

Google

Ford

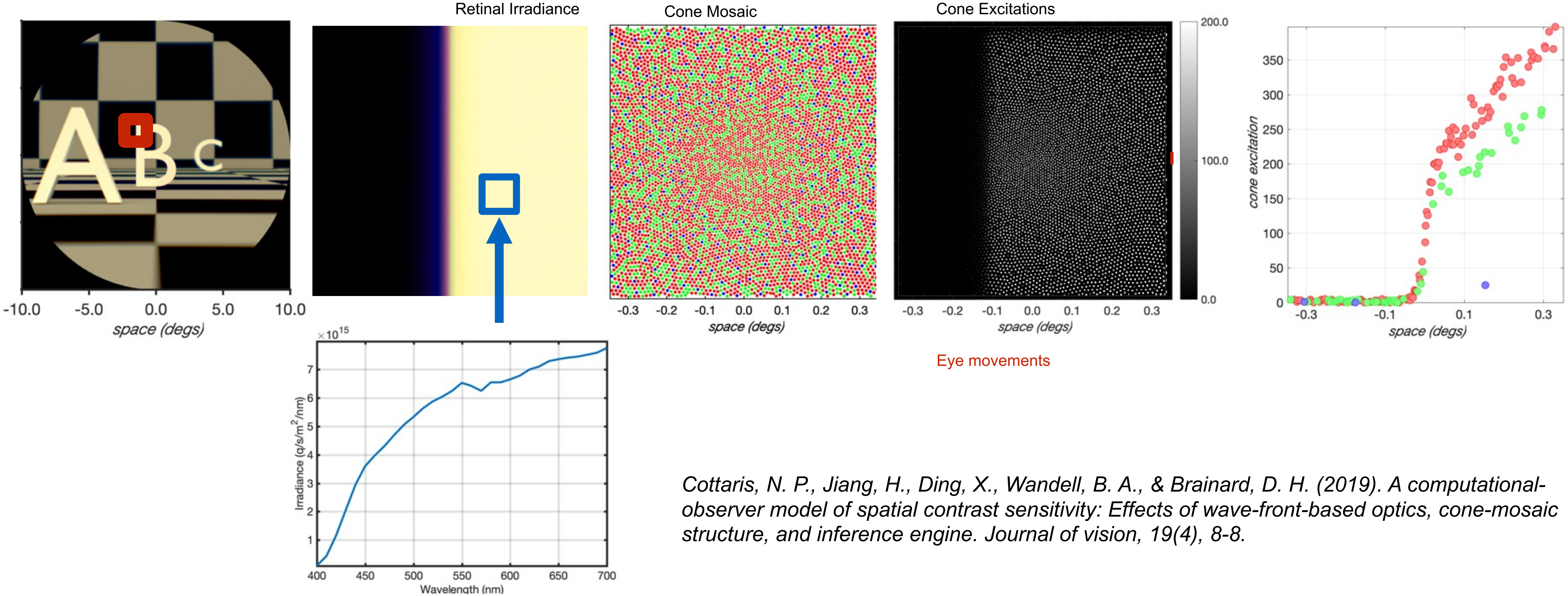
Ray trace and depth occlusions: The point spread at occluding edges

- The point spread function depends on the distance of the point (depth of field; geometric blur)
- **In addition**, the point spread depends on the presence of occluding edges in the scene
- Rays from a distant point are blocked by the near (occluding) surface
- Knowledge of the point spread as function of distance is not enough for an accurate 3D scene rendering – the rendering is scene dependent!



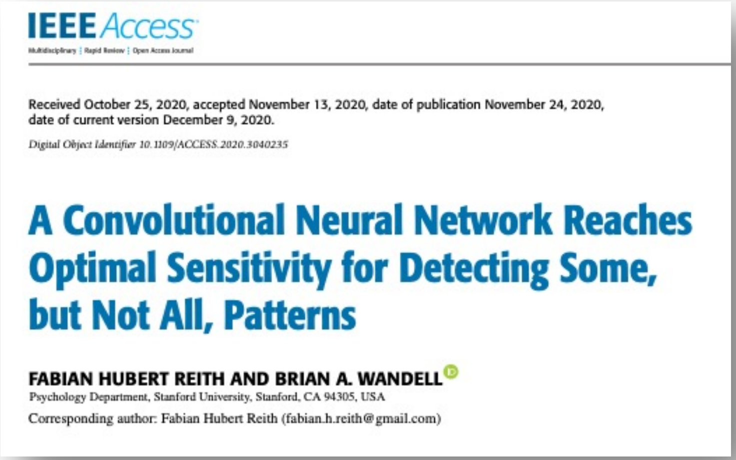
Calculating cone responses and eye movements

