

Oz Vision – A New Principle for Color Display

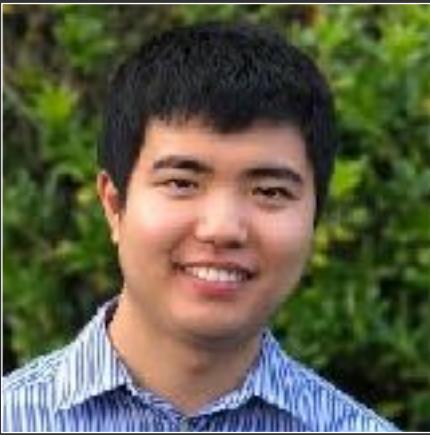
Ren Ng, James Fong, Utkarsh Singhal, Peter Manohar,
Andrew Aikawa, Jay Shenoy, Yi Zong, Rishi Uphadhyay,
Hugh Johnson, Li Yang Kat, Jesse Ku, Varsha Ramakrishnan,
Arjun Sabnis, Steven Sun, Jiaqi Zhang

Emma Alexander

- Department of Electrical Engineering & Computer Sciences

Alexandra Boehm, John Erik Vanston, Brian Schmidt,
Pavan Tiruveedhula, Will Tuten, Austin Roorda

- School of Optometry and Vision Sciences



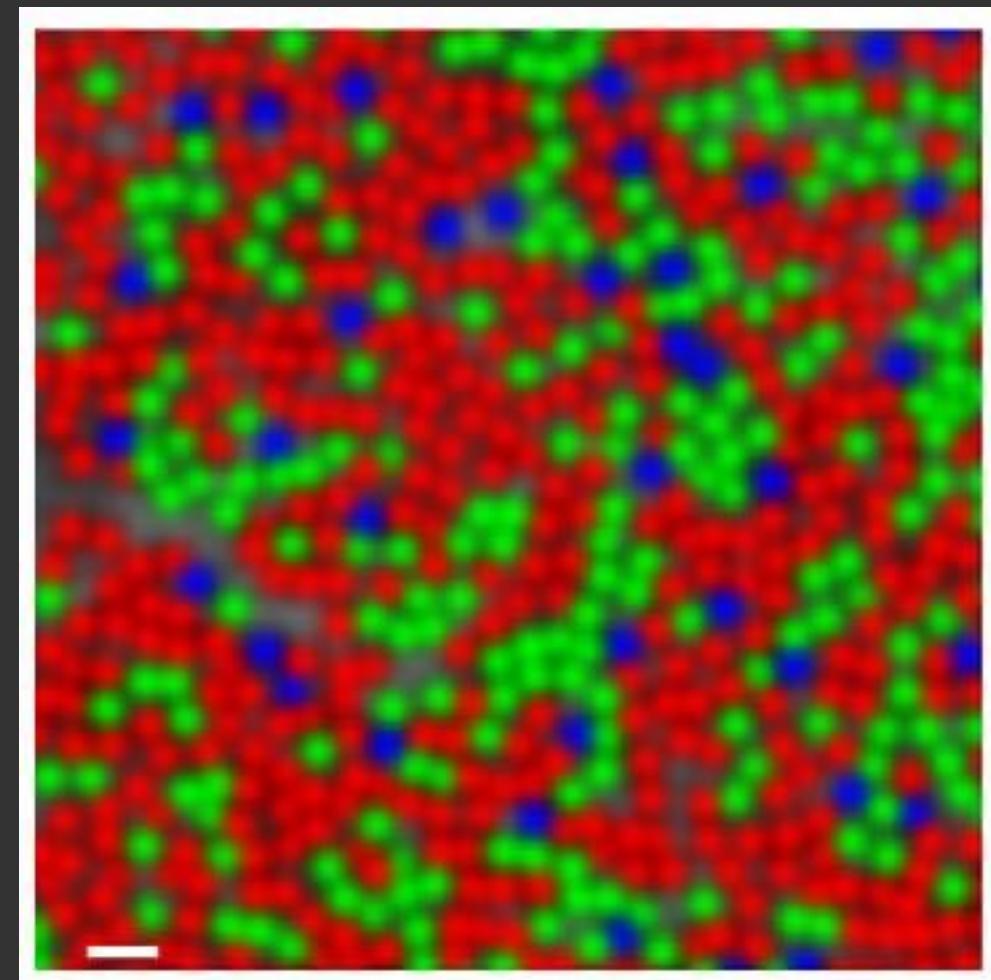
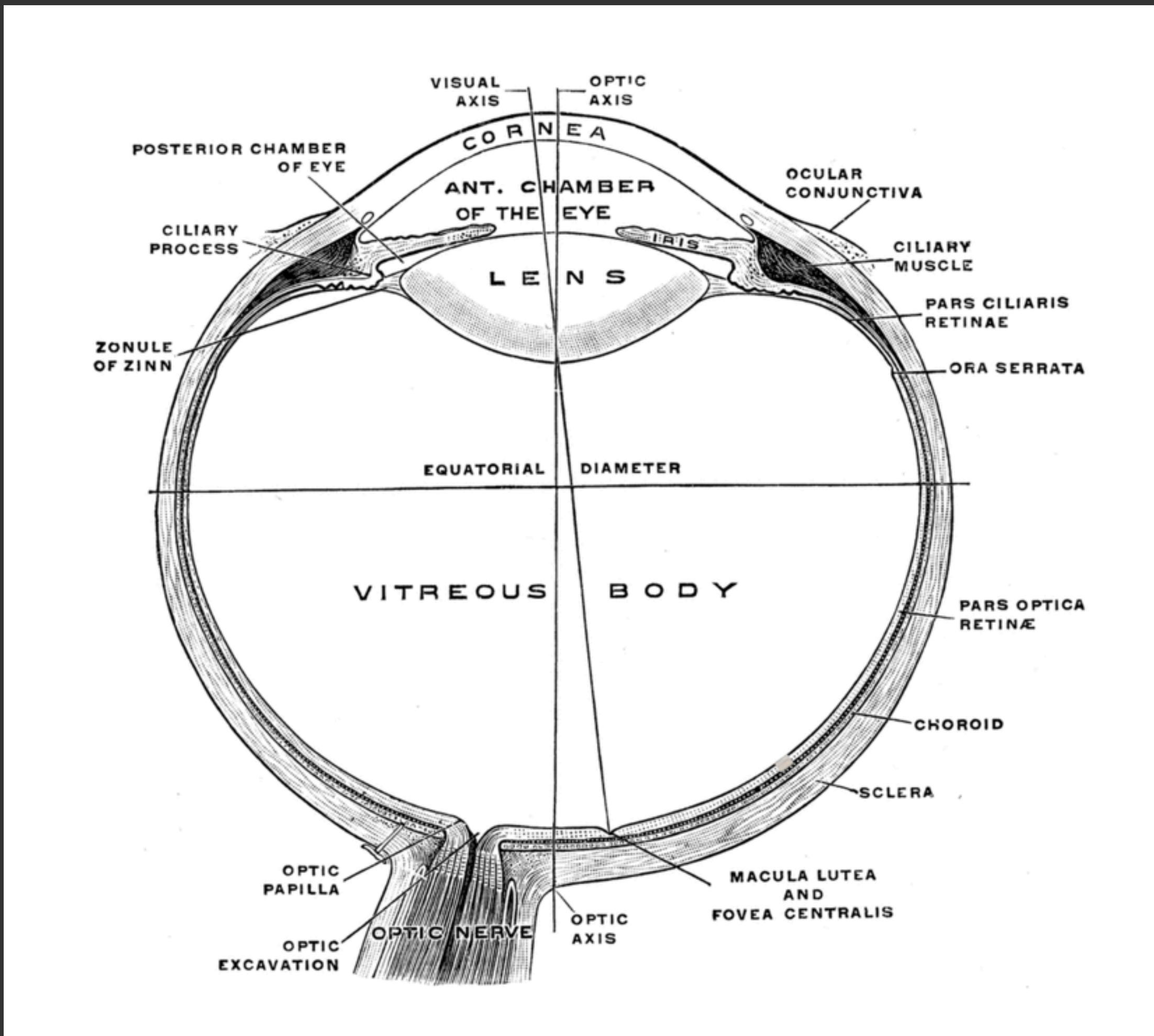
Slide credits: James Fong, Jay Shenoy

This is a Living Research Project -
Early-Stage, Unpublished.
Please Do Not Distribute These Slides

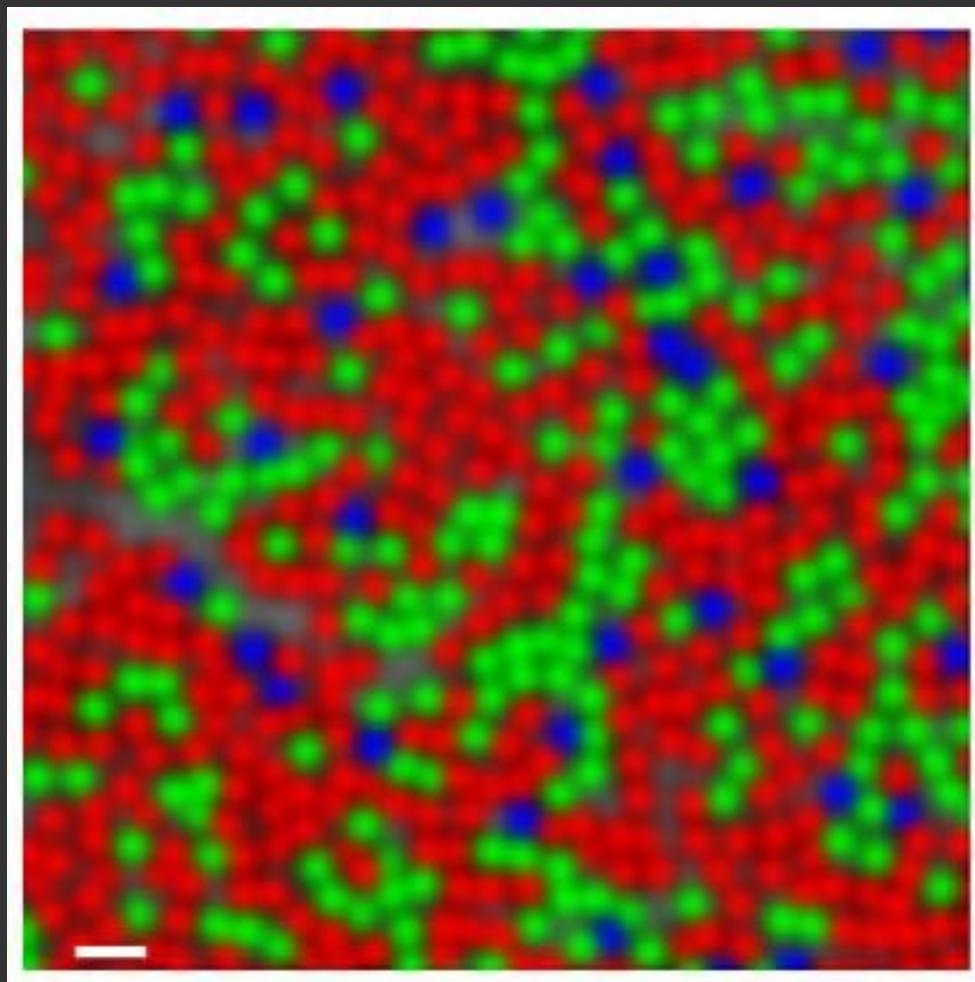
Oz Vision in 2050 - A Tale of Science Fiction

- In 2050, Oz Vision is a ubiquitous AR headset
- Thin glasses with laser writing directly to the retina
- Realtime tracking of retina at cellular accuracy
- Laser micro-dose delivered to each cell at video rate
- In Oz, the most popular virtual worlds have indescribable colors, unlike anything in reality
- Oz headsets with hyperspectral camera allow users to perceive world in 5D color
- And, Oz functionally cures color blindness

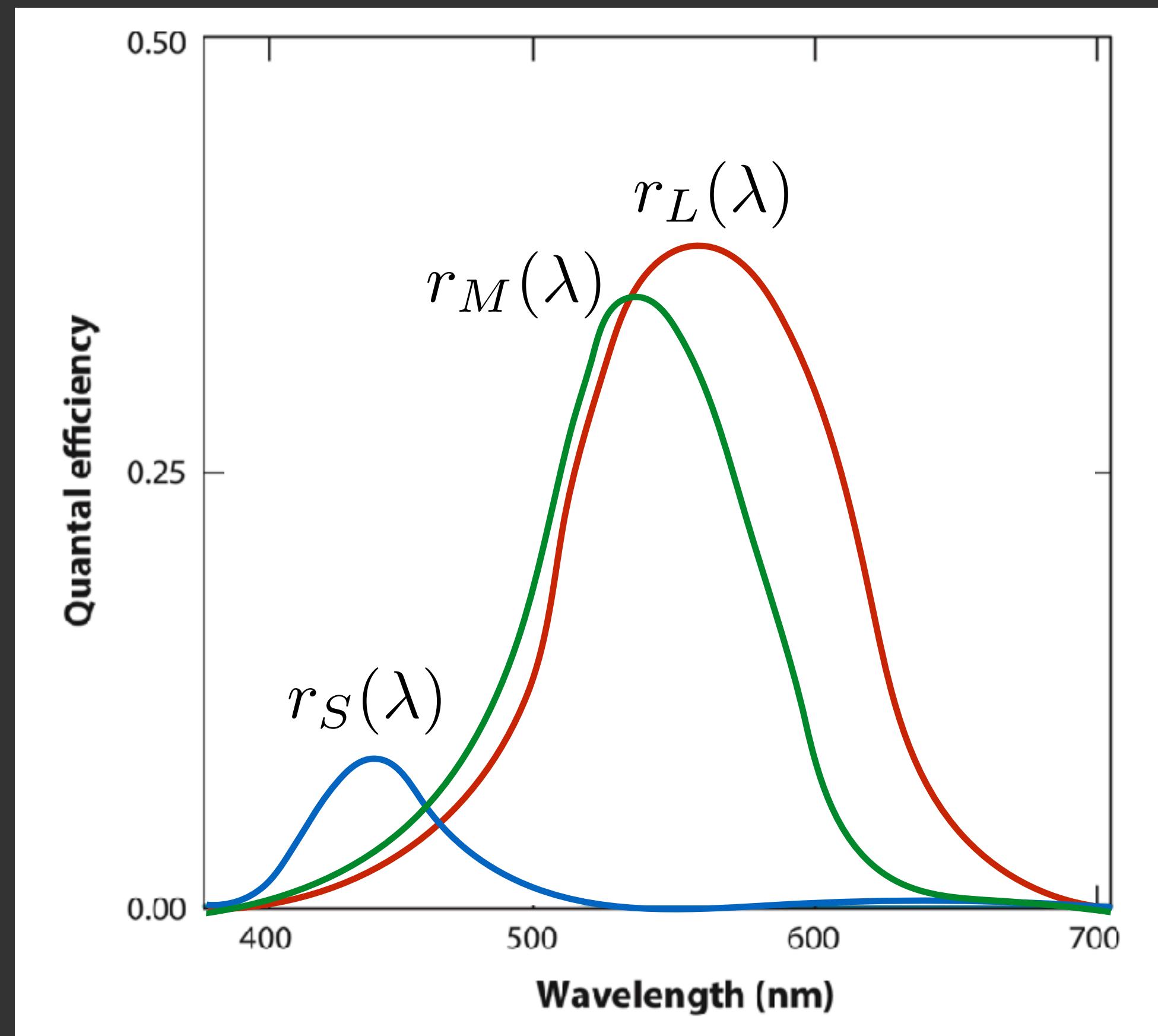
Human Color Vision: L, M, S Retinal Cone Cells



Human Color Vision: L, M, S Retinal Cone Cells



Probability that a photon will cause a photopigment isomerization



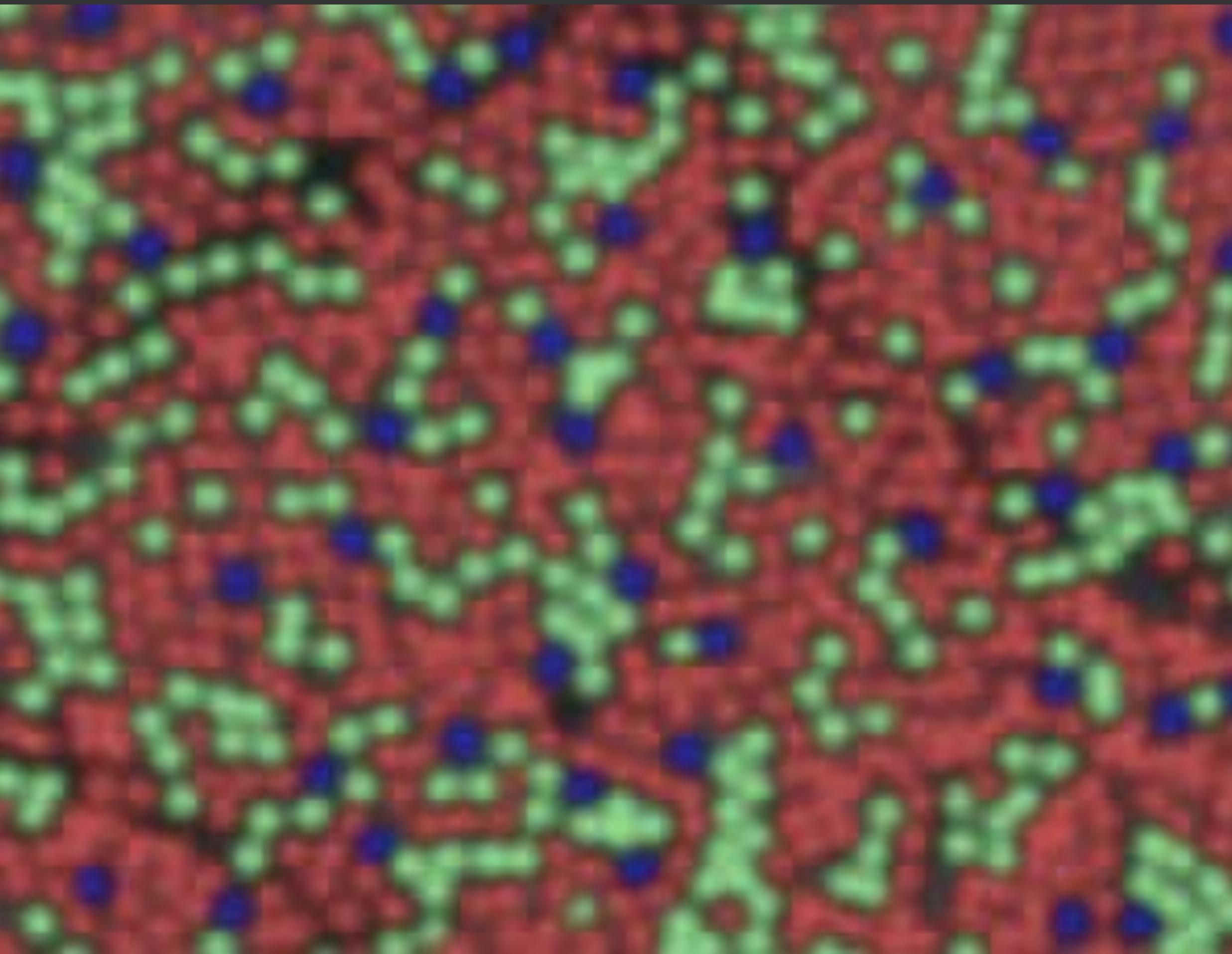
From: Brainard, Color and the Cone Mosaic, 2015.

Oz Vision: Per Photoreceptor Computer Graphics

Oz Vision: Per-Photoreceptor Computer Graphics



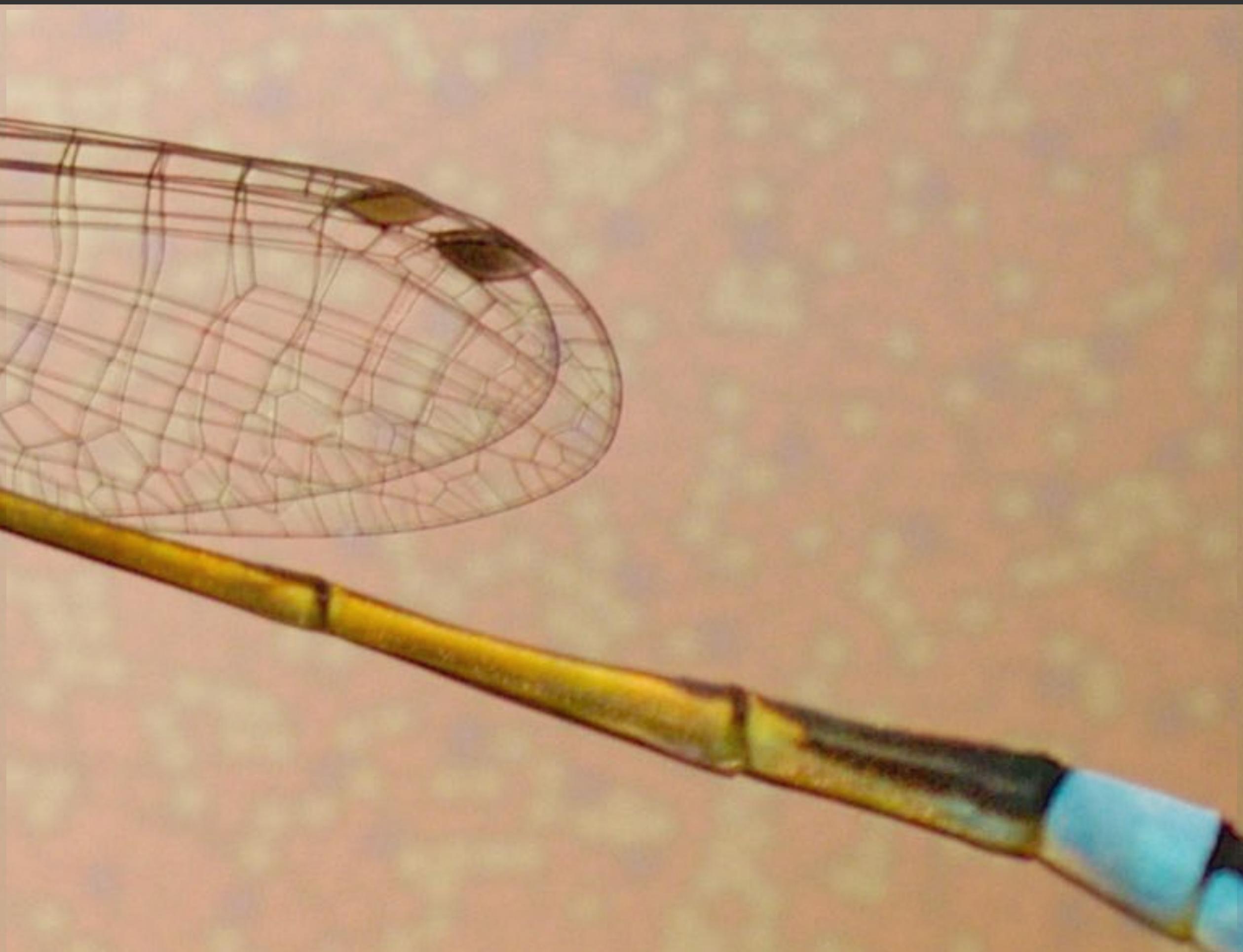
Oz Vision: Per-Photoreceptor Computer Graphics



Retinal cone cell mosaic

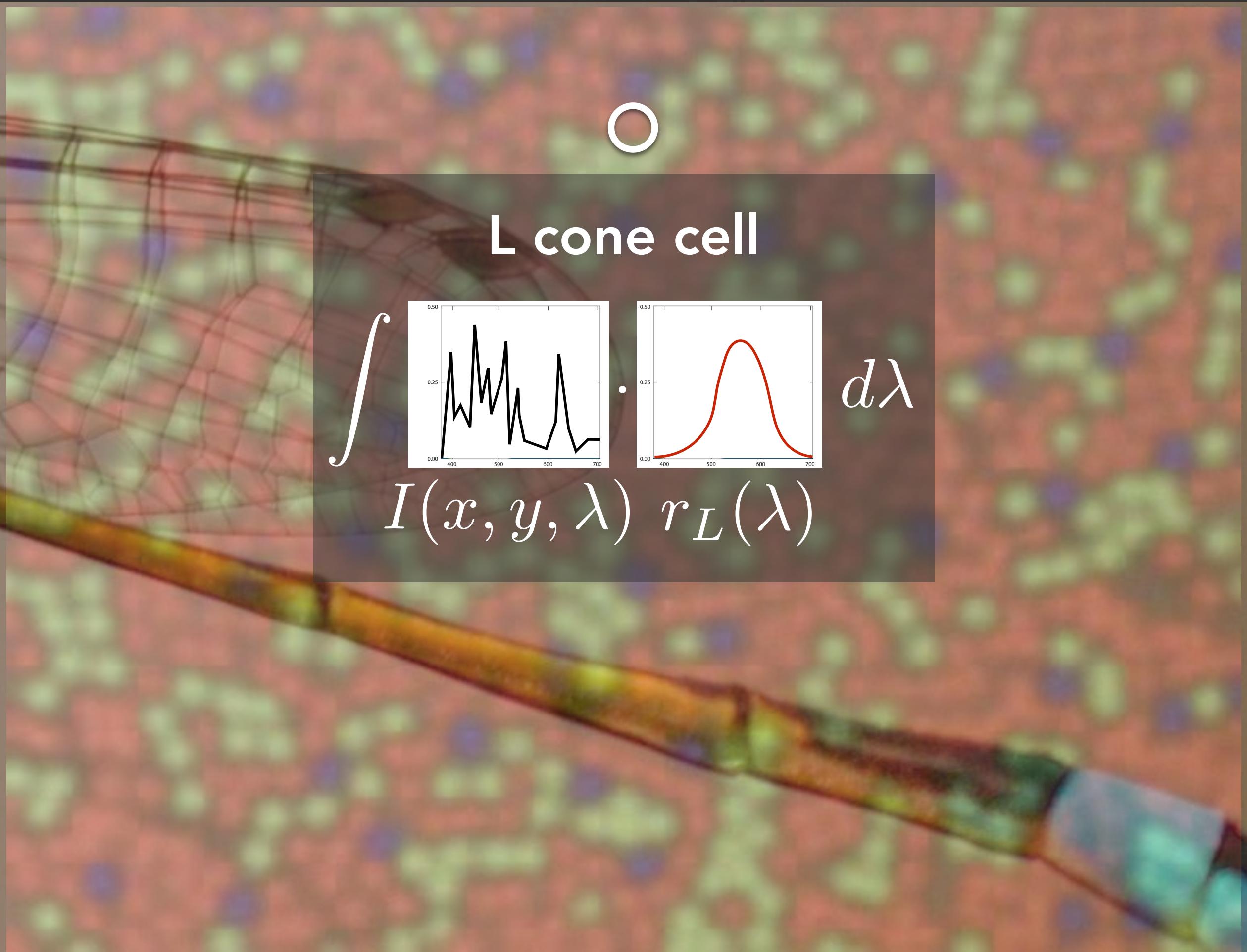
Credit: Sabesan, <http://depts.washington.edu/sabaolab/>

Oz Vision: Per-Photoreceptor Computer Graphics



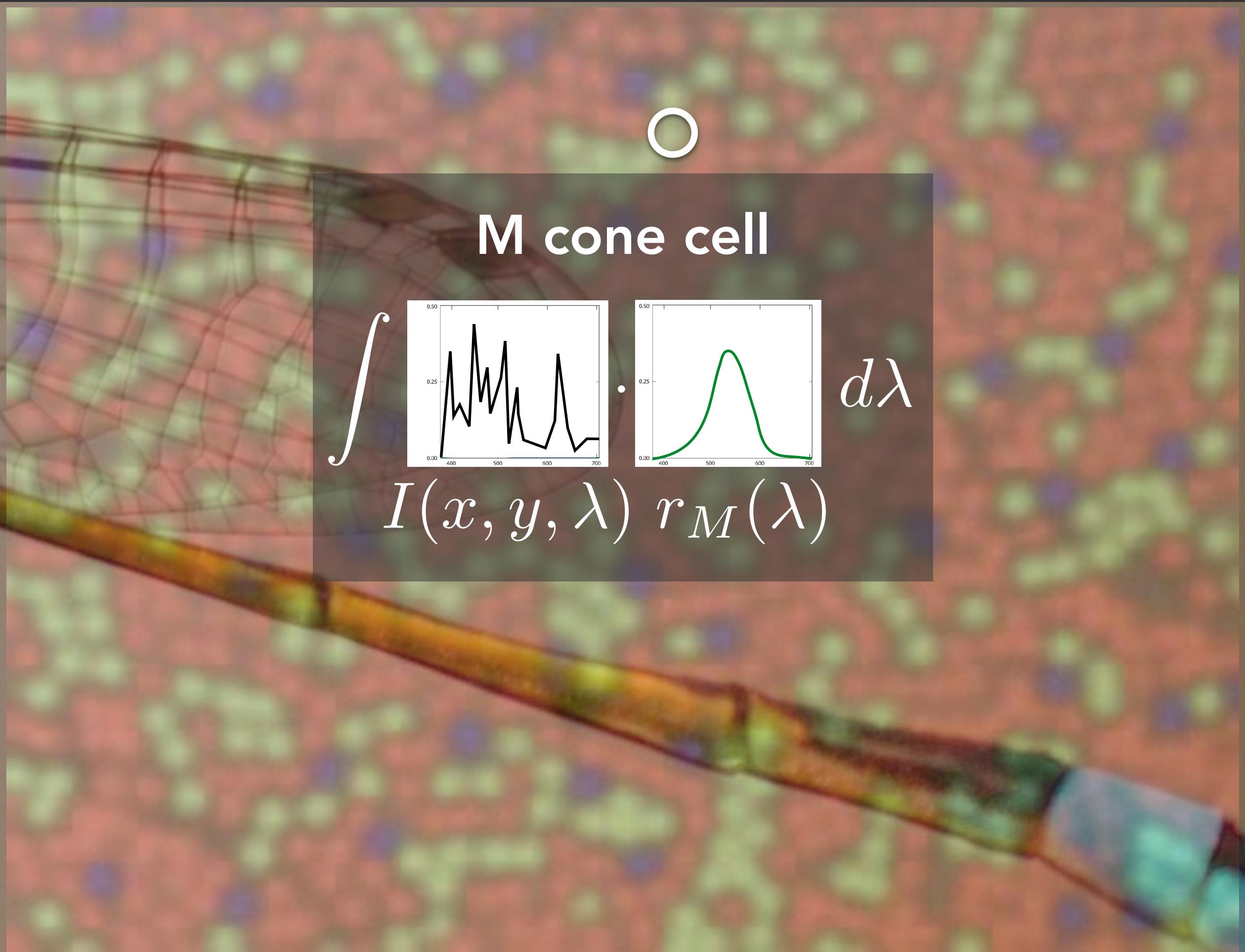
Scene projected onto retina

Oz Vision: Per-Photoreceptor Computer Graphics



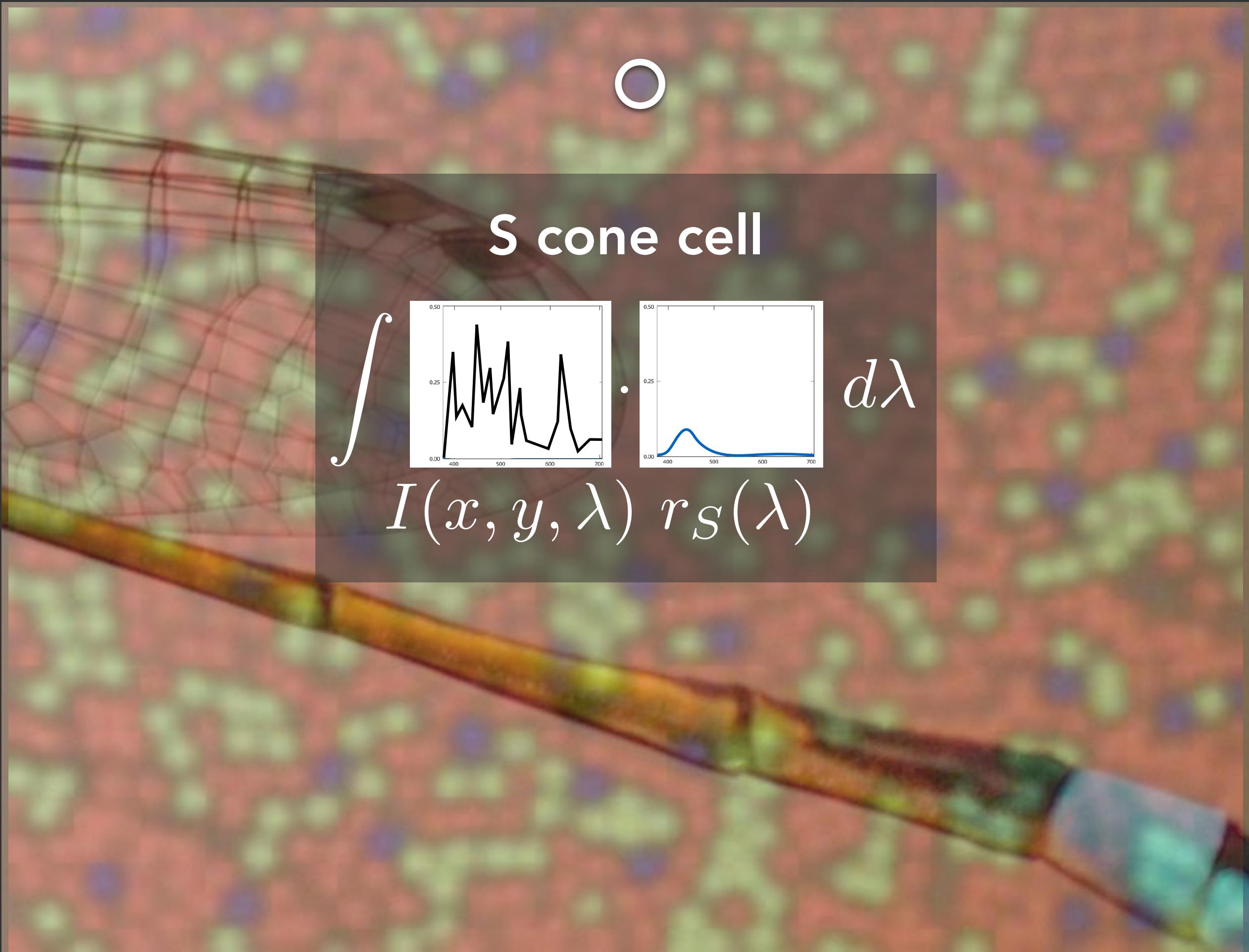
For each cone cell, compute required signal value,
and individually stimulate it with targeted laser microdose.

Oz Vision: Per-Photoreceptor Computer Graphics



For each cone cell, compute required signal value,
and individually stimulate it with targeted laser microdose.

Oz Vision: Per-Photoreceptor Computer Graphics



For each cone cell, compute required signal value,
and individually stimulate it with targeted laser microdose.

