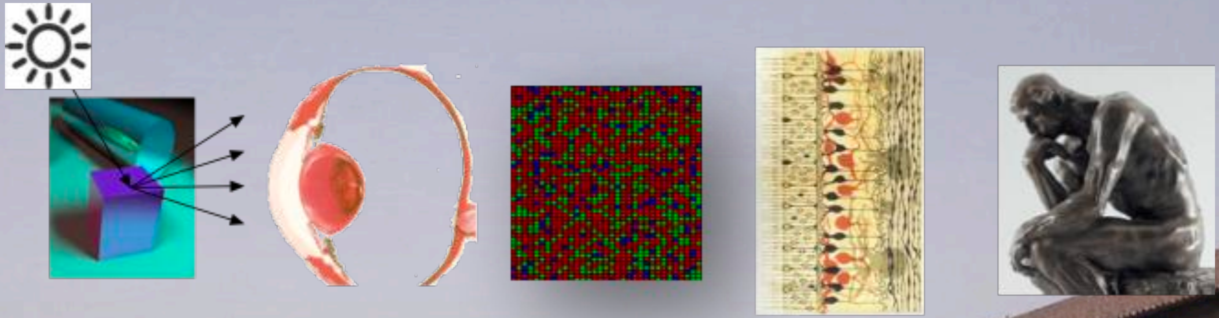
Modeling the Initial Steps of Human Vision

Brian Wandell, Stanford University
David Brainard, University of Pennsylvania

ISETBio and ISET3d: Modeling 3D scenes and human image formation

Brian Wandell and David Brainard



QUANTITATIVE MEASUREMENTS

∞

COMPUTATIONAL MODELS

∞

CHECK AND SHARE

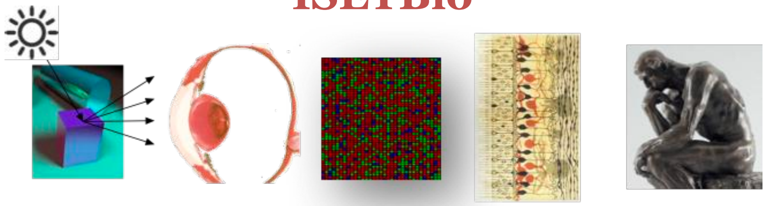
What I review and why

- **Background:** ISETBio (Image Systems Engineering Tools for Biology) provides computational tools that implement the ideas developed by vision scientists.

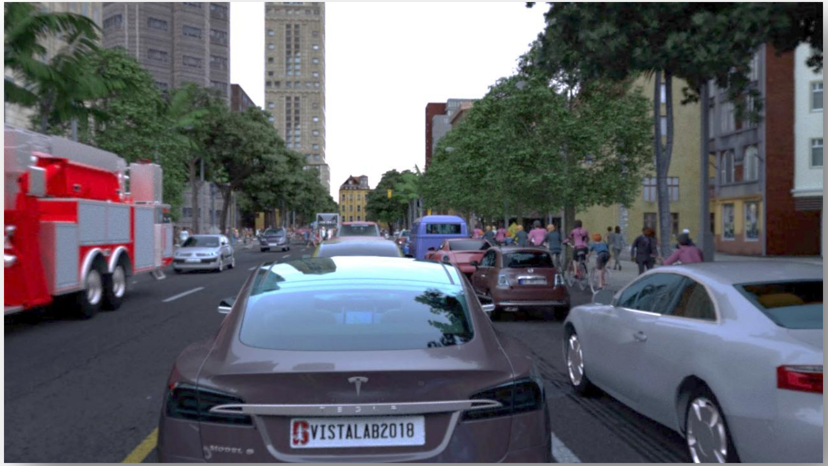
- **What:** ISET3d is are tools that extend ISETBio computations from planar images into three-dimensional scenes. My goal today is to explain ISET3d.

- **Why:** The extension to 3D may be 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.

ISETBio

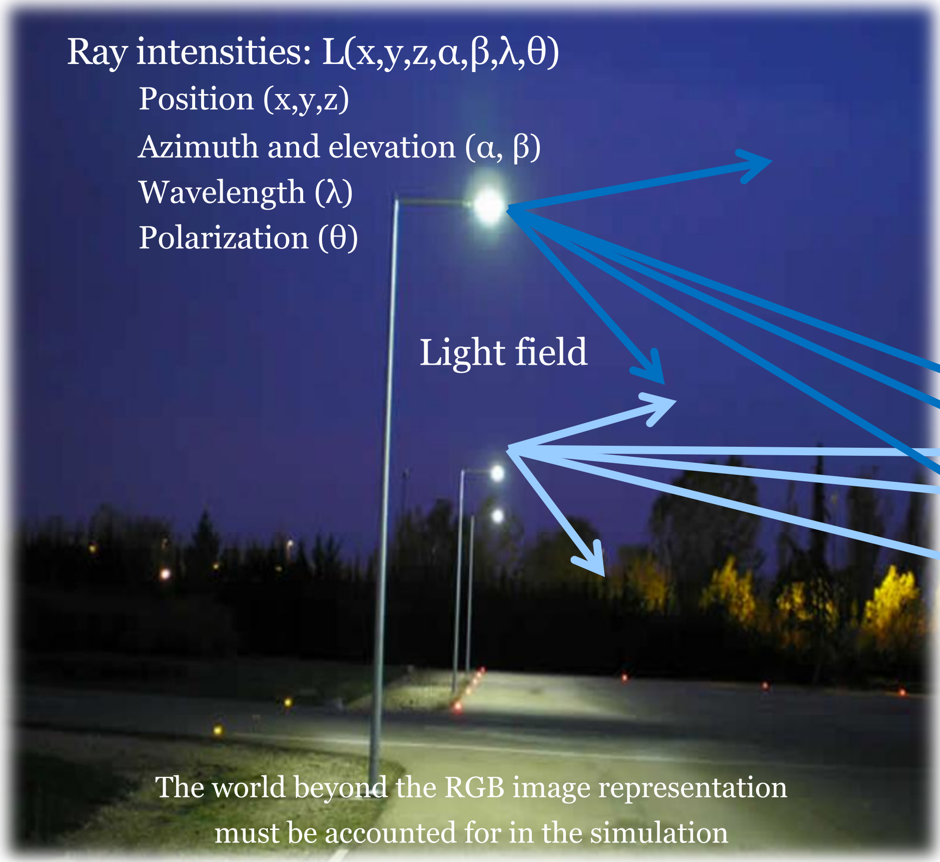


ISET3d



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

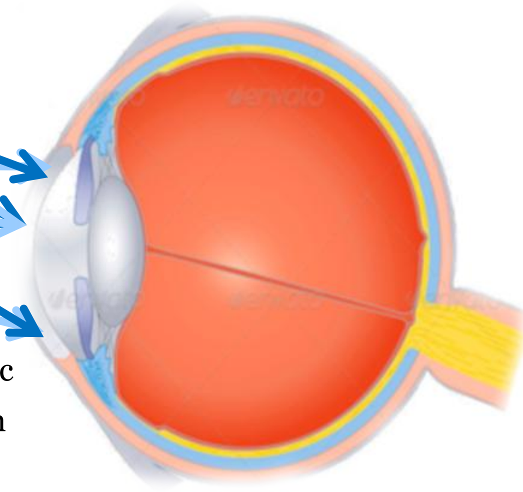
Gershun (1936)



Adelson and Bergen (1991)

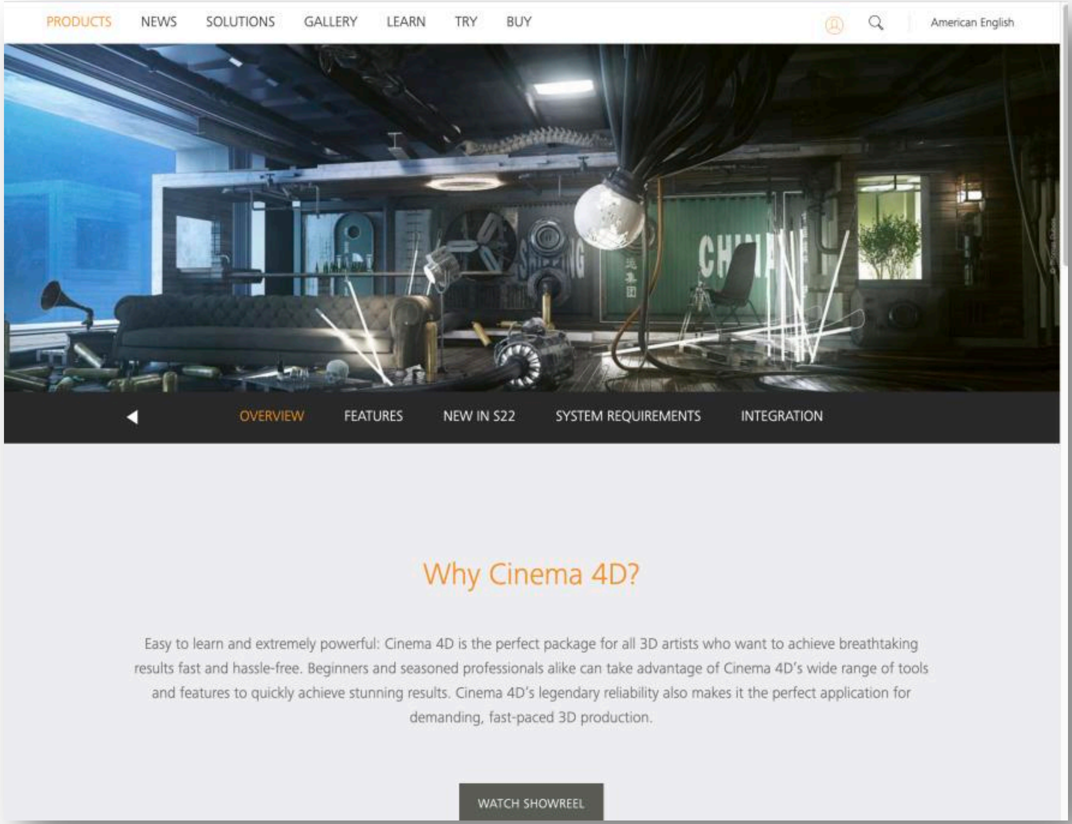
Ray intensities: L(u,v,α,β,λ)

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



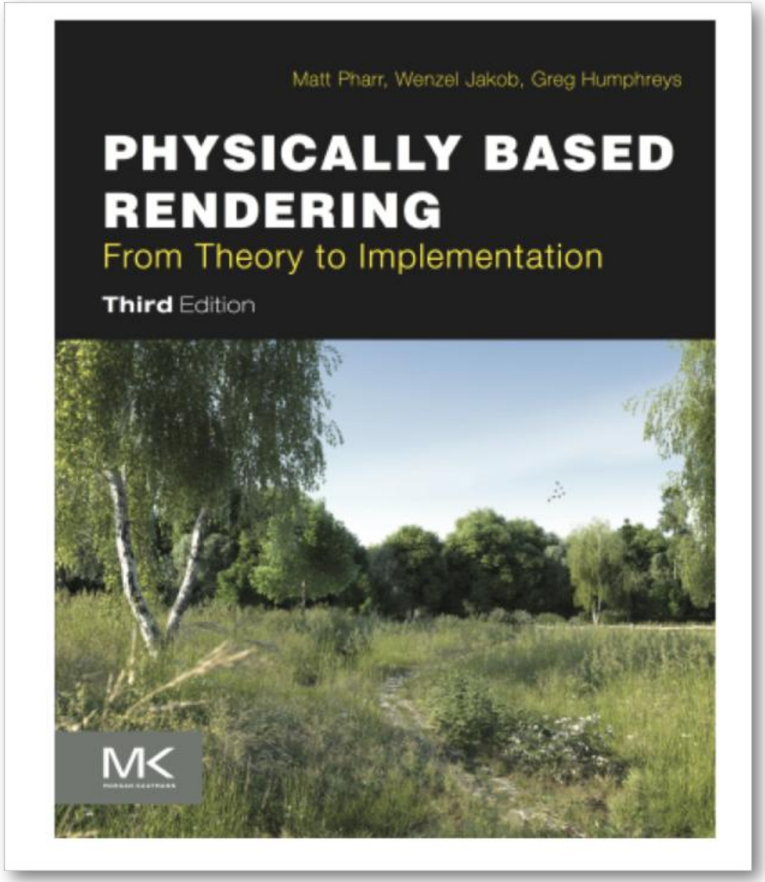
Graphics tools: Cinema 4D

- There are many tools for creating realistic 3D scene geometries
- We use Cinema 4D from Maxon because it integrates well with ray tracing methods
- Maxon offers **free** Cinema 4D licenses to students and teachers, and low- or no-cost “lab” licenses for schools.