https://github.com/isetbio/isetbio/wiki/ISETBio-Videos
https://github.com/iset/isetcam/wiki/ISETCam-Videos
GitHub wiki video pages



Cottaris, N. P., Jiang, H., Ding, X., Wandell, B. A., & Brainard, D. H. (2019). A computational-observer model of spatial contrast sensitivity: Effects of wave-front-based optics, cone-mosaic structure, and inference engine. Journal of vision, 19(4), 8-8.

For many types of stimuli the Ideal and ResNet had the same sensitivity!


IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

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Digital Object Identifier 10.1109/ACCESS.2020.3040235

A Convolutional Neural Network Reaches Optimal Sensitivity for Detecting Some, but Not All, Patterns

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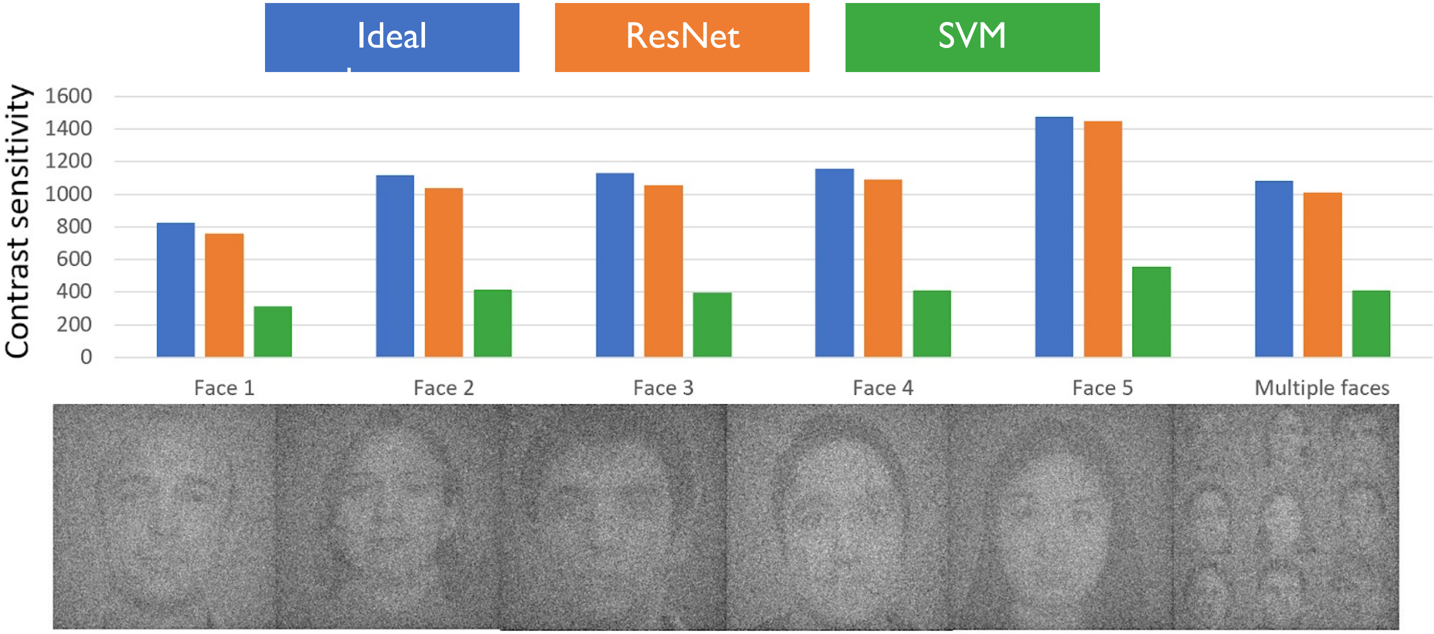
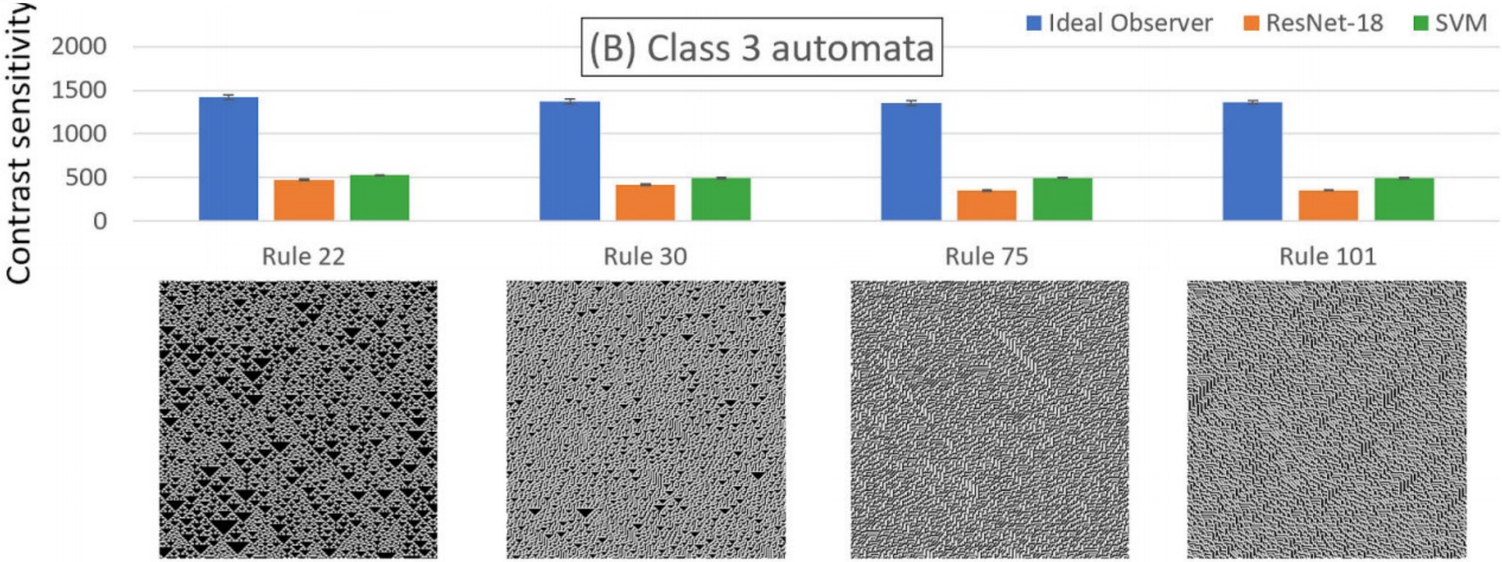
Psychology Department, Stanford University, Stanford, CA 94305, USA
Corresponding author: Fabian Hubert Reith (fabian.h.reith@gmail.com)