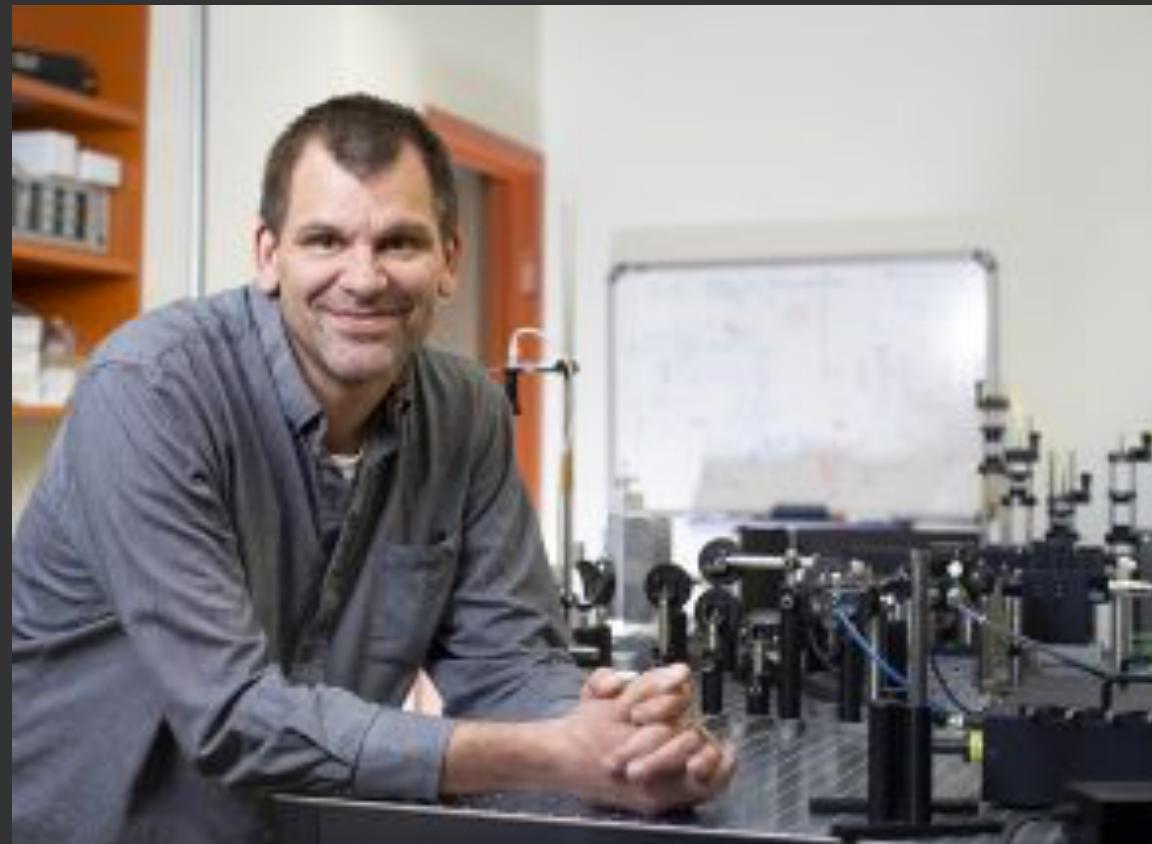
Conventional displays create color through
spectrally-based metamerism.

Oz Vision displays create color through
spatially-based "metamerism".

Conventional displays need
three (or more) spectral light sources.

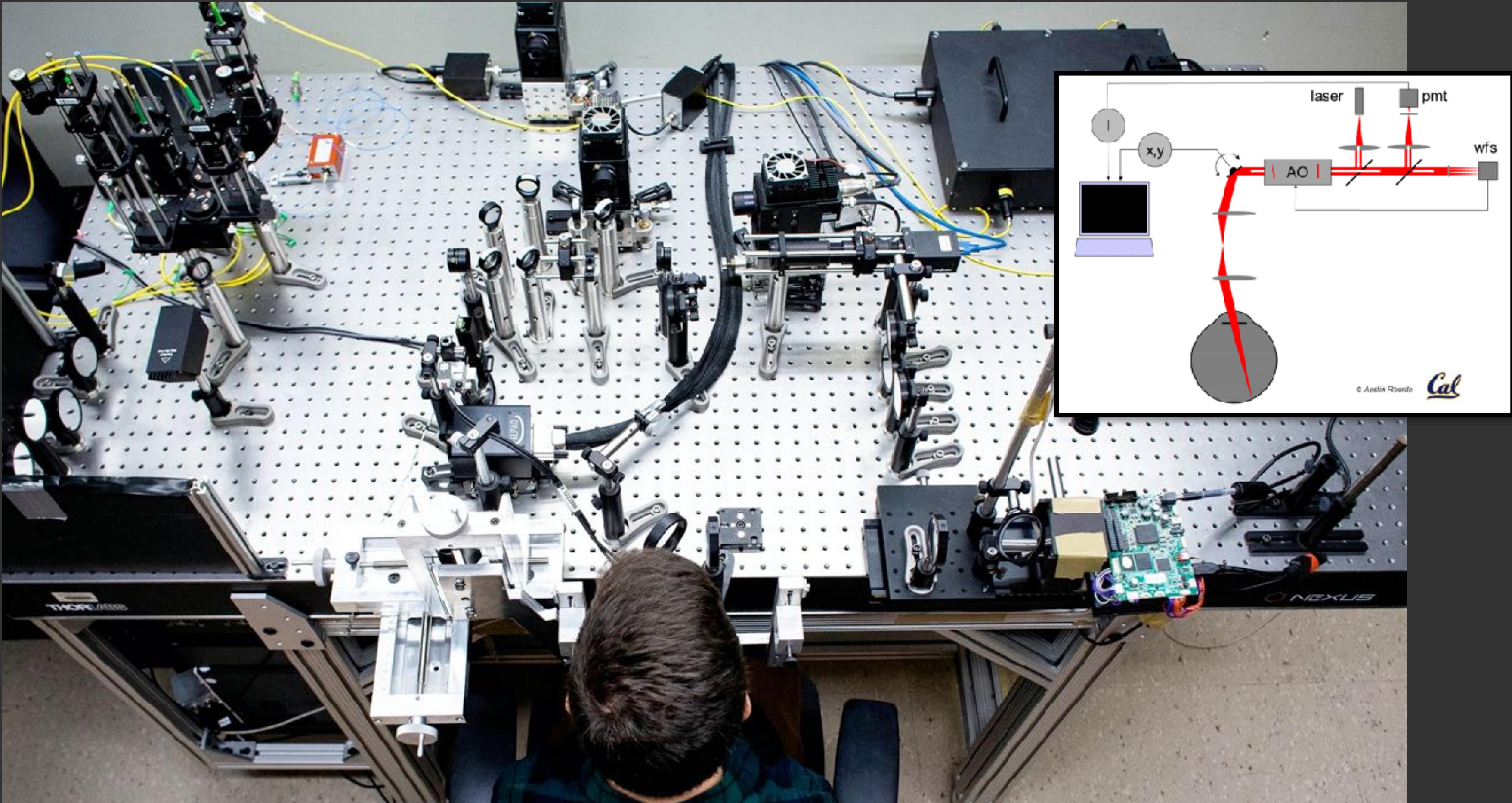
Oz Vision displays need
only a single spectral light source.

Imaging, Tracking, Stimulating Retina Cells



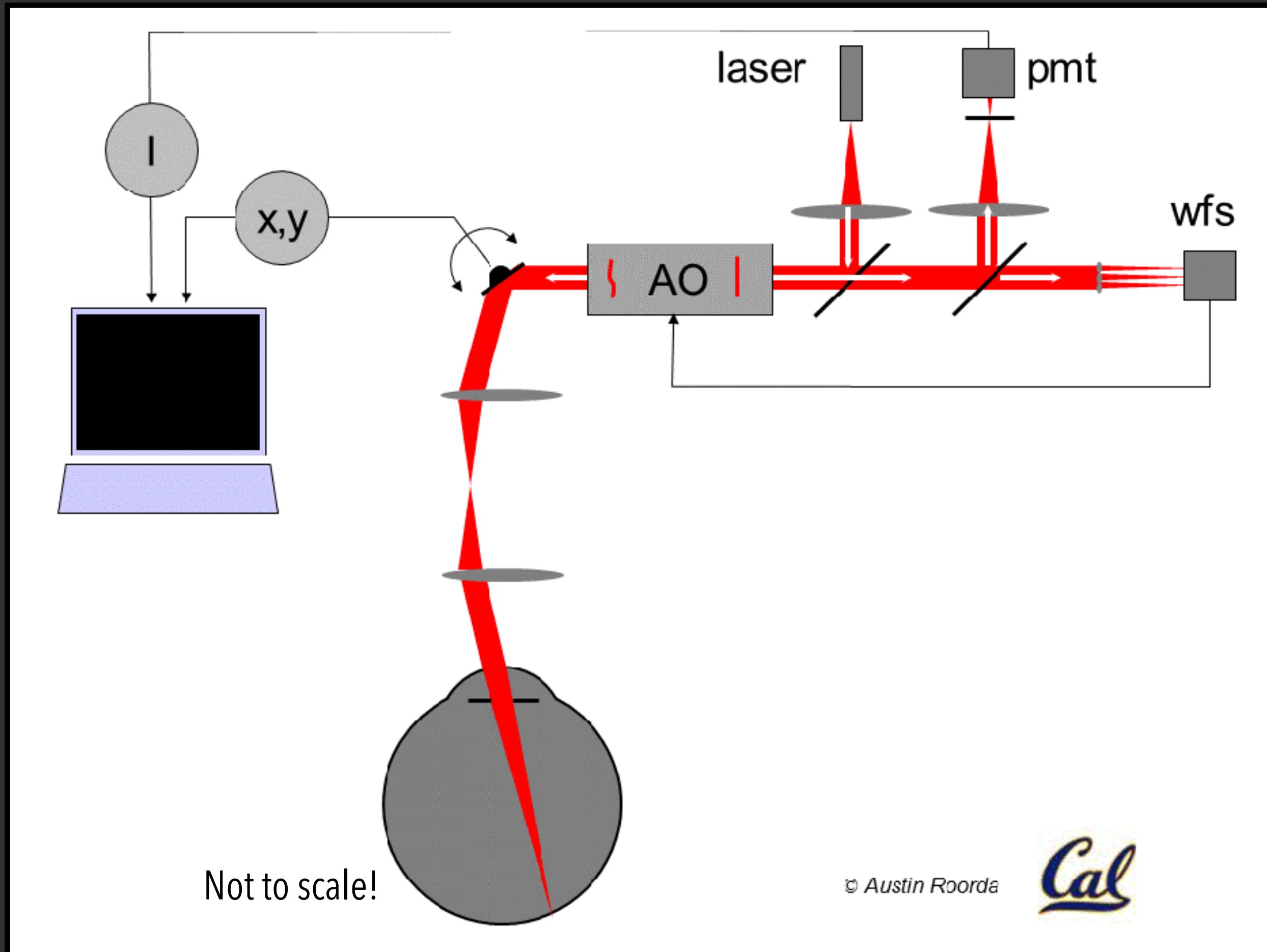
Slides courtesy of Austin Roorda

Roorda Lab AOSLO



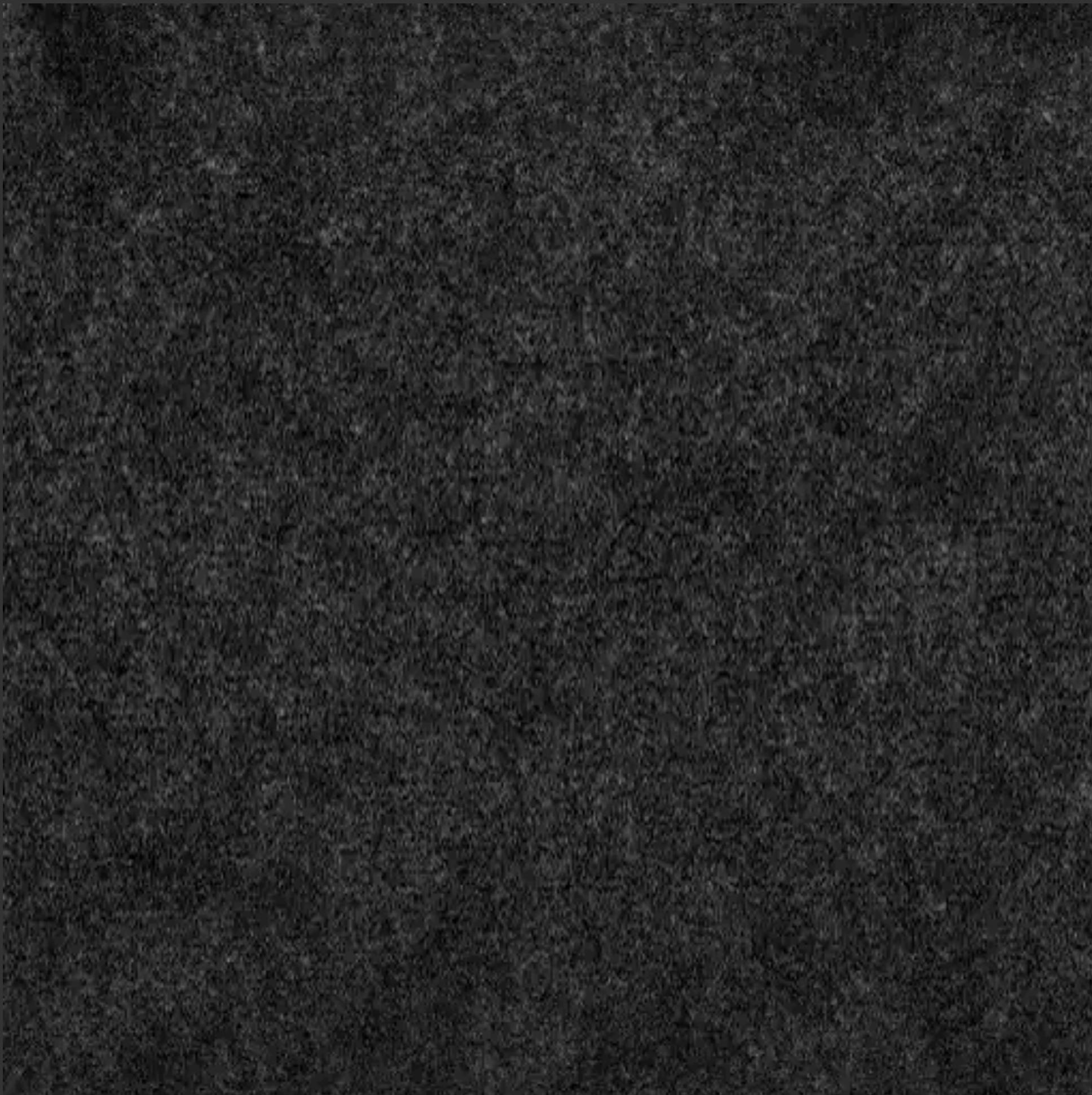
Adaptive Optics Scanning Laser Ophthalmoscope

Roorda Lab AOSLO

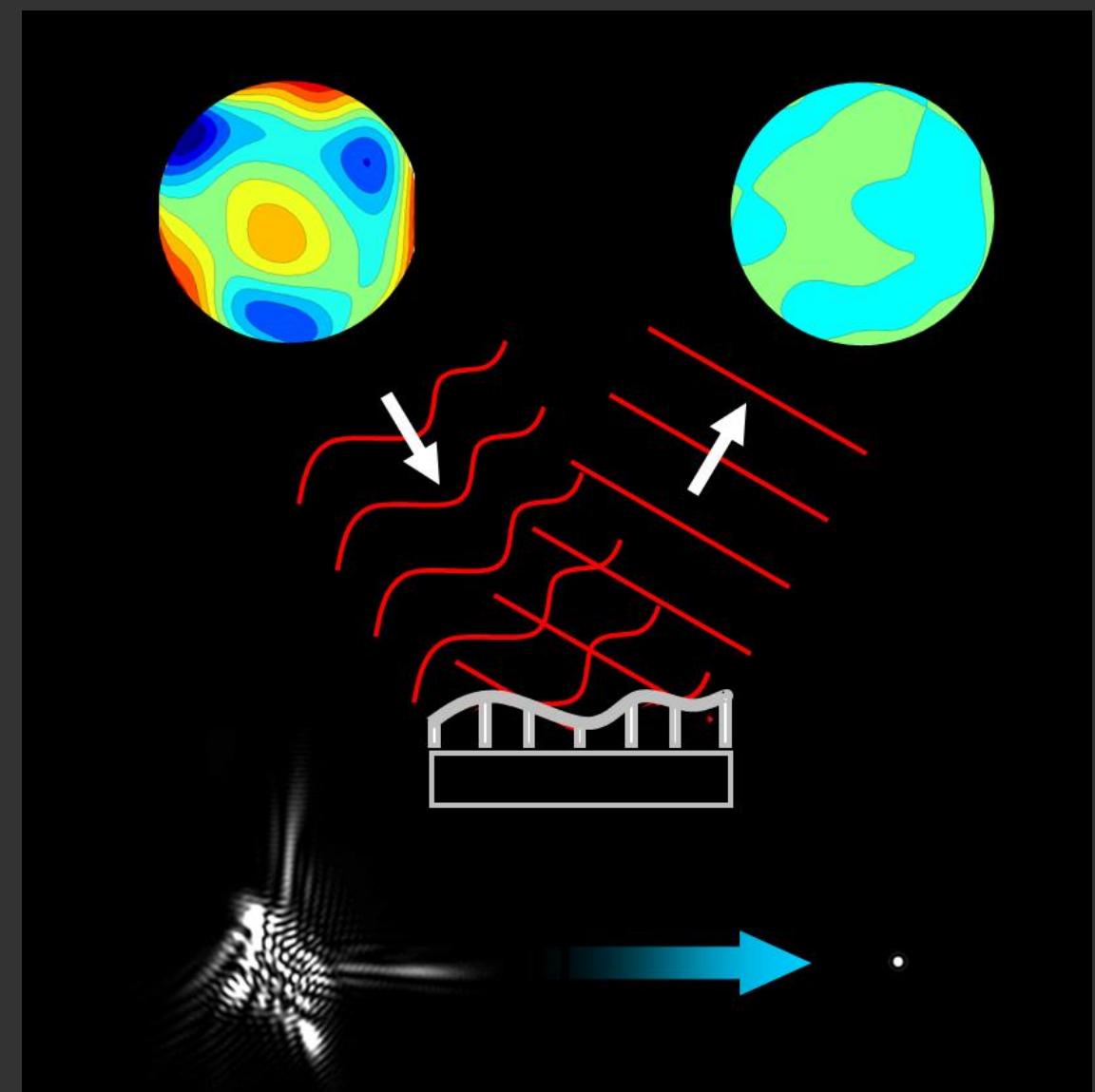


Adaptive Optics Scanning Laser Ophthalmoscope

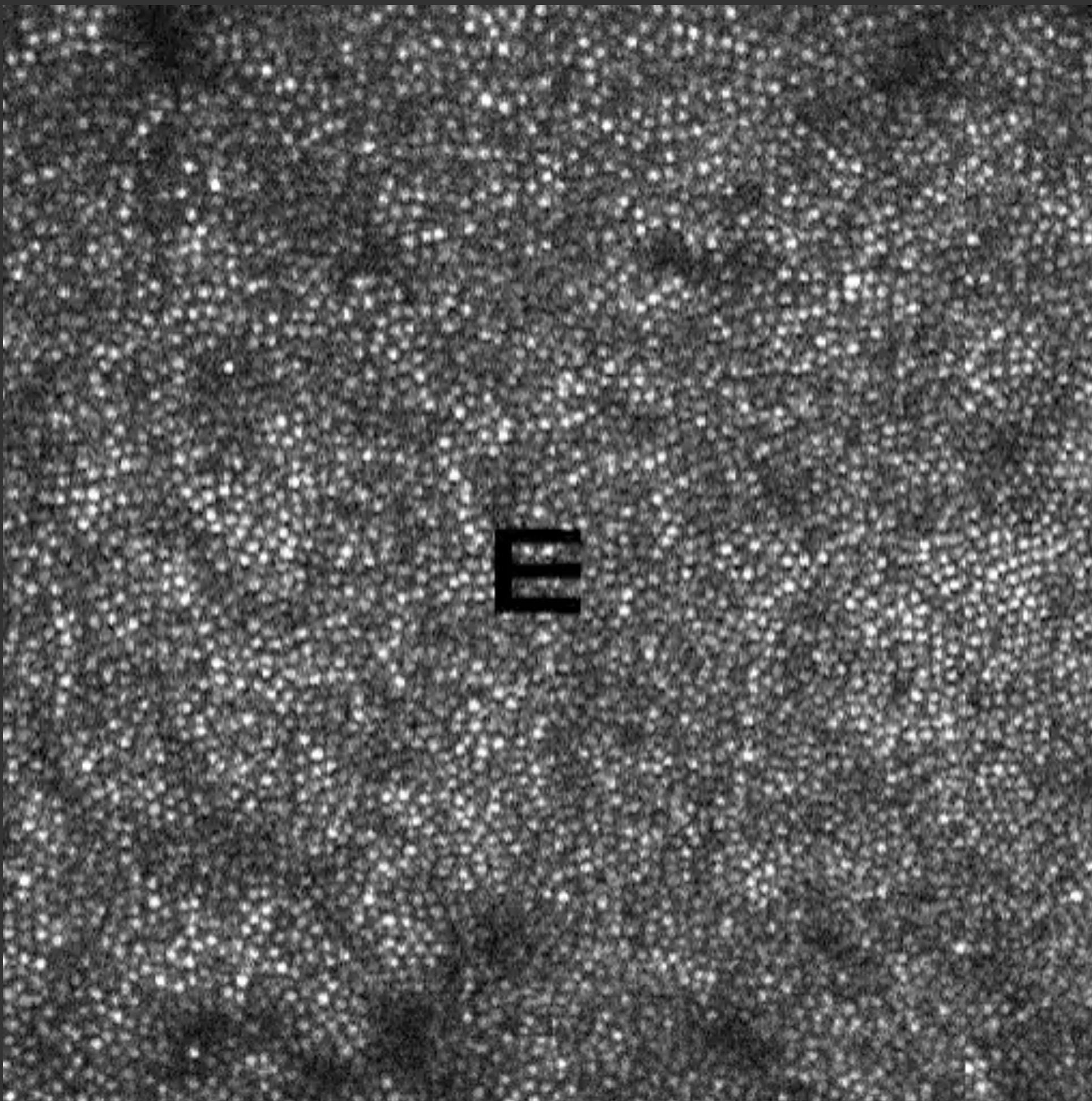
The Adaptive Optics Retinal Microstimulator (Roorda Lab)



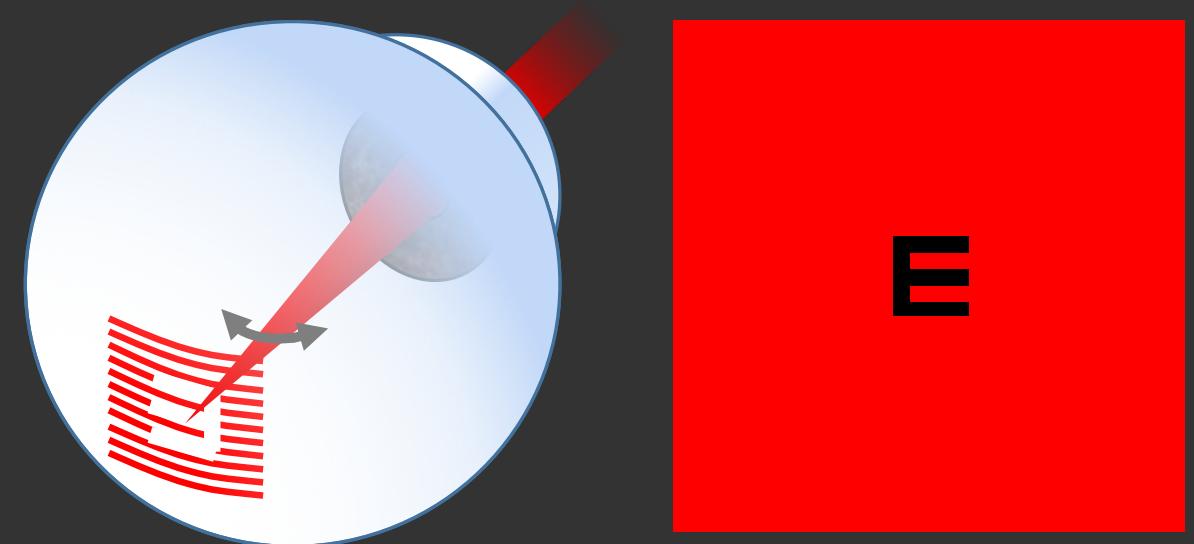
- AO correction
- Stimulus delivery
- Stabilization
- Targeted delivery



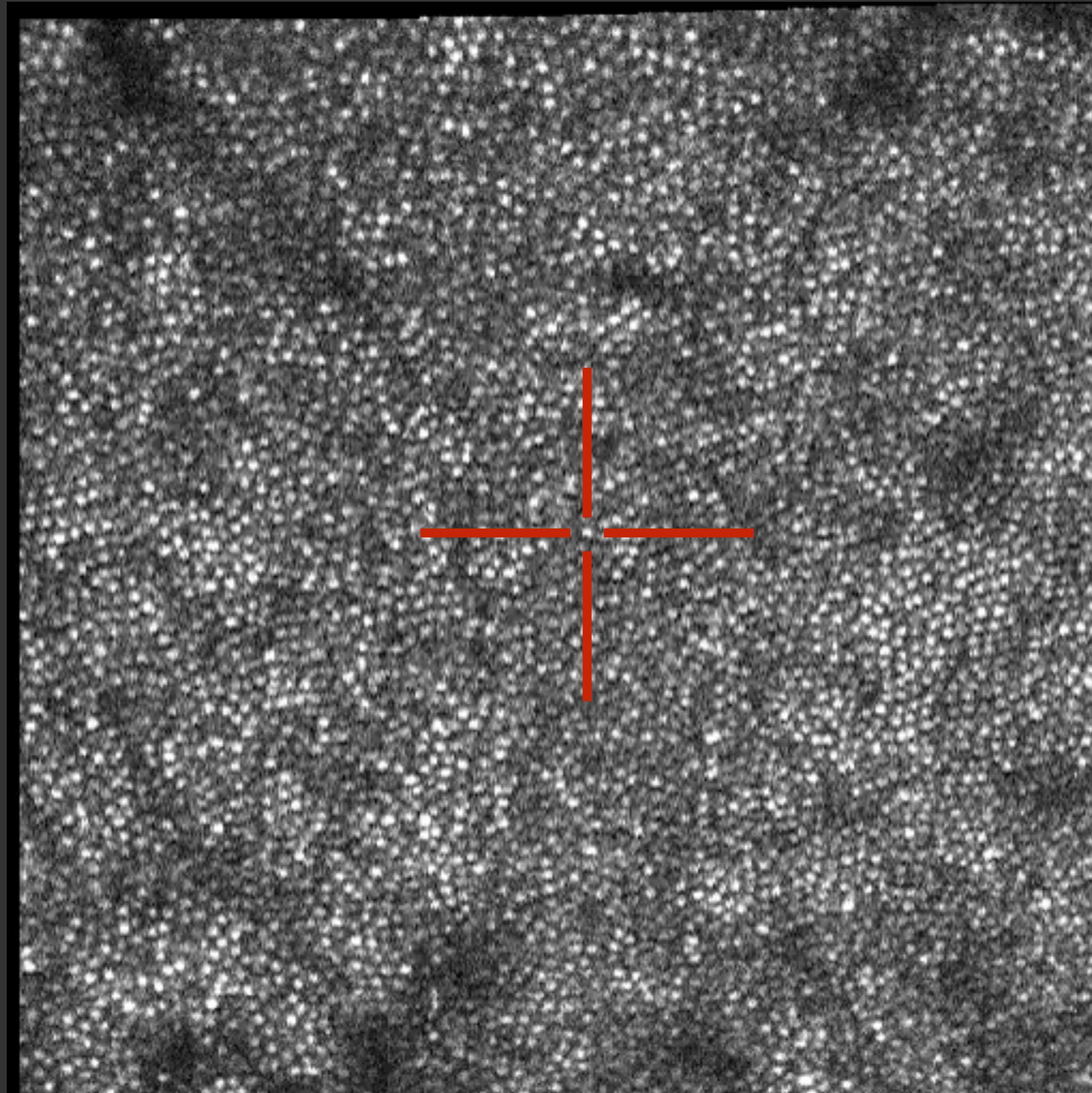
The Adaptive Optics Retinal Microstimulator (Roorda Lab)



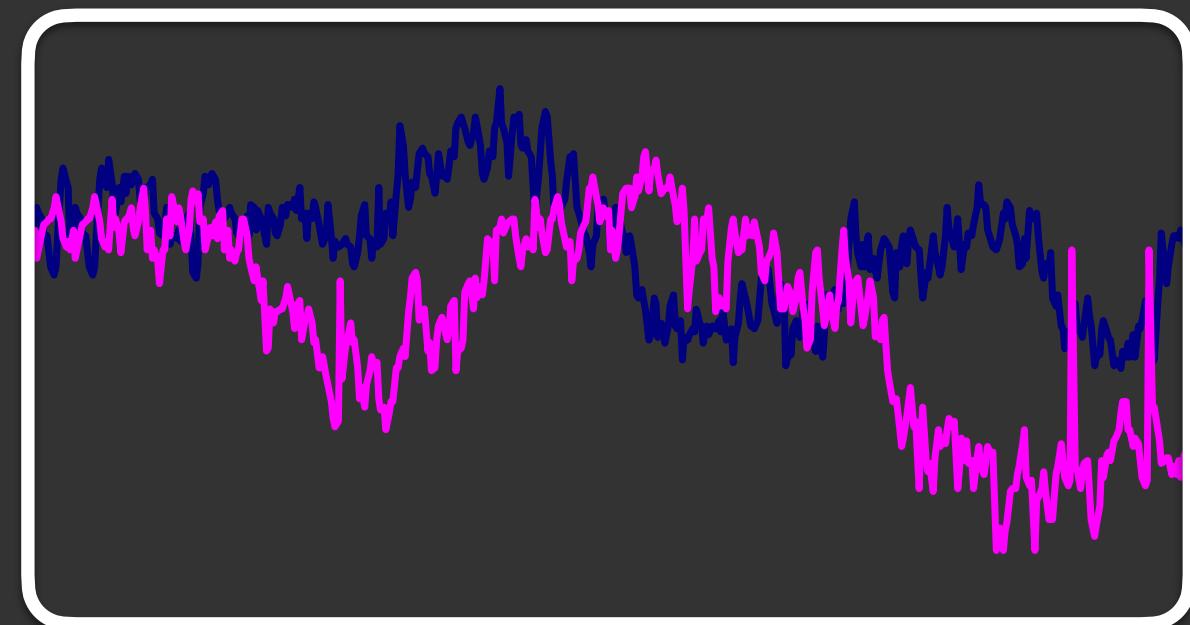
- AO correction
- Stimulus delivery
- Stabilization
- Targeted delivery



The Adaptive Optics Retinal Microstimulator (Roorda Lab)

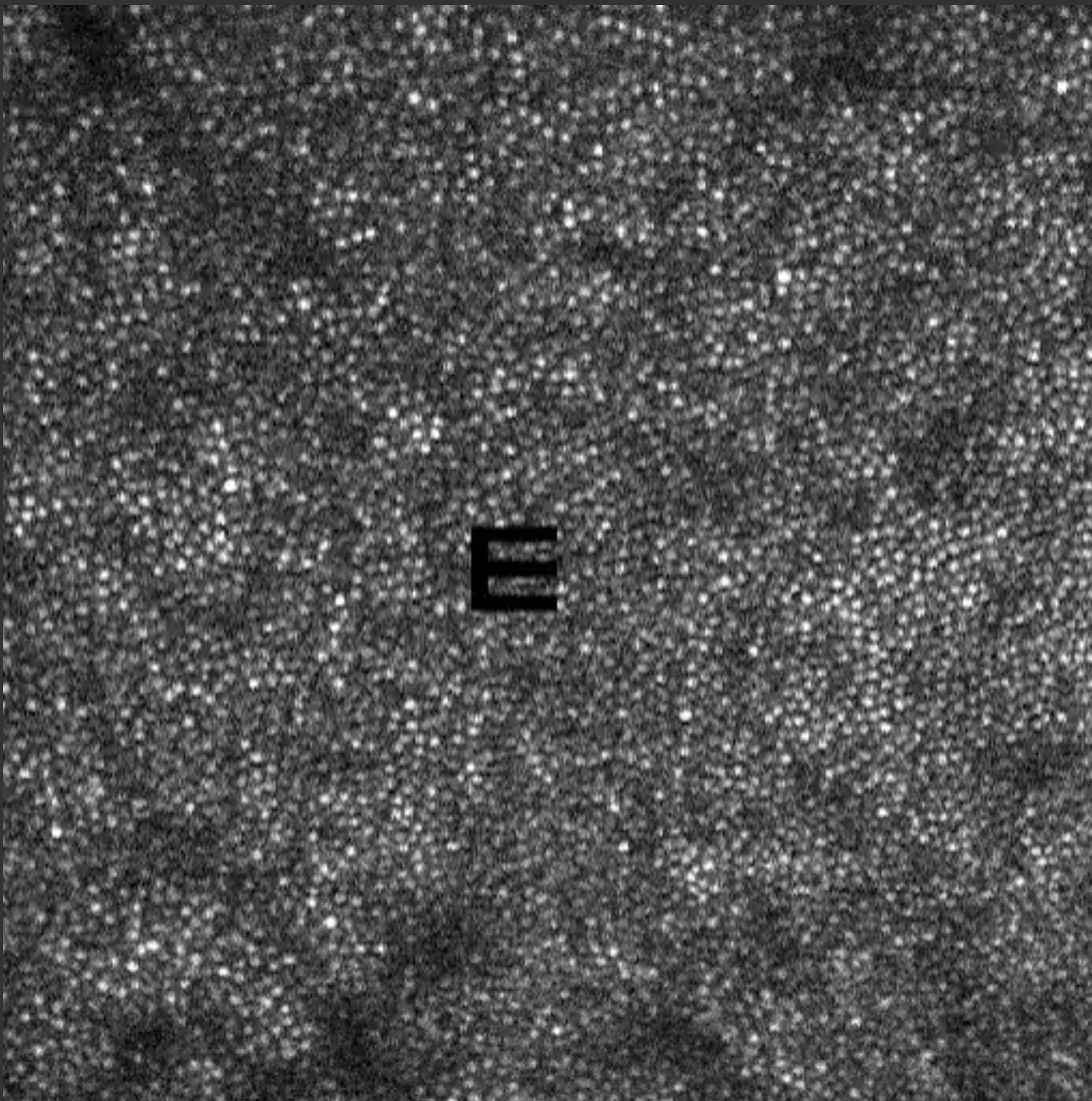


- AO correction
- Stimulus delivery
- Stabilization
- Targeted delivery



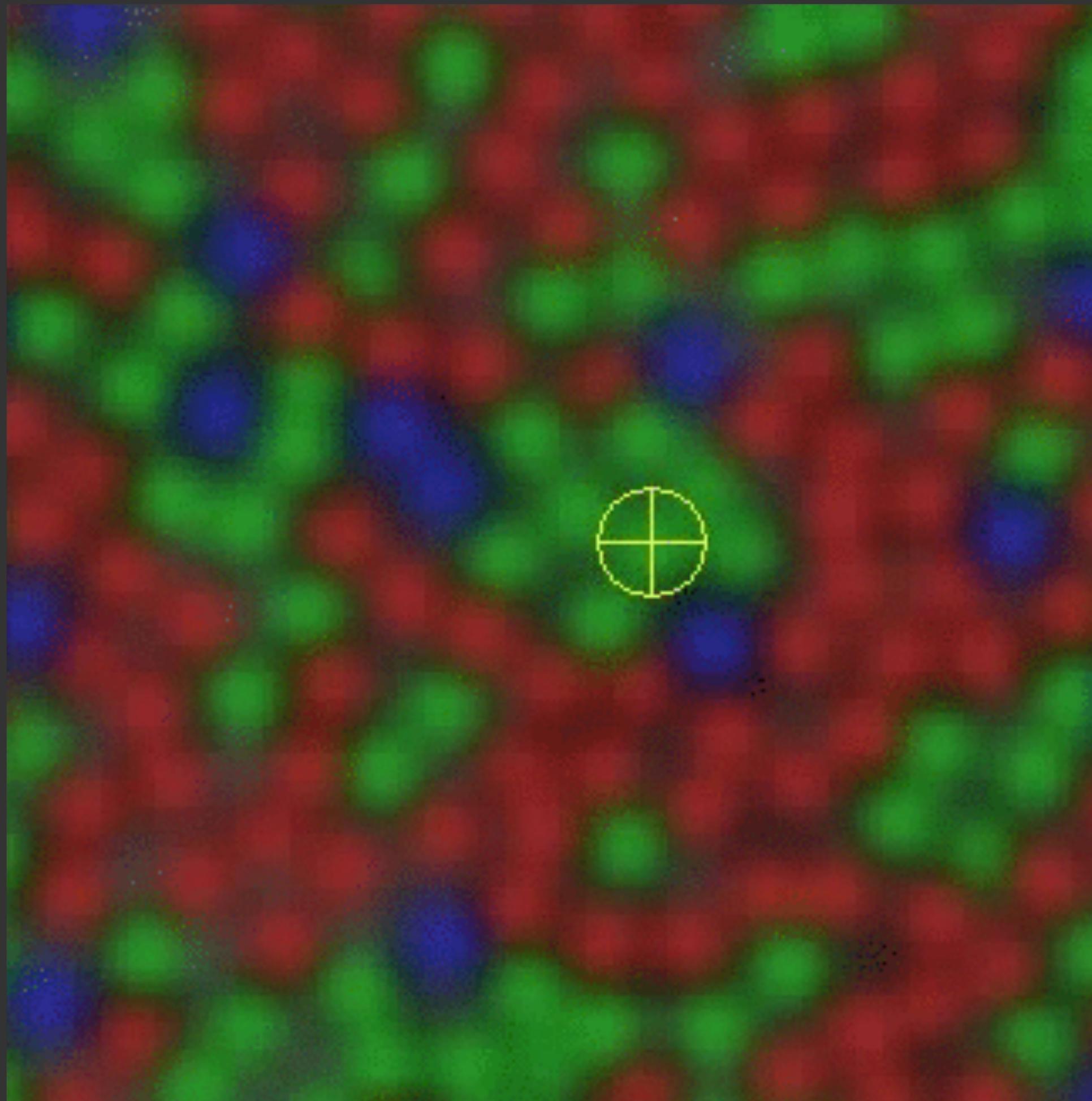
Real-time eye motion trace

The Adaptive Optics Retinal Microstimulator (Roorda Lab)