Graphics tools: Quantitative computer graphics is a necessary component

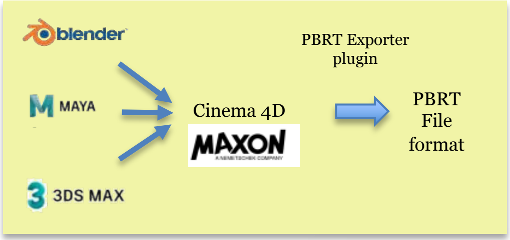
- Progress in computer graphics enables us to create synthetic and yet highly realistic input data.
- We use PBRT because it is open-source, extensible, and taught at Stanford
- The simulations can maintain meaningful units; quantitative computer graphics
- A GPU version is scheduled to be released by Pharr et al. in about 2 months



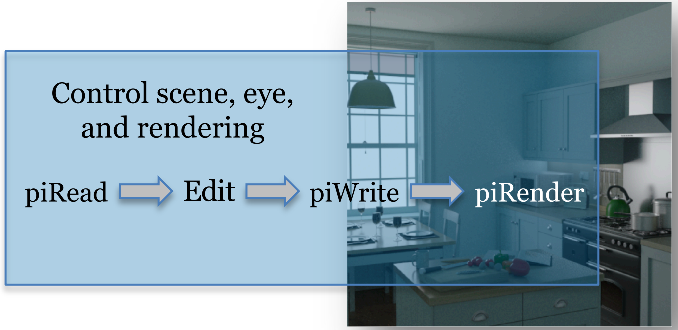
ISET3d: From PBRT to ISETBio (pi)

- In the next 15 minutes I illustrate the ISET3d computational framework
- I will show you
  - The **kinds of stimuli** that we are producing and
  - The programming approach in the specific case of simulating human **physiological optics** (image formation)
- David and I are producing YouTube videos of the tools that illustrate many more computations
- We use ISET3d for camera design, as well.

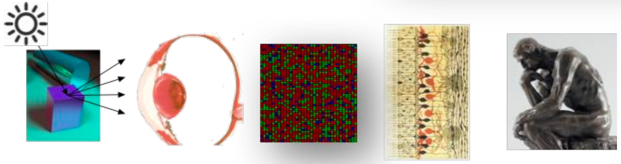
3d models

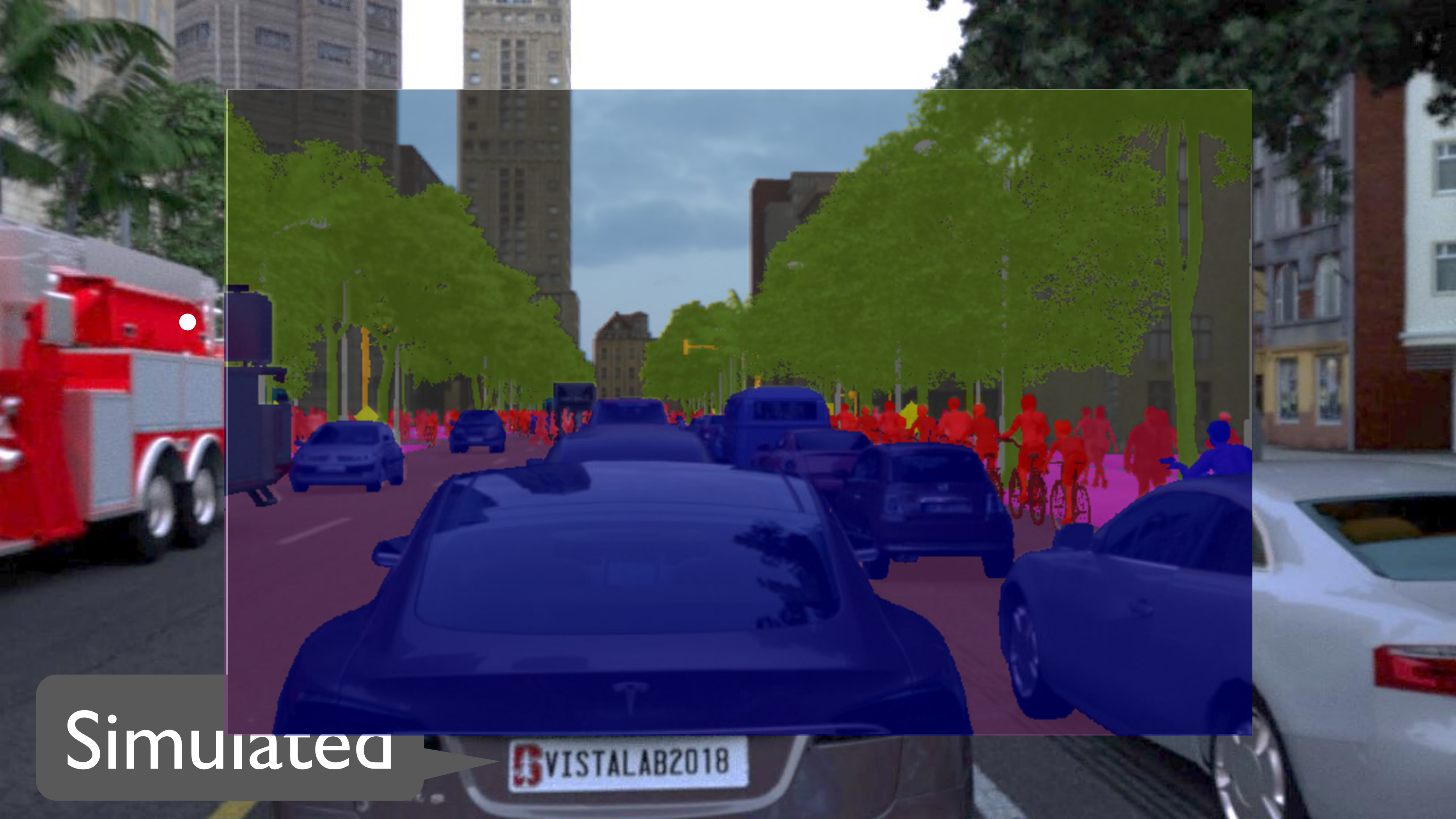


ISET3d



ISETBio




Simulated
VISTALAB2018

ISET3D extension to incorporate human optics


OPEN ACCESS

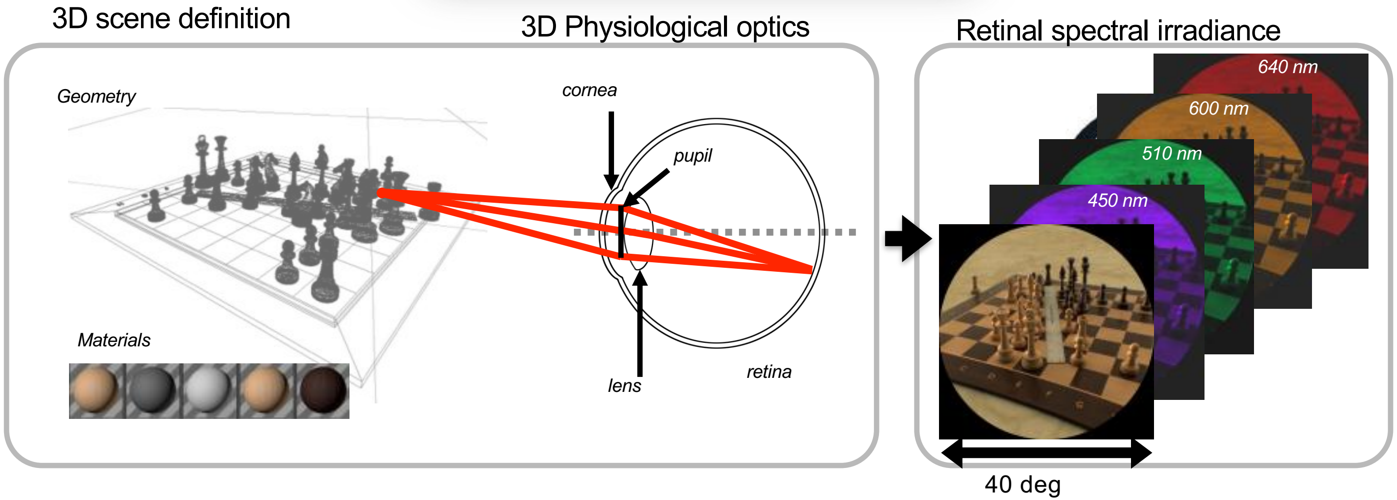
Article | October 2019

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

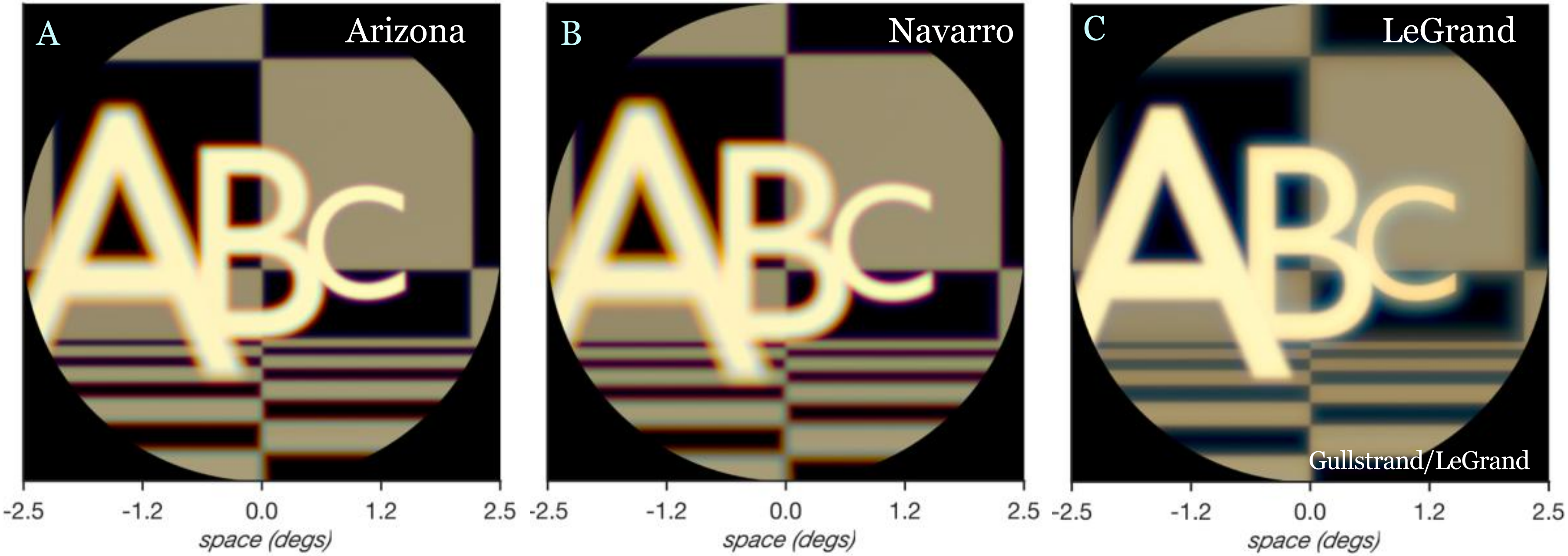
Journal of Vision October 2019, Vol.19, 23. doi:https://doi.org/10.1167/19.12.23



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).



Example code

- This is script illustrates the programming philosophy from the user's perspective
- By default the sceneEye uses the Navarro model to render a 3D scene; LeGrand and Arizona eye models are also included

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

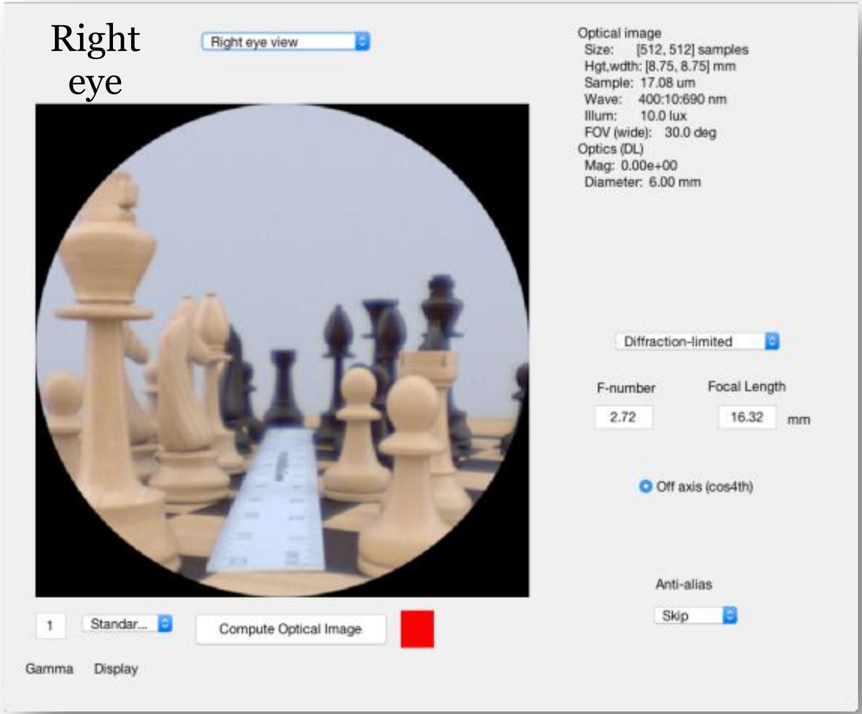
- The code doing the computational work in ISET3d is managed within
  - The set/get methods
  - PBRT calculations
- You can ‘set’ many camera, rendering, and scene parameters
- You can ‘get’ many more parameters by calculation
- There are a number of methods ‘render’,’summary’ and others