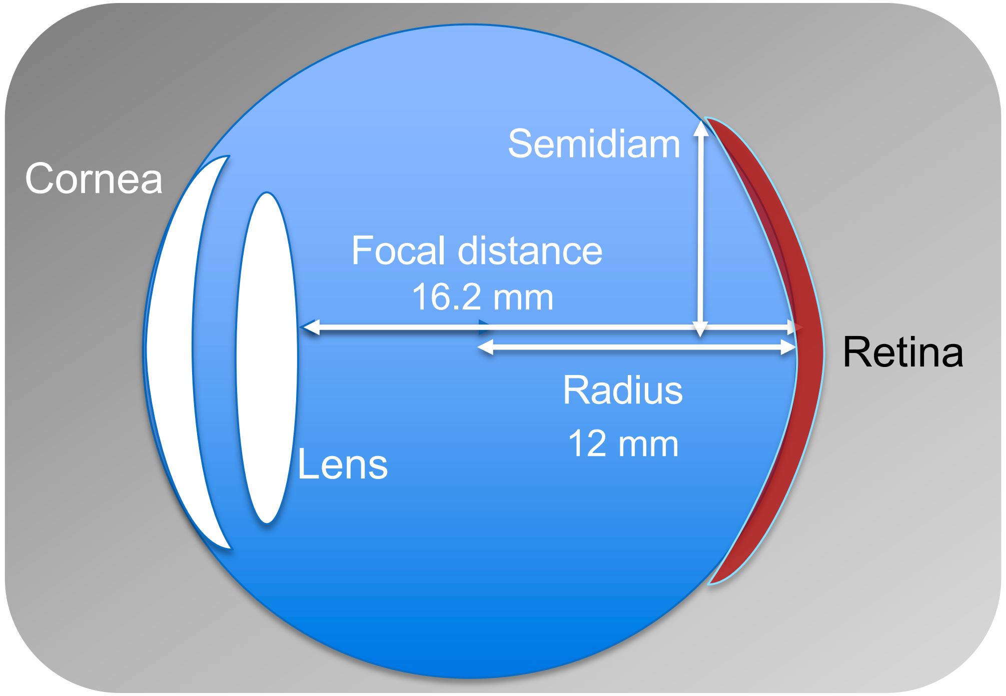




Example code: User's perspective

- We aim to make the top-level code easily understood. The computations are embedded in methods, often the set/get methods

- The sceneEye models a spherical eyeball and a curved retina, with inert pigments



The sceneEye class constructor

thisSE = sceneEye('letters at depth', 'human eye', 'legrand');

PBRT files   Human eye model

```
>> thisSE

thisSE =

  sceneEye with properties:

         name: 'lettersAtDepth'
    modelName: 'legrand'
   usePinhole: 0
       recipe: [1×1 recipe]
  lensDensity: 1
```

Example code

- The code doing the computational work in ISET3d is managed within
  - The set/get methods
  - PBRT calculations
- You can ‘set’ many camera, rendering, and scene parameters
- You can ‘get’ many more parameters by calculation
- There are a number of methods ‘render’,’summary’ and others

```
% Suppose you are in focus at the proper distance to the edge. And we turn
% on chromatic aberration.  That will slow down the calculation, but makes
% it more accurate and interesting.  We only use 8 spectral bands for
% speed.  You can use up to 31.
nSpectralBands = 8;
thisSE.set('chromatic aberration',nSpectralBands);

% This is the distance we calculate above
thisSE.set('focal distance',1);

% Controls the rendering noise vs. speed by setting the number of rays.
thisSE.set('rays per pixel',128);

% Increase the spatial resolution by adding more spatial samples.
thisSE.set('spatial samples',384);

% This takes longer than the pinhole rendering, so we do not bother with
% the depth.
oi = thisSE.render('render type','radiance');
oiWindow(oi);
```

ISET3d: Making a stereo pair

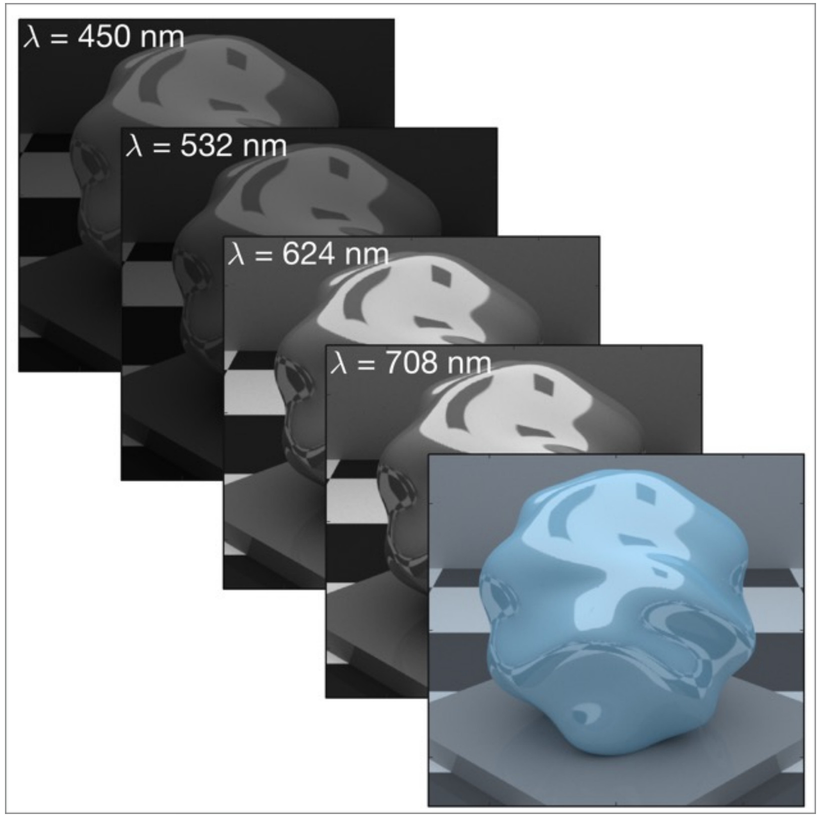
- This ISET3d code makes the stereo pair of the Chess retinal irradiance, imaged through the Navarro model eye