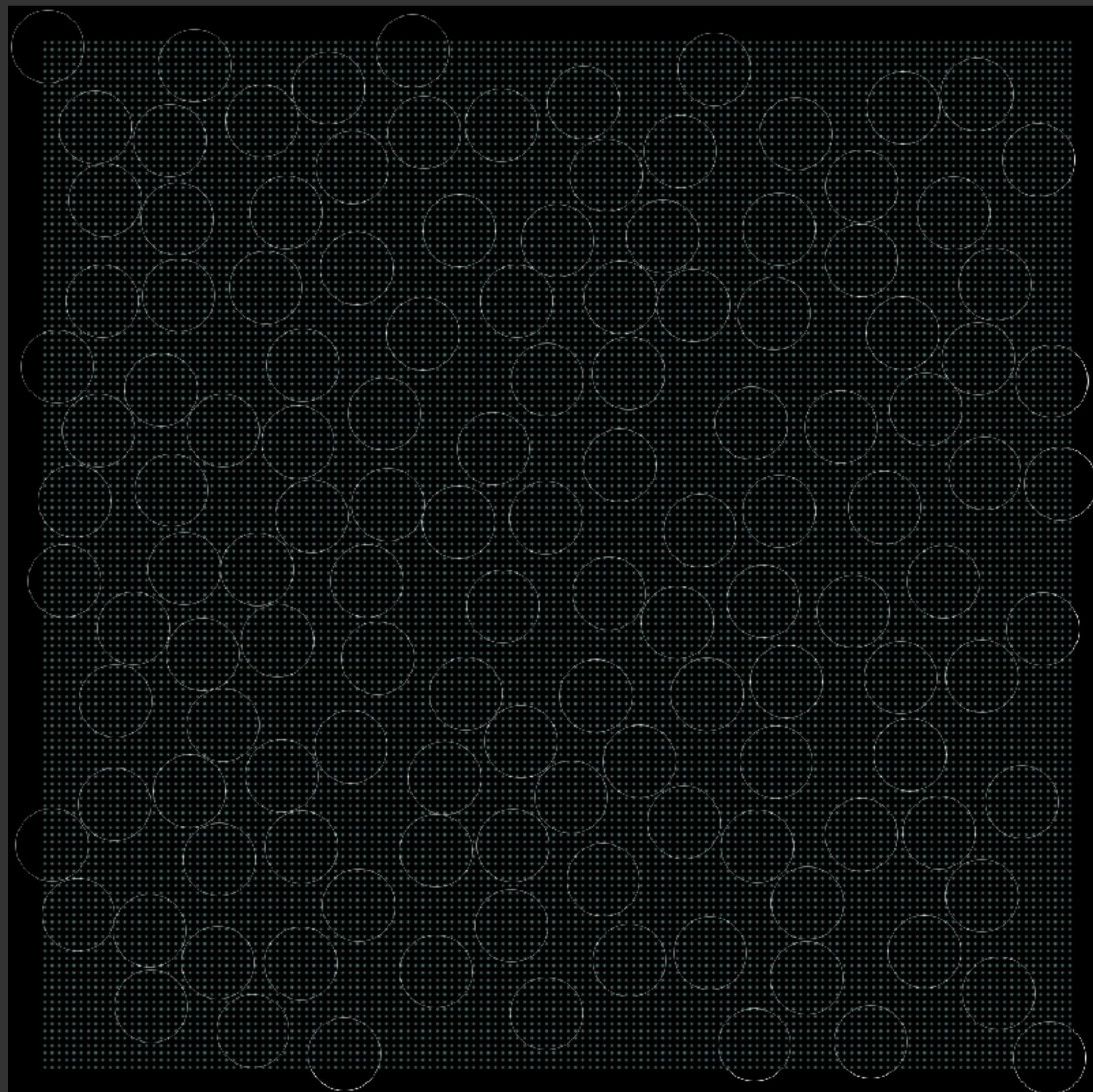
- AO correction
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The Adaptive Optics Retinal Microstimulator (Roorda Lab)



- AO correction
- Stimulus delivery
- Stabilization
- Targeted delivery

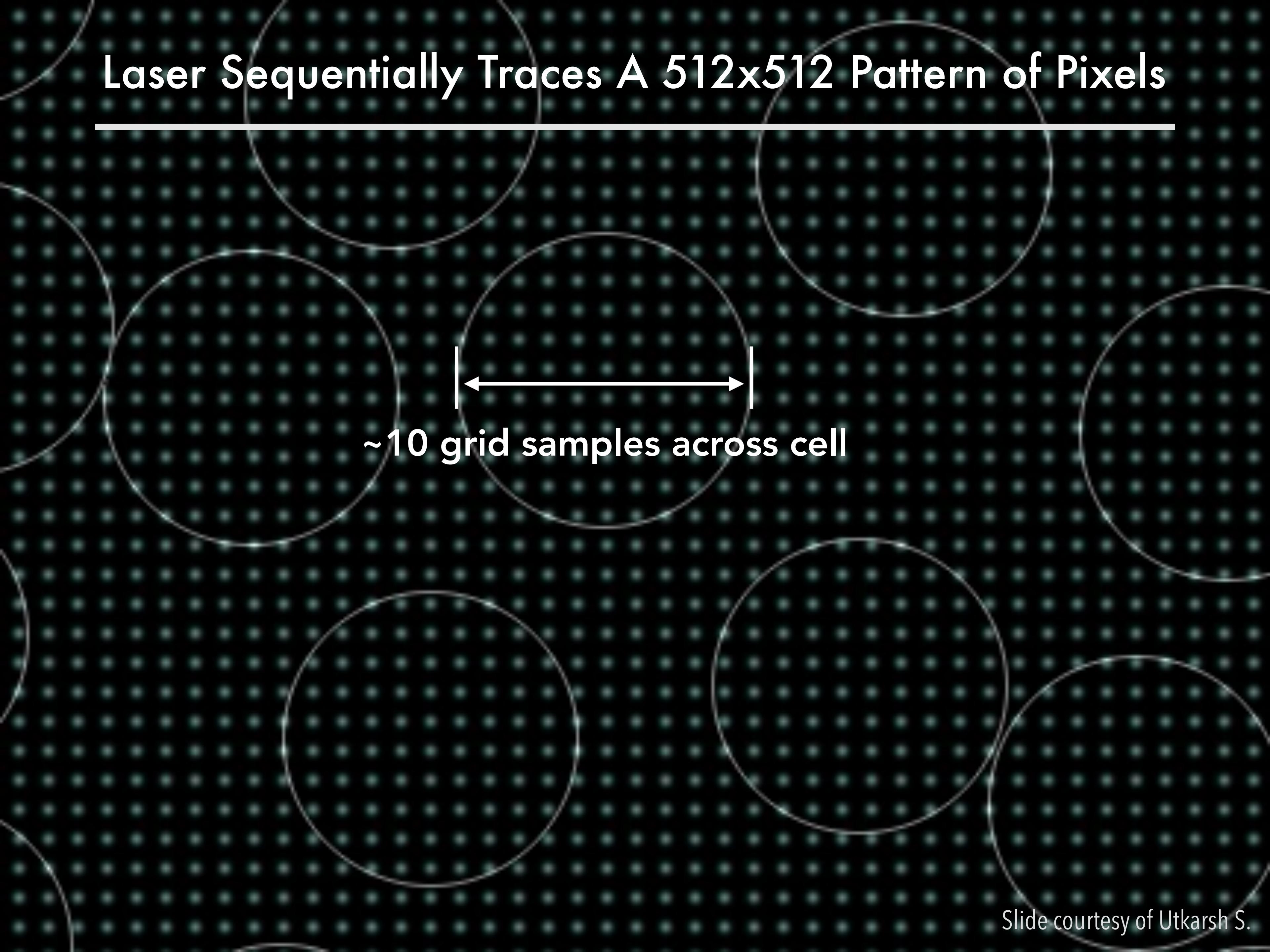
Laser Sequentially Traces A 512x512 Pattern of Pixels



Laser sample positions over cells

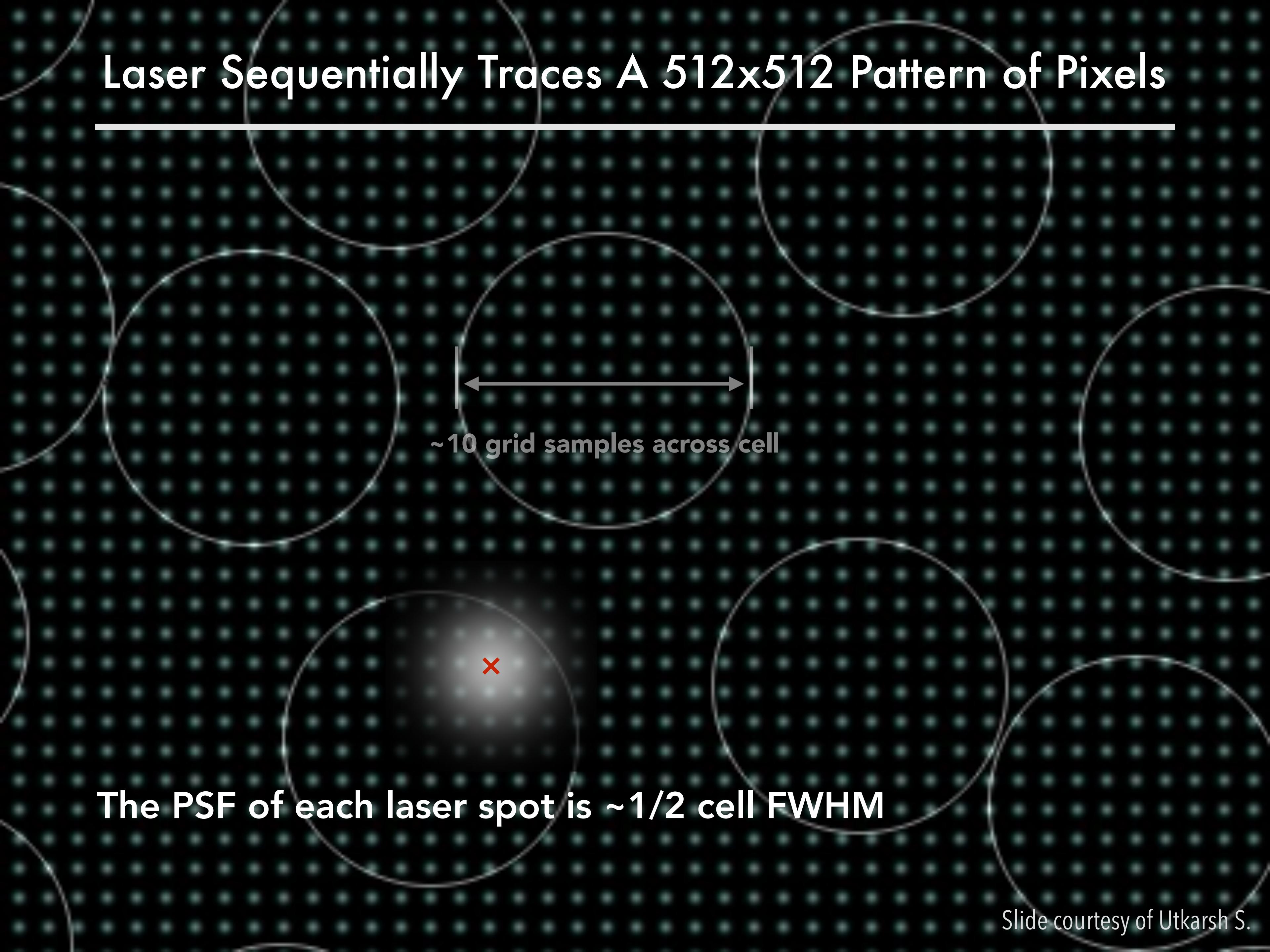
Slide courtesy of Utkarsh S.

Laser Sequentially Traces A 512x512 Pattern of Pixels



~10 grid samples across cell

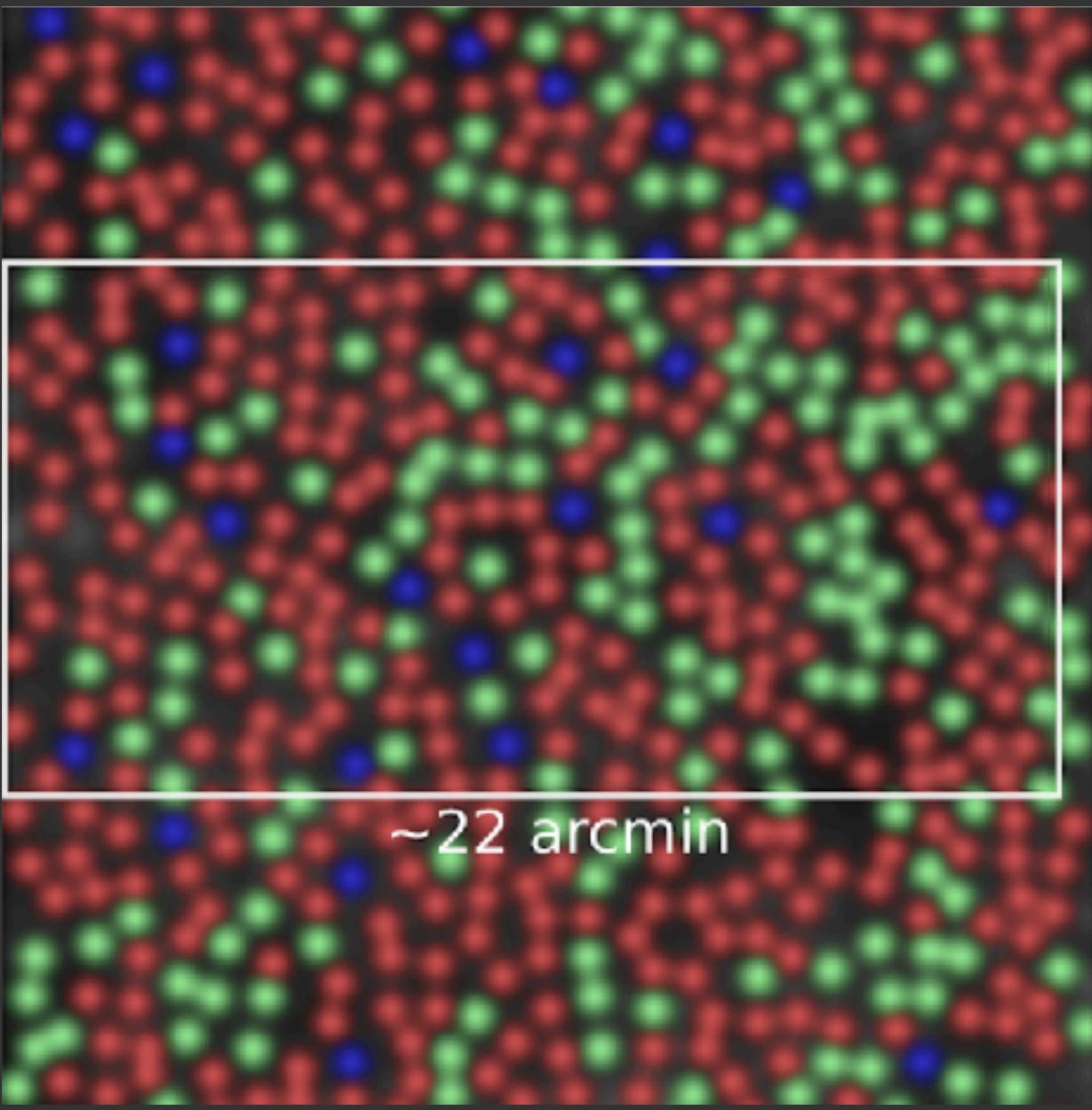
Laser Sequentially Traces A 512x512 Pattern of Pixels



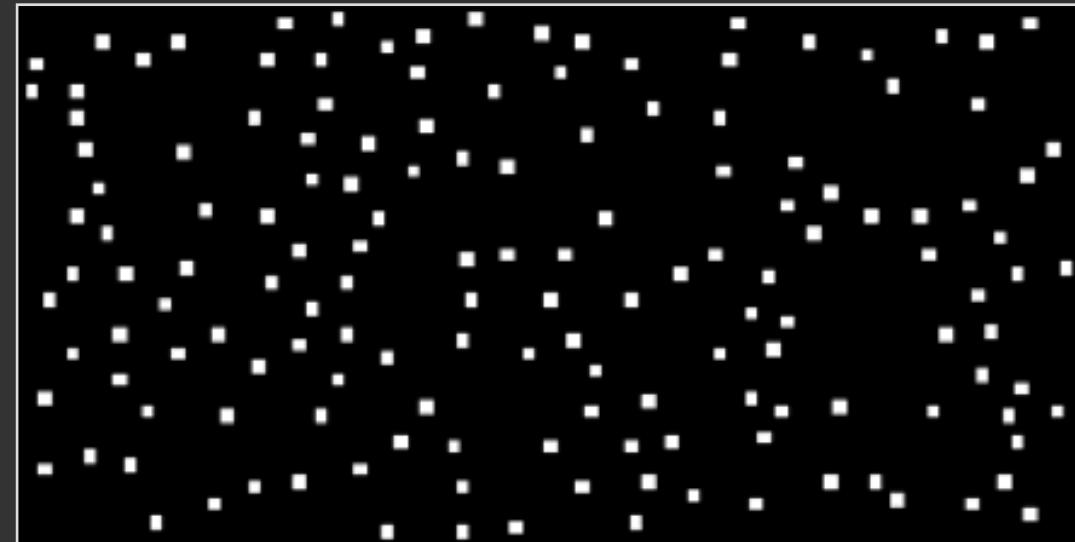
~10 grid samples across cell

The PSF of each laser spot is ~1/2 cell FWHM

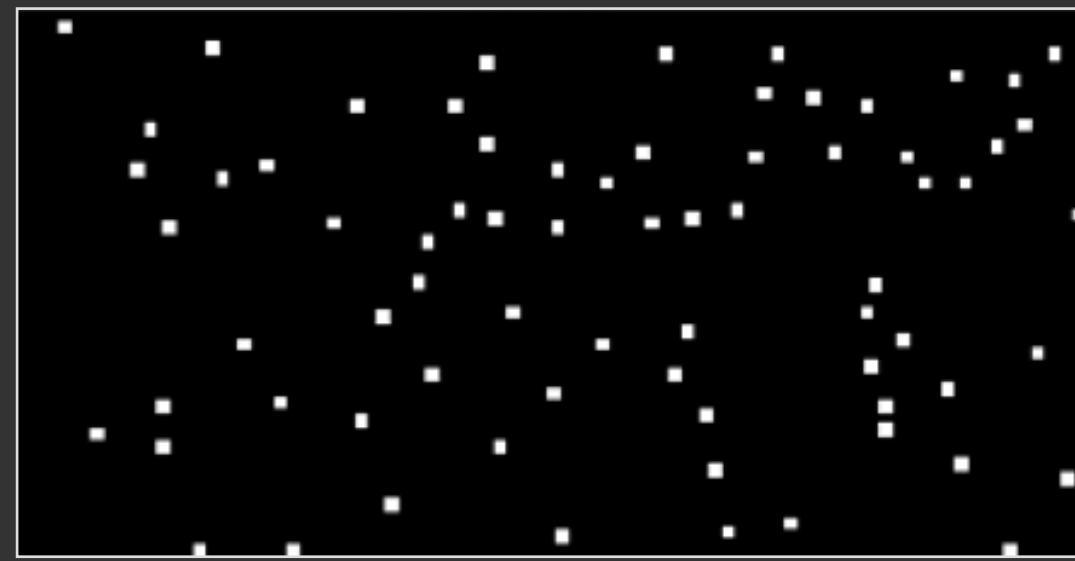
Oz Vision Prototype Display



Retinal area stimulated



L-cones



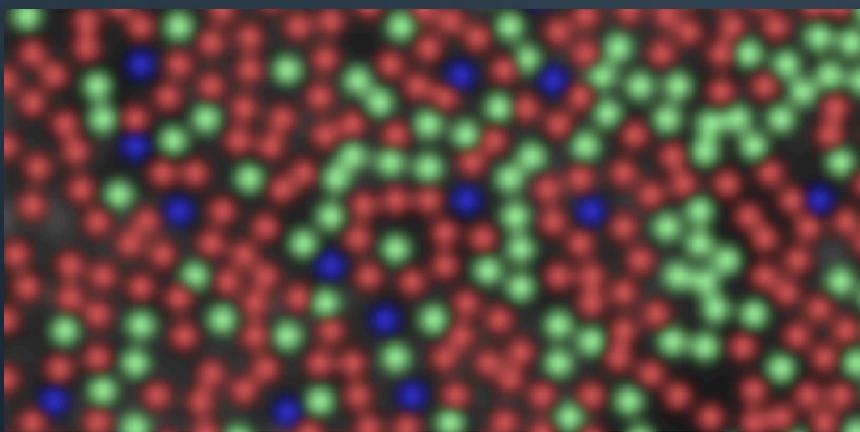
M-cones

- Retinal patch area: $0.37^\circ \times 0.19^\circ$
- Cone map: 150 L-type and 73 M-type
- Position: 1.5° eccentricity

Visual Field of View of Oz Prototype



Moon diameter:
 0.5°



Retinal patch stimulated in Oz:
 $0.37^\circ \times 0.19^\circ$

Visual Field of View of Oz Prototype



<https://newwallpapers.org/hd-wallpaper-night-sky-moon/>

What Does 1.5° Eccentricity Mean?



←..... Fixation point

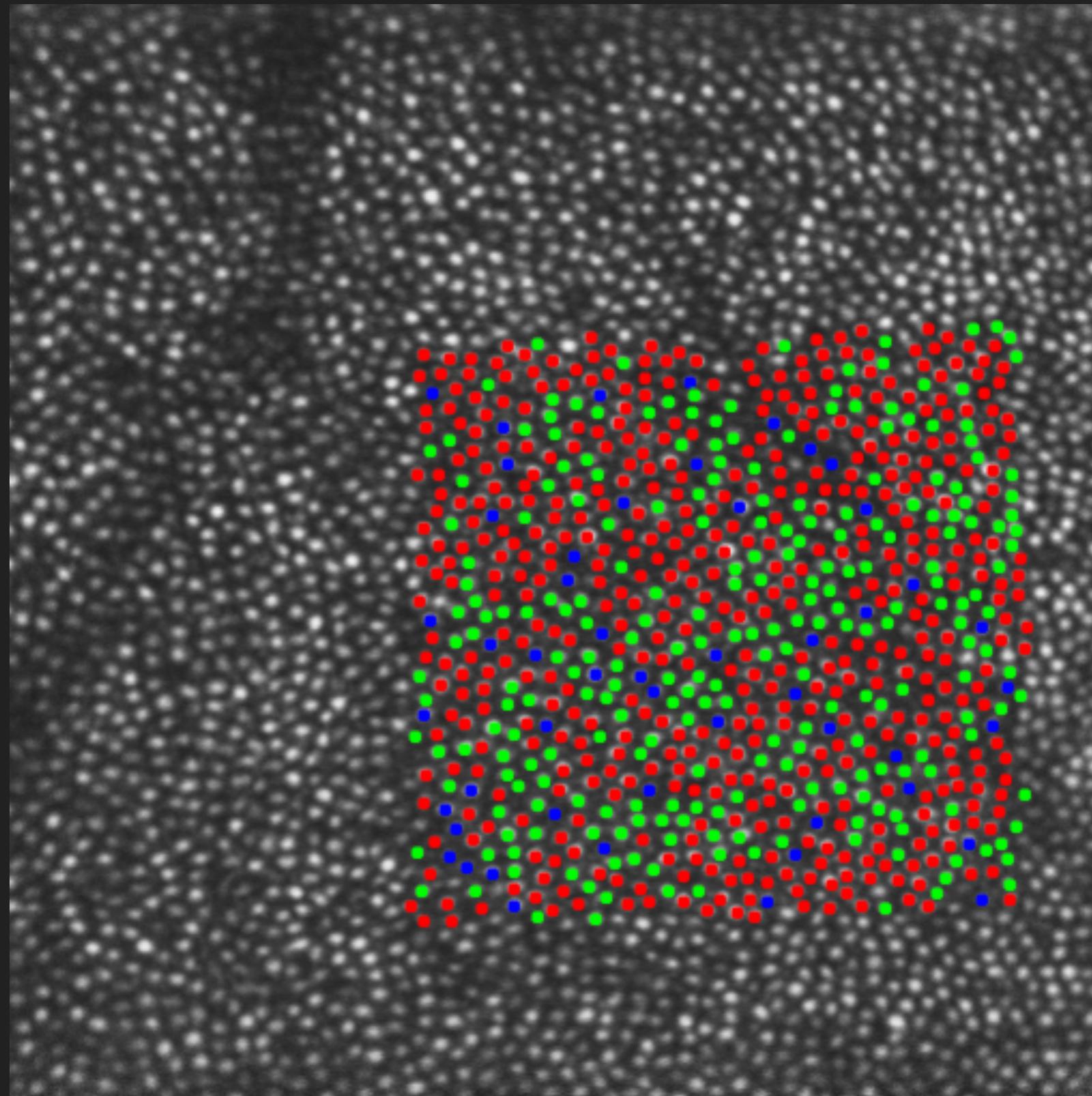
Rule of thumb: thumbnail at arm extension is approximately 1° visual angle. Where is the display relative to the fixation point?

Prototype v2.0 in Development

- v1.0 prototype
 - FPGA control
 - FOV = $0.37^\circ \times 0.19^\circ$
 - 1/8 sec flash of color
 - Costly to reconfigure
 - ...
- v2.0 prototype (in dev)
 - New real-time C++ API
 - FOV = $1^\circ \times 1^\circ$
 - Sustained color
 - Programmable graphics
 - ...

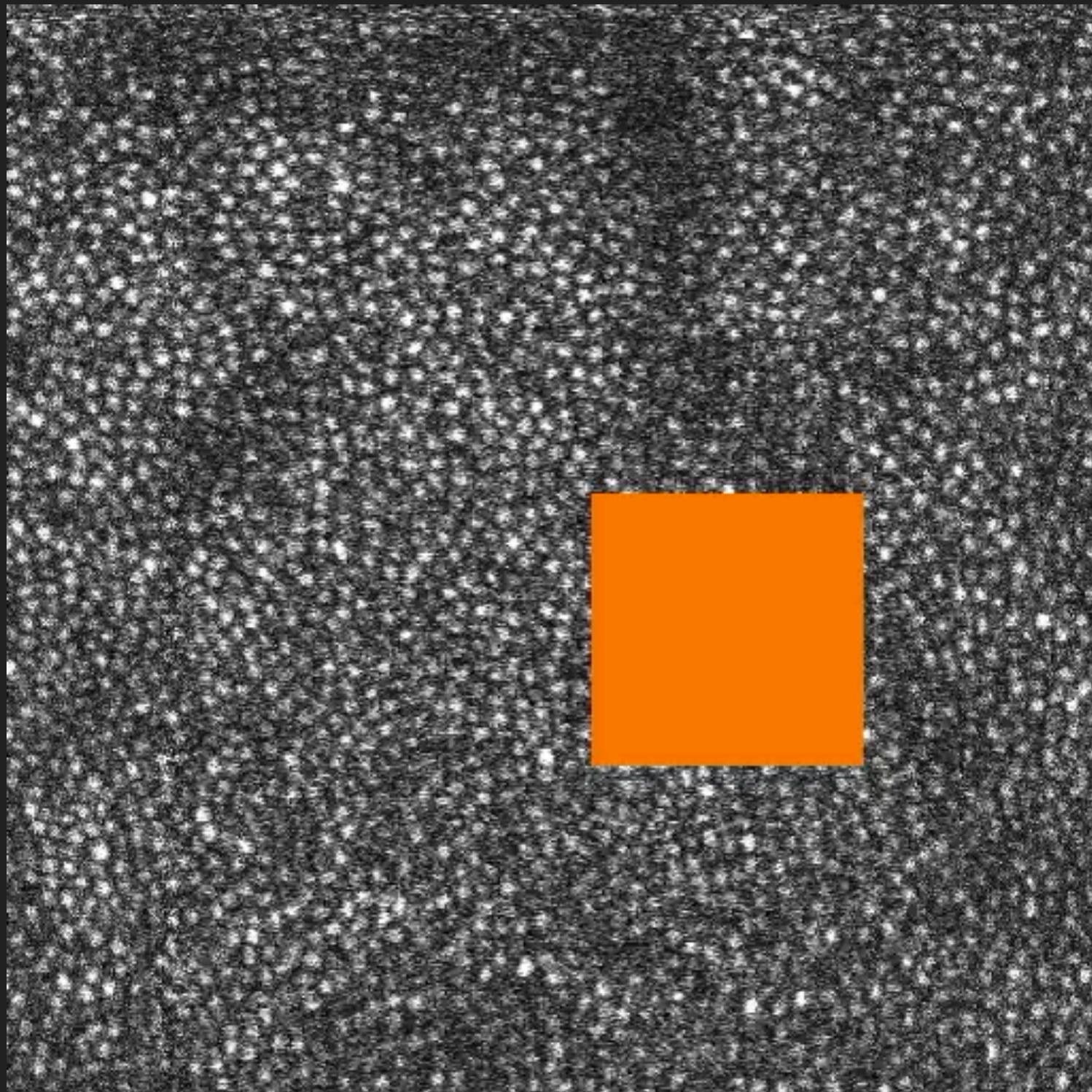
Existing Proof-of-Concept Study:
Reproducing a Flashed Color Rectangle, Cone-by-Cone