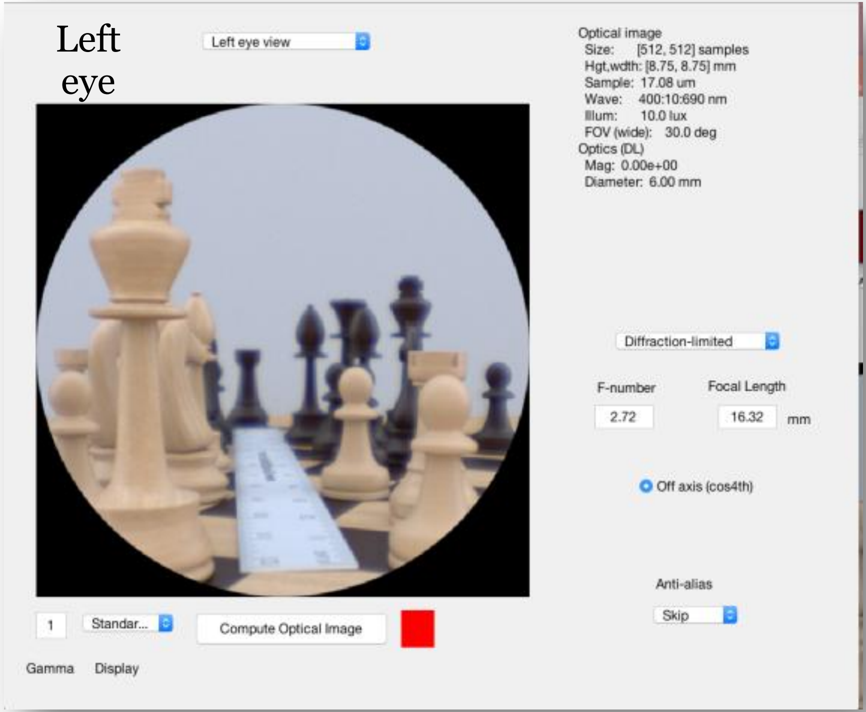
```
% Suppose you are in focus at the proper distance to the edge. And we turn
% on chromatic aberration.  That will slow down the calculation, but makes
% it more accurate and interesting.  We only use 8 spectral bands for
% speed.  You can use up to 31.
nSpectralBands = 8;
thisSE.set('chromatic aberration',nSpectralBands);

% 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);
```

Image formation (optics) models and quantitative graphics

Stereo pairs: move the camera position by 6 cm

thisEye.set('from',loc)





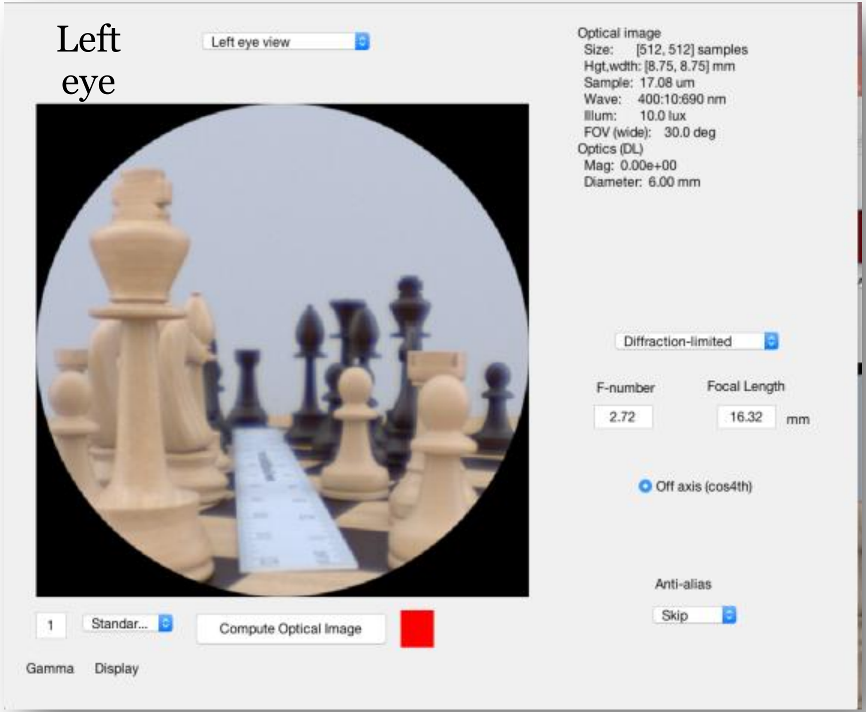
- This ISET3d code makes the stereo pair of the Chess retinal irradiance, imaged through the LeGrand model eye

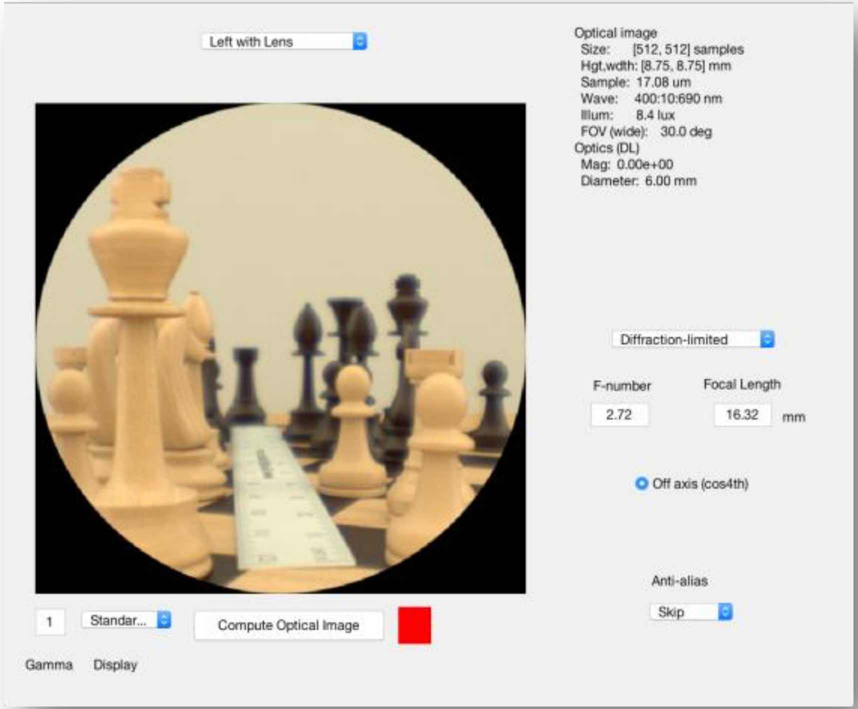
- I set the lens density to 0 so the scene would not look very yellow. I will explain this in a moment

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

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

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 and 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 mm