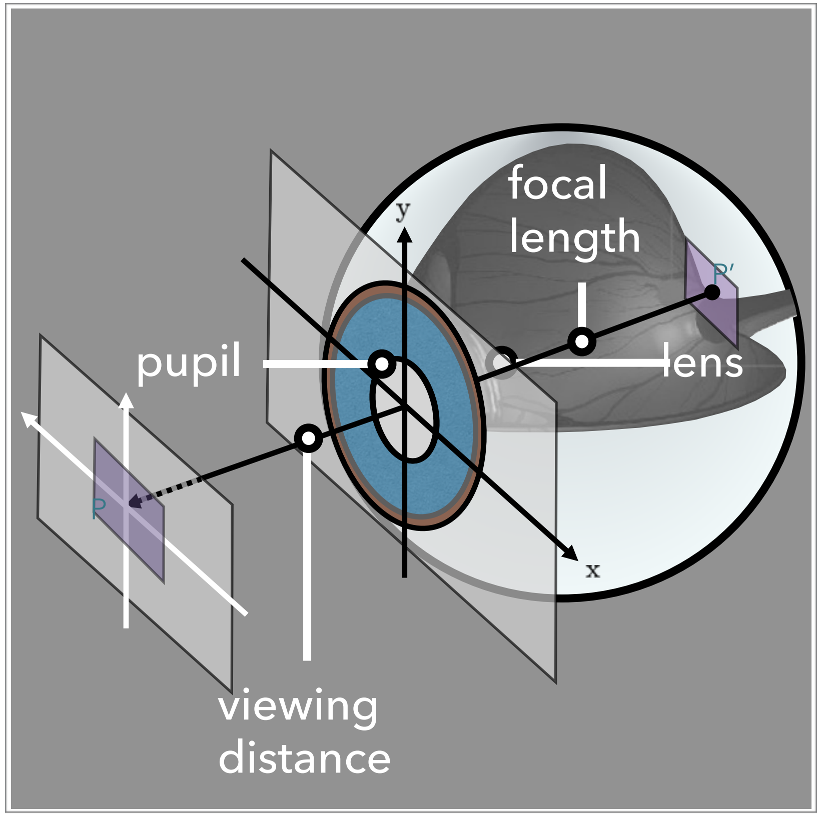
- I set the lens density to "0" so the scene would not look very yellow. I will explain this in a moment

```
%% Make an oi of the chess set scene using the LeGrand eye model

thisSE = sceneEye('chess set scaled','human eye','navarro');

thisSE.set('lens density',0);    % Just because I can

thisSE.set('rays per pixel',512);  % Pretty quick, but not high quality

oiLeft = thisSE.render;  % Render radiance and depth, and then show
oiWindow(oiLeft);

%% Shift the eye position

% Change the eye position (from) but stay focused on the same object (to).
% I shifted the eye position by a lot (12 mm) so the image difference is be
% easy to see.  The inter-pupil difference is really only 6-8 cm

fromLeft = thisSE.get('from');            % Current camera location
fromRight = fromLeft + [6,0,0]*1e-2;     % Shift it 6 cm
thisSE.set('from',fromRight);

oiRight = thisSE.render('render type','radiance');
oiWindow(oiRight);
```