Subject's Retina Map with Real Cone Classifications

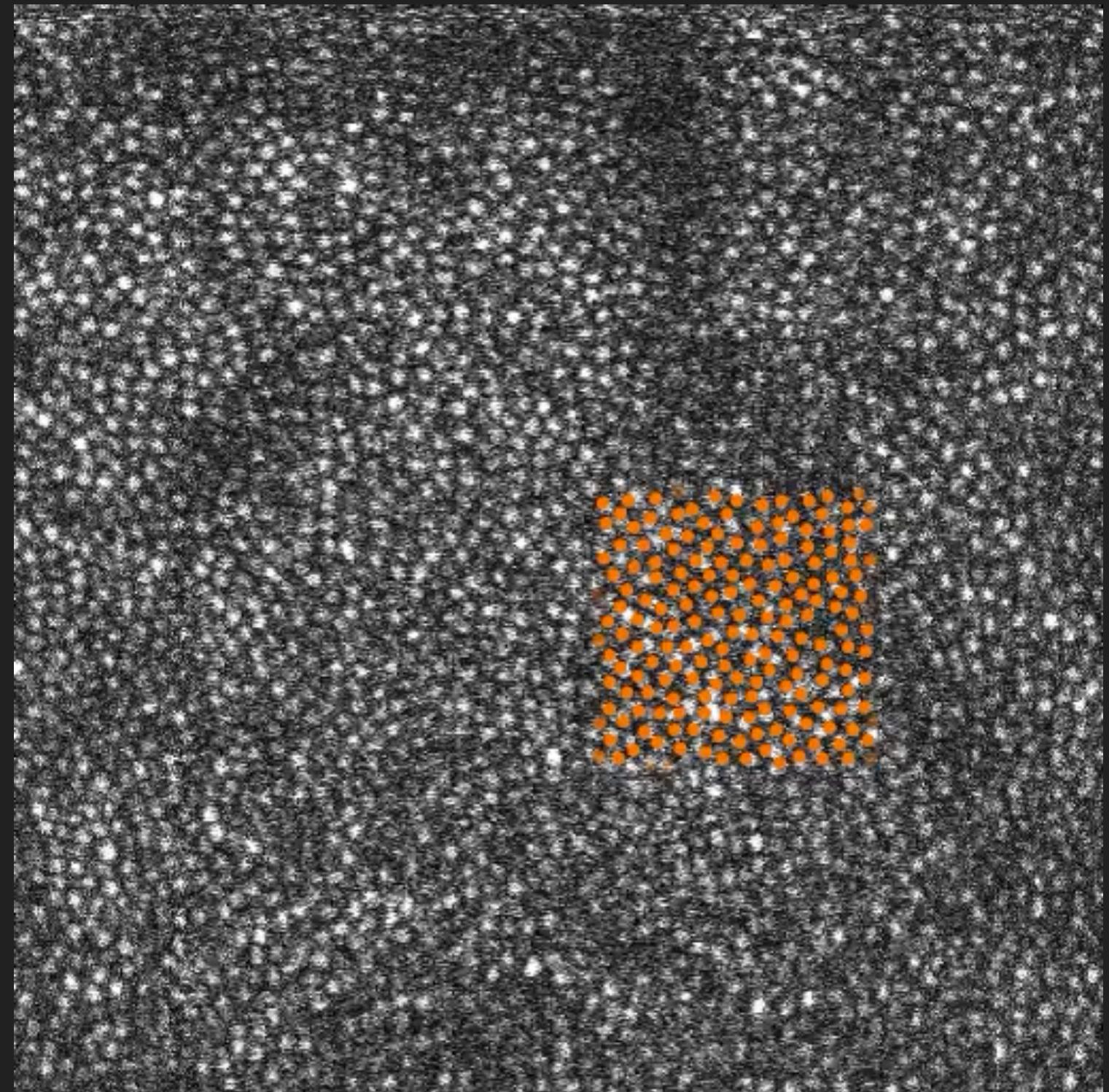


Approximately 800 cones spectrally classified

Oz Color: Reproducing a Flashed Color Rectangle Cone-by-Cone



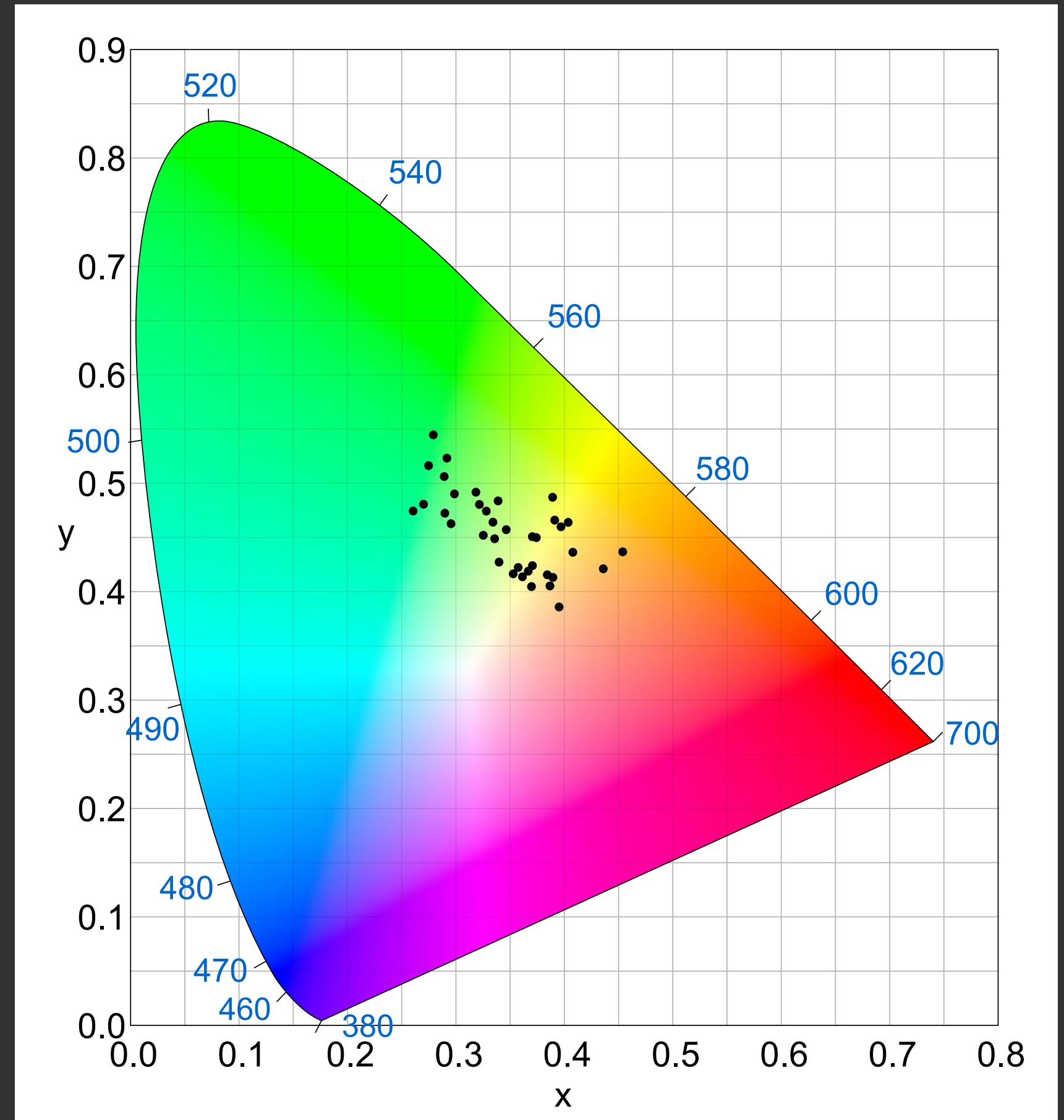
Target Color Rectangle, 1/8 Sec. Flash



RGB Targets Per Cone

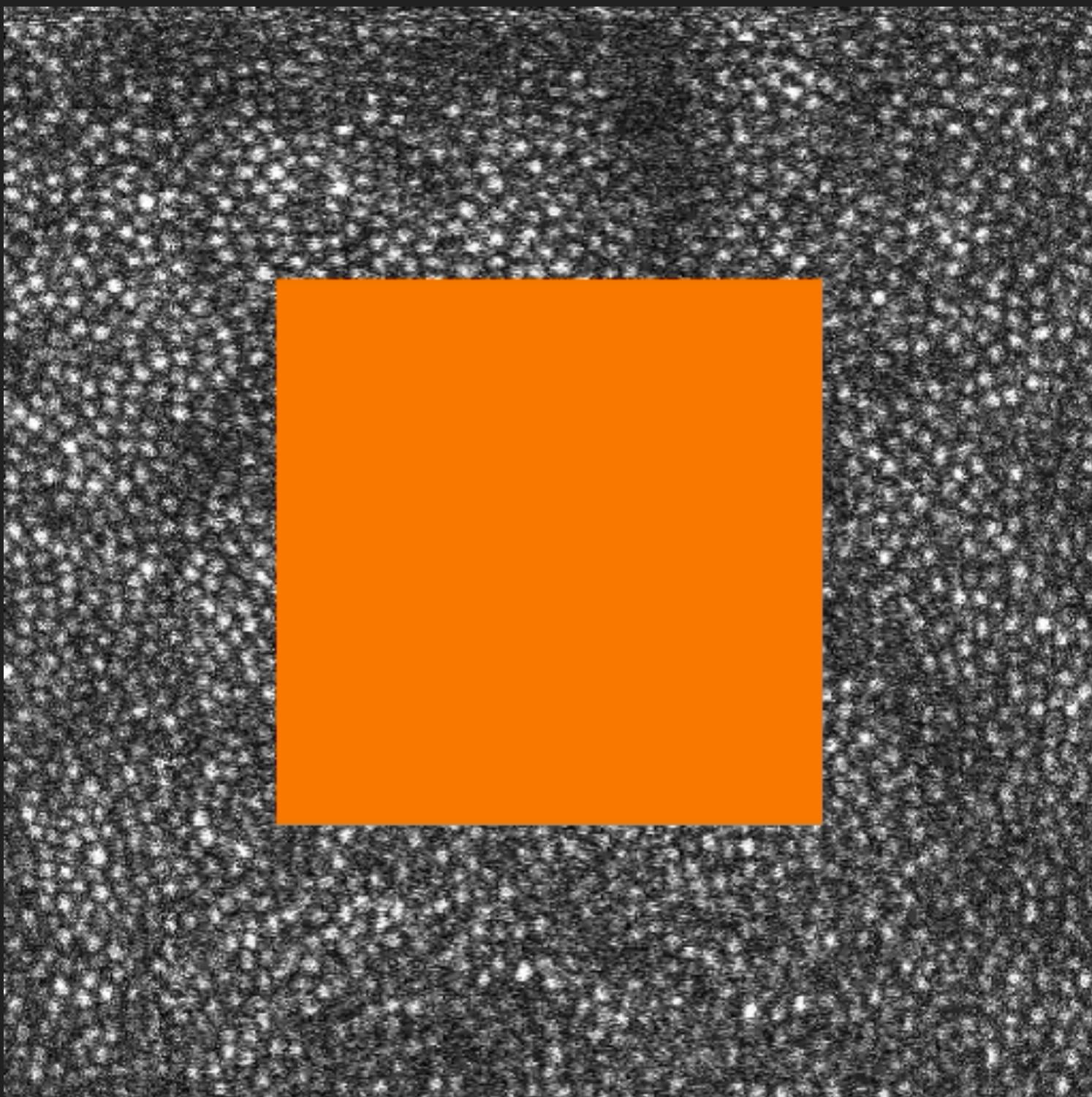
Oz Vision Display v.1.0 Prototype - Results

- Oz stimulation with pure 543nm laser
- Percept from red to orange to yellow to green to blue-green
- Quantitative color matching to RGB LCD display (black dots)

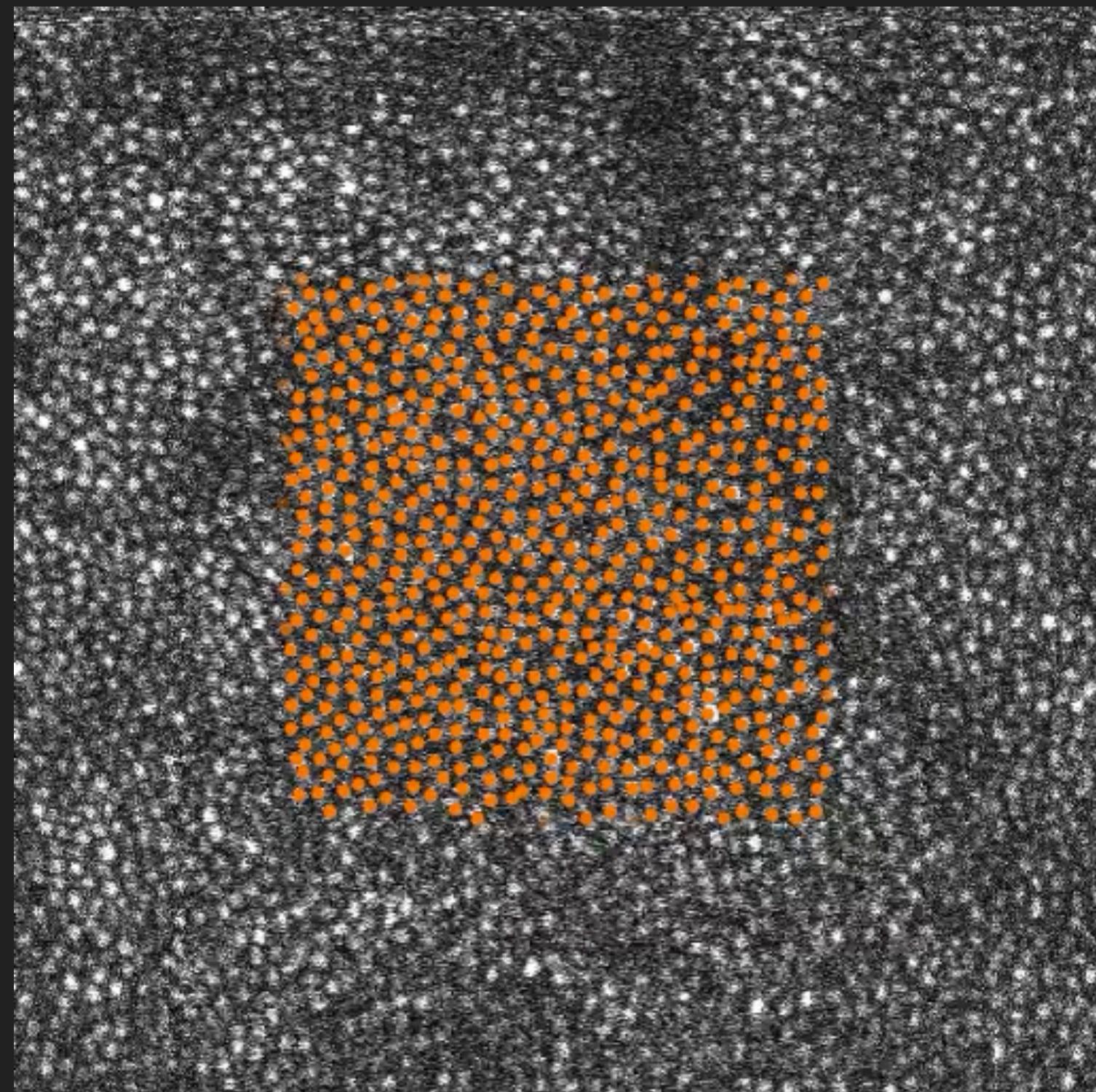


Current Research:
Reproducing a Sustained Color Rectangle, Cone-by-Cone

Sustained Color Rectangle, World-Fixed

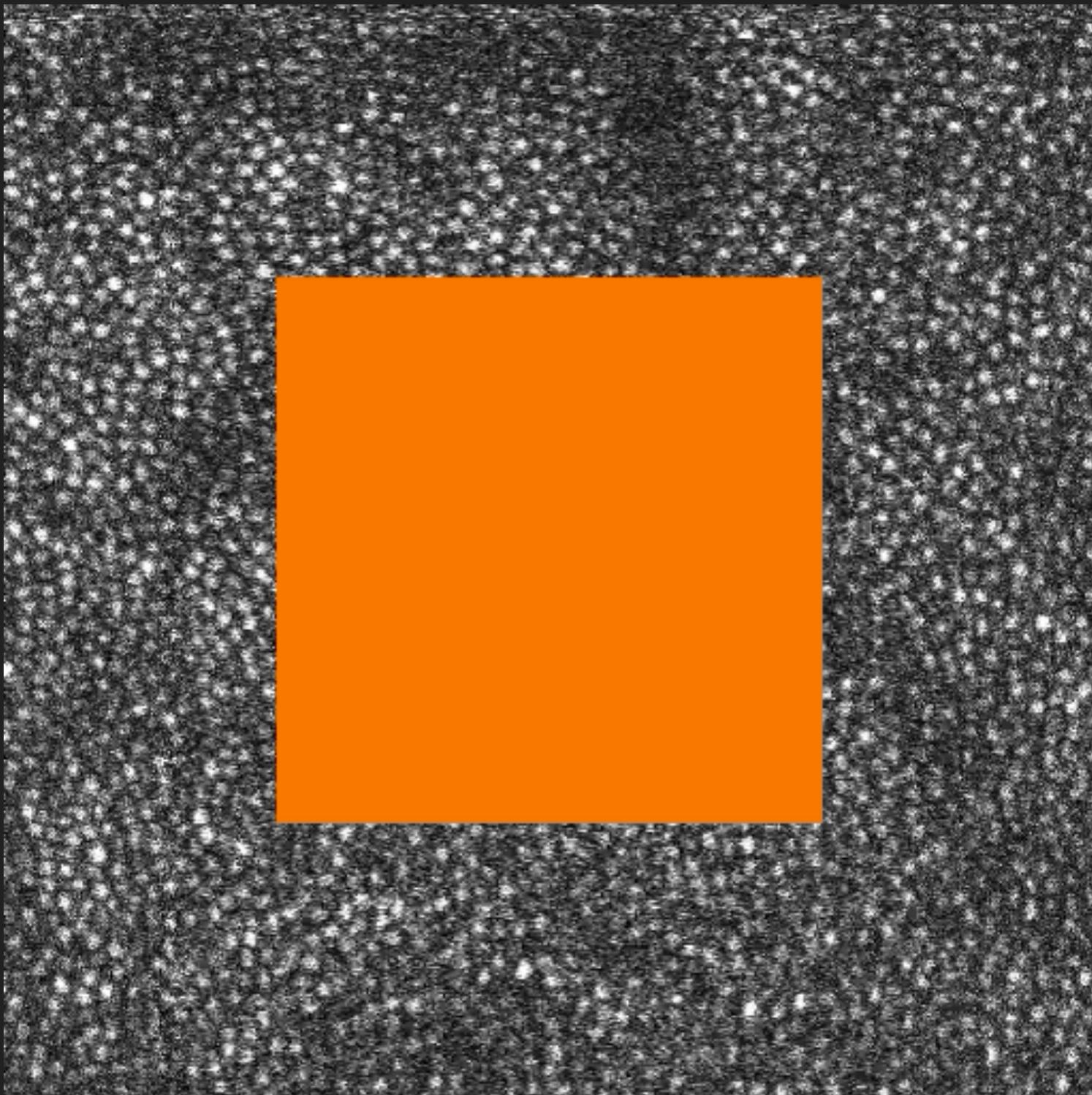


Target Color Rectangle

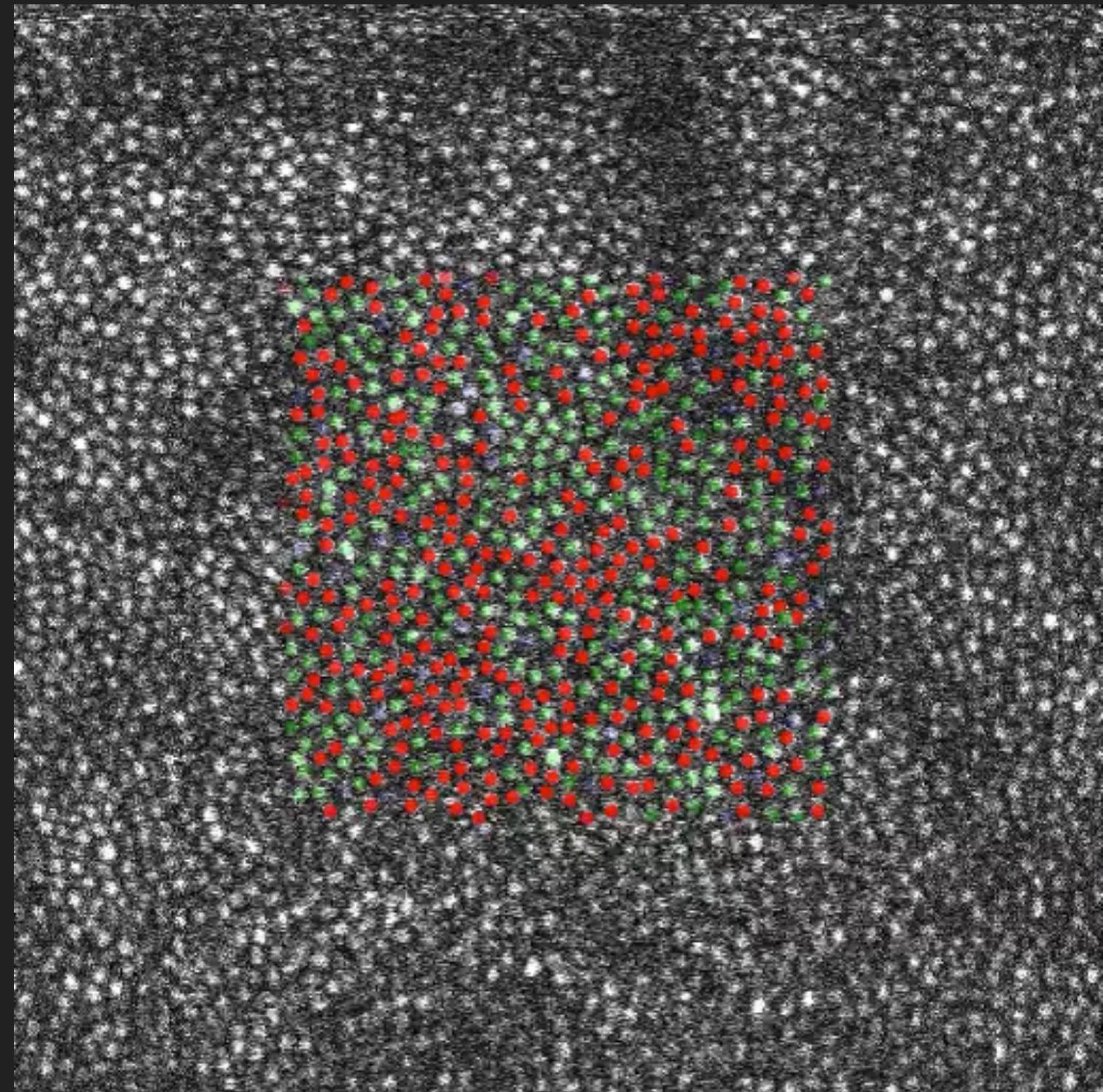


RGB Targets Per Cone

Sustained Color Rectangle, World-Fixed

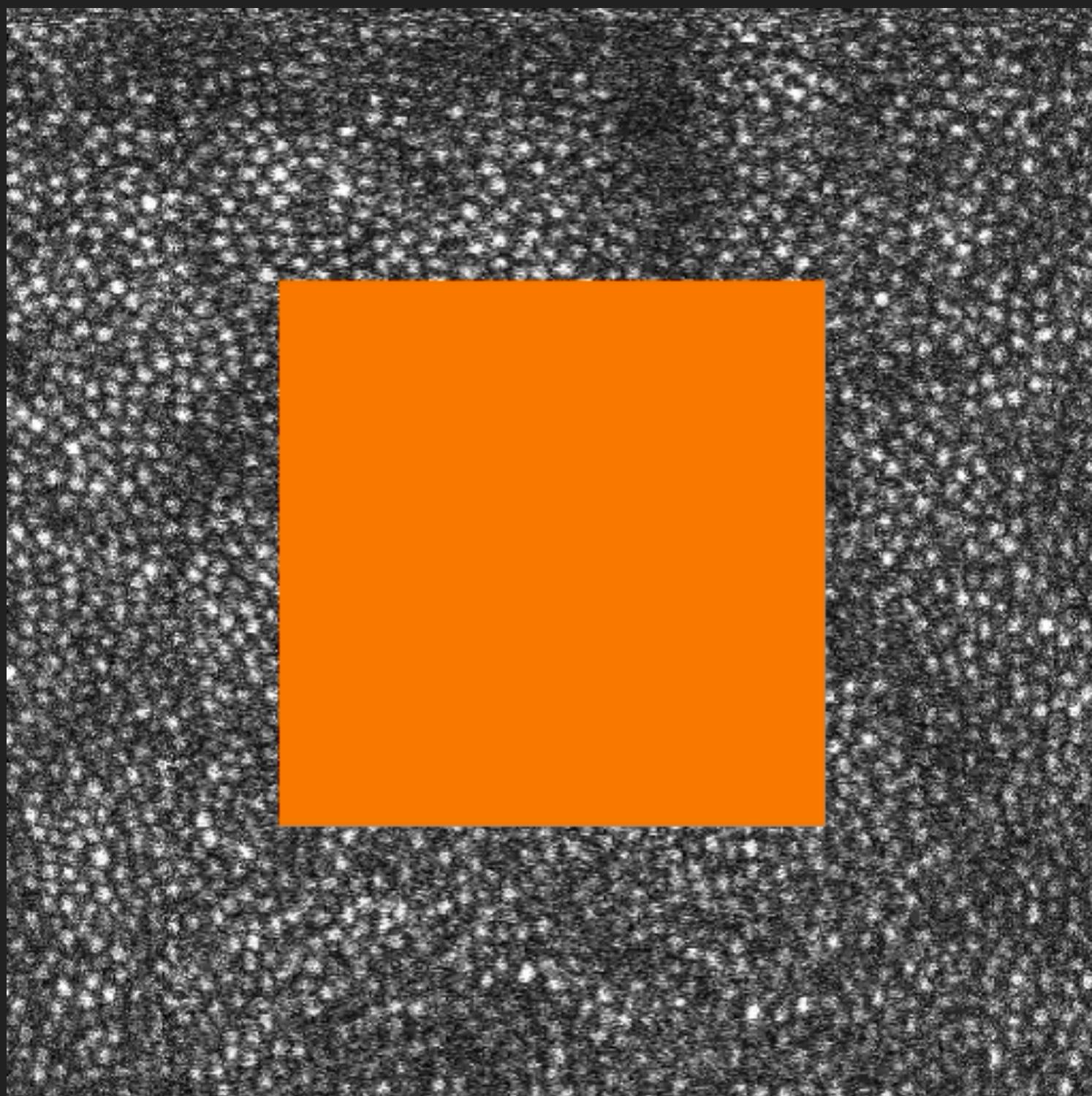


Target Color Rectangle

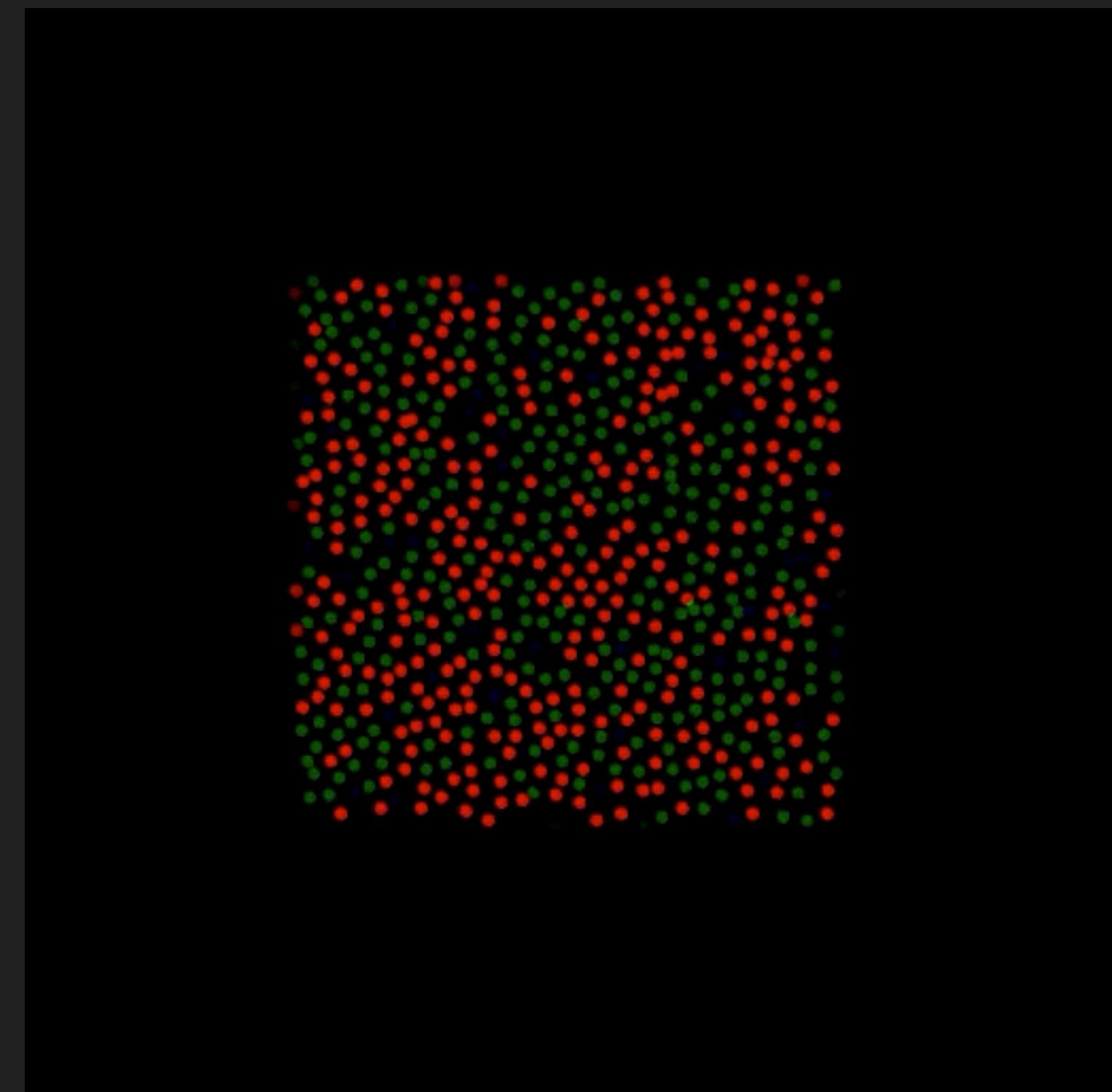


LMS Activations (False Color)

Sustained Color Rectangle, World-Fixed

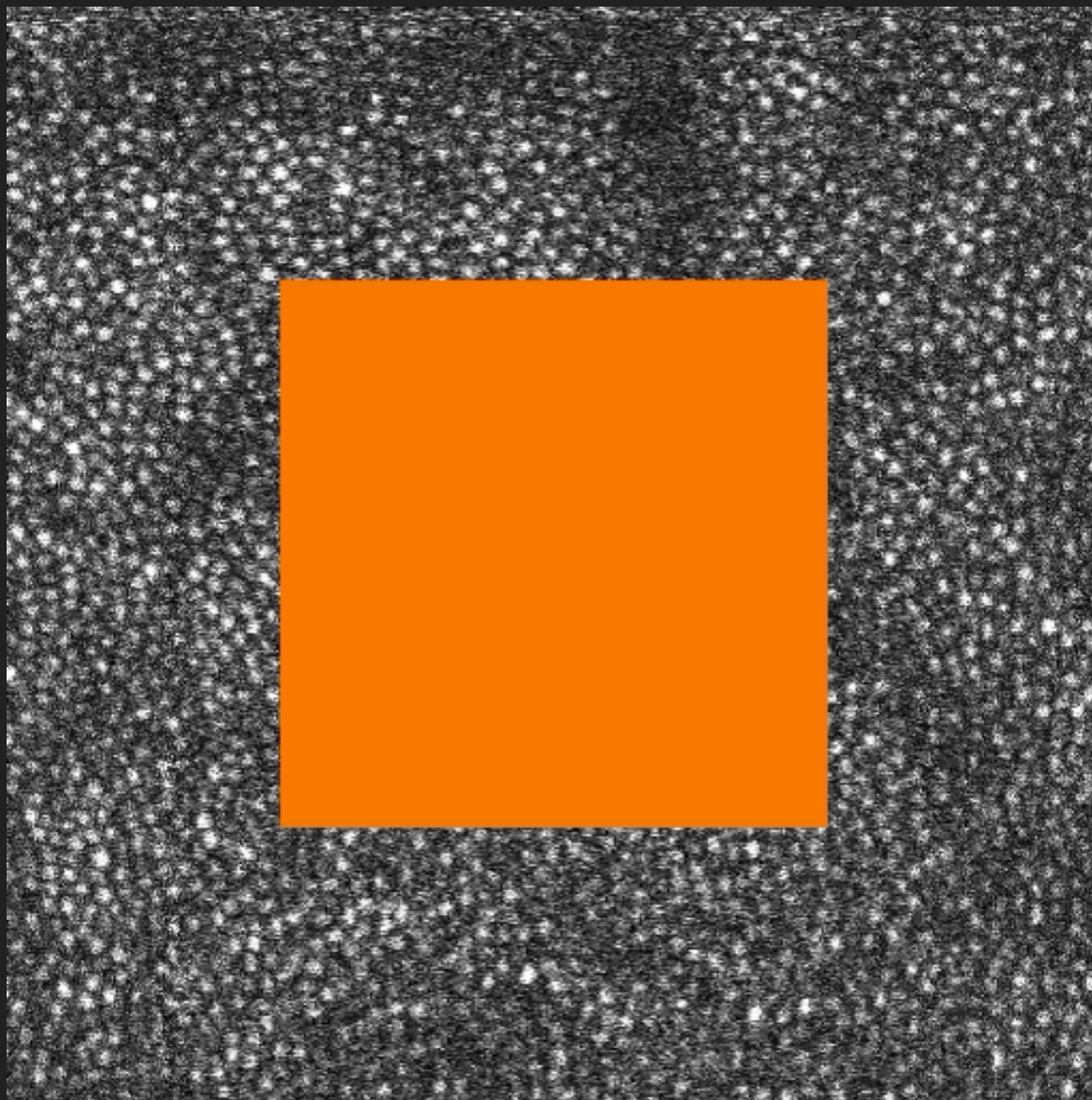


Target Color Rectangle

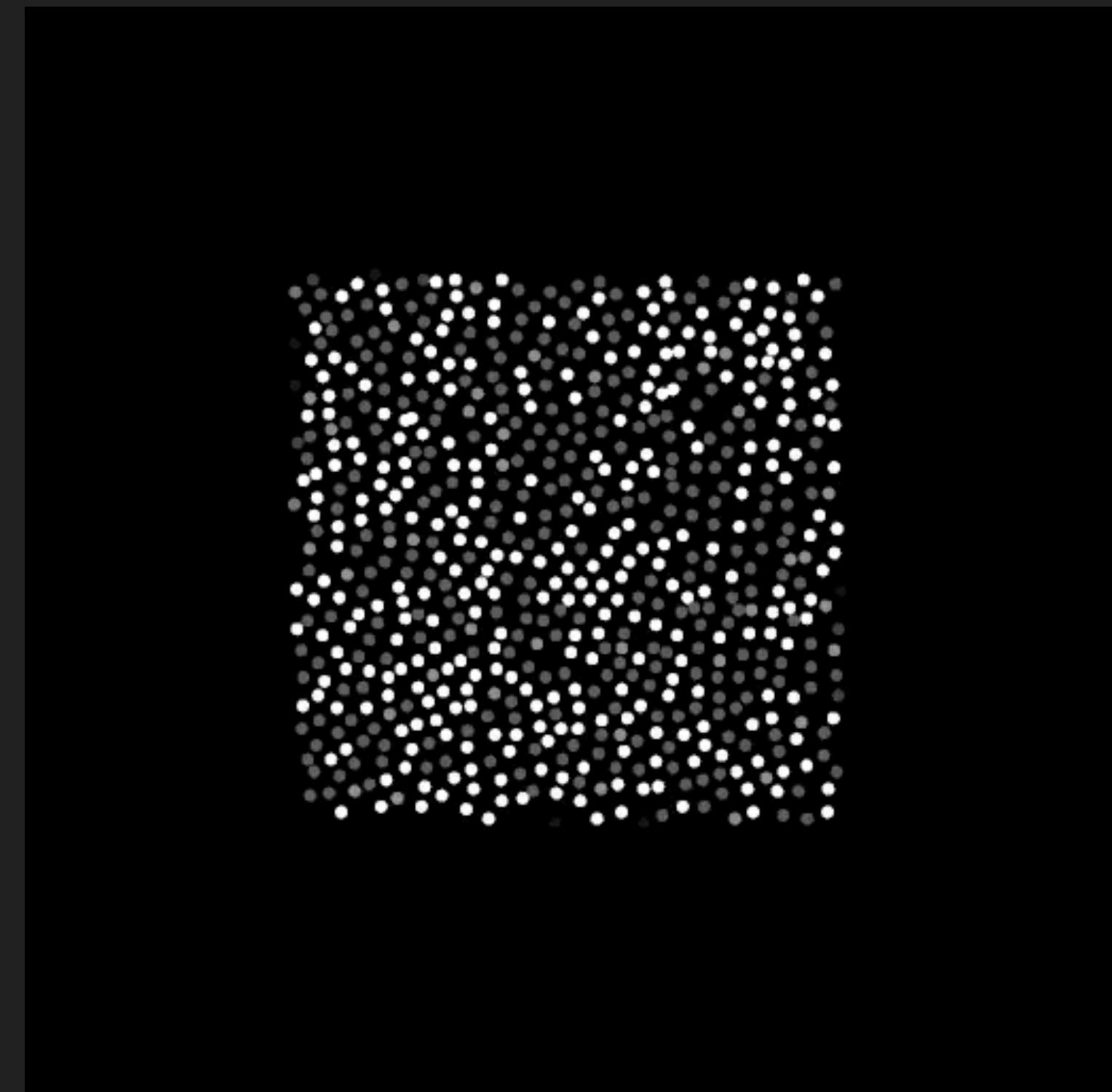


LMS Activations (False Color)