from = thisSE.get('from');   % Current camera location

thisSE.set('from',from + [0.012,0,0]);  % Shift it 12 mm

oiRight = thisSE.render;
oiWindow(oiRight);
```

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

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

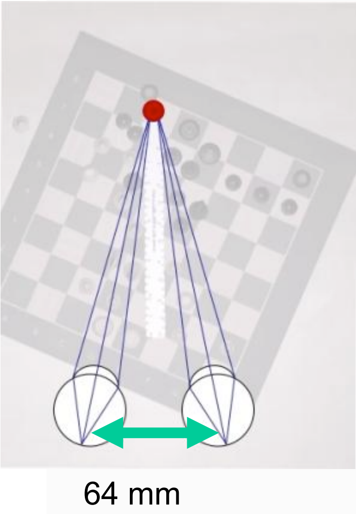


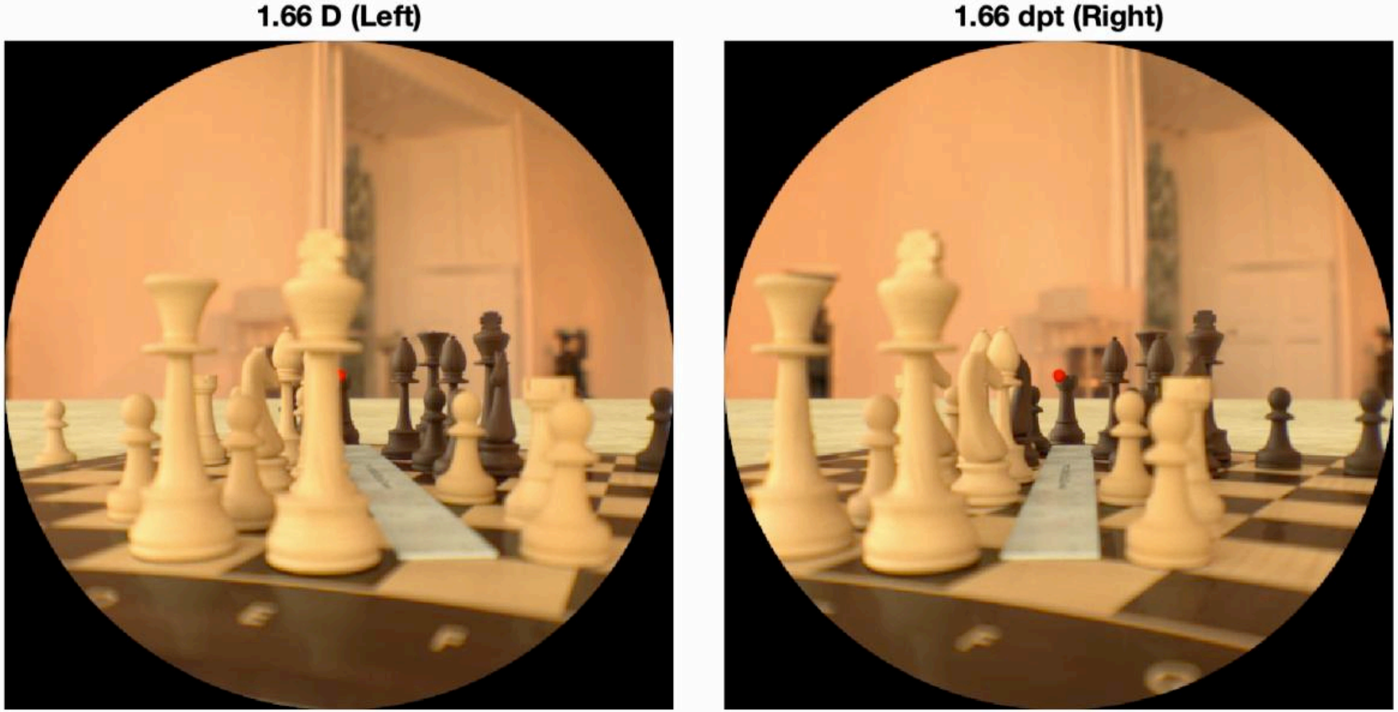


Vergence and Accommodation

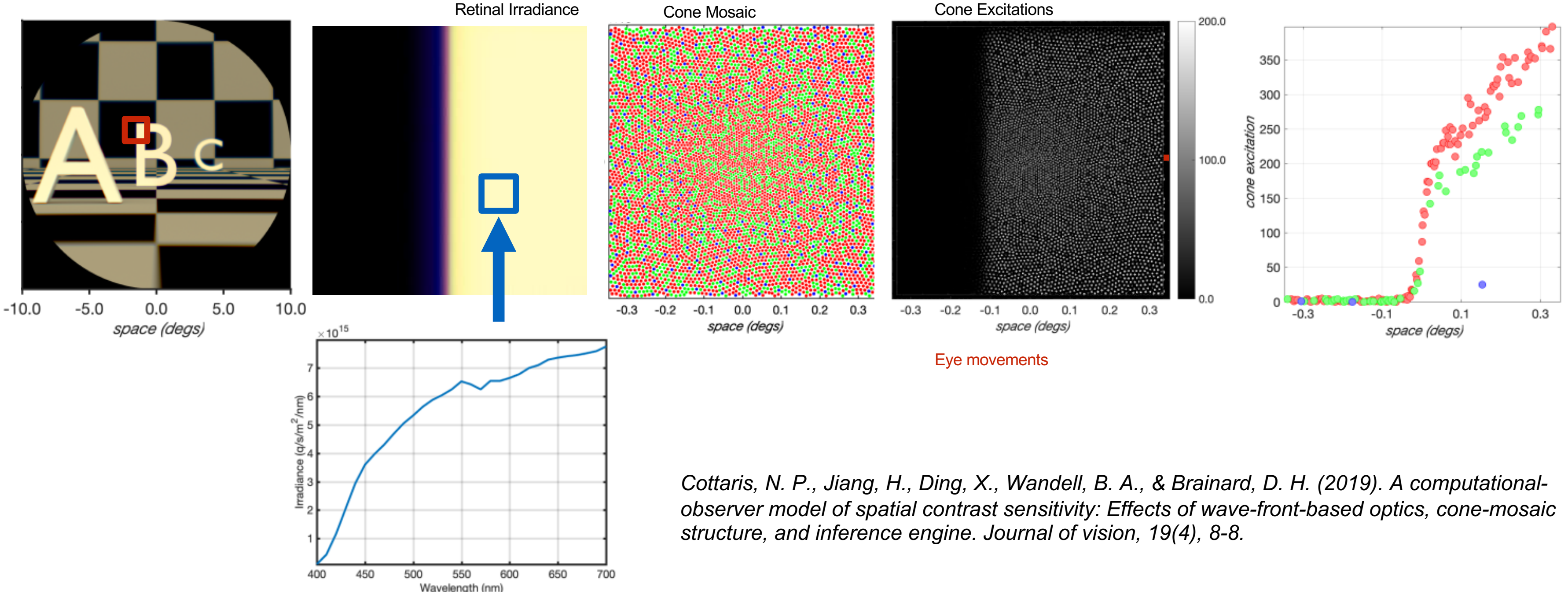
Where the eye (or eyes) is looking is controlled

thisEye.set('to',loc)





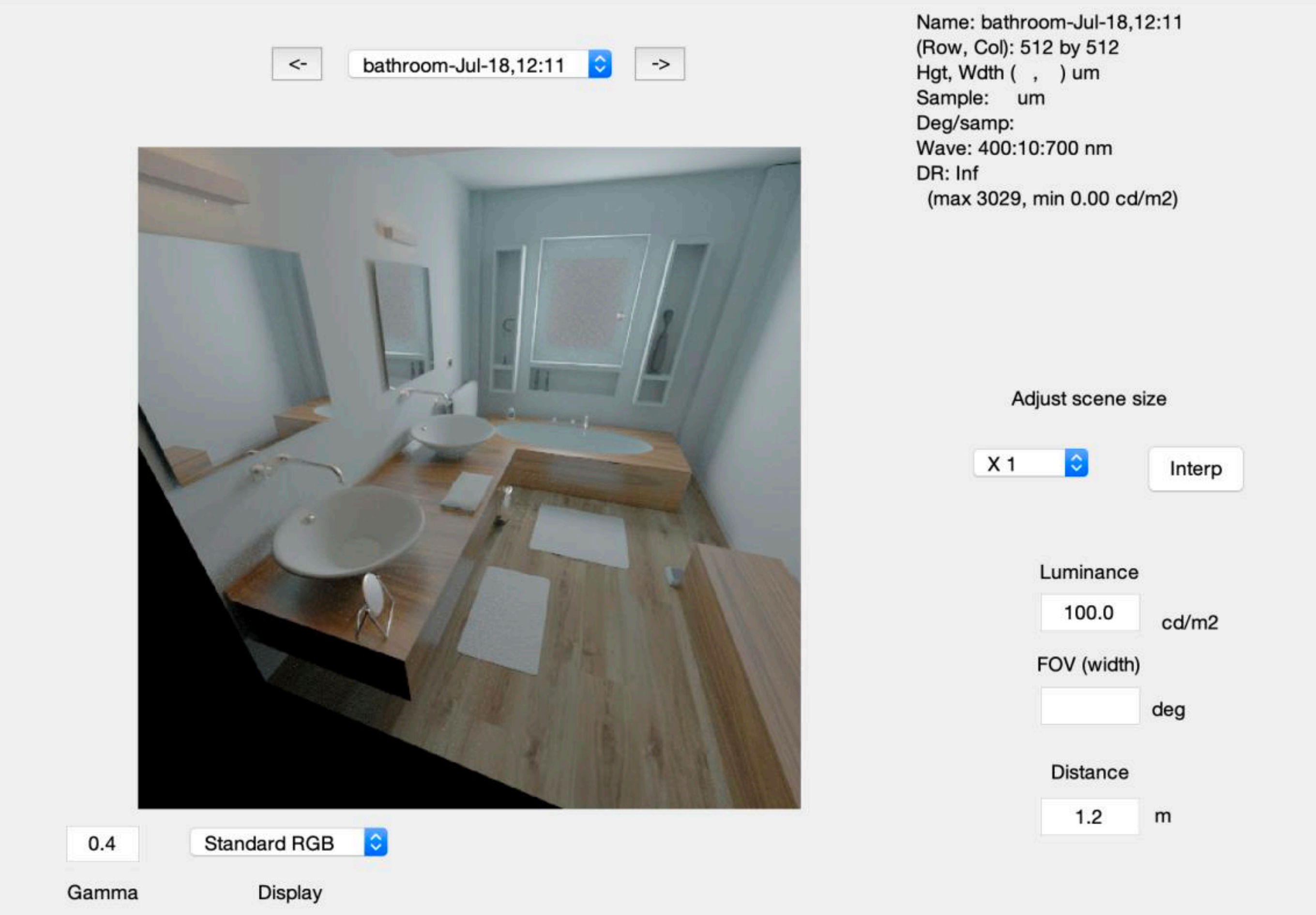
Calculating cone responses and eye movements



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.

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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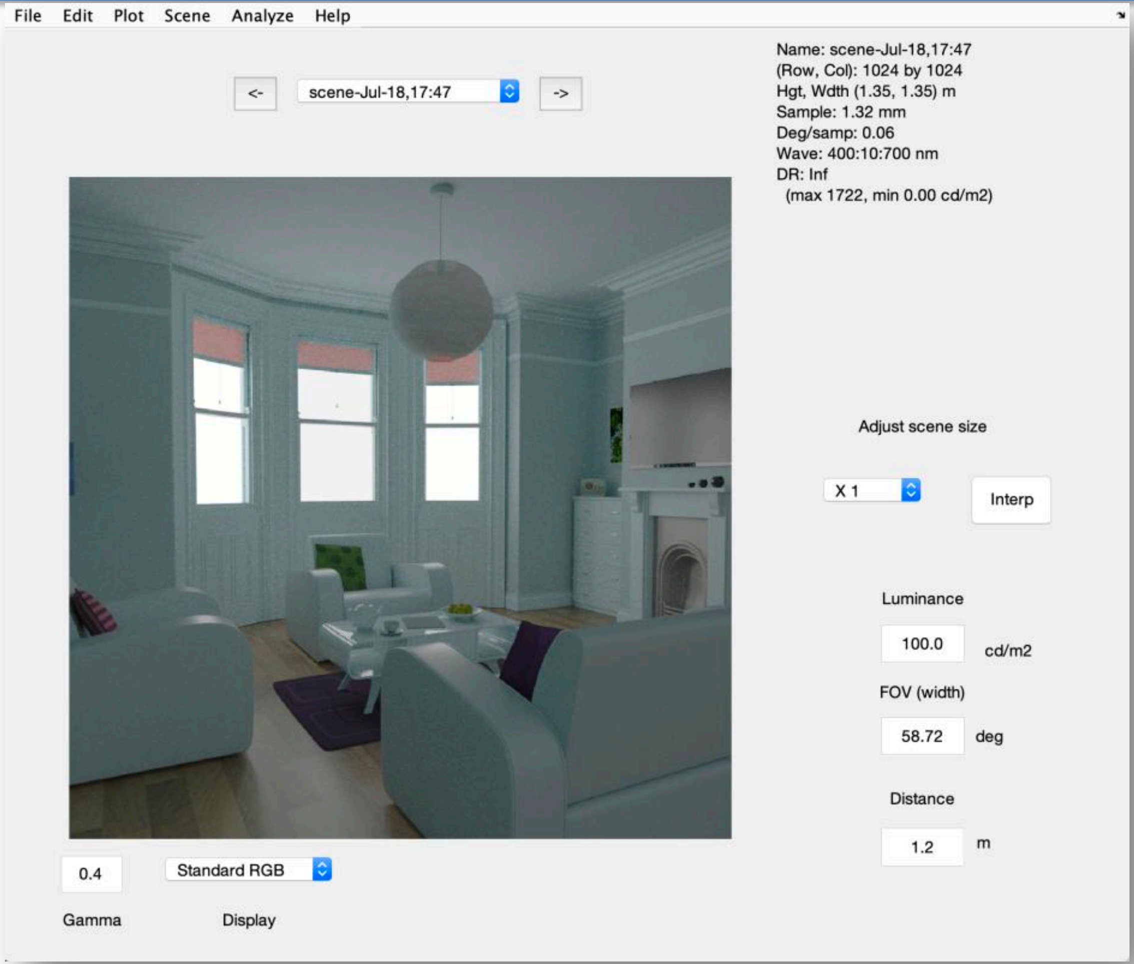

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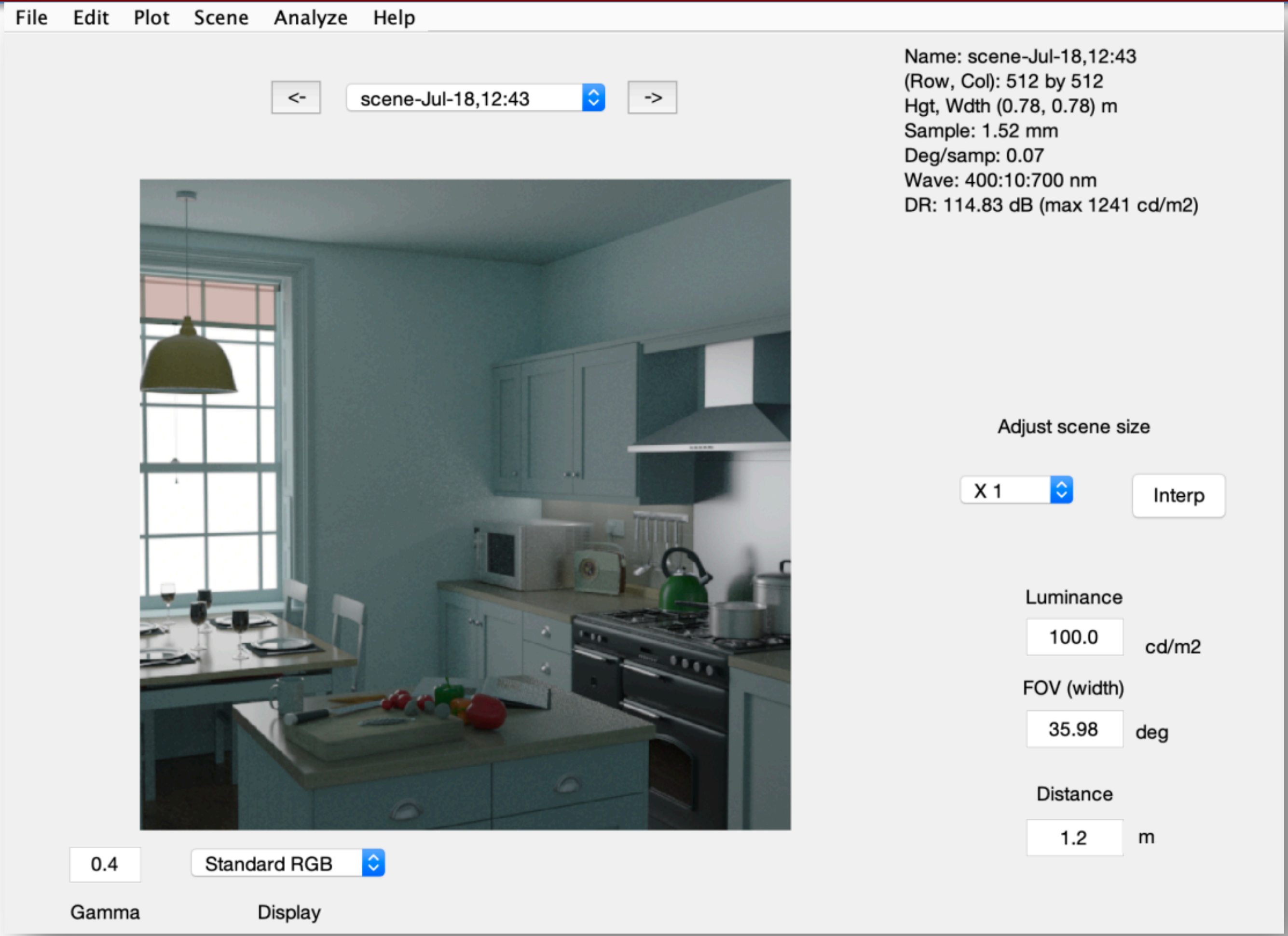

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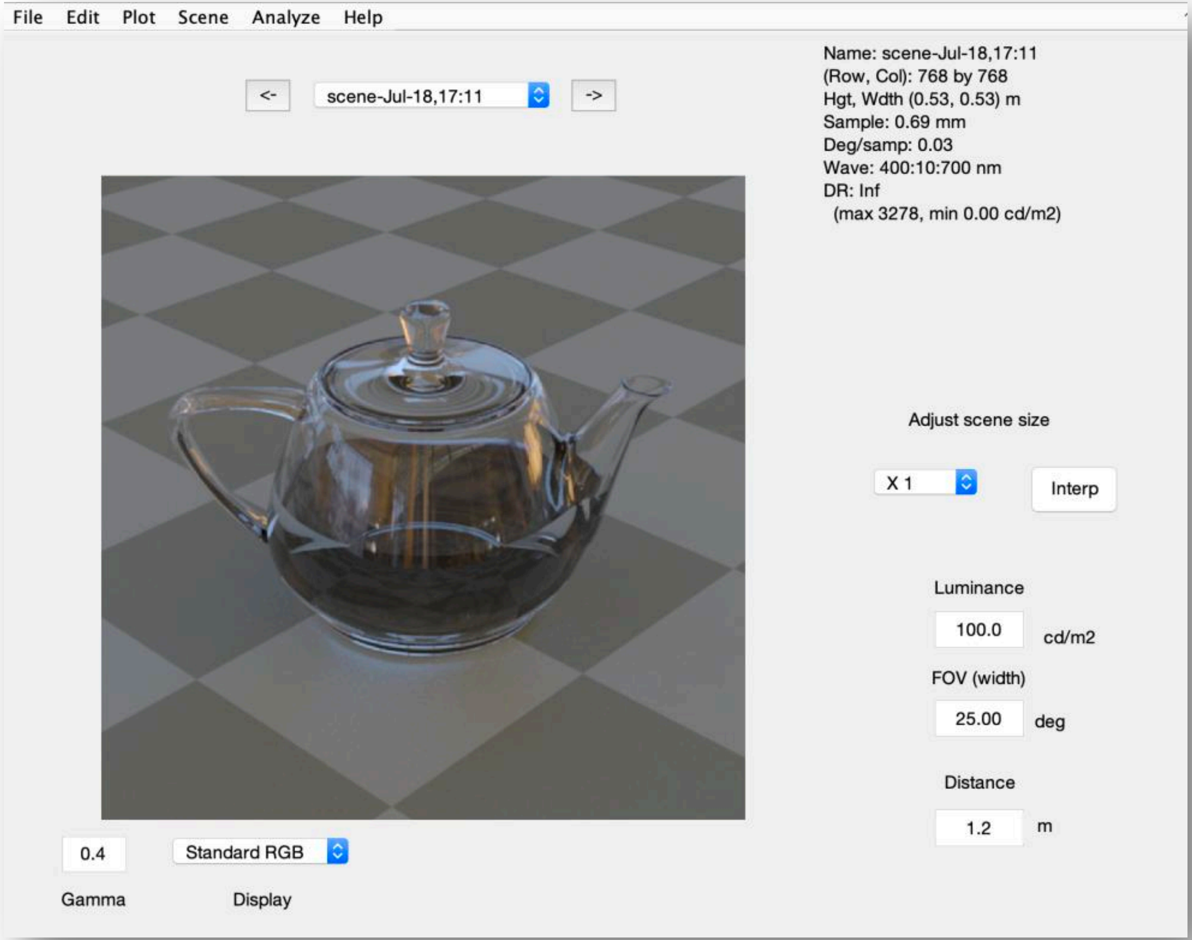

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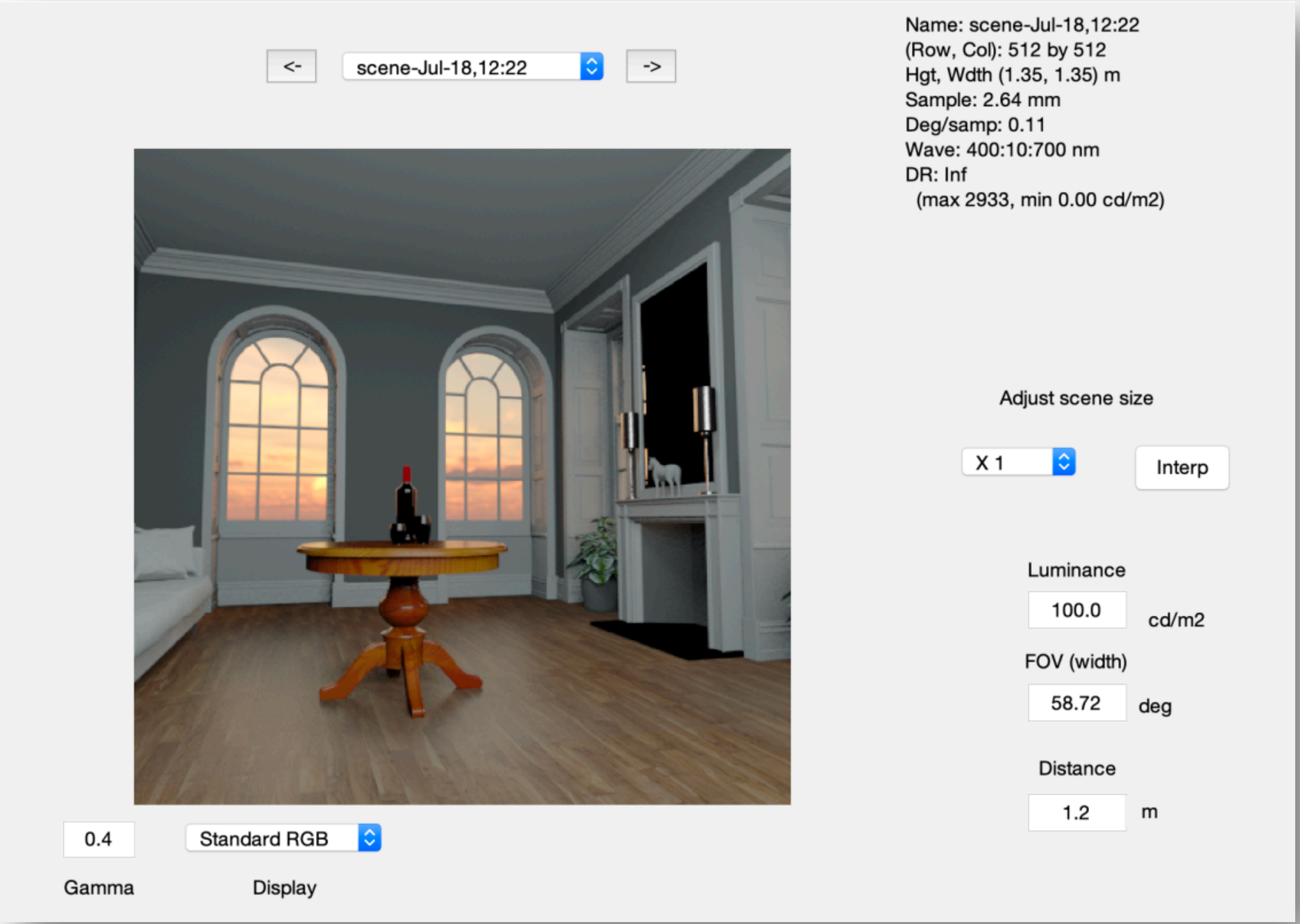
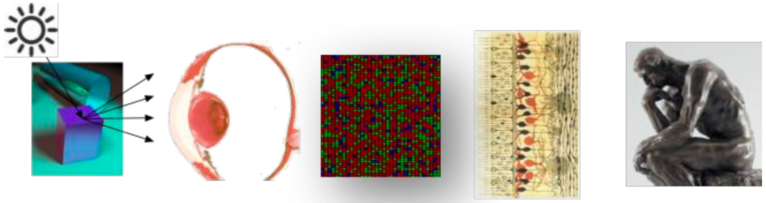
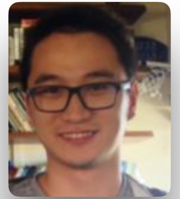


ISETBio Team and Funding




Brian Wandell


Trisha Lian


Haomio Jiang


James Golden


David Brainard


Nicolas Cottaris


Xiaomao Ding


Lingqi Zhang


E.J. Chichilnisky


Fred Rieke


Joyce Farrell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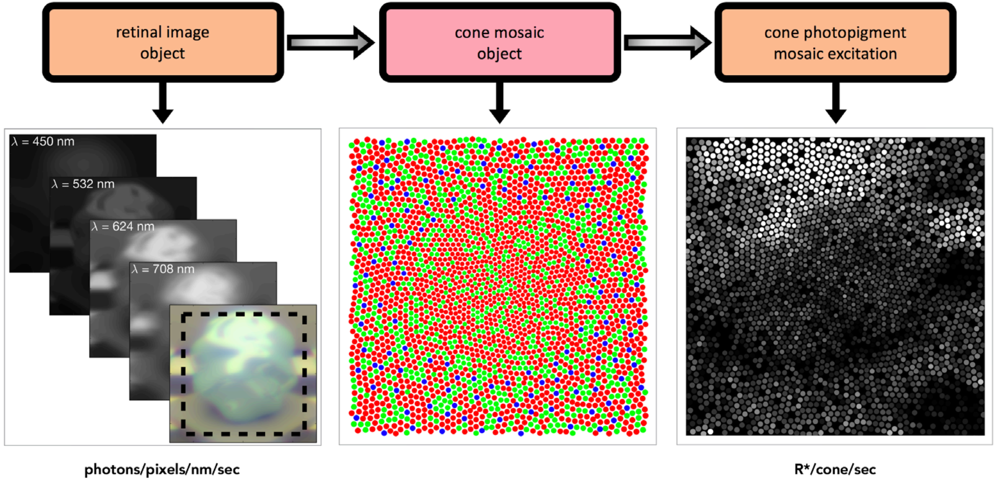
ISETBio: Modeling the Initial Steps of Human Vison

David H. Brainard and Brian A. Wandell