ISETBio components – scene and retinal image

scene object → optics object

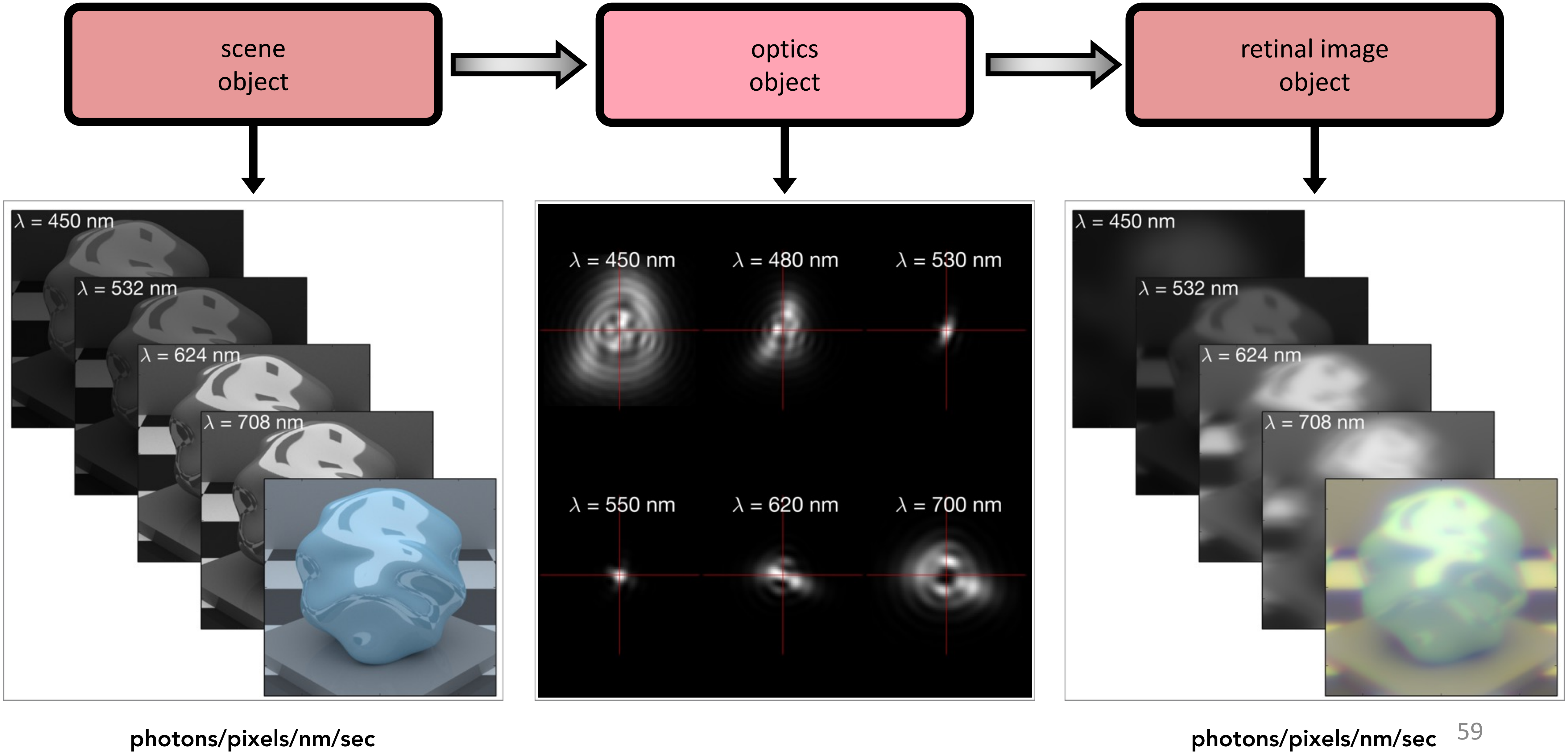




photons/pixels/nm/sec

Courtesy Nicolas Cottaris

ISETBio components – scene and retinal image



Sixth point

Many modern computer science methodologies can make these ideas into a useful industrial and academic tool – database extensions, cloud-scaling, platform independence.