Sustained Color Rectangle, World-Fixed

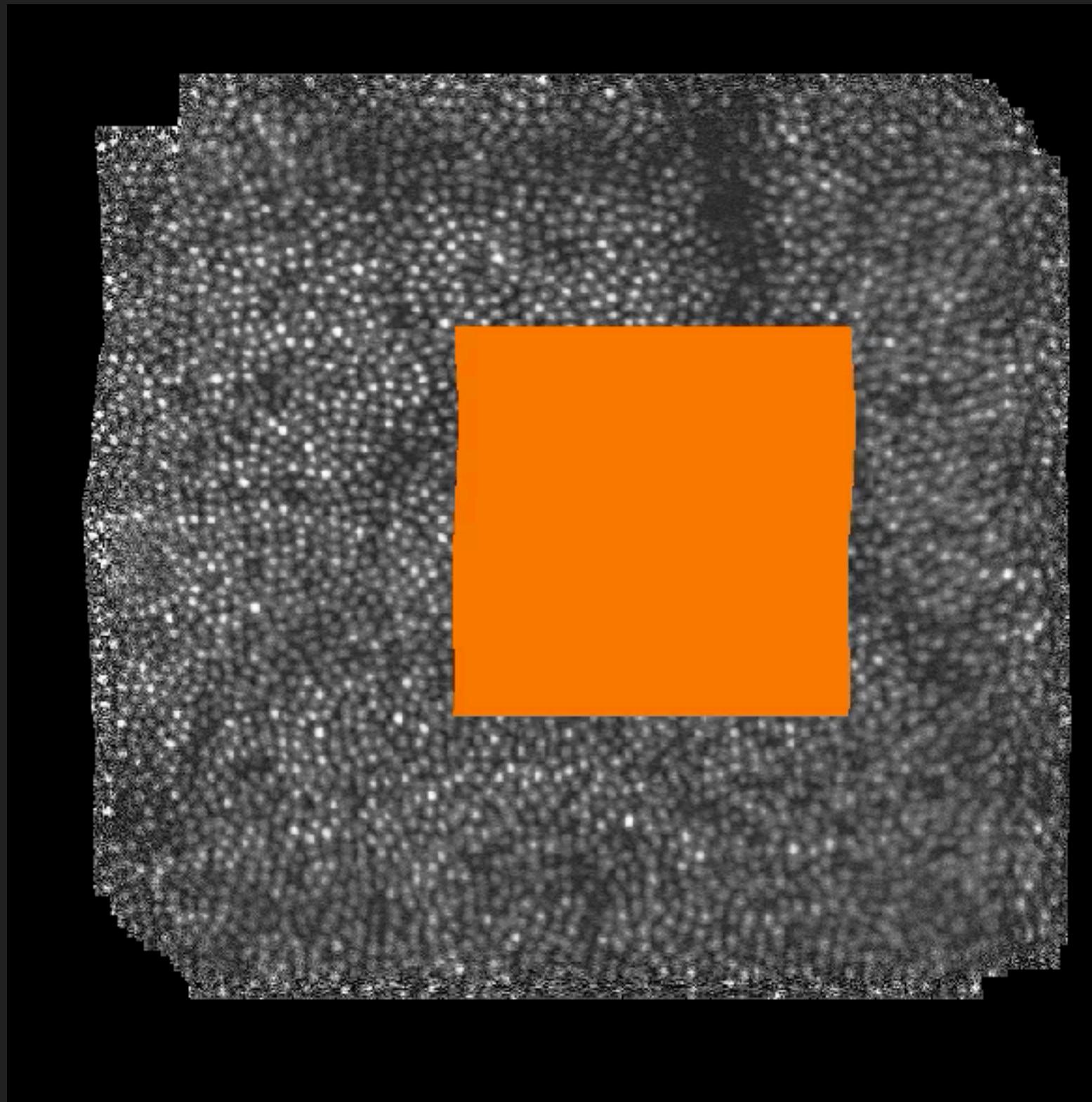


Target Color Rectangle

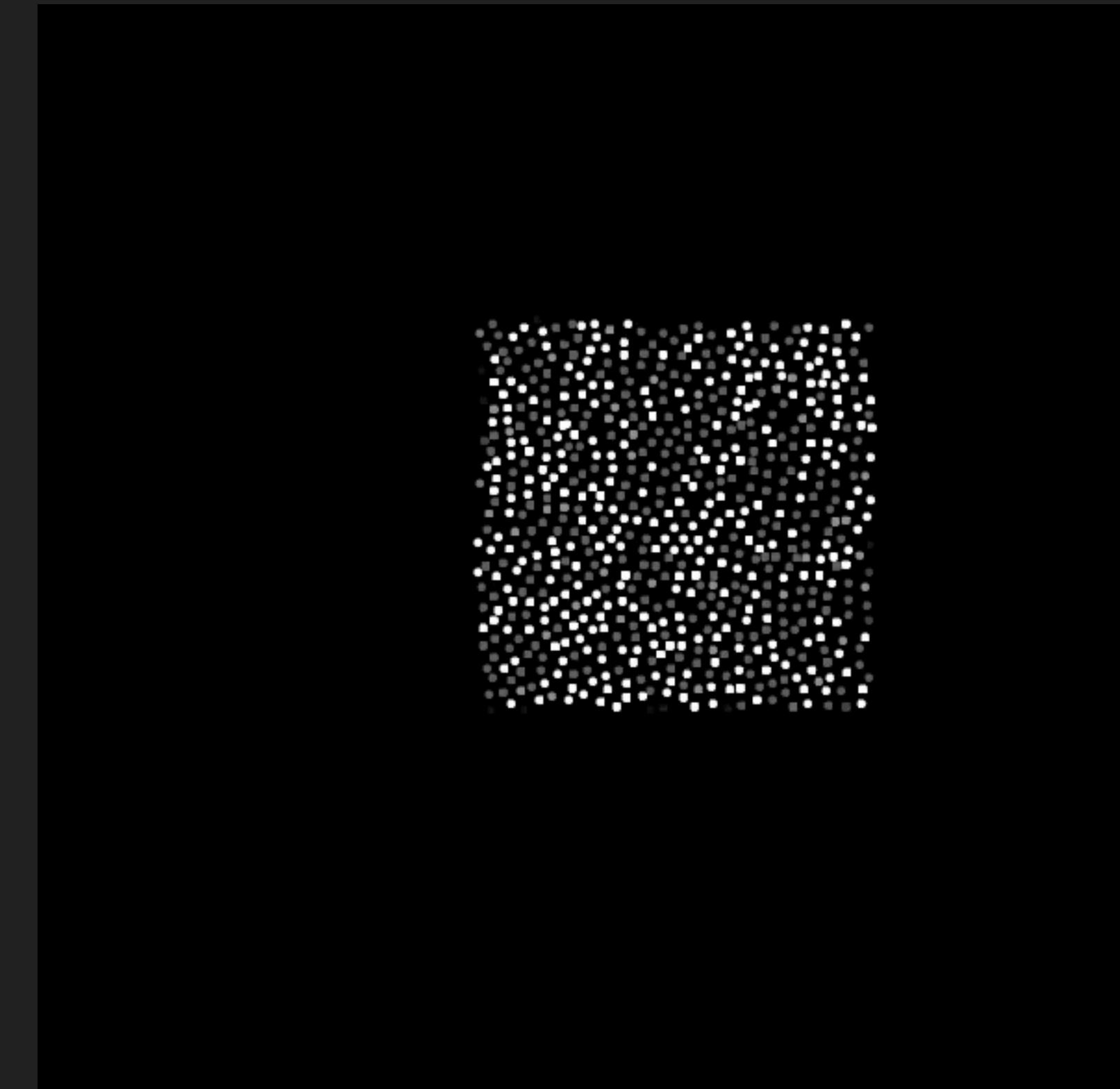


Laser Microdoses (500 nm)

Sustained Color Rectangle, World-Fixed - Retina Space



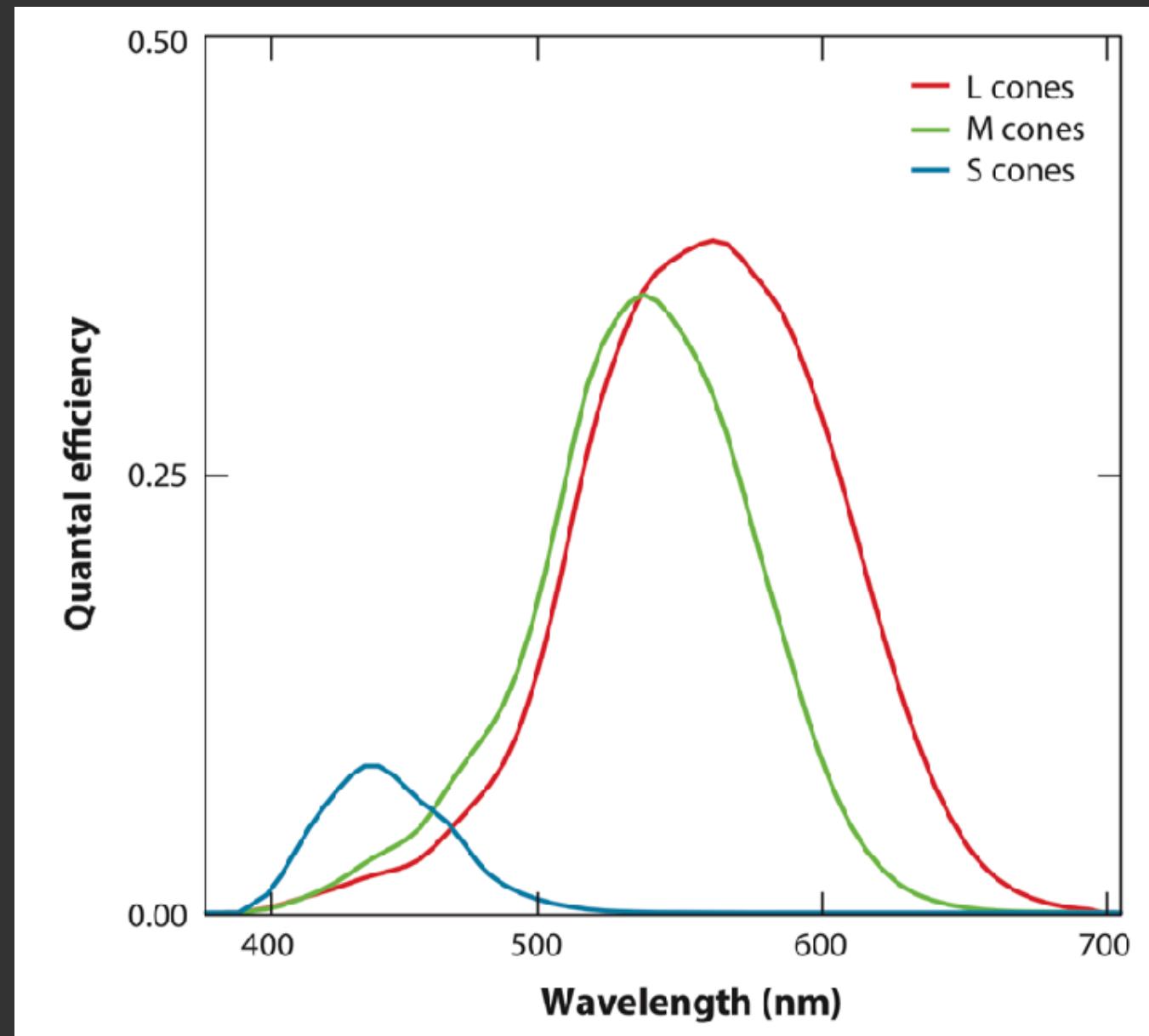
Target Color Rectangle



Laser Microdoses (500 nm)

What is the Color Gamut of Oz Vision?

Observe: Spectral Response Curves for Cone Cells Overlap



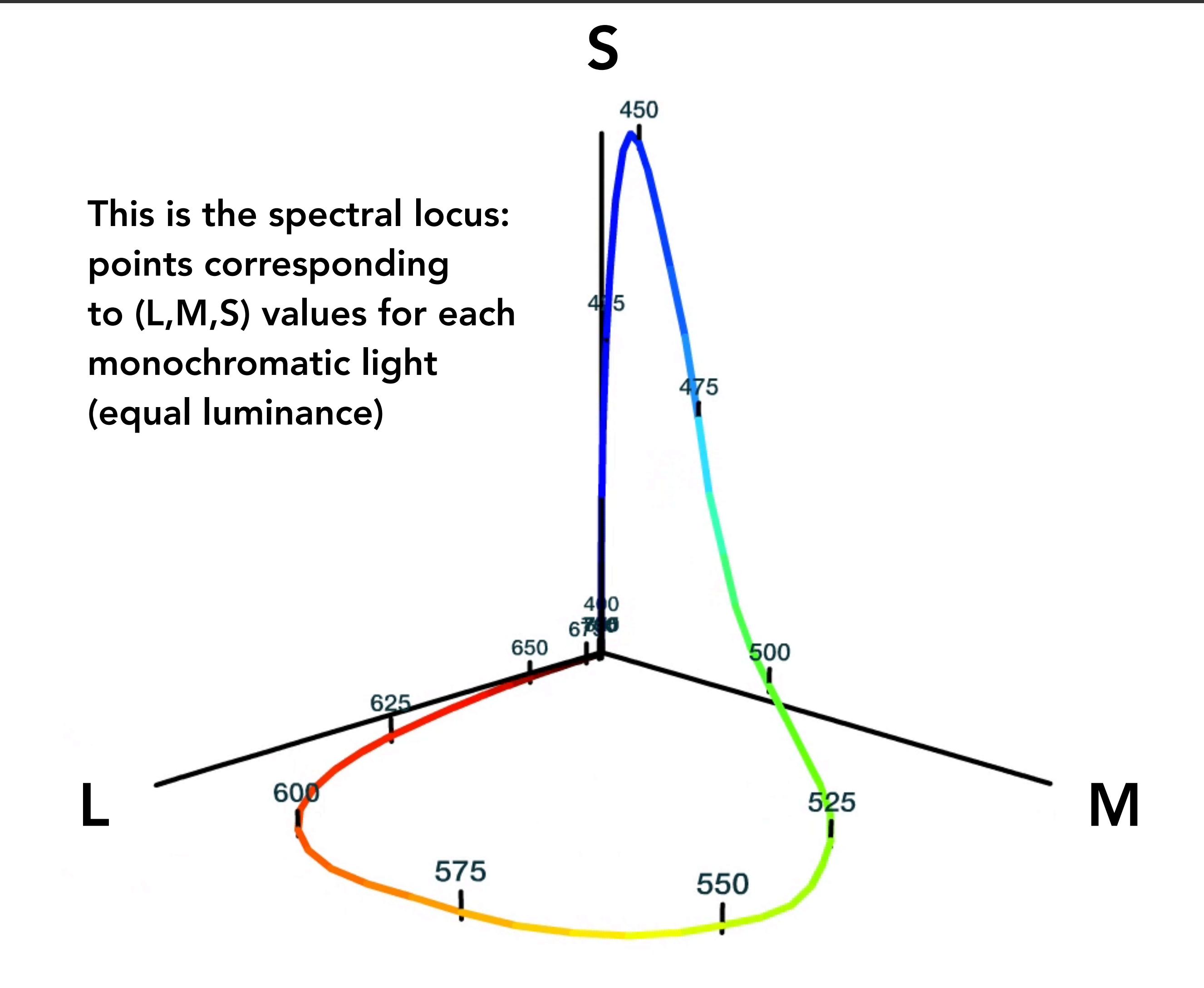
No wavelength exists where only M cone responds

- Result: no real light can cause only M cone cells to fire

But: Oz Vision can stimulate only M cone cells!

- This sends an unprecedented color signal to the brain

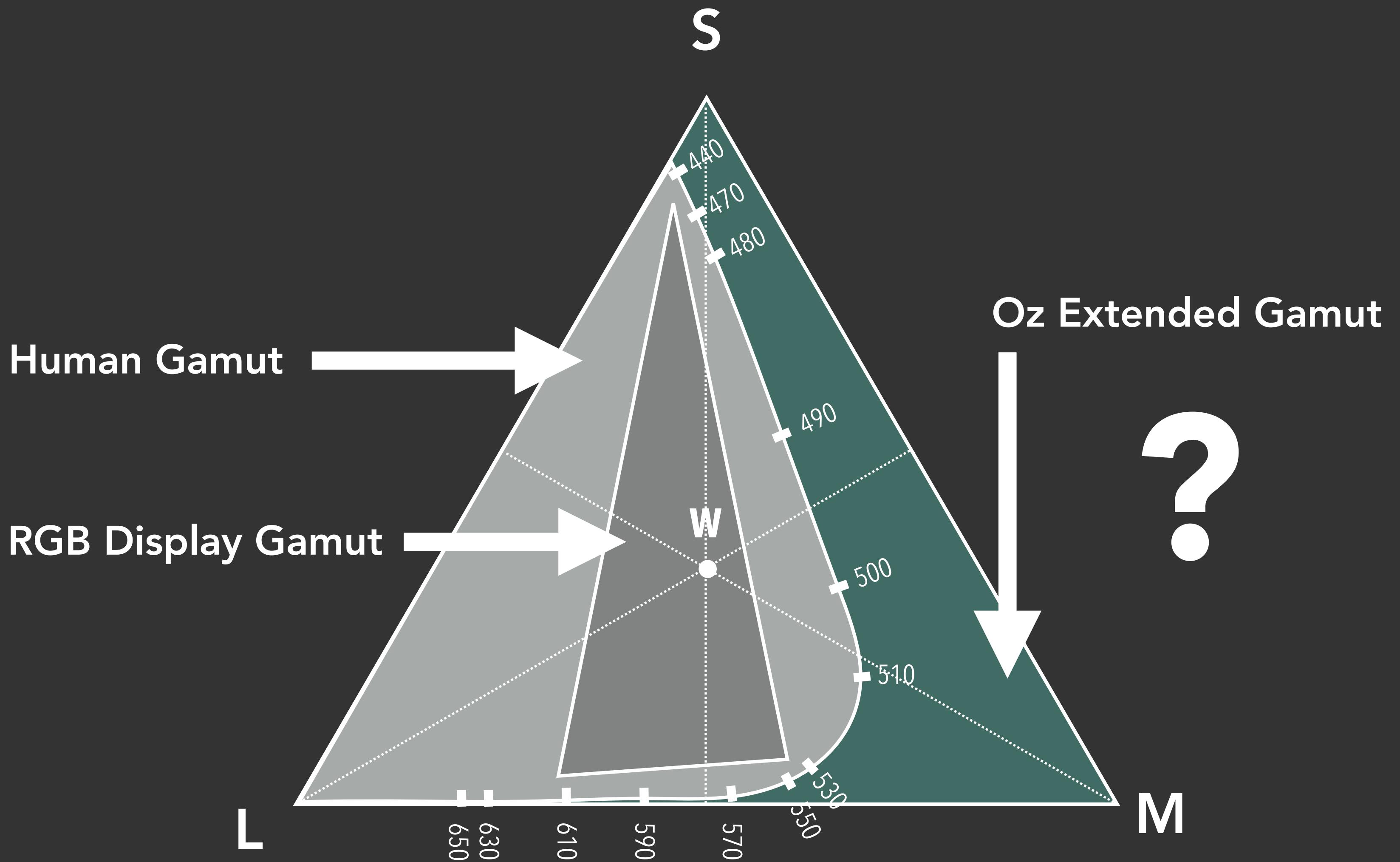
LMS Responses Plotted as 3D Color Space



<https://graphics.stanford.edu/courses/cs178-10/applets/locus.html>

Dektar, Adams, Levoy

What is the Full Color Gamut of Oz Vision?



What is the Full Color Gamut of Oz Vision?

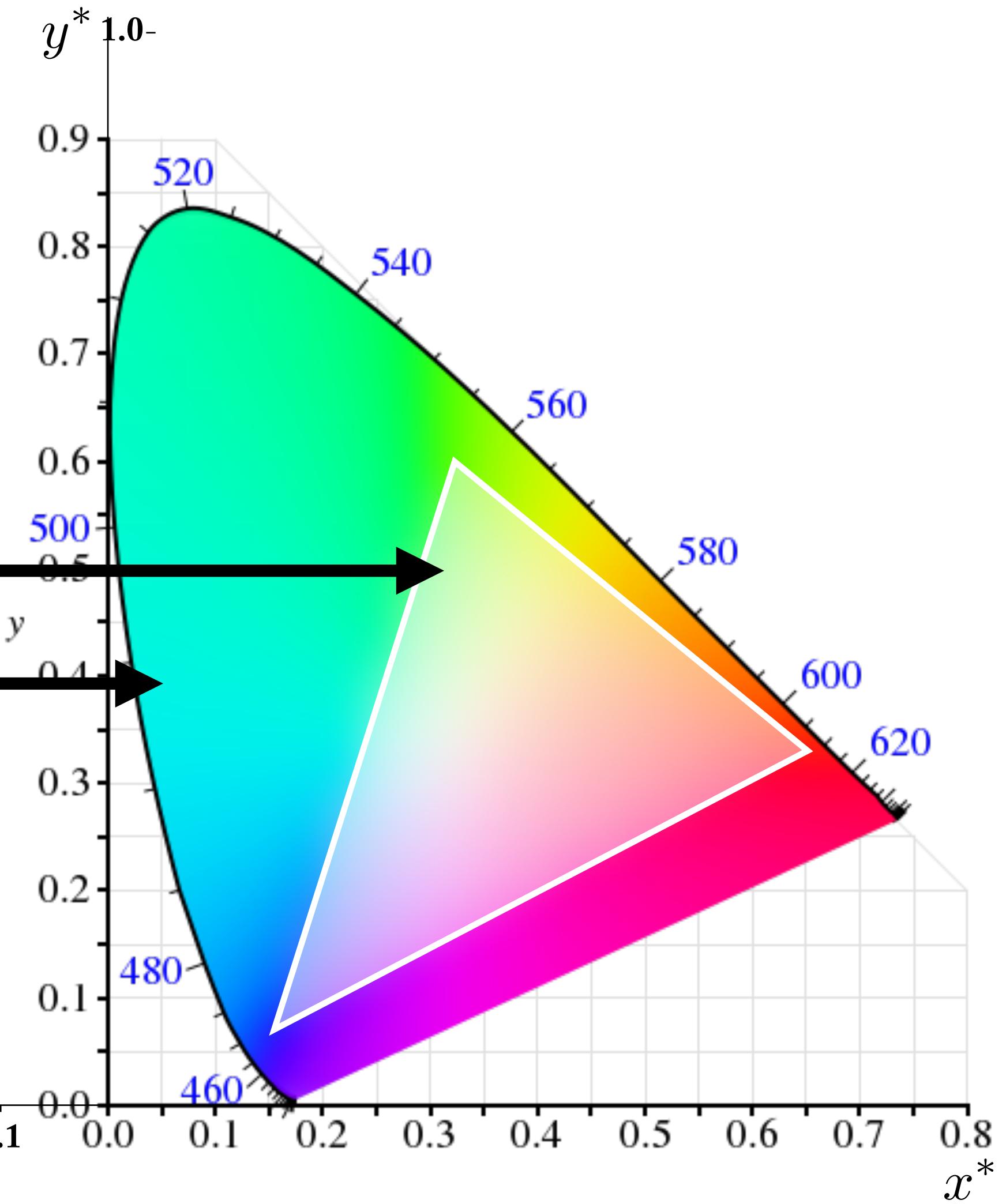
$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 1.9121 & -1.1121 & 0.2019 \\ 0.3709 & 0.6291 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} L \\ M \\ S \end{bmatrix}$$

$$x^* = \frac{X}{|X| + |Y| + |Z|}$$

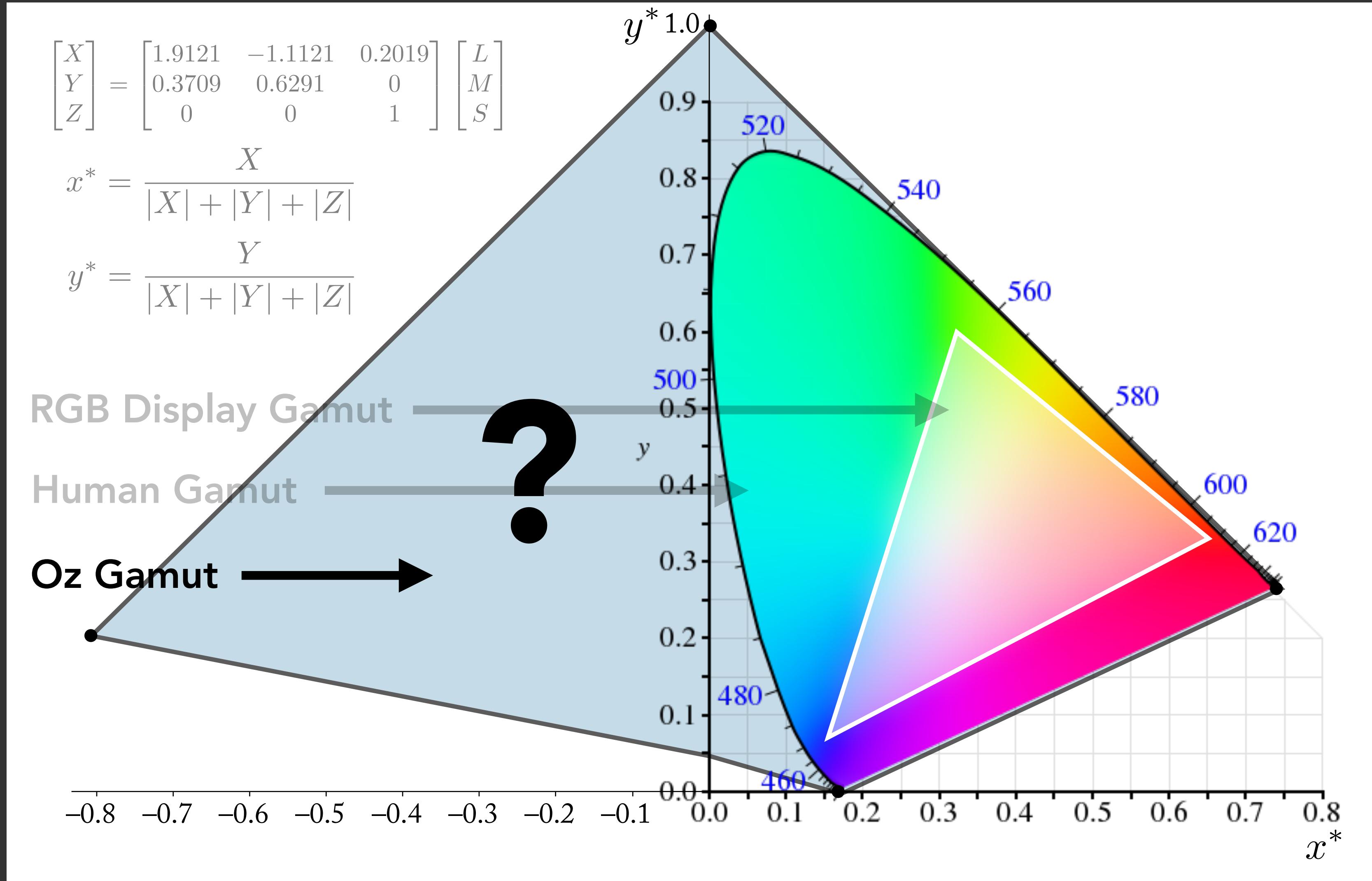
$$y^* = \frac{Y}{|X| + |Y| + |Z|}$$

RGB Display Gamut

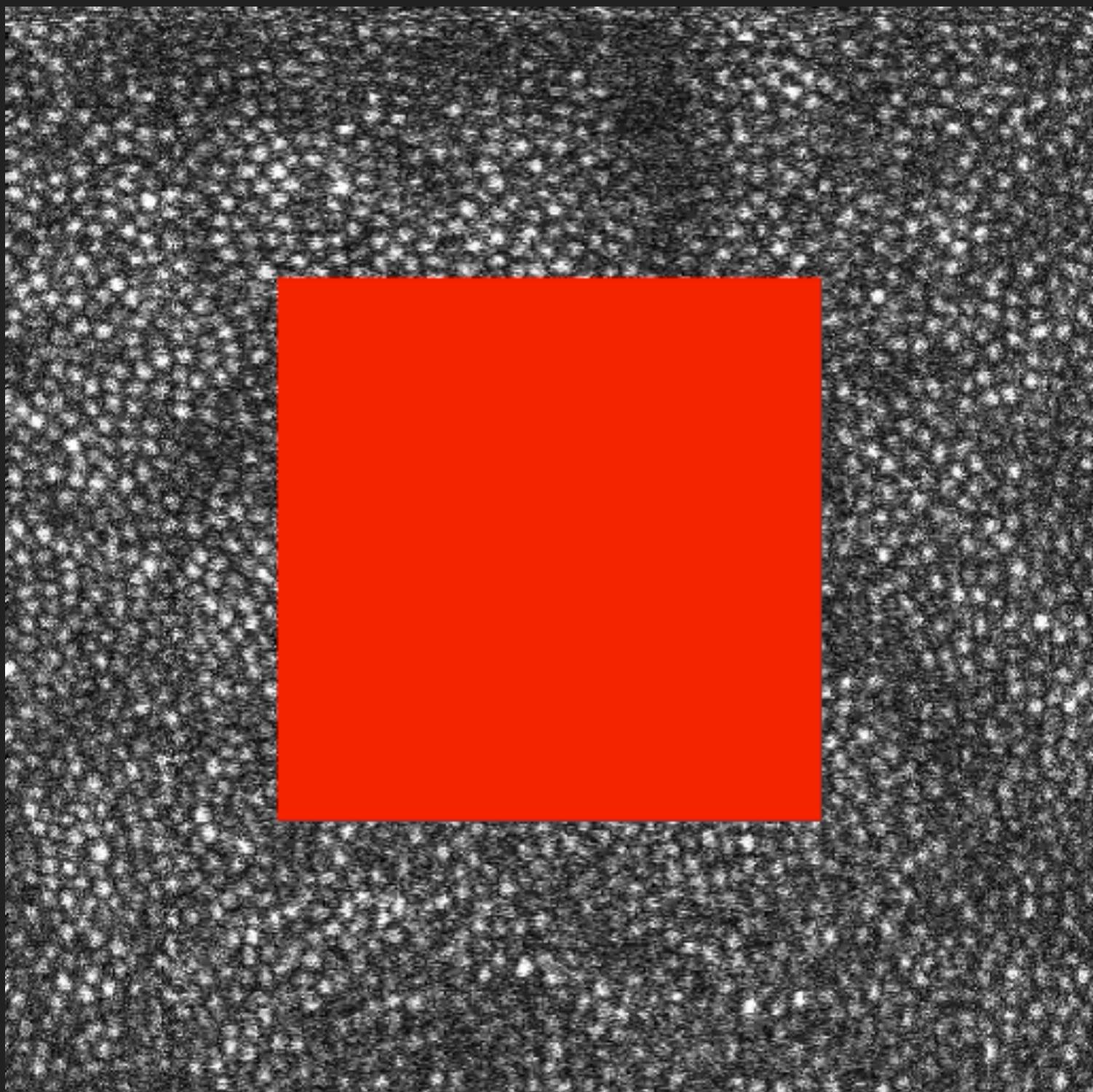
Human Gamut



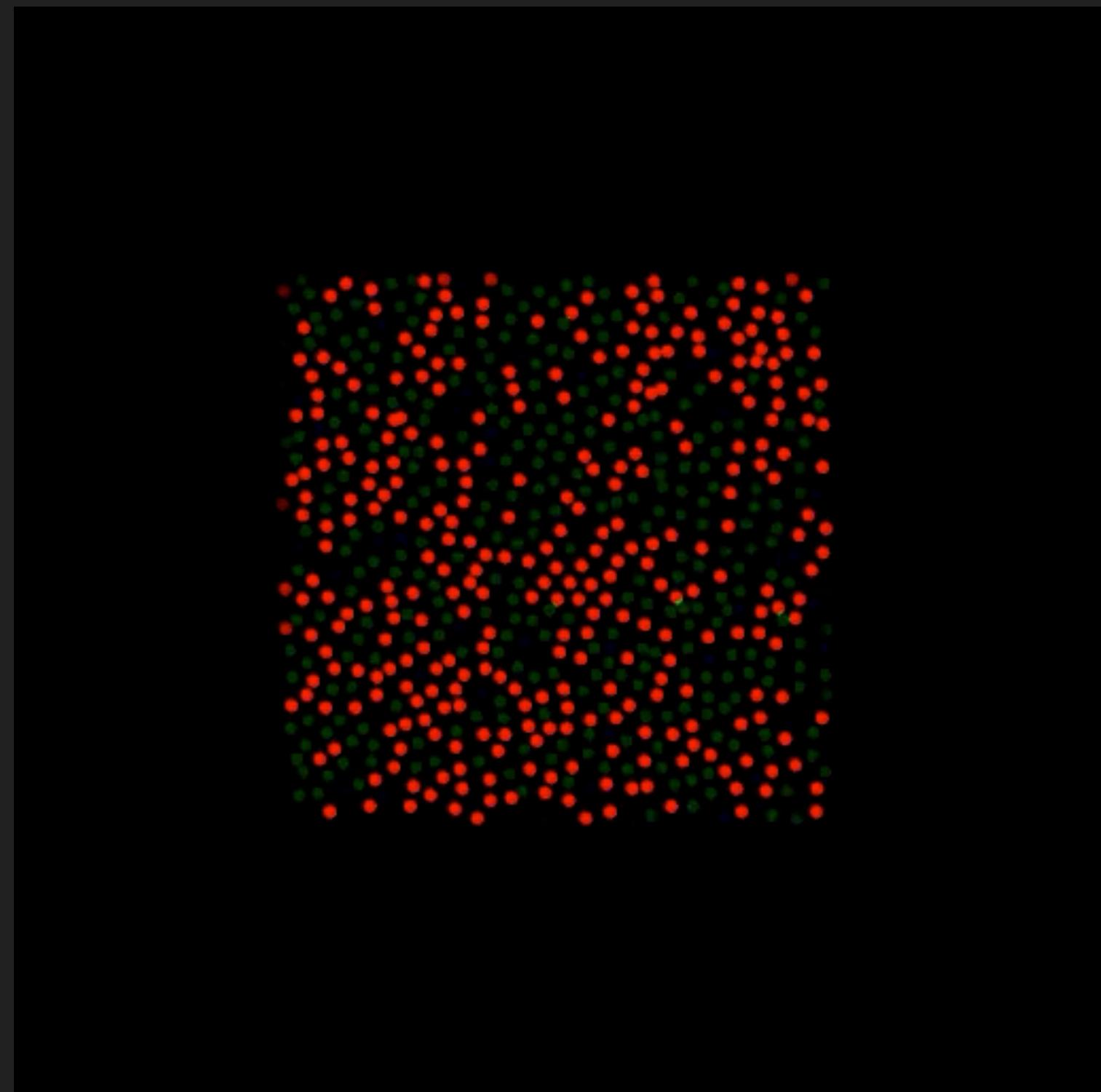
What is the Full Color Gamut of Oz Vision?