Thanks to Nicolas P. Cottaris



ISETBio Team and Funding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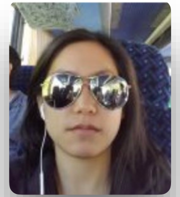
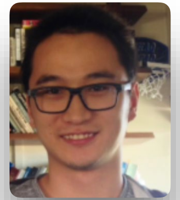

Trisha Lian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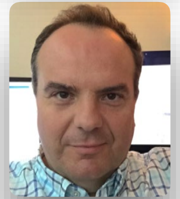
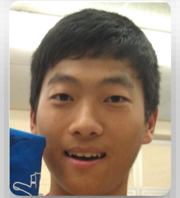

Nicolas Cottaris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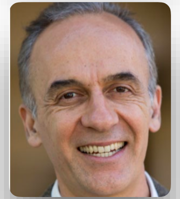
Lingqi Zhang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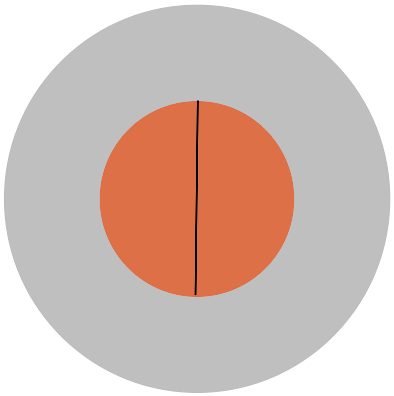
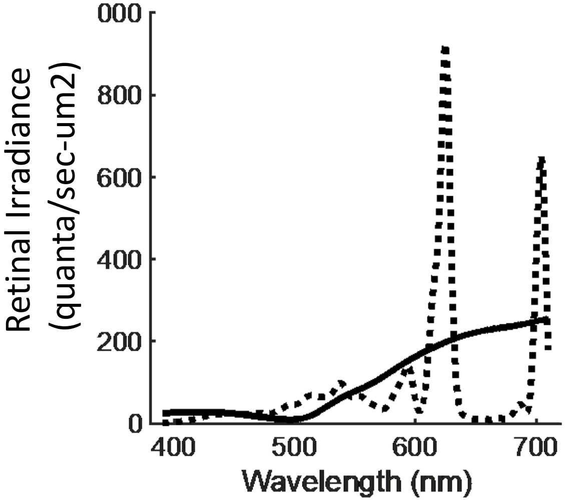
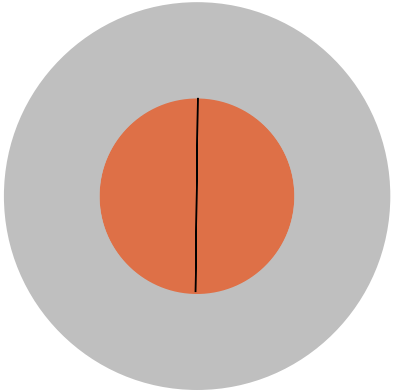
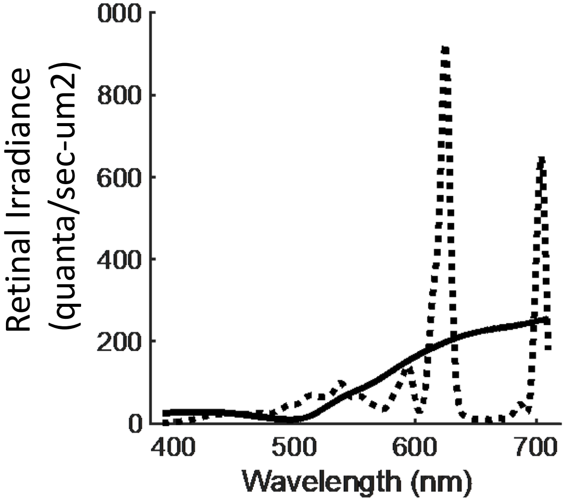
Encoding of light at the retina has large implications for perception

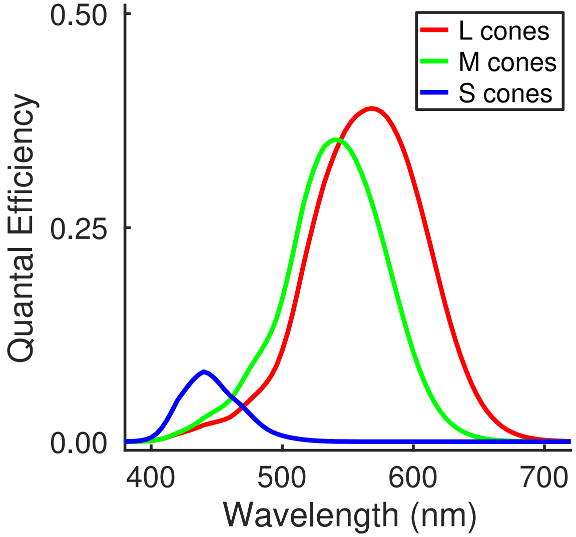


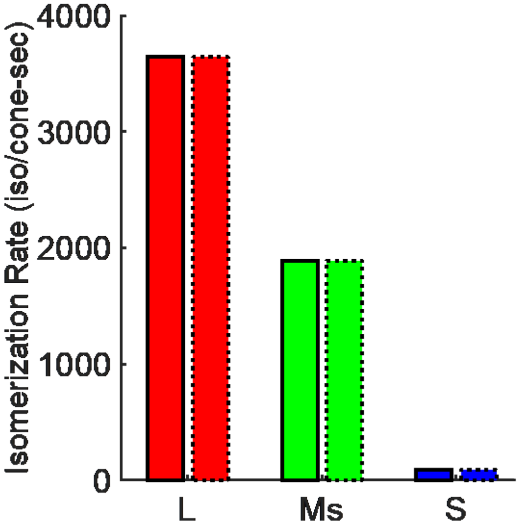


Color matching is mediated by encoding of light spectra by the cnoes

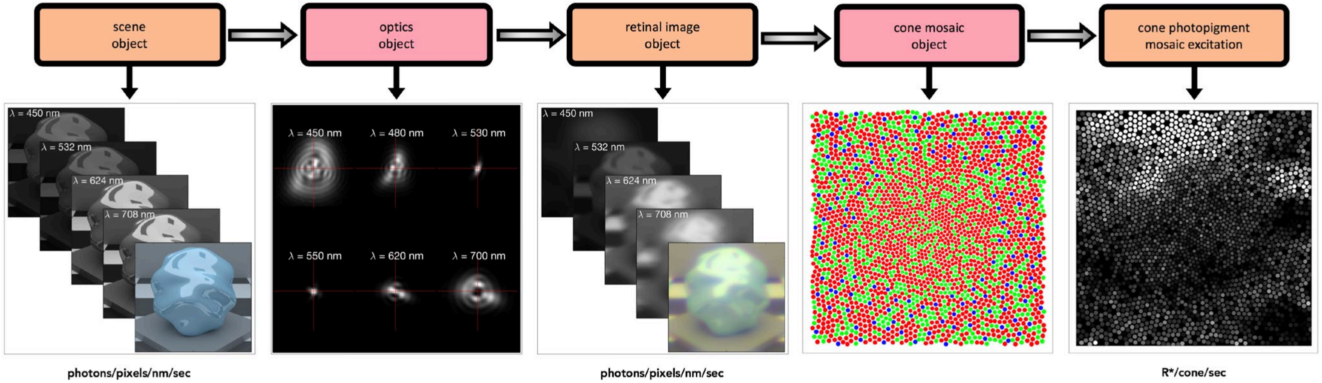






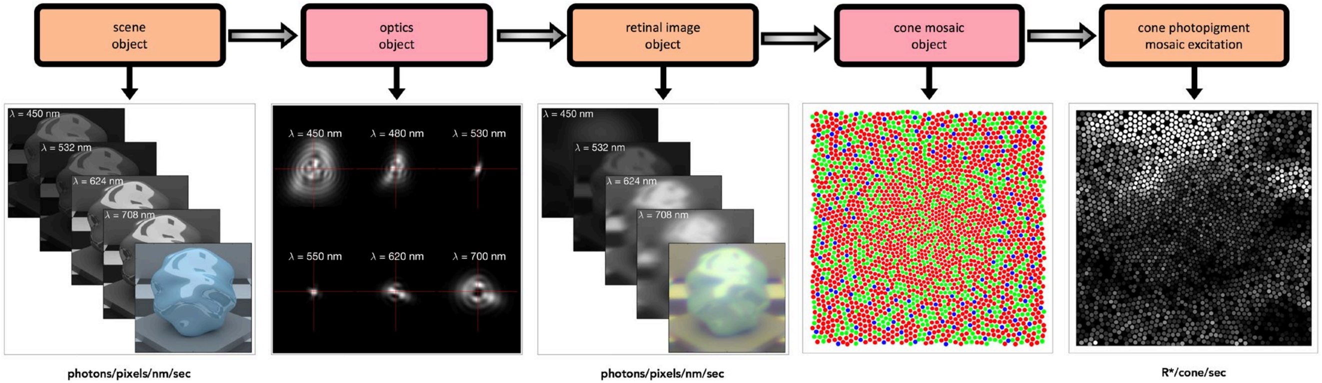


We would like to understand more generally implications of early vision



- Formation of the retinal image and optical blur
    - Including effects of 3D scene structure
- Spatial and spectral sampling by the interleaved cone mosaic
- Phototransduction
- Fixational eye movements
- Bipolar and retinal ganglion cell processing

Image System Engineering Tools for Biology (ISETBio)

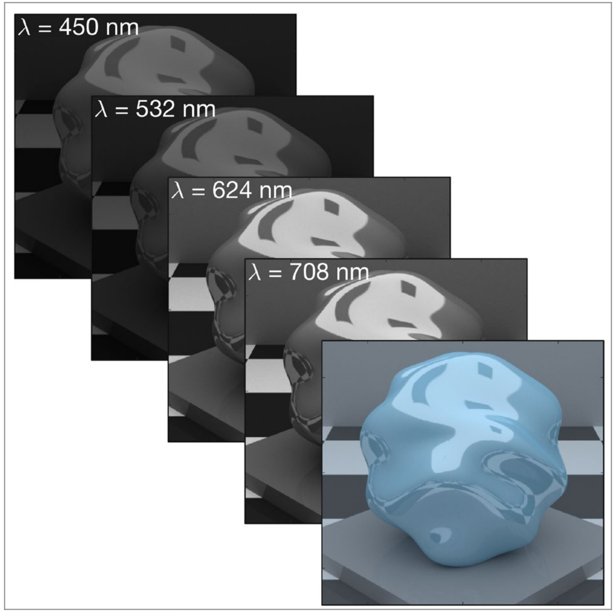


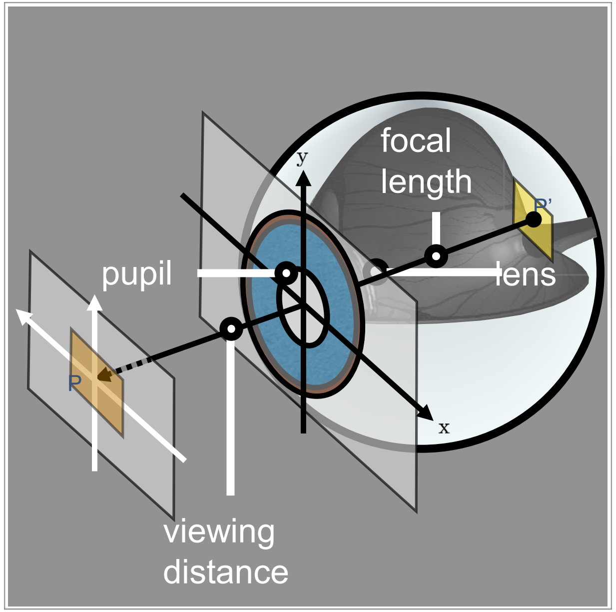
- ISETBio is a set of open source Matlab tools that quantitatively model early vision.