Building a consensus (validated) platform will be beneficial to the imaging industry

Thank you for your attention

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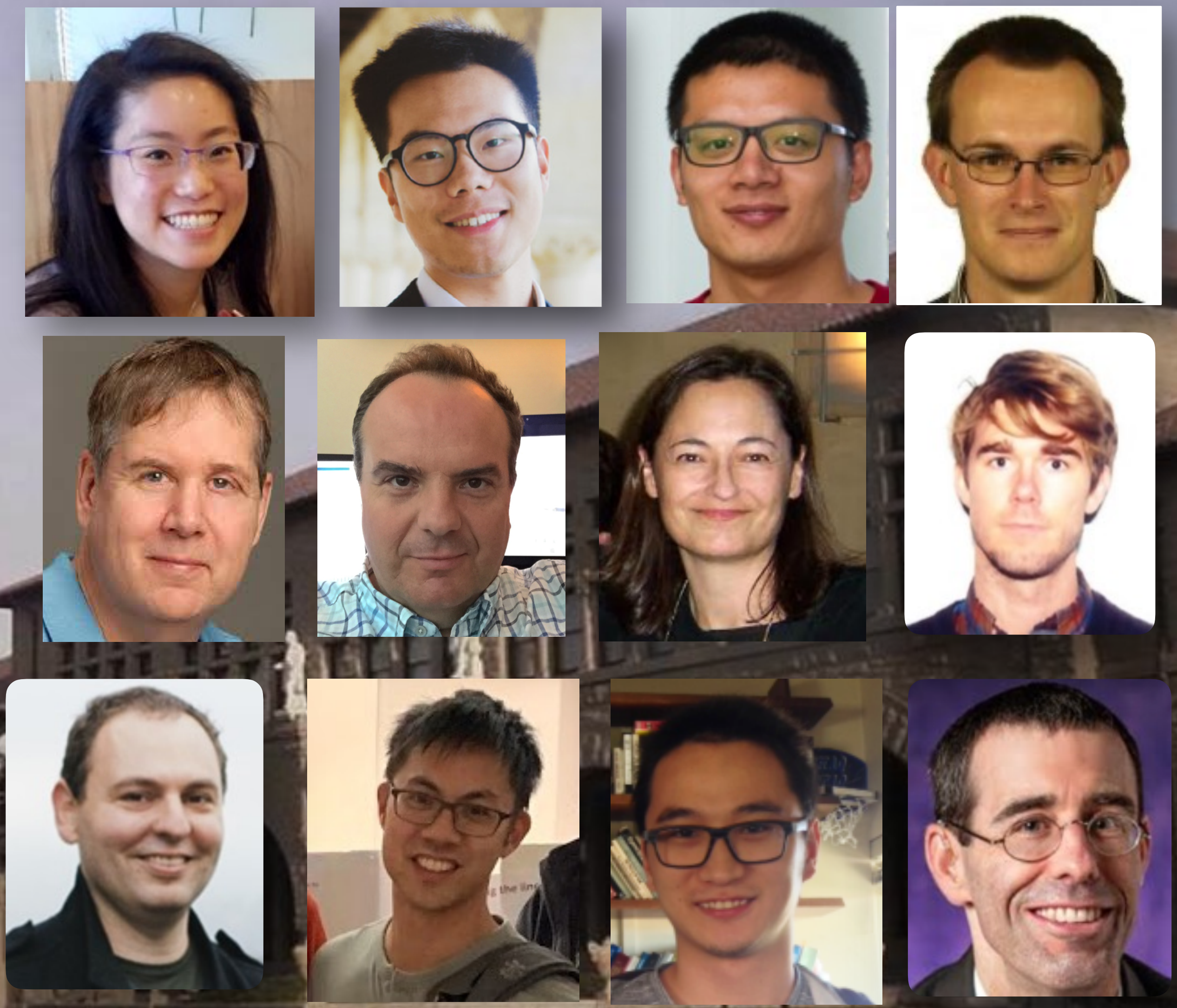
QUANTITATIVE MEASUREMENTS

∞

COMPUTATIONAL MODELS

∞

CHECK AND SHARE



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