Red Reproduced Cone-by-Cone

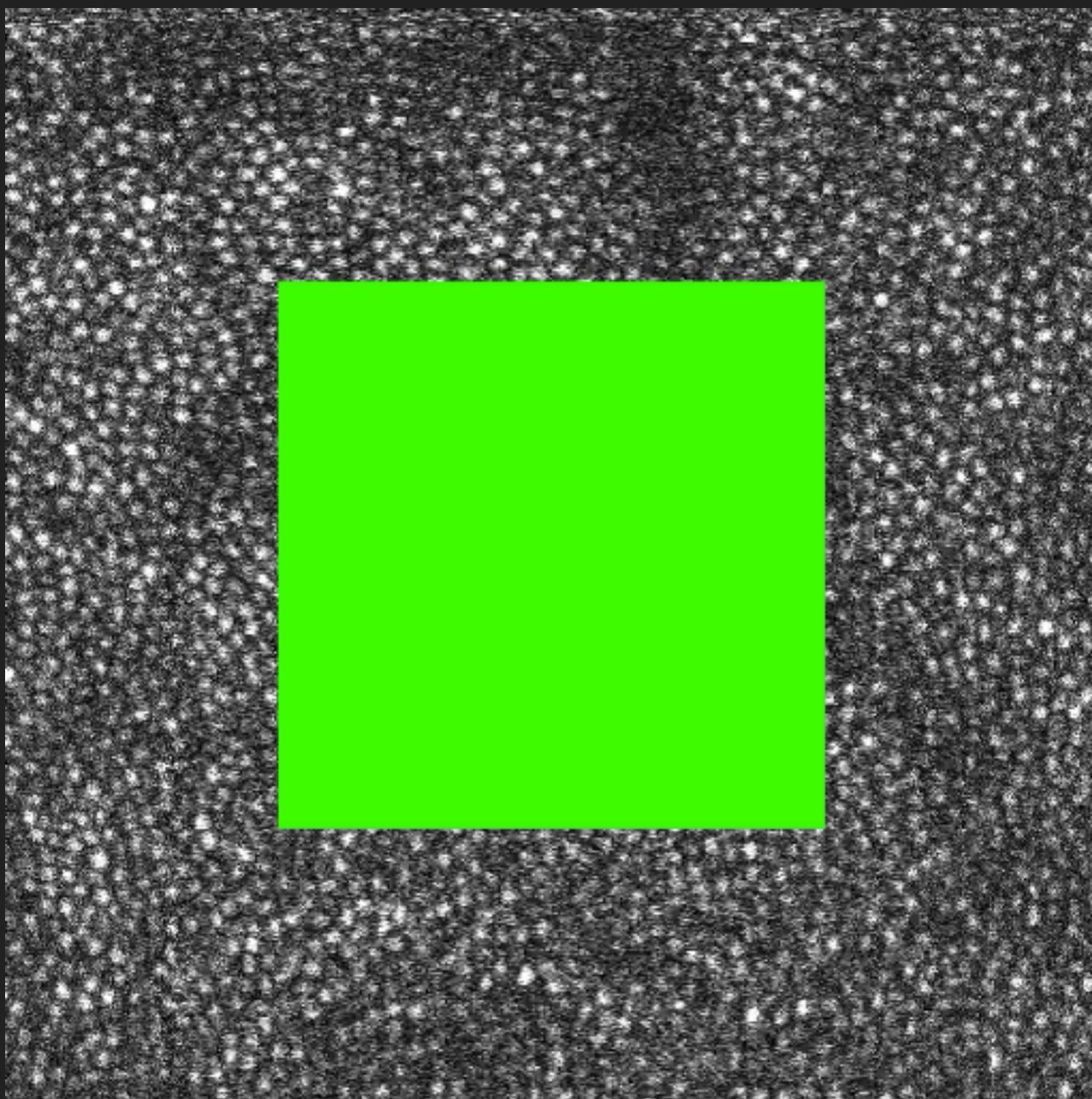


Target Color Rectangle

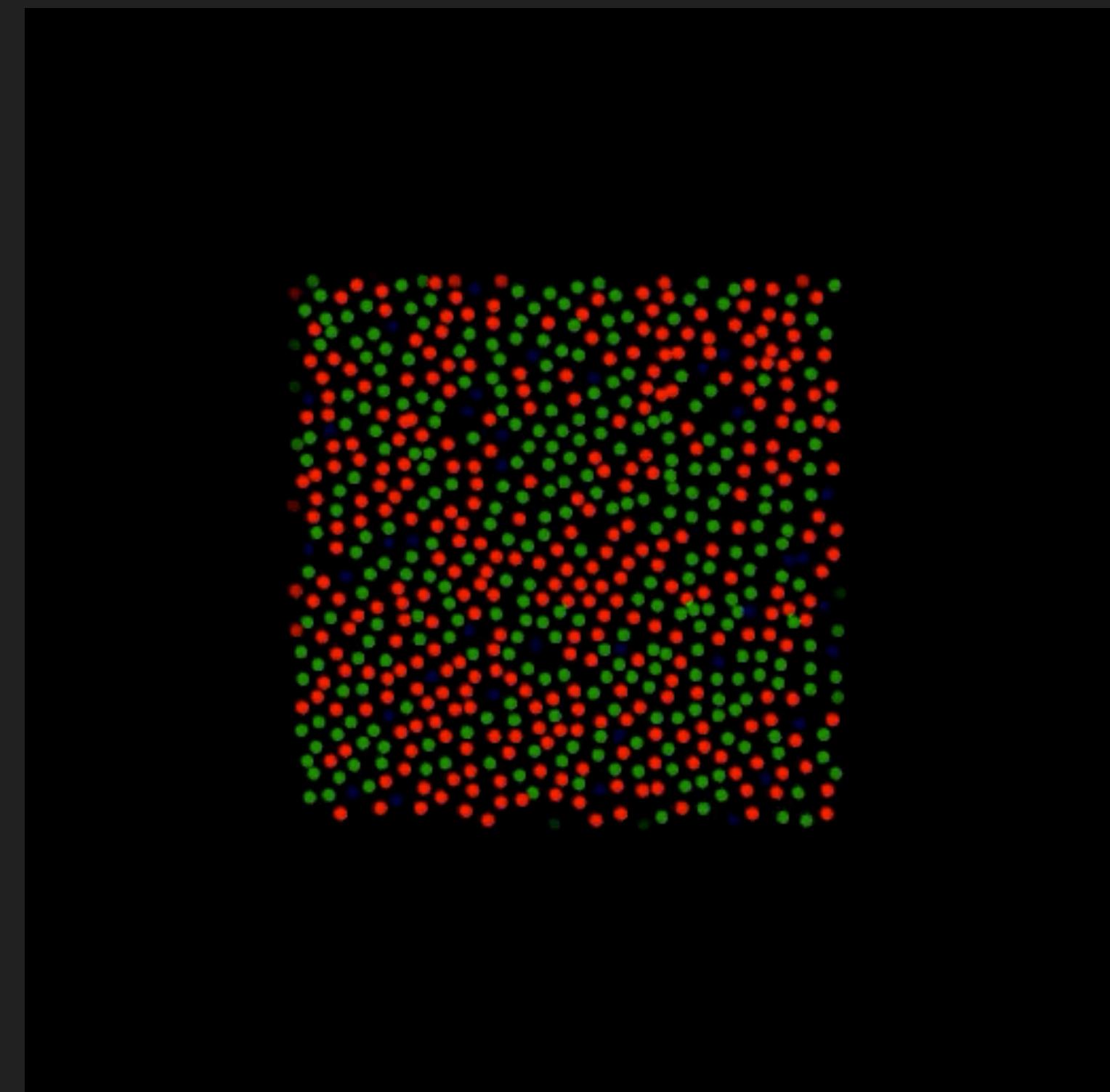


LMS Activations (False Color)

Green Reproduced Cone-by-Cone

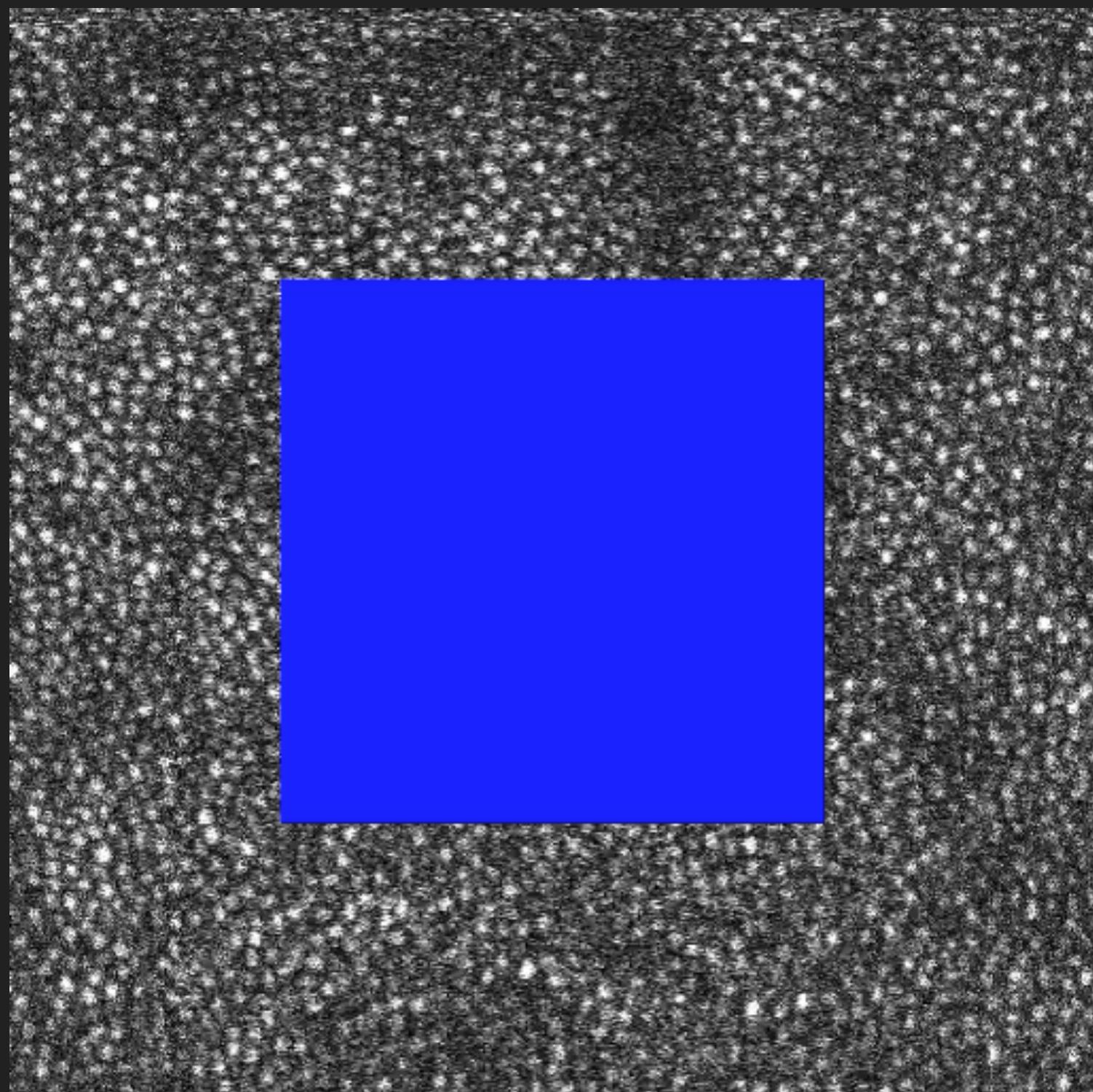


Target Color Rectangle

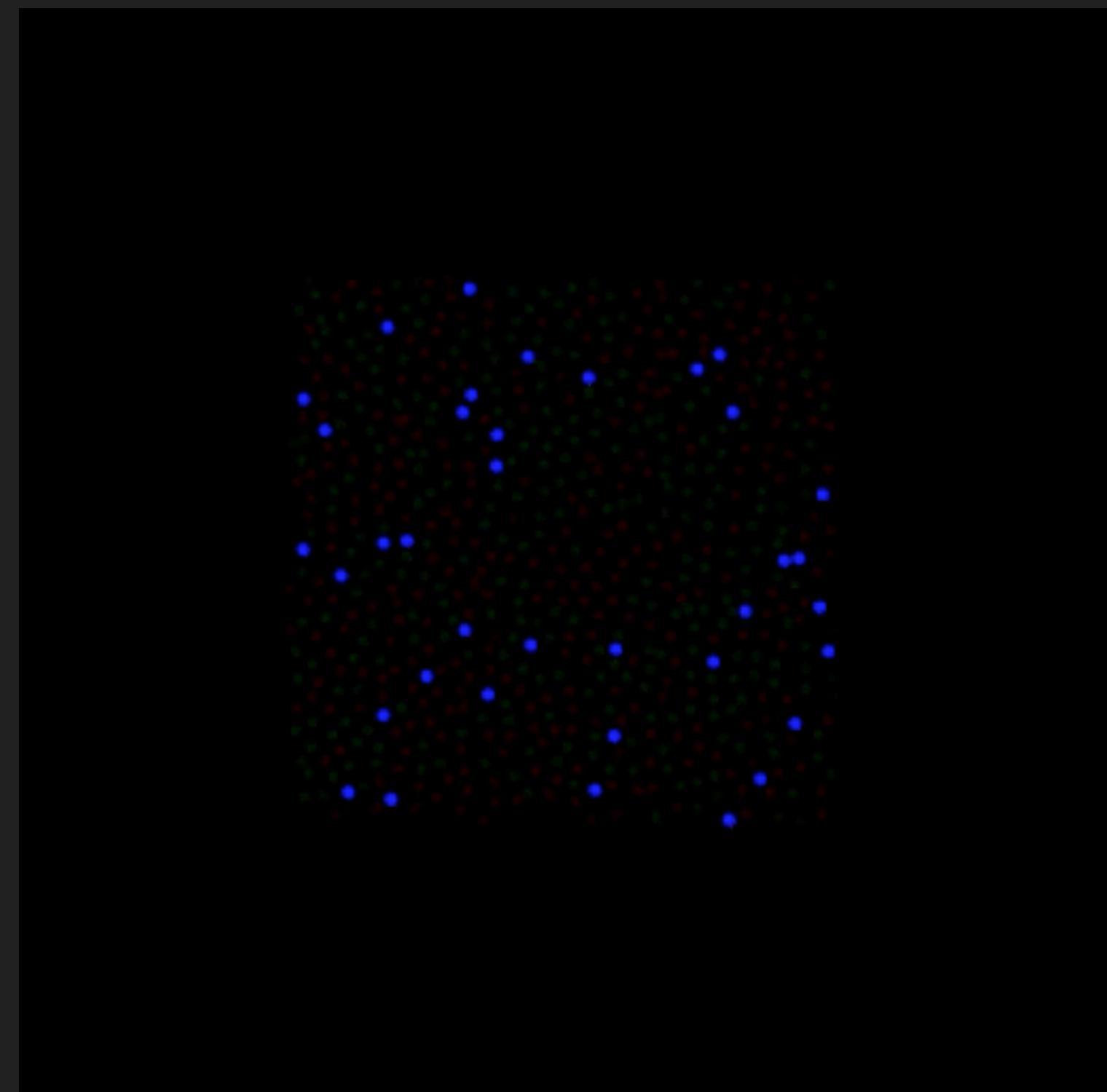


LMS Activations (False Color)

Blue Reproduced Cone-by-Cone

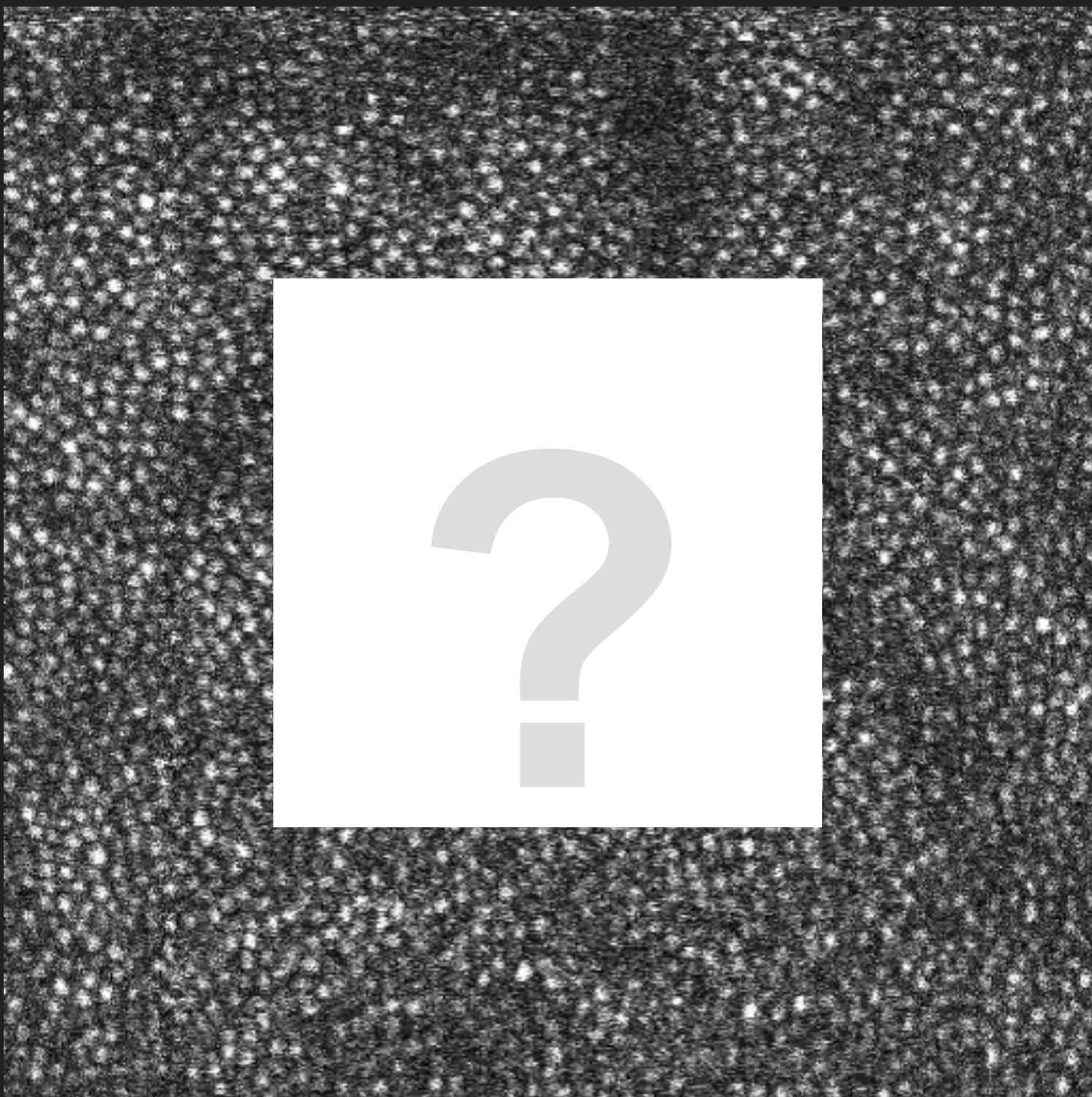


Target Color Rectangle

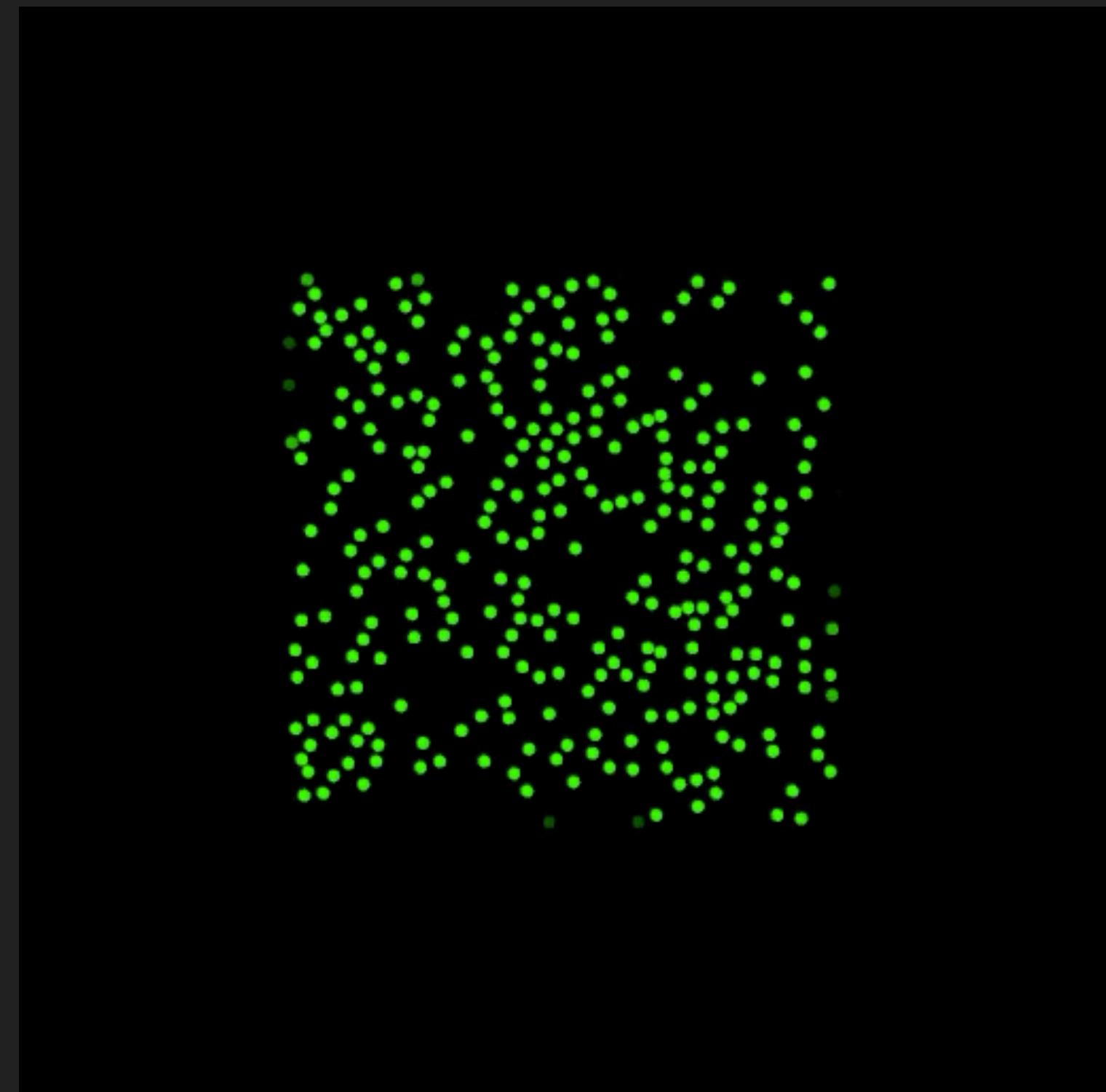


LMS Activations (False Color)

Novel Color LMS(0,1,0) Produced Cone-by-Cone

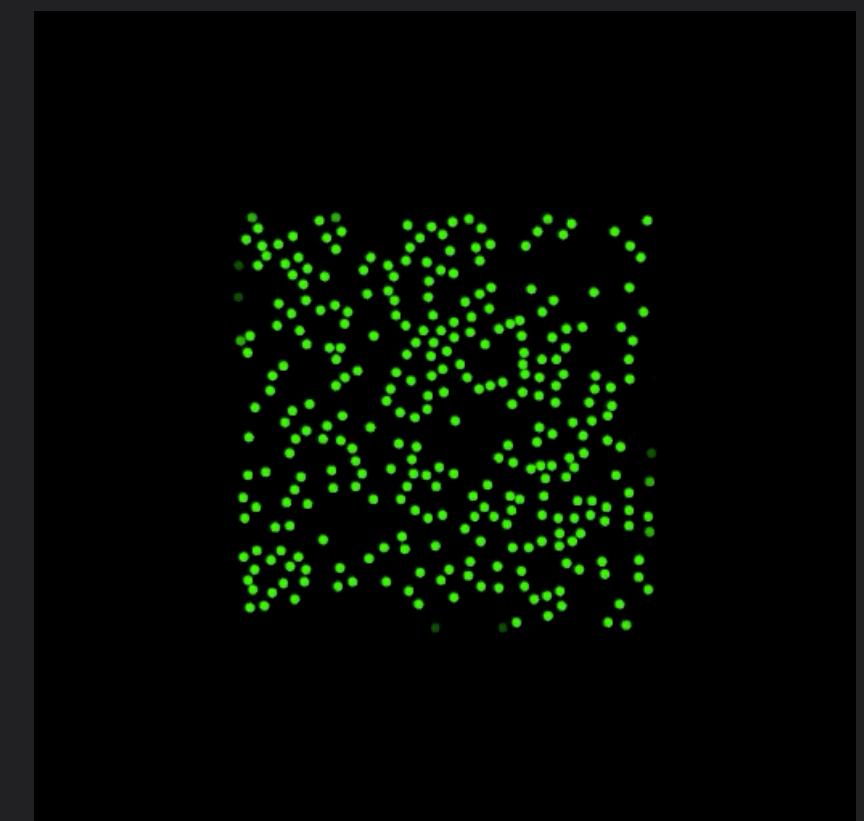
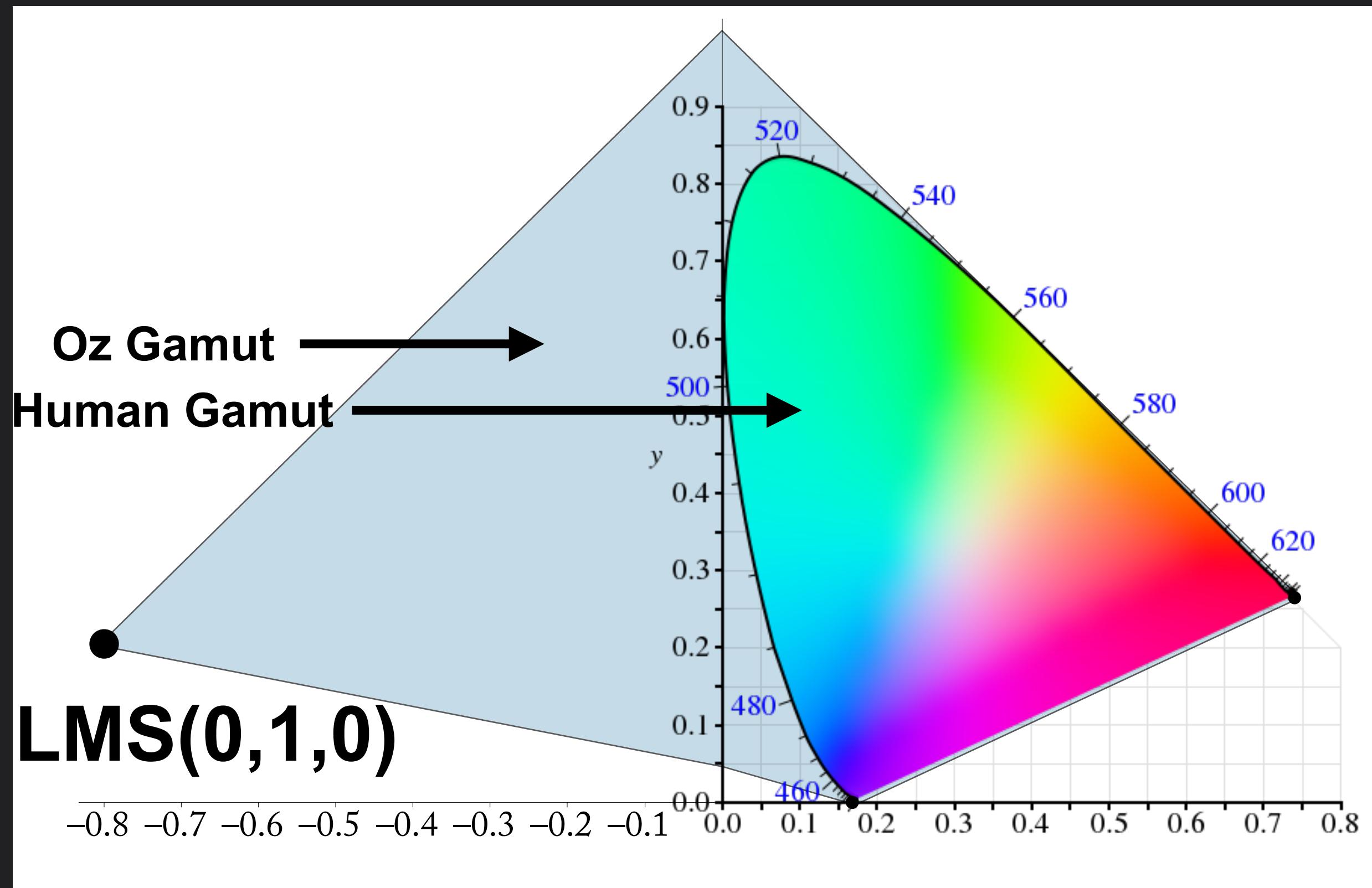


Target Color Rectangle



LMS Activations (False Color)

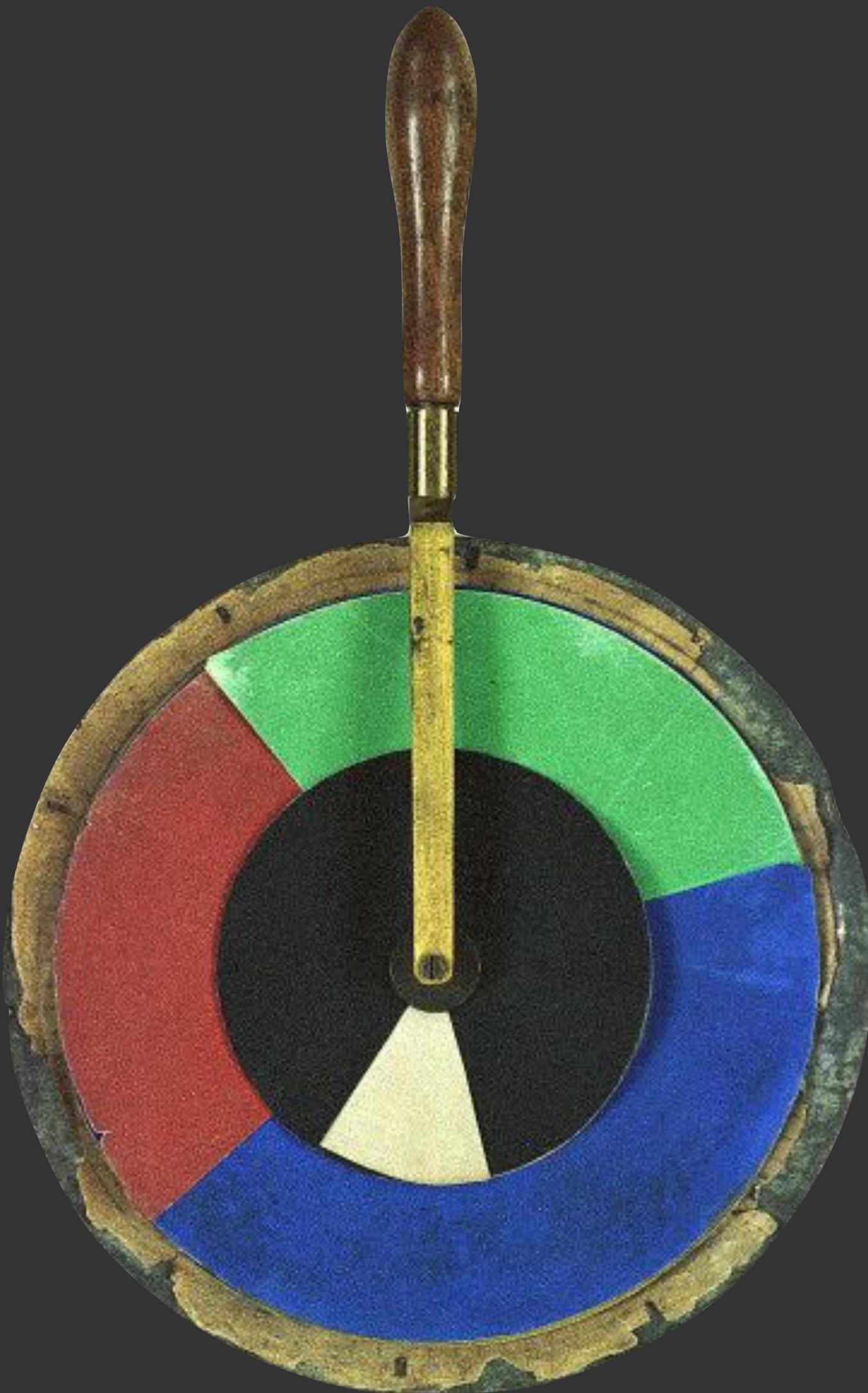
$LMS(0,1,0)$ Lies Outside the Natural Human Gamut



$LMS(0,1,0)$

Design of Key Oz Perceptual Experiment

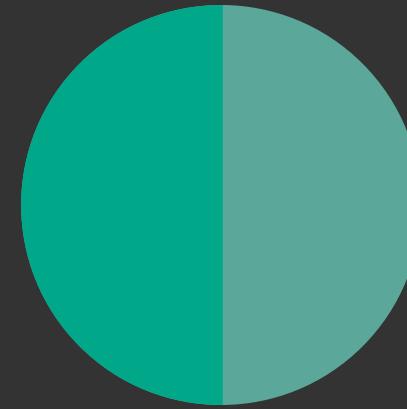
Inspiration: Maxwell's Color Matching Experiments



Portrait: <http://rsta.royalsocietypublishing.org/content/366/1871/1685>
<http://designblog.rietveldacademie.nl/?p=68422>

Oz Color Matching Experiment

Oz display
Per-cell retinal stimulus



Reference display
Controllable spectrum

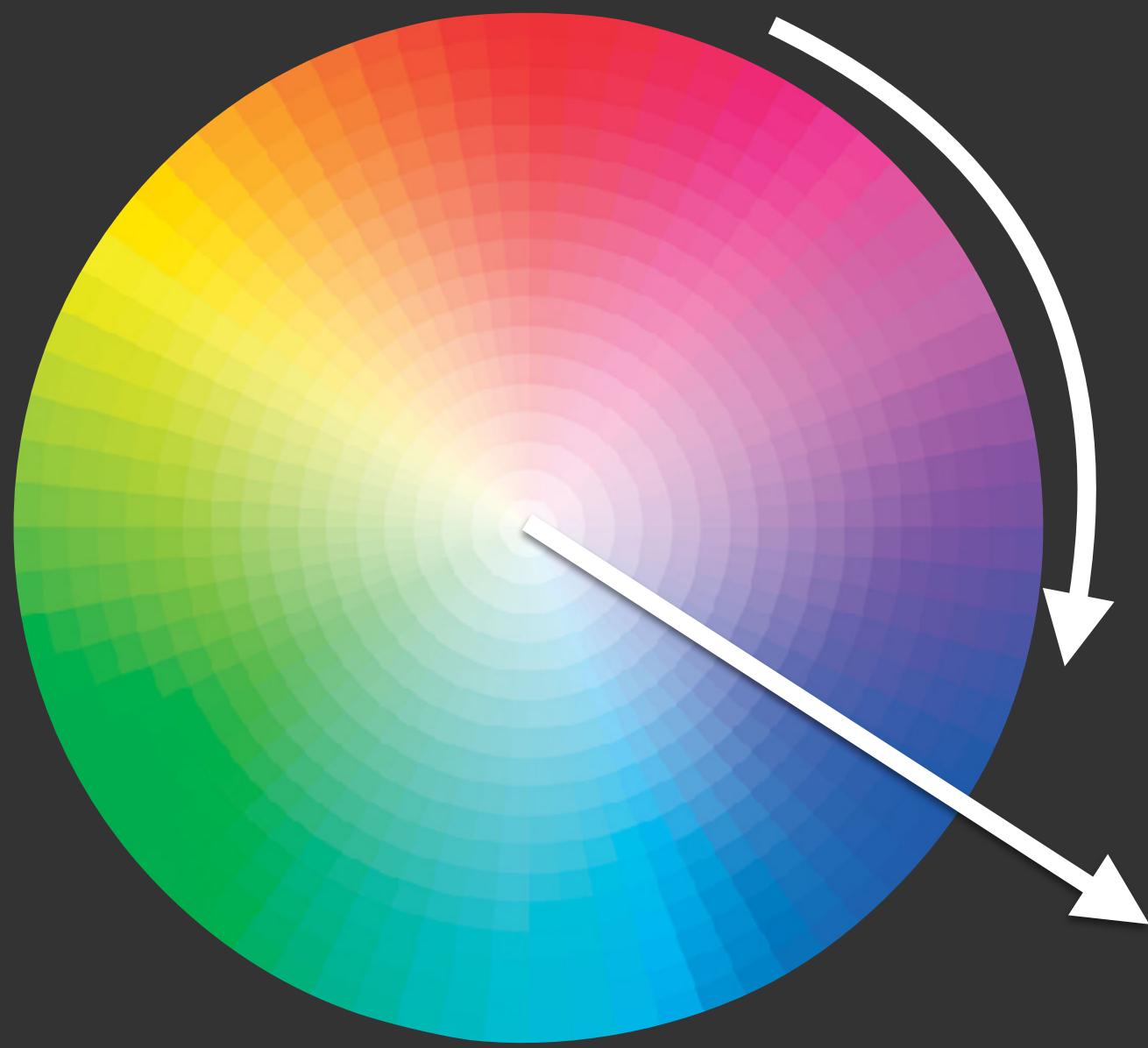
- Experimental subject's task is to control the reference display to match the appearance of the Oz display.