- ISETBio is image computable.
- Helps clarify how different elements of the eye and neural processing impact visual perception.
- Today's webinar is an introduction to ISETBio.

ISETBio components – scene and retinal image

scene
object

optics
object

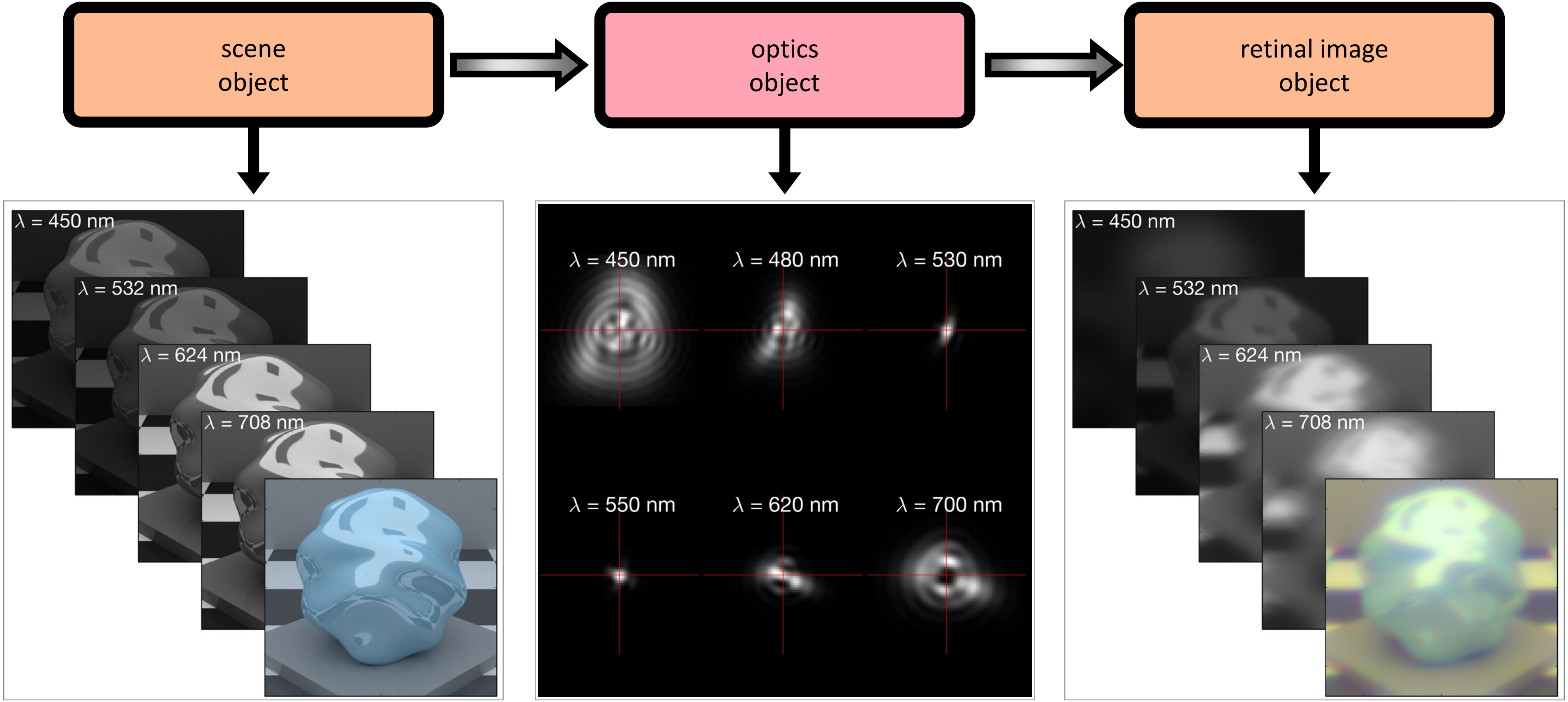




photons/pixels/nm/sec

Courtesy Nicolas Cottaris

ISETBio components – scene and retinal image

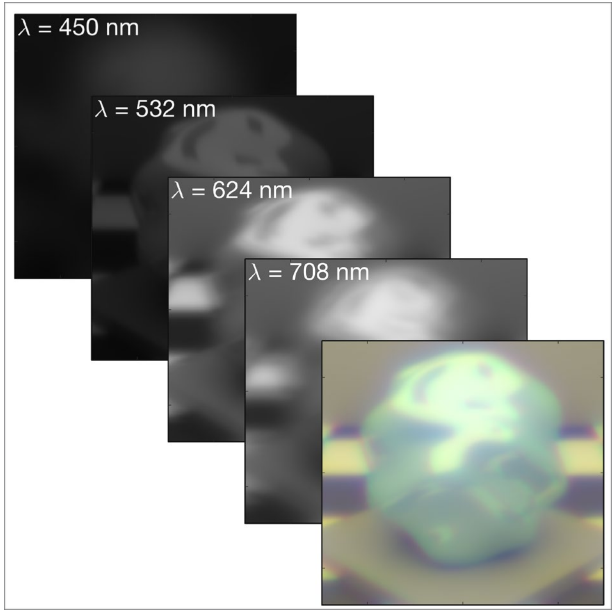


photons/pixels/nm/sec

photons/pixels/nm/sec

ISETBio components – retinal image and cone isomerizations

retinal image object → cone mosaic object



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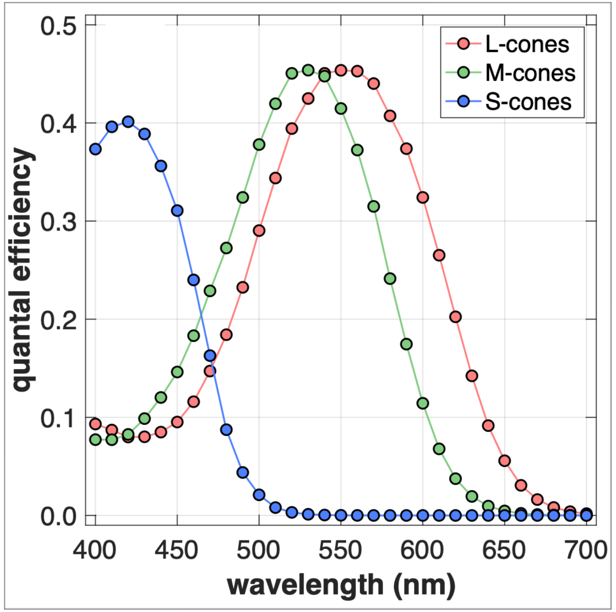
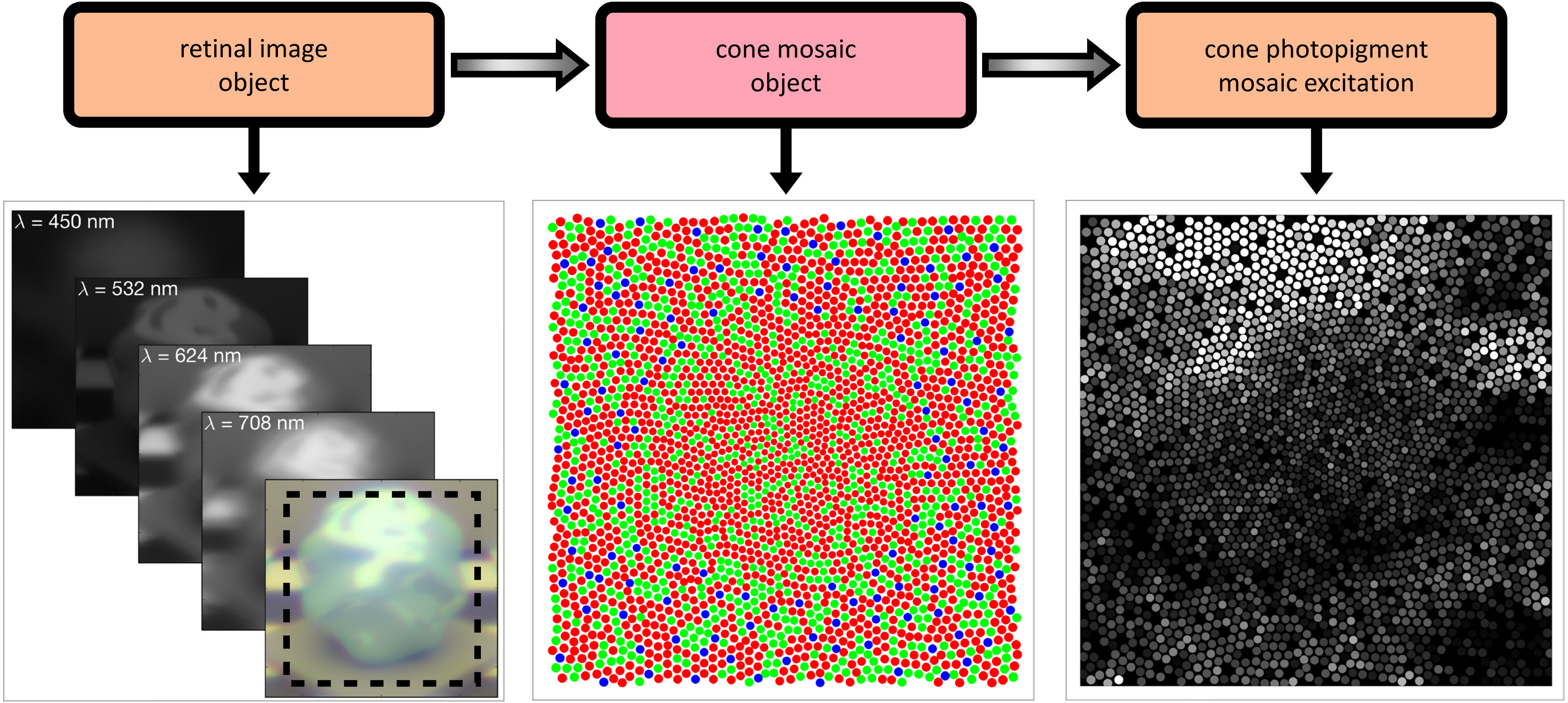


Courtesy Nicolas Cottaris

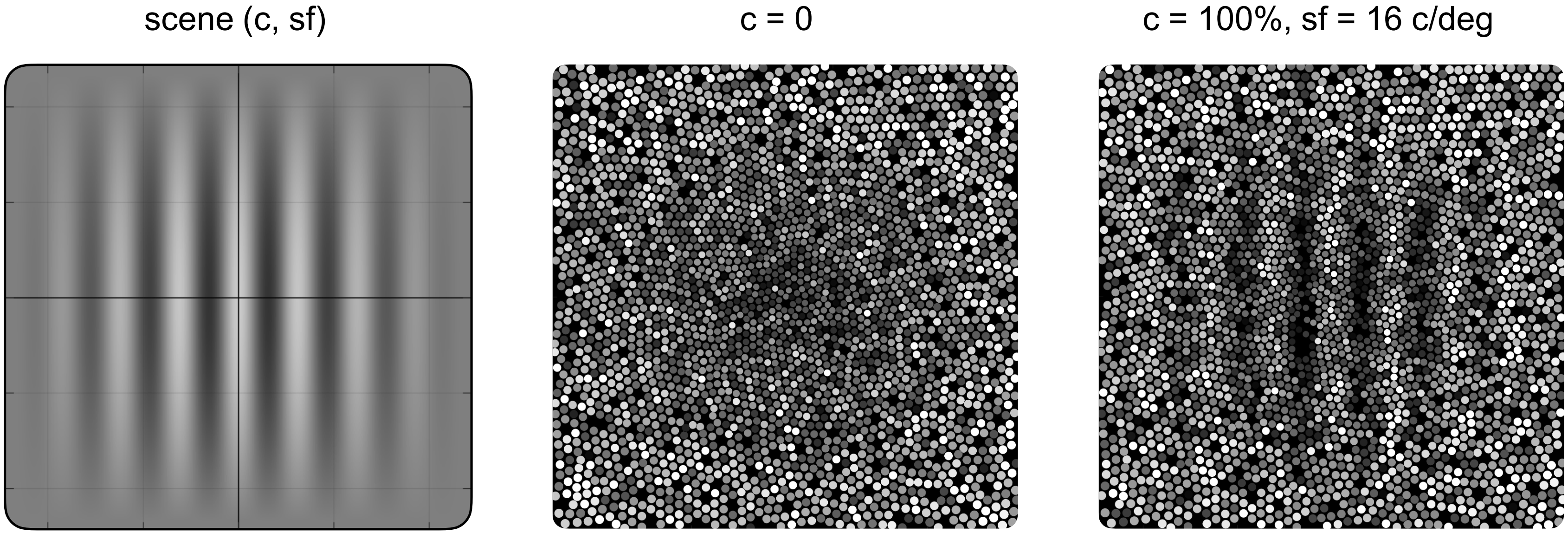
ISETBio components – retinal image and cone isomerizations



photons/pixels/nm/sec

R*/cone/sec

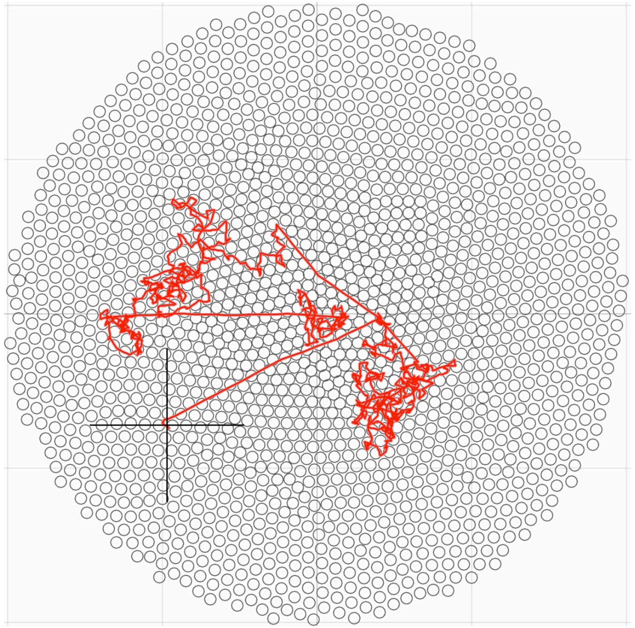
Example: cone mosaic isomerizations to gratings at different contrasts

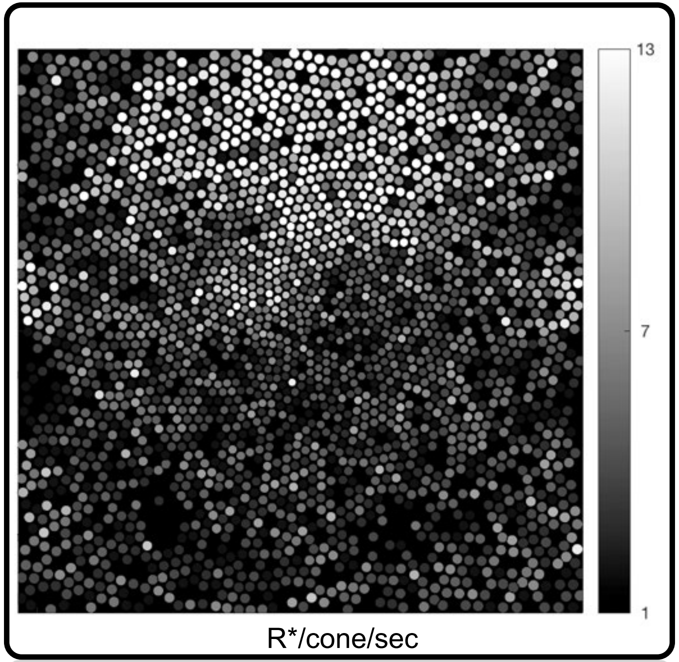


Courtesy Nicolas Cottaris

Accounting for absolute sensitivity: fixational drift

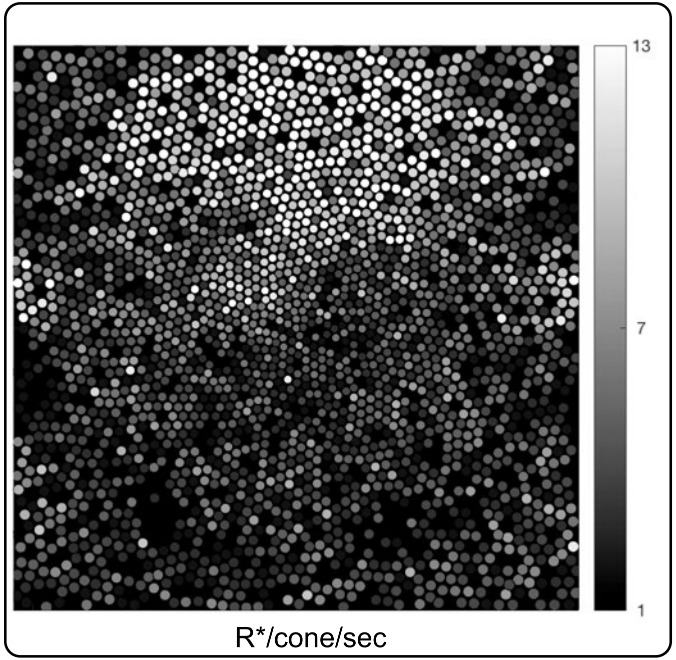
cone photopigment excitation → fixational eye movement object → cone photopigment excitation sequence

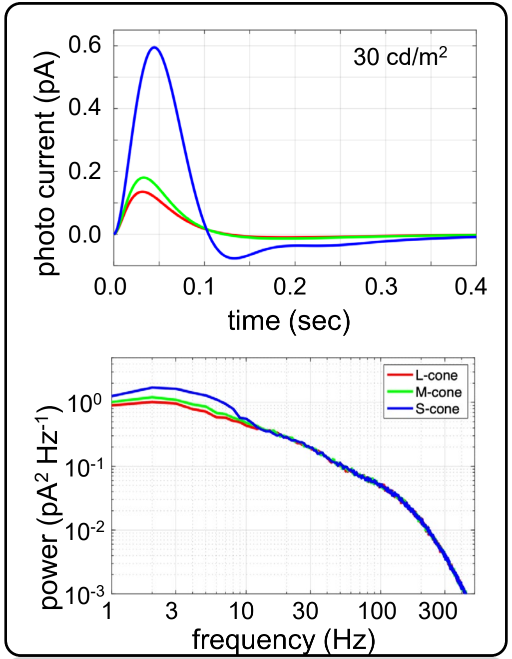


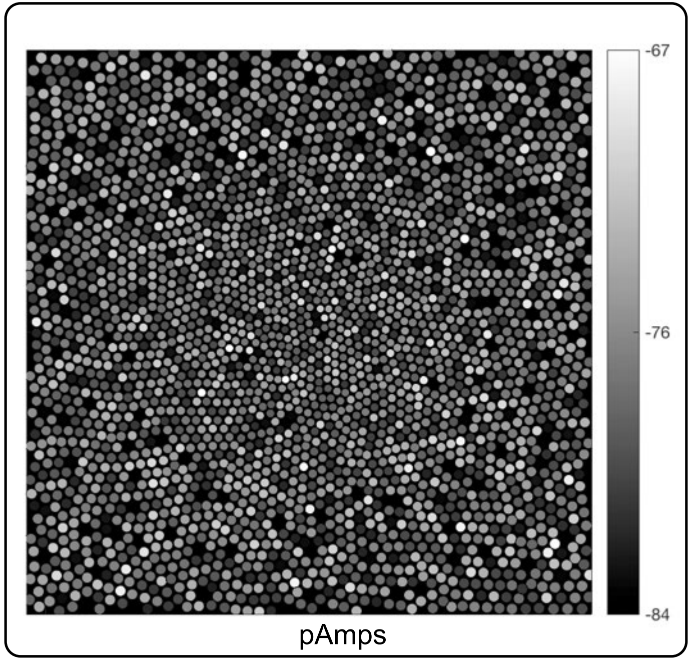


Accounting for absolute sensitivity: photocurrent transduction

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







Accounting for contrast sensitivity

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).

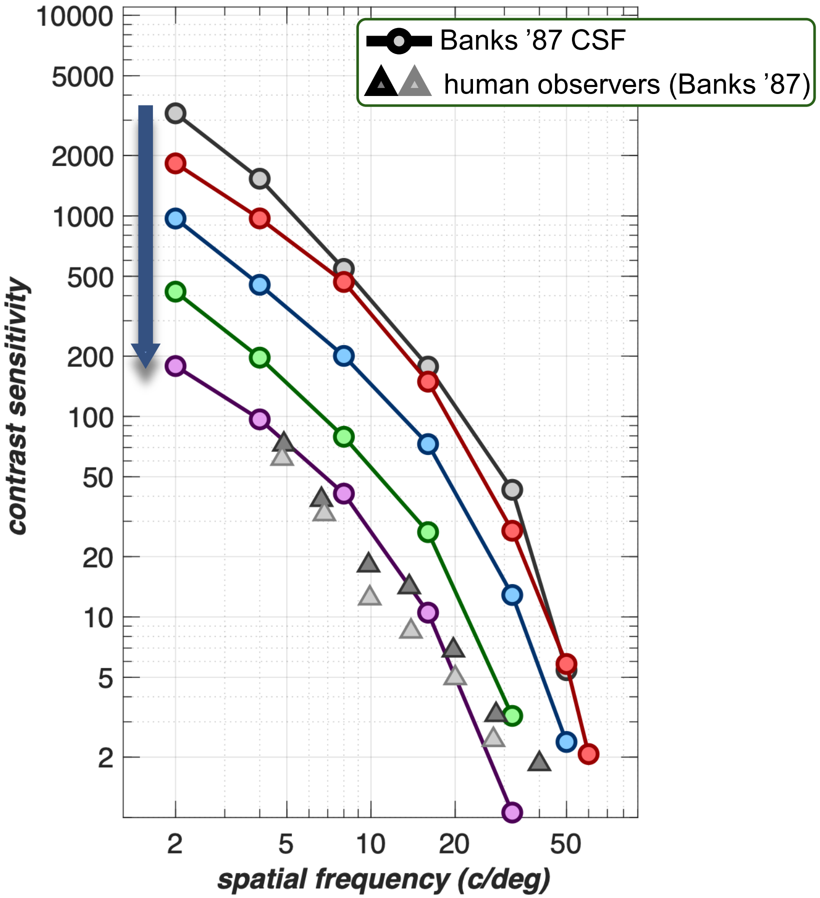
3. Inclusion of fixational eye movements, requires non-linear computational observers, and further reduces sensitivity across the entire spatial frequency range (accumulated factor: 7-10).

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

A computational observer model of spatial contrast sensitivity: Effects of photocurrent encoding, fixational eye movements and inference engine

Nicolas P. Cottaris, Brian A. Wandell, Fred Rieke, David H. Brainard

doi: https://doi.org/10.1101/759811



ISETBio Code and Examples

Open-Source, Matlab. ISETBio itself is available here:

https://github.com/isetbio/isetbio

Download and add to your Matlab path

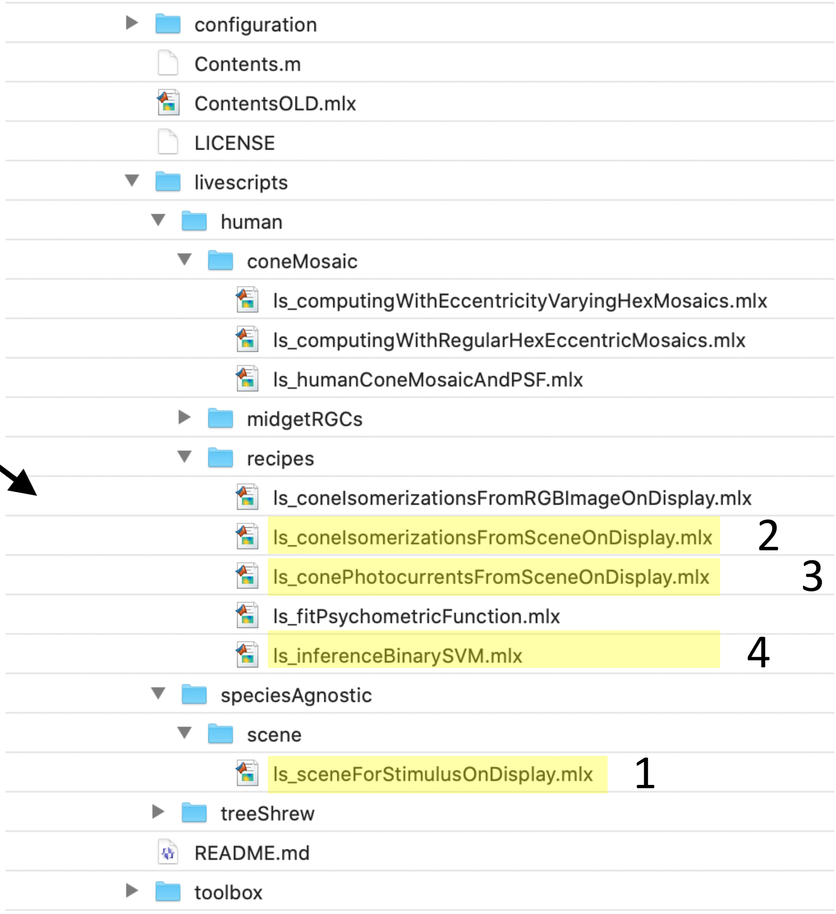
Examples from the next part of this talk are here:

https://github.com/isetbio/ISETBioLiveScript

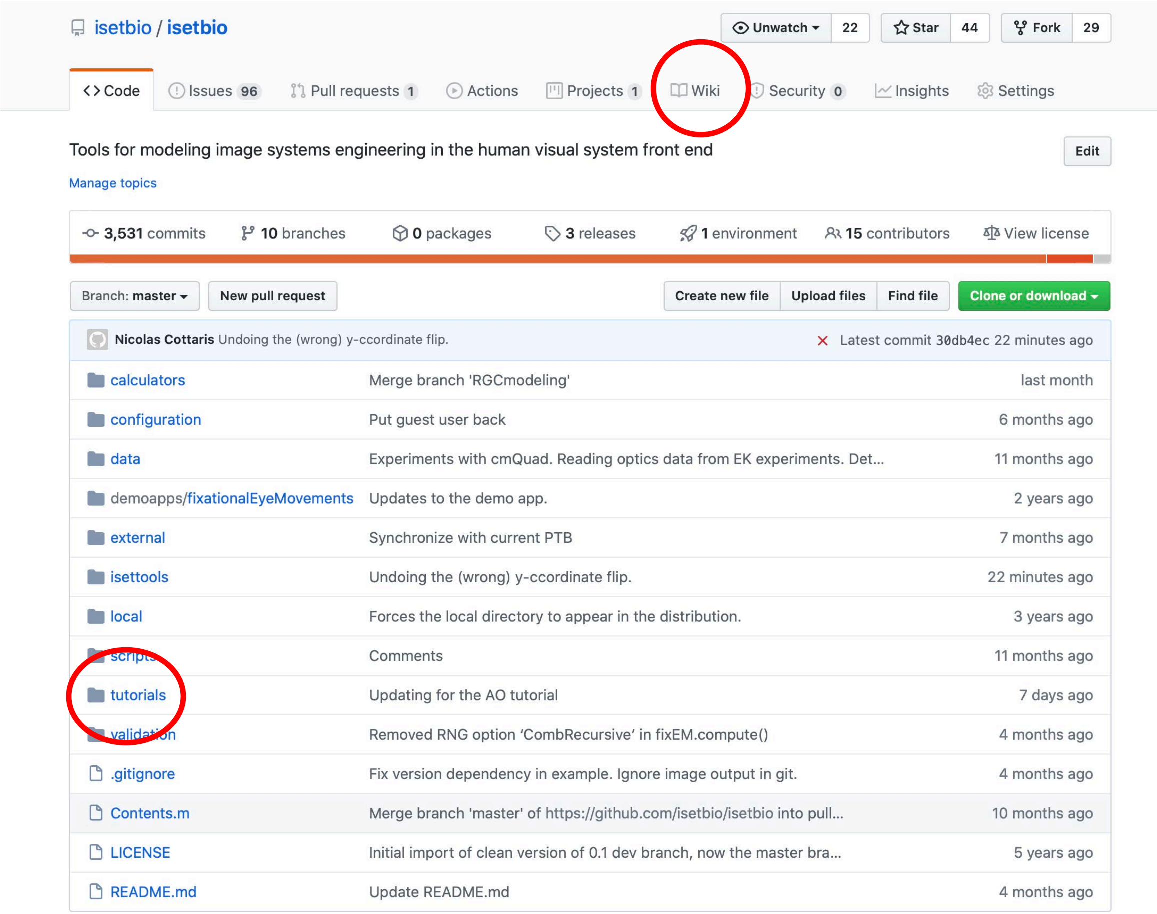
Download and put wherever you like

Videos on YouTube. Search Google with “ISETBio Tutorials” and look under videos:

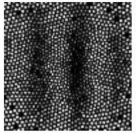
1) ISETBio SceneLiveScriptTutorial
2) ISETBio ComputeIsomerizationsTutorial
3) ISETBio EyeMovementsPhotocurrentTutorial
4) ISETBio ContrastDetectionPerformanceTutorial



ISETBio Documentation



Some Papers that Use ISETBio



A computational-observer model of spatial contrast sensitivity: Effects of wave-front-based optics, cone-mosaic structure, and inference engine OPEN ACCESS

Nicolas P. Cottaris; Haomiao Jiang; Xiaomao Ding; Brian A. Wandell; David H. Brainard