Reference Display: Select Any Natural Color

Oz display
Per-cell retinal stimulus



Reference display
Controllable spectrum

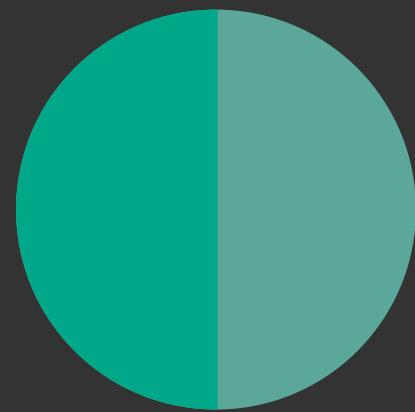


Dial 1: select hue

Dial 2: select saturation

Oz Color Matching Experiment

Oz display
Per-cell retinal stimulus



Reference display
Controllable spectrum

- Validation experiment: show natural colors on Oz and verify subjects achieve a numerical match.
- New gamut experiment: try matching LMS (0,1,0) and other points in Oz extended gamut

Discussion: Hypothesized Result of Oz Color Matching?

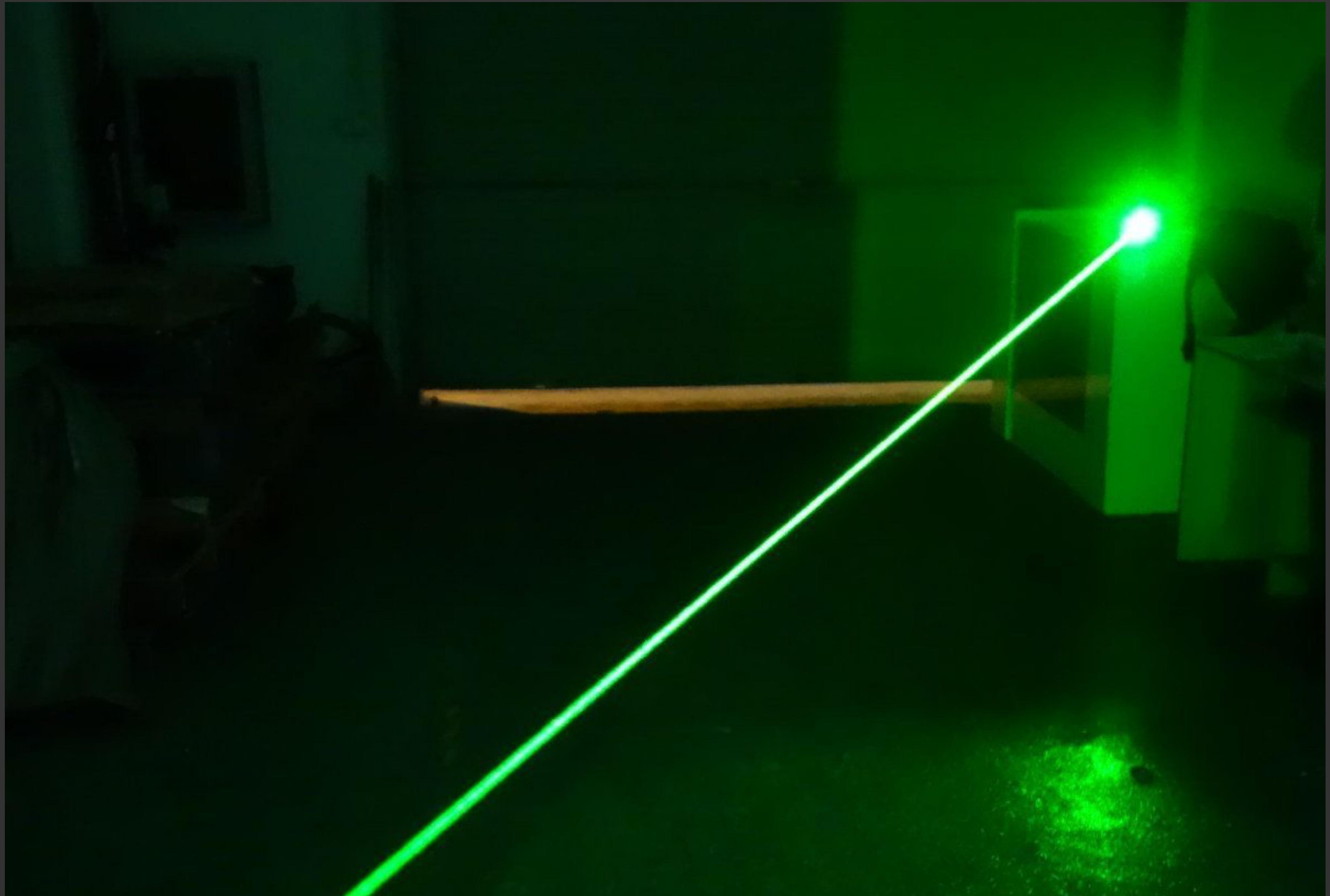
E.g. what color do you think LMS(0,1,0) will be? Why?

Hypothesized Outcomes of Oz Color Matching Experiment

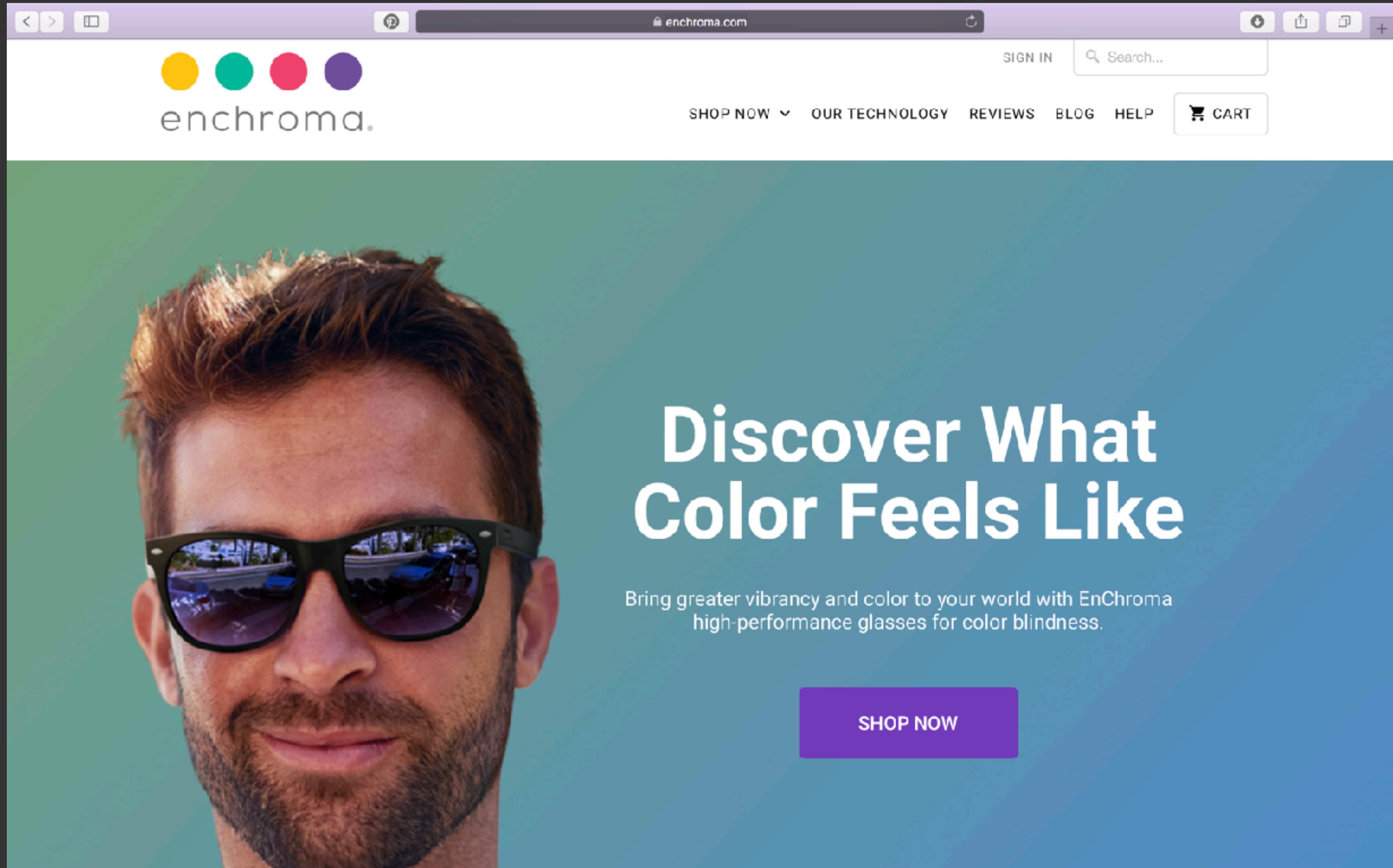
1. "Mental palette" hypothesis
 - LMS(0,1,0) matches a natural hue / saturation
2. "Saturation extension" hypothesis
 - LMS(0,1,0) is more saturated than any natural color
3. "New hue" hypothesis
 - LMS(0,1,0) does not match any hue

Clues?

Clue? Green Laser Pointer - Recall Your First Time



Clue? Enchroma User Reactions

A screenshot of a web browser displaying the Enchroma website. The page features a large banner image of a man with a beard wearing Enchroma sunglasses. The background of the banner transitions from green on the left to blue on the right. Overlaid on the banner is the text "Discover What Color Feels Like" in large white font, followed by a smaller text block: "Bring greater vibrancy and color to your world with EnChroma high-performance glasses for color blindness." Below this is a purple "SHOP NOW" button. The browser's header shows the URL "enchroma.com" and various navigation icons. The website's main navigation menu includes "SIGN IN", "Search...", "SHOP NOW", "OUR TECHNOLOGY", "REVIEWS", "BLOG", "HELP", and "CART".

enchroma.

SIGN IN

Search...

SHOP NOW

OUR TECHNOLOGY

REVIEWS

BLOG

HELP

CART

Discover What Color Feels Like

Bring greater vibrancy and color to your world with EnChroma high-performance glasses for color blindness.

SHOP NOW

Clue? Reactions to Perceiving New Colors



Enchroma, <https://www.youtube.com/watch?v=-rMjUsG--zo>

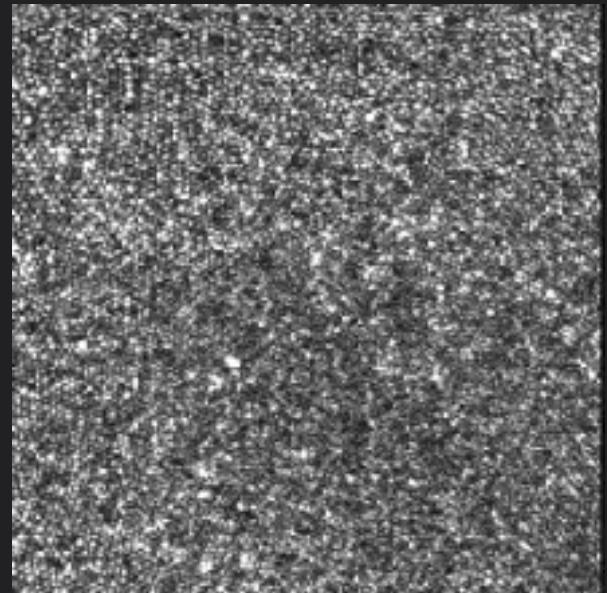
Clue? Reactions to Perceiving New Colors



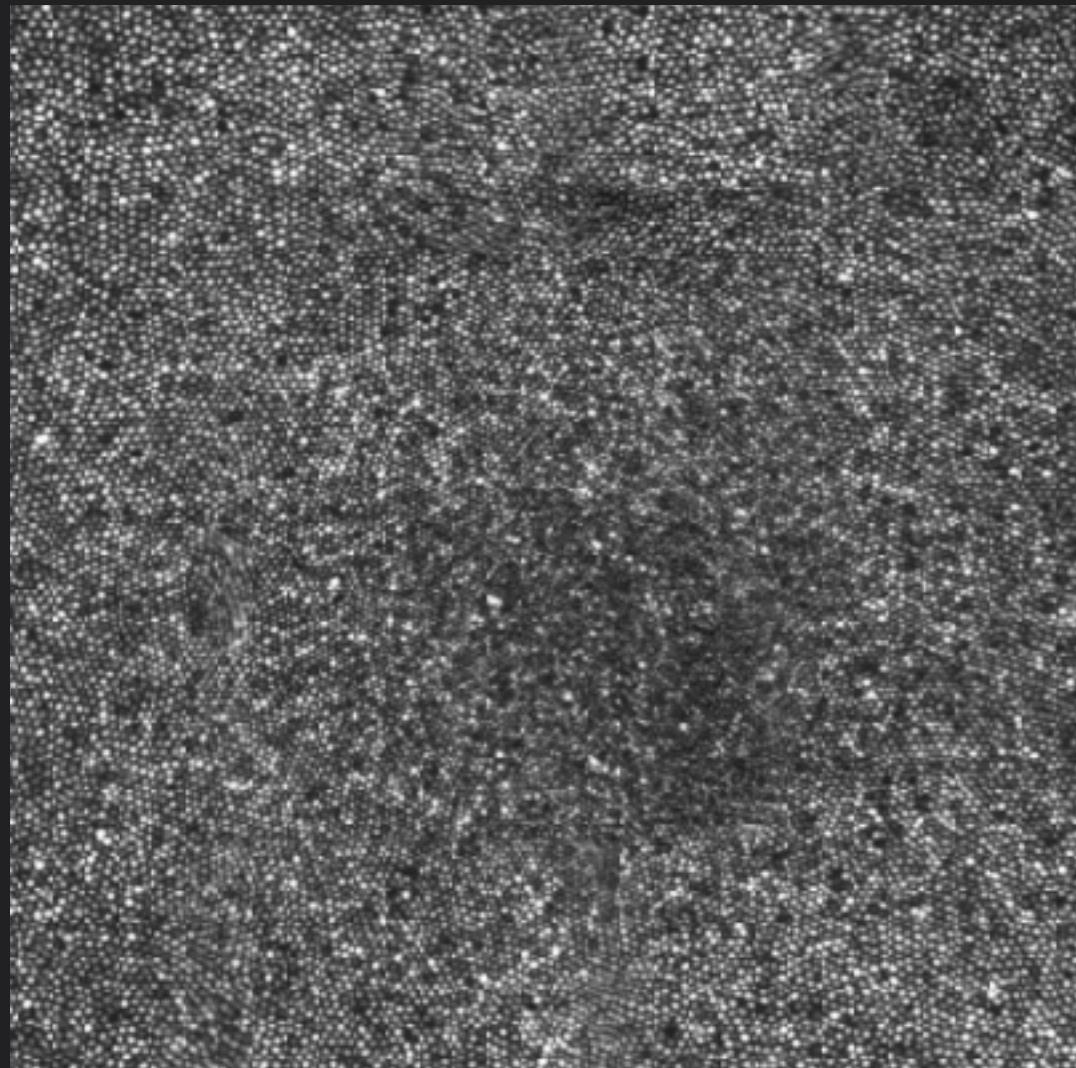
Enchroma, <https://www.youtube.com/watch?v=-rMjUsG--zo>

Free Gaze Oz Vision
Reproducing Vision Cone-by-Cone Under
Natural Viewing Conditions
(Project and Research Opportunities)

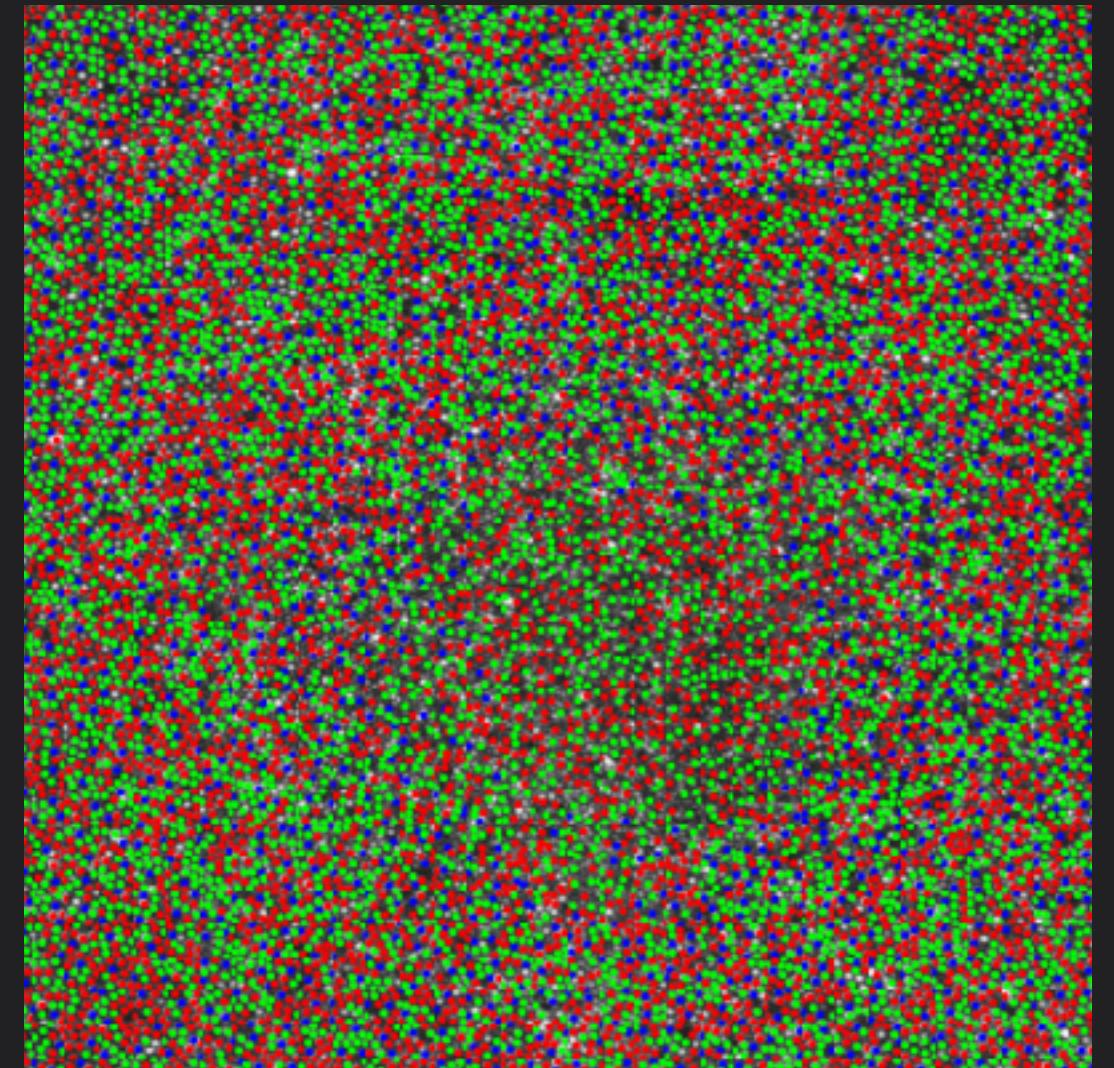
Free Gaze Oz Vision Rendering – Inputs



AOSLO Retinal Target Percept
Video RGB Video



Stitched Retina Map

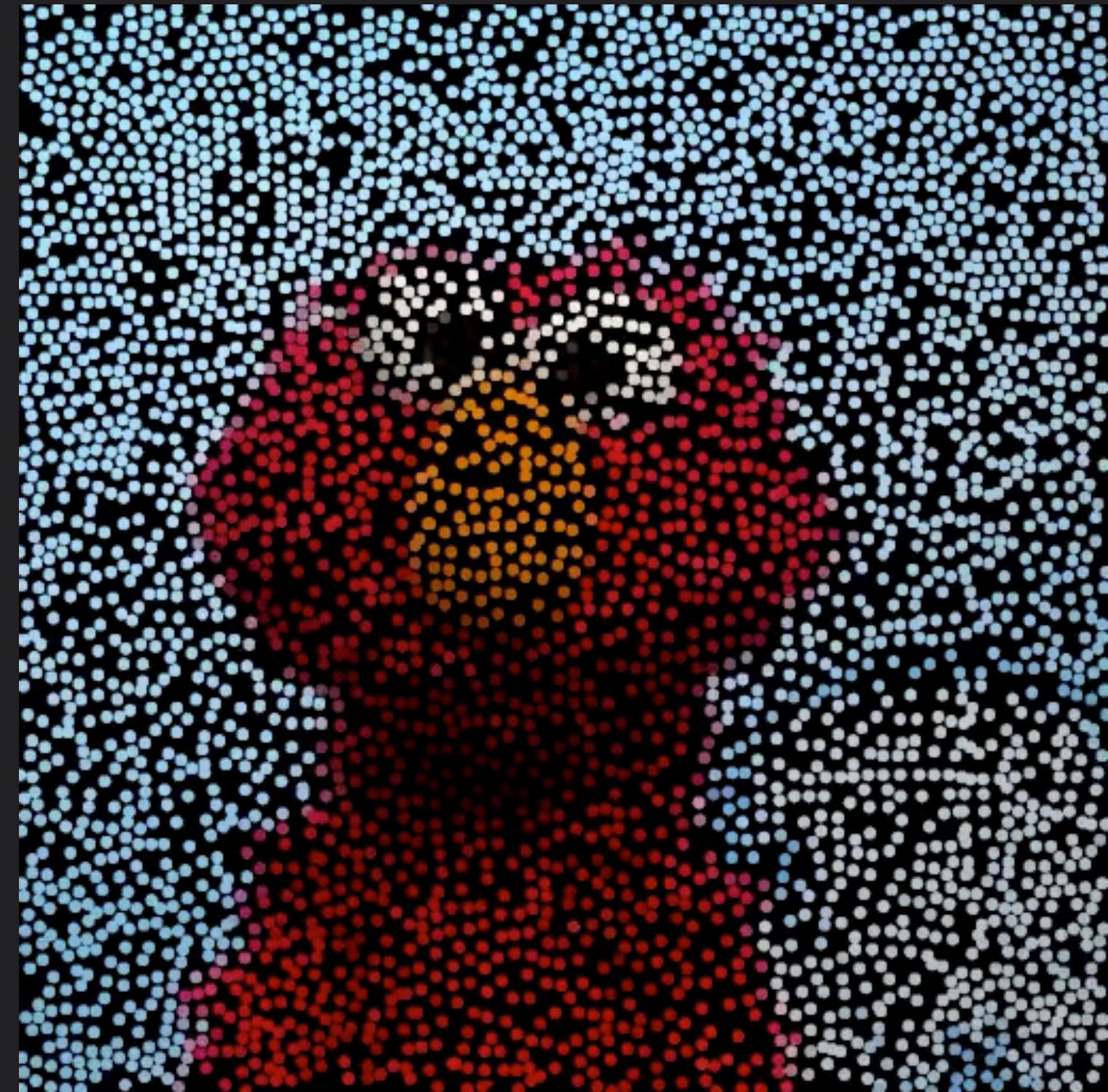


Classified Cone Map (Simulated)

Free Gaze Oz Vision Rendering – RGB Per Cone

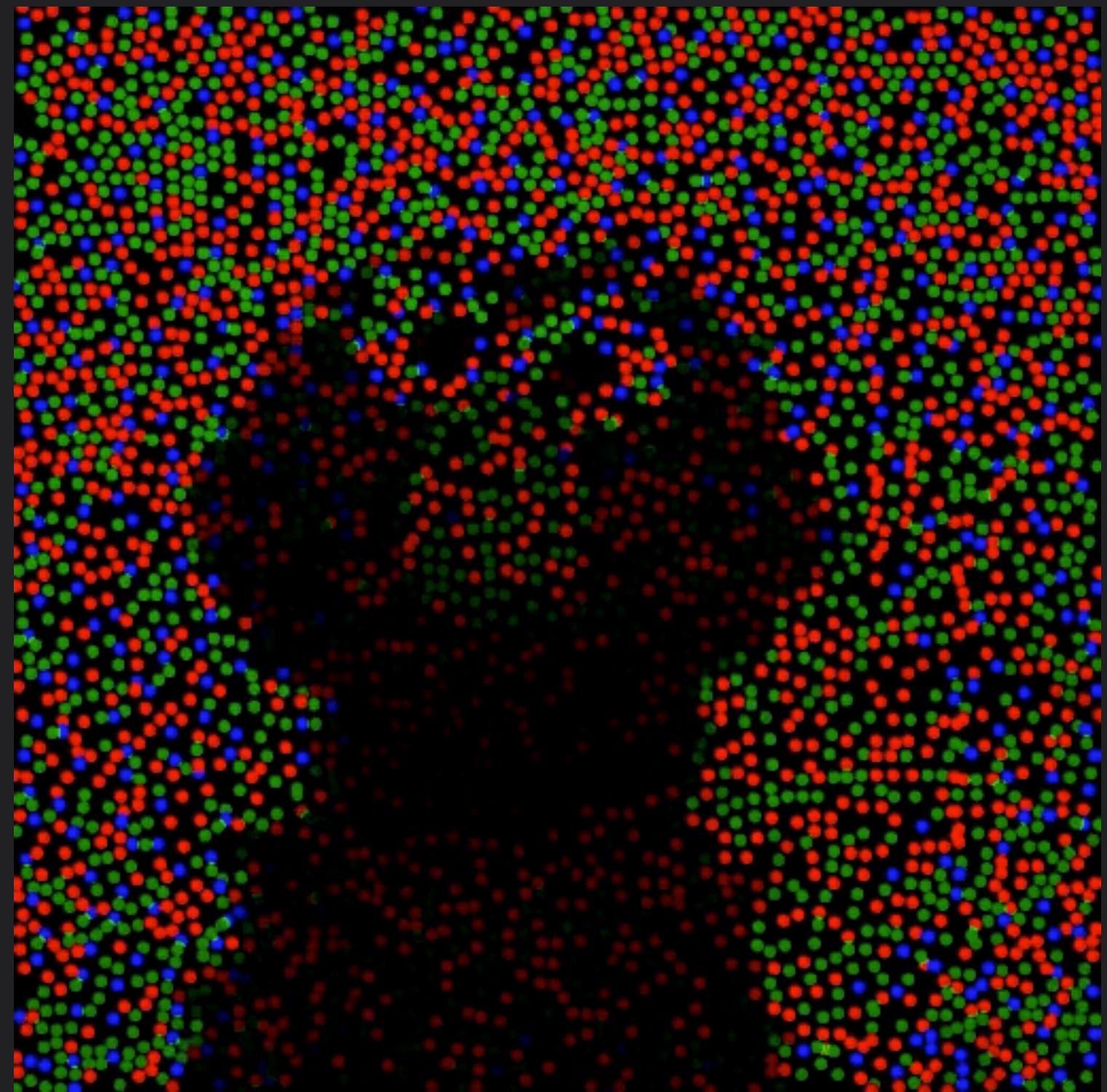


Target Video on AOSLO Retinal Video



RGB Value Per Cone

Free Gaze Oz Vision Rendering – LMS Per Cone

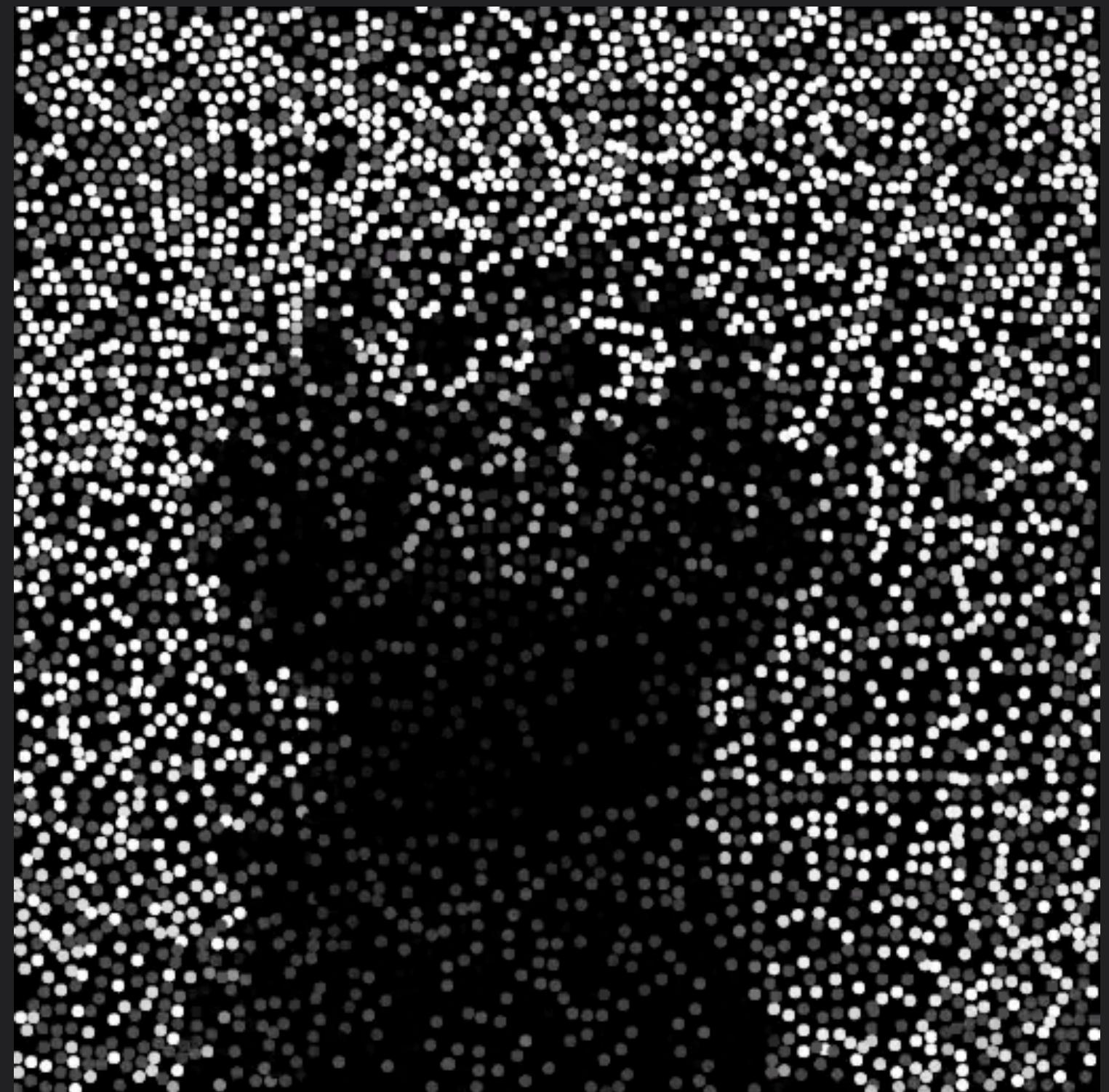


Target Video on AOSLO Retinal Video LMS Activities Per Cone (False Color)

Free Gaze Oz Vision Rendering – Laser Microdoses



Target Video on AOSLO Retinal Video

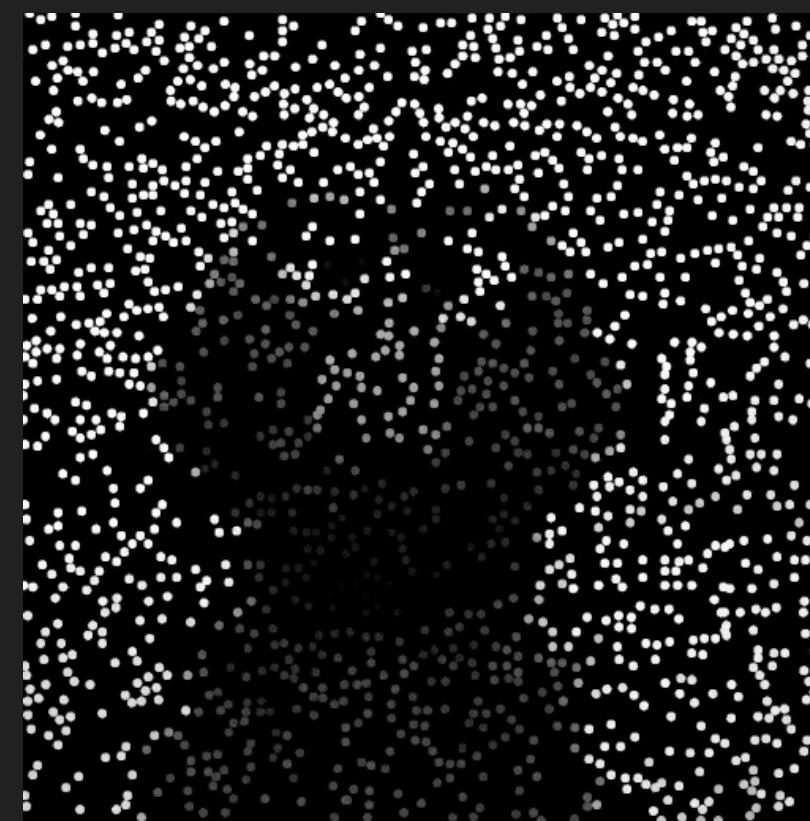


Laser Microdoses (500 nm)

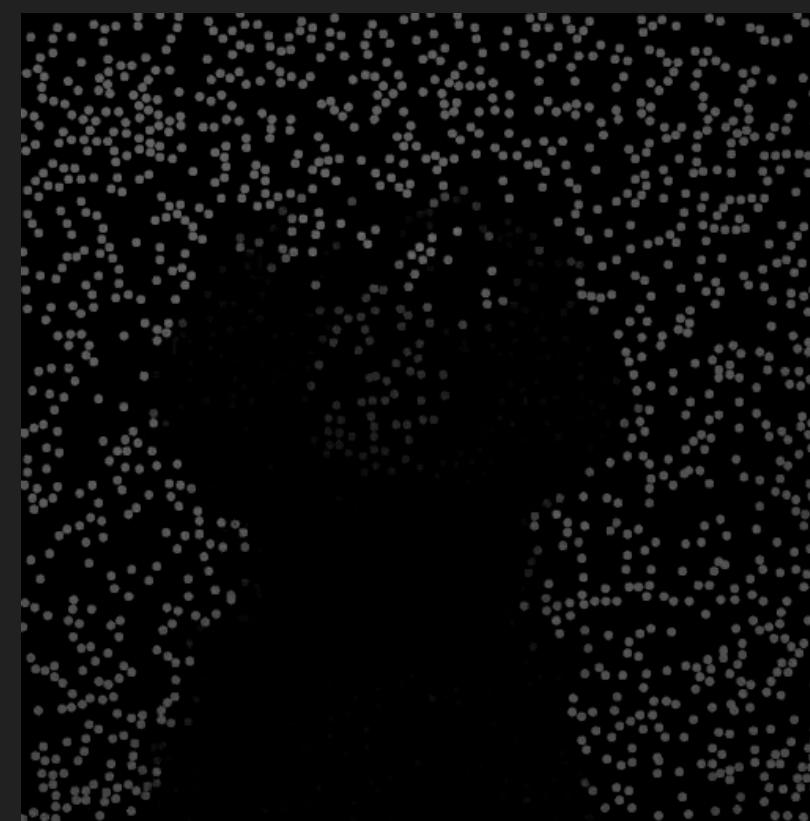
Free Gaze Oz Vision Rendering – Laser Microdoses