Journal of Vision April 2019, Vol.19, 8. doi:https://doi.org/10.1167/19.4.8

A computational observer model of spatial contrast sensitivity: Effects of photocurrent encoding, fixational eye movements and inference engine

Nicolas P. Cottaris, Brian A. Wandell, Fred Rieke, David H. Brainard

doi: https://doi.org/10.1101/759811

Ray tracing 3D spectral scenes through human optics models

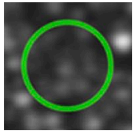
Trisha Lian; Kevin J. MacKenzie; David H. Brainard; Nicolas P. Cottaris; Brian A. Wandell

Journal of Vision October 2019, Vol.19, 23. doi:https://doi.org/10.1167/19.12.23

Modeling visual performance differences 'around' the visual field: A computational observer approach

Eline R. Kupers, Marisa Carrasco, Jonathan Winawer

Version 2 Published: May 24, 2019 • https://doi.org/10.1371/journal.pcbi.1007063



Spatial summation in the human fovea: Do normal optical aberrations and fixational eye movements have an effect? OPEN ACCESS

William S. Tuten; Robert F. Cooper; Pavan Tiruveedhula; Alfredo Dubra; Austin Roorda; Nicolas P. Cottaris; David H. Brainard; Jessica I. W. Morgan

Journal of Vision August 2018, Vol.18, 6. doi:https://doi.org/10.1167/18.8.6

Eye Movement Model Demo

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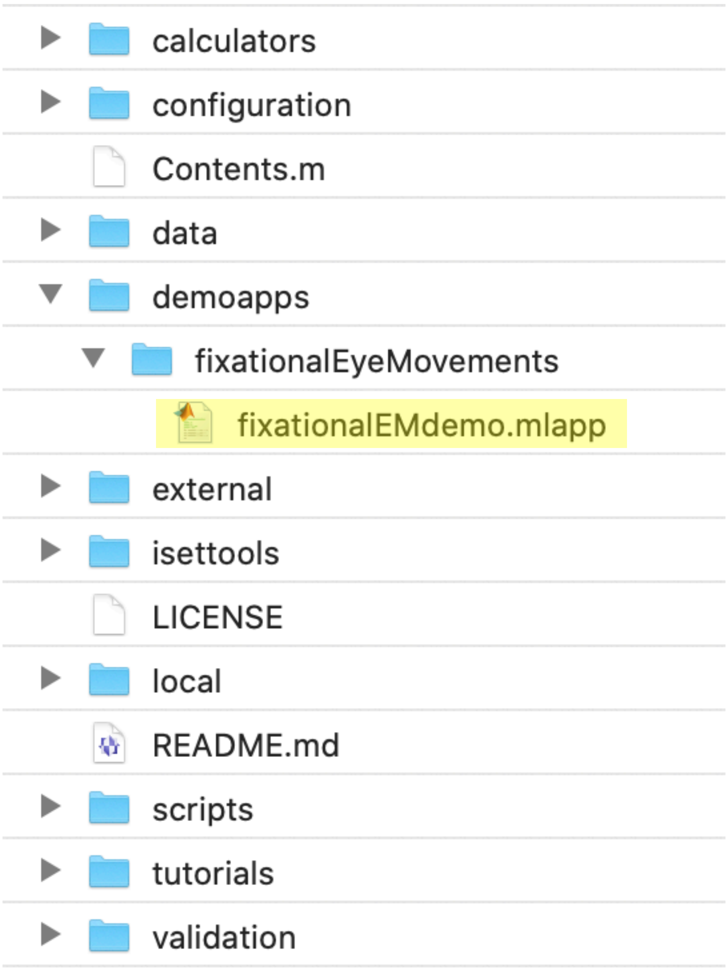

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Mergenthaler, K., & Engbert, R. (2007). Modeling the control of fixational eye movements with neurophysiological delays. Phys. Rev. Lett., 98, 138104.