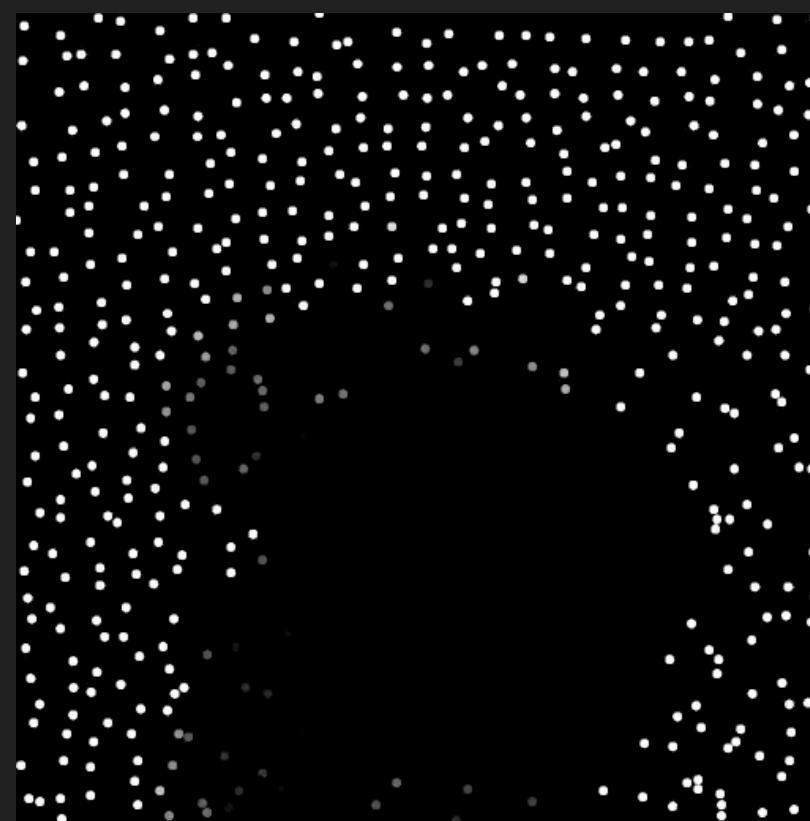
target Video on AOSLO Retinal Video



L-Cones



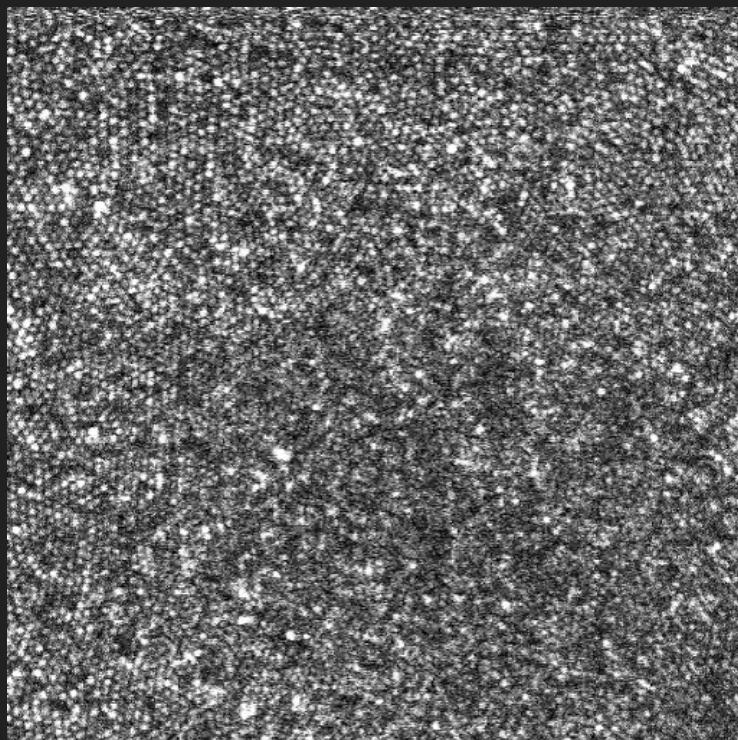
M-Cones



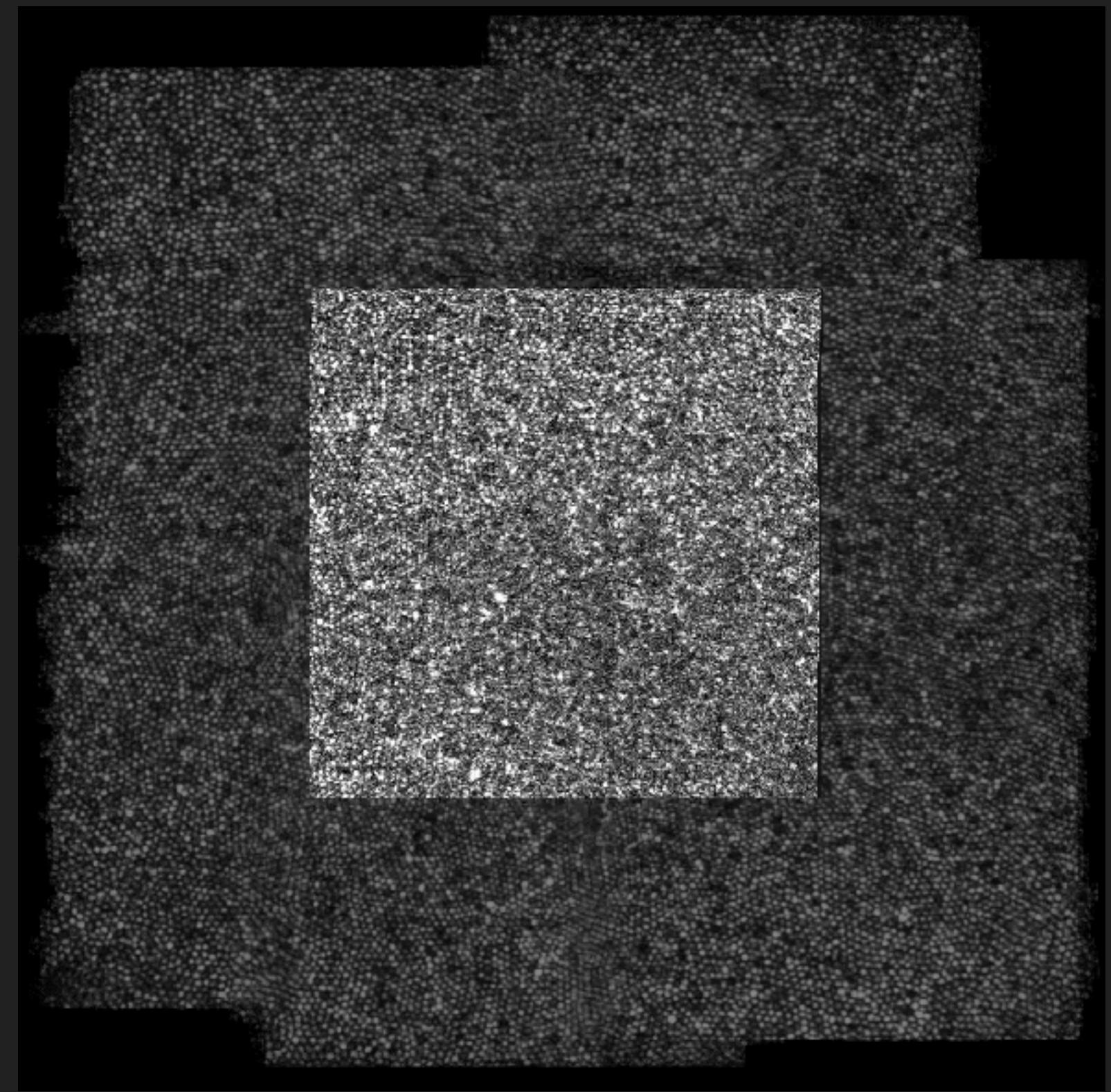
S-
Cones

Laser Microdoses (500 nm)

AOSLO Retina Video in Two Coordinate Systems

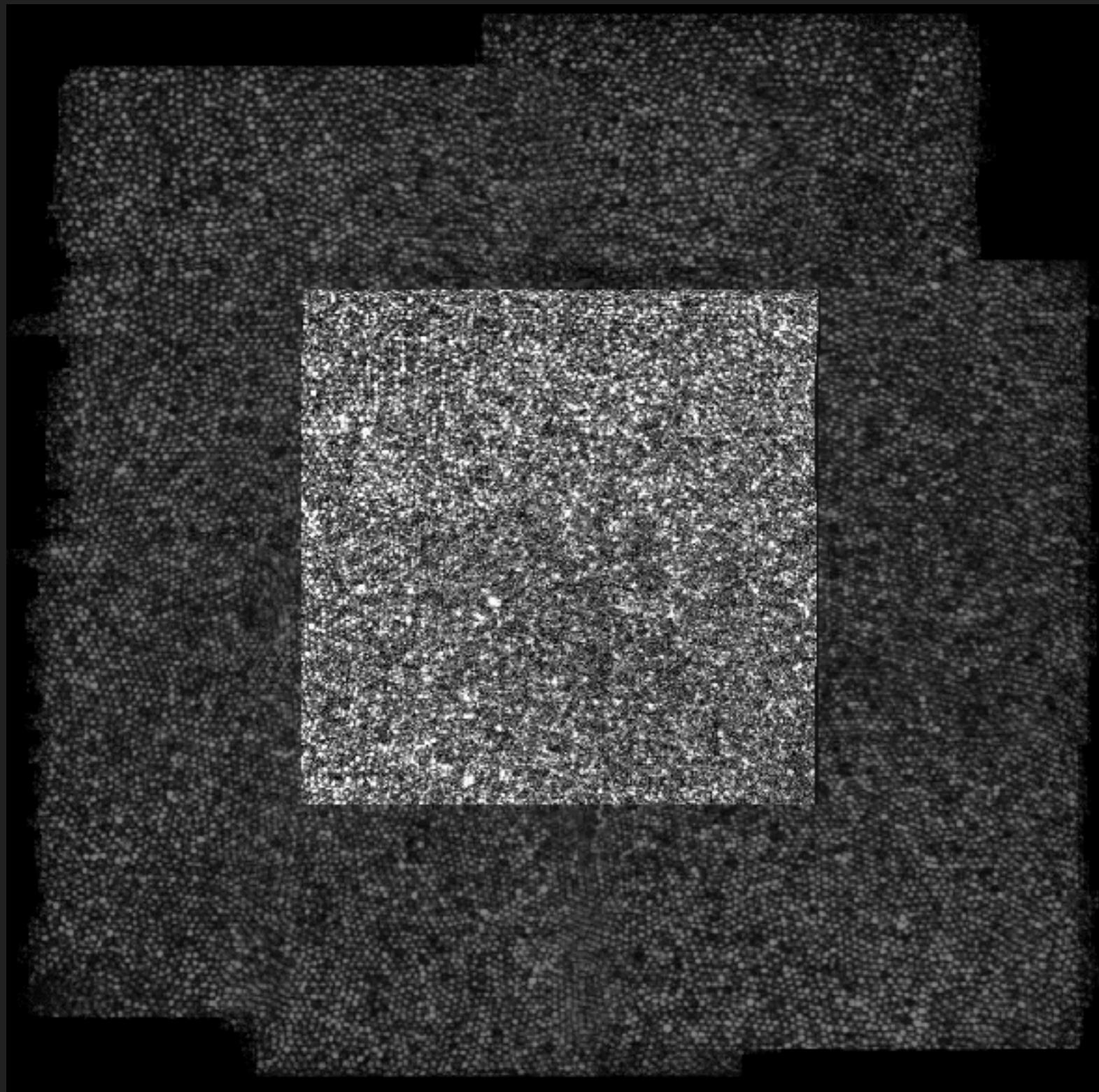


Video Space



Retina Space

Target Video in Retina Space



AOSLO Video in Retina Space

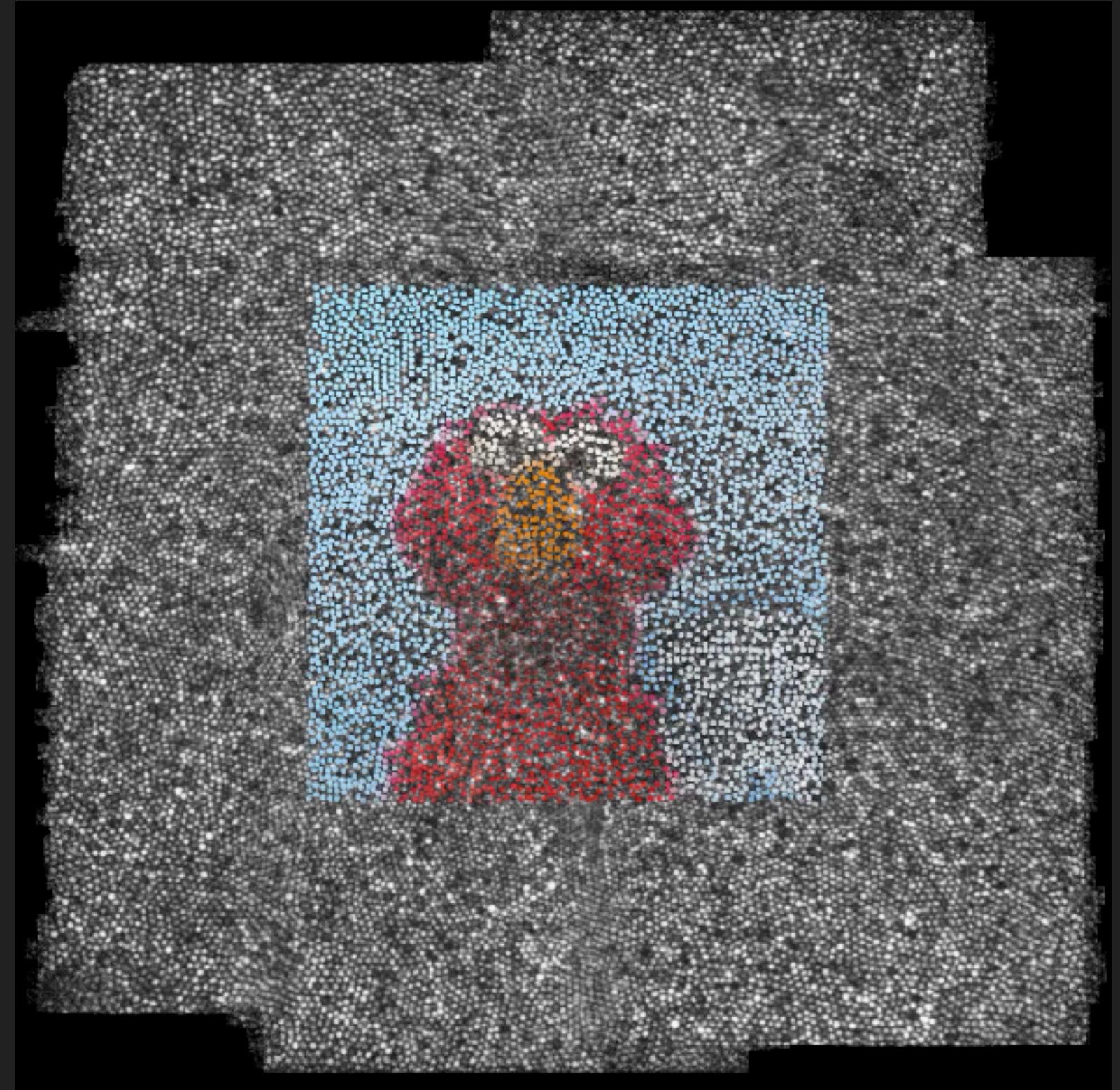


Target Video in Retina Space

Free Gaze Oz Vision Rendering - RGB per Cone



Target Video in Retina Space

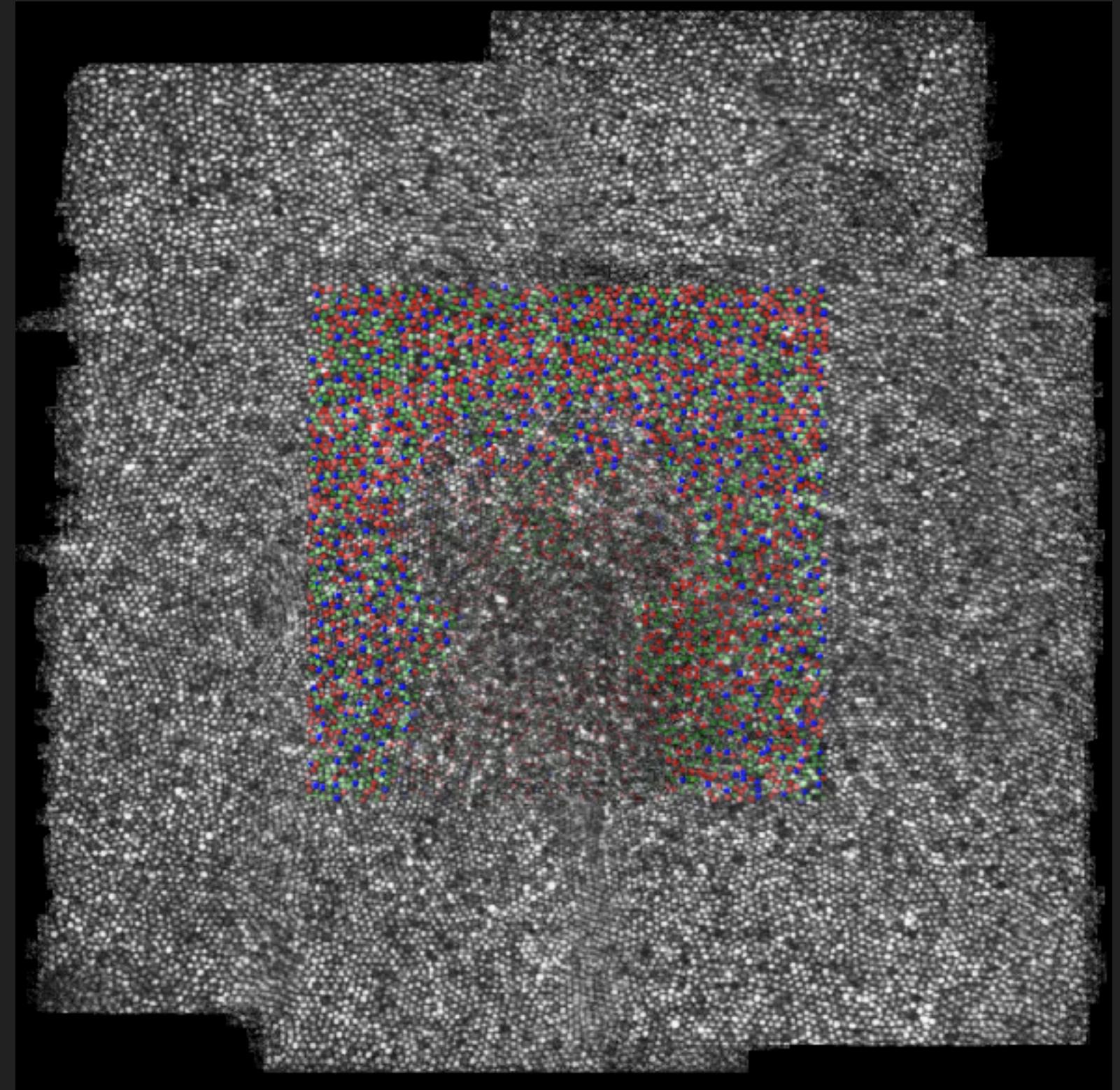


RGB Value Per Cone

Free Gaze Oz Vision Rendering - LMS per Cone



Target Video in Retina Space

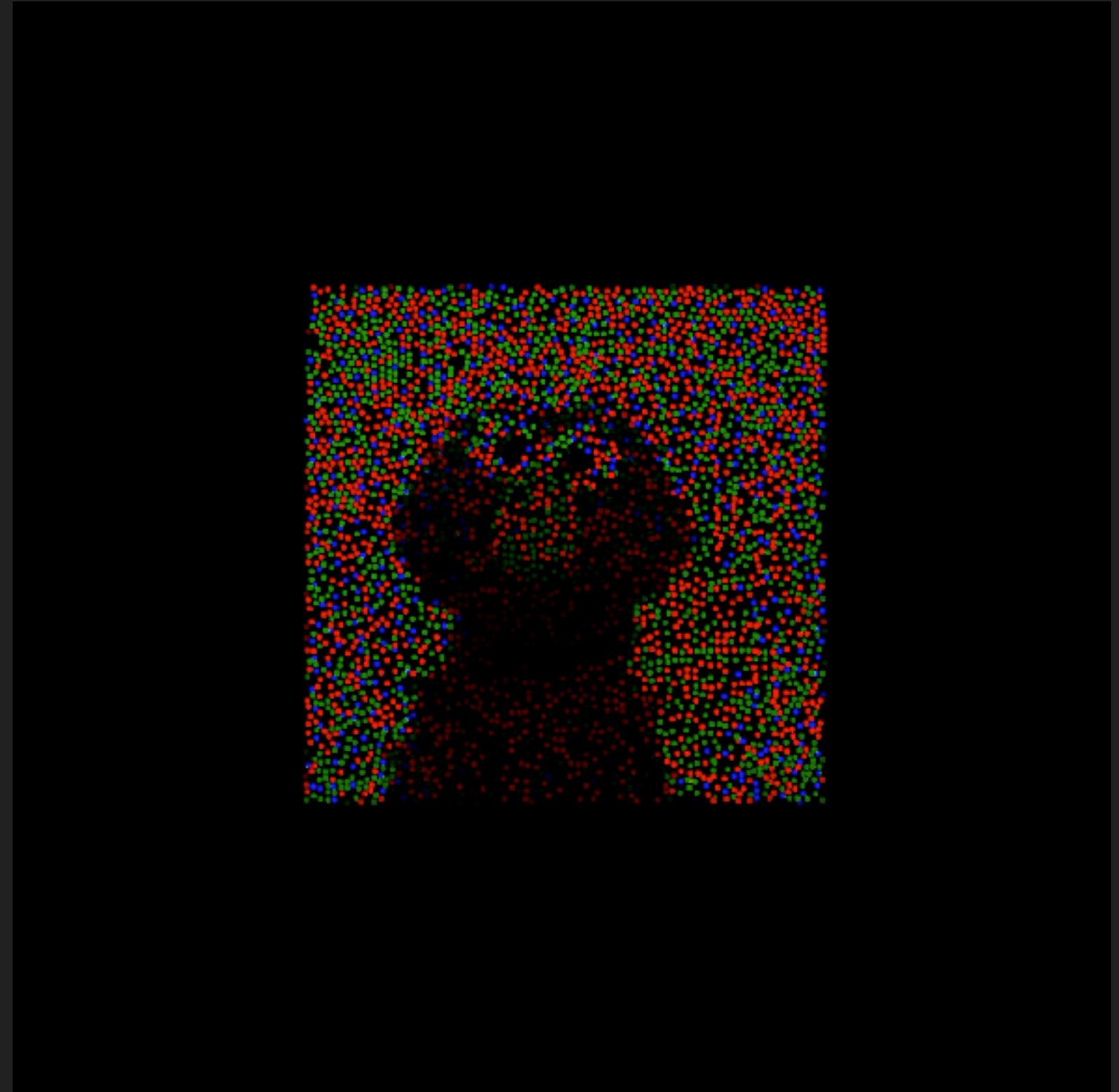


LMS Activities Per Cone (False Color)

Free Gaze Oz Vision Rendering - LMS per Cone



Target Video in Retina Space

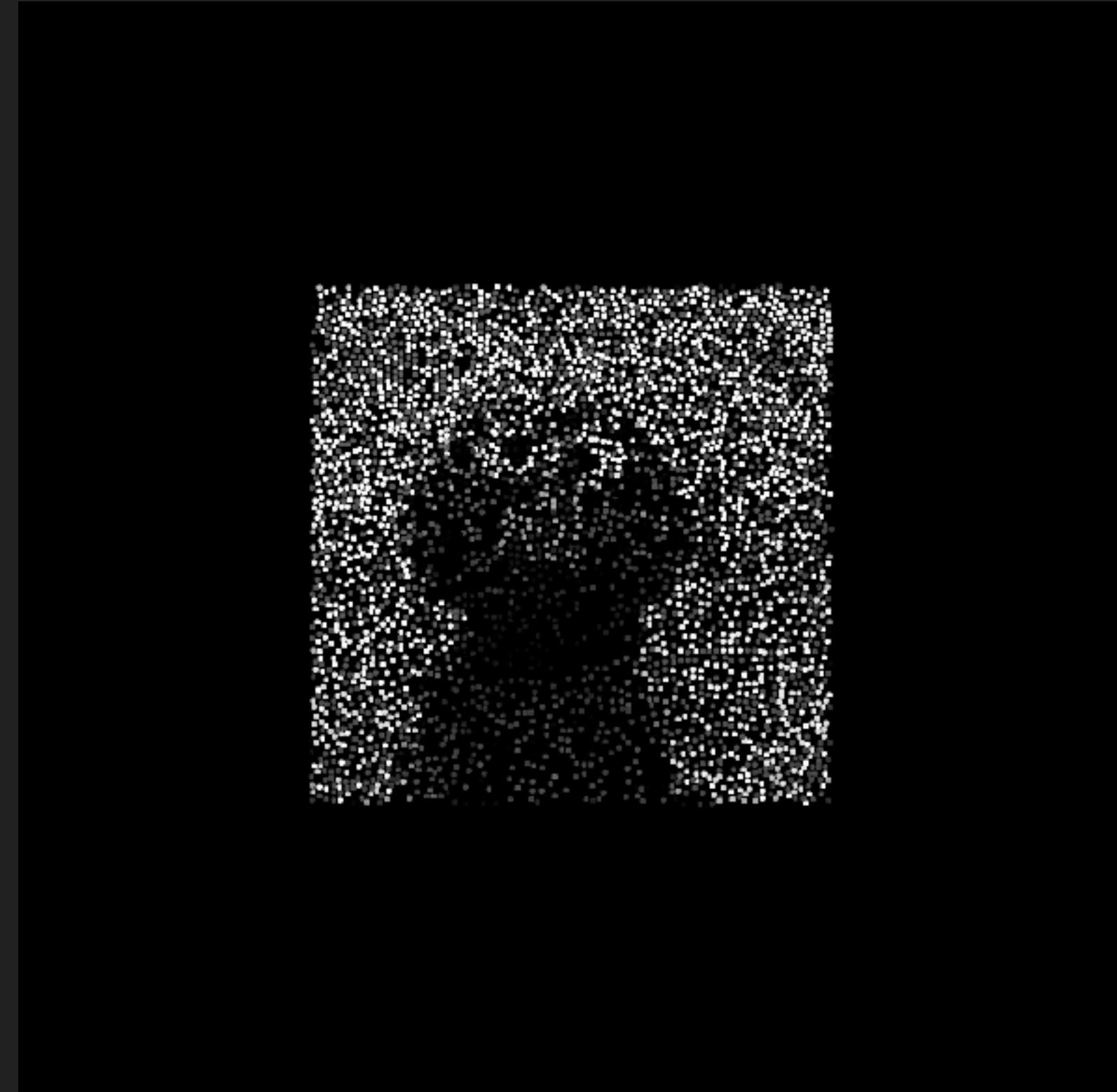


LMS Activities Per Cone (False Color)

Free Gaze Oz Vision Rendering - Laser Microdoses



Target Video in Retina Space



Laser Microdoses (500nm)

Application to Color Blindness

Clue? Gene Therapy Towards Treating Color Blindness



- Adult dichromat monkeys were given gene therapy that effectively added a third cone type
- i.e. Their retinal mosaics changed from 2-type to 3-type
- These monkeys gained the ability to perform tasks requiring full color (trichromatic) perception

Mancuso et al., 2009. Gene therapy for red-green colour blindness in adult primates.
<https://www.nature.com/articles/nature08401>

Coretsumo /koh-reht-su-mo/ Computational Retinal Super Mosaicking

- Using the Oz Vision system to add virtual photoreceptor types
- Boost dimensionality of color perception

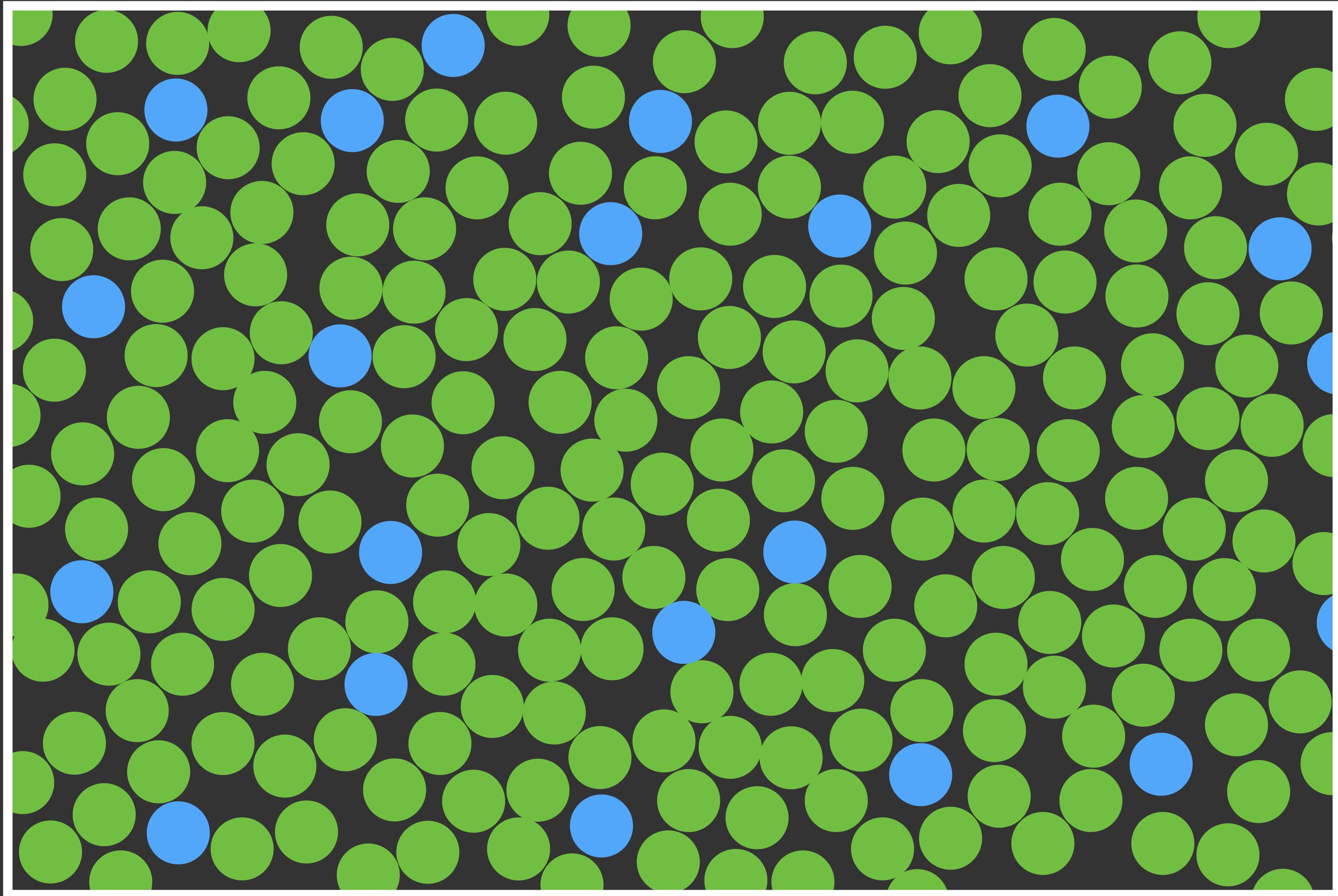
Using Coretsumo to "Treat" Color Blindness

Coretsumo 2D > 3D

Reprogramming Visual Perception & Eliciting Anomalous Color Percepts (1.5 / 3.5)

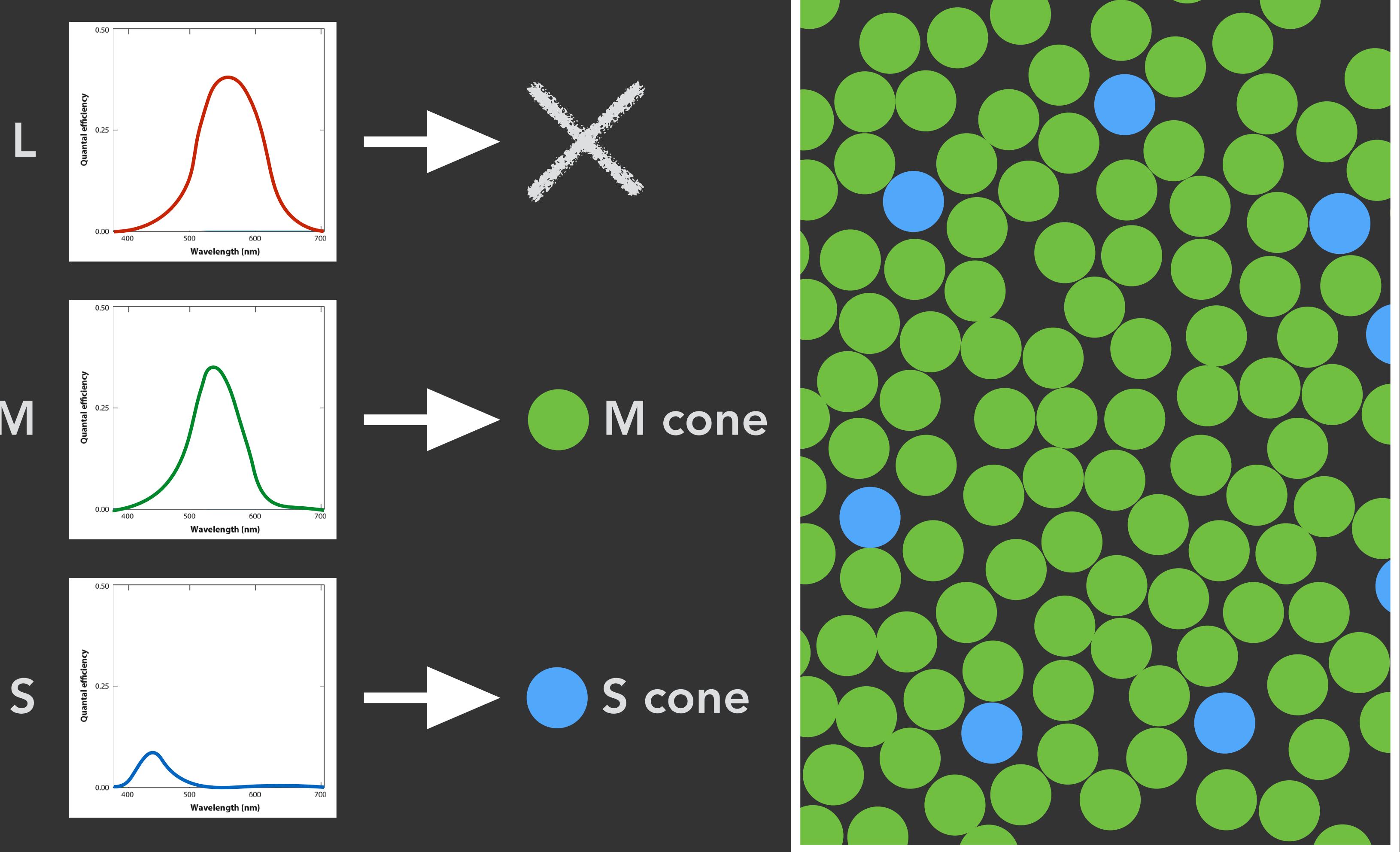
Eliciting Trichromacy in a Dichromat

Real Retina Cone Map (Protanope)



Real Cones: ● M-type ● S-type (Missing L cones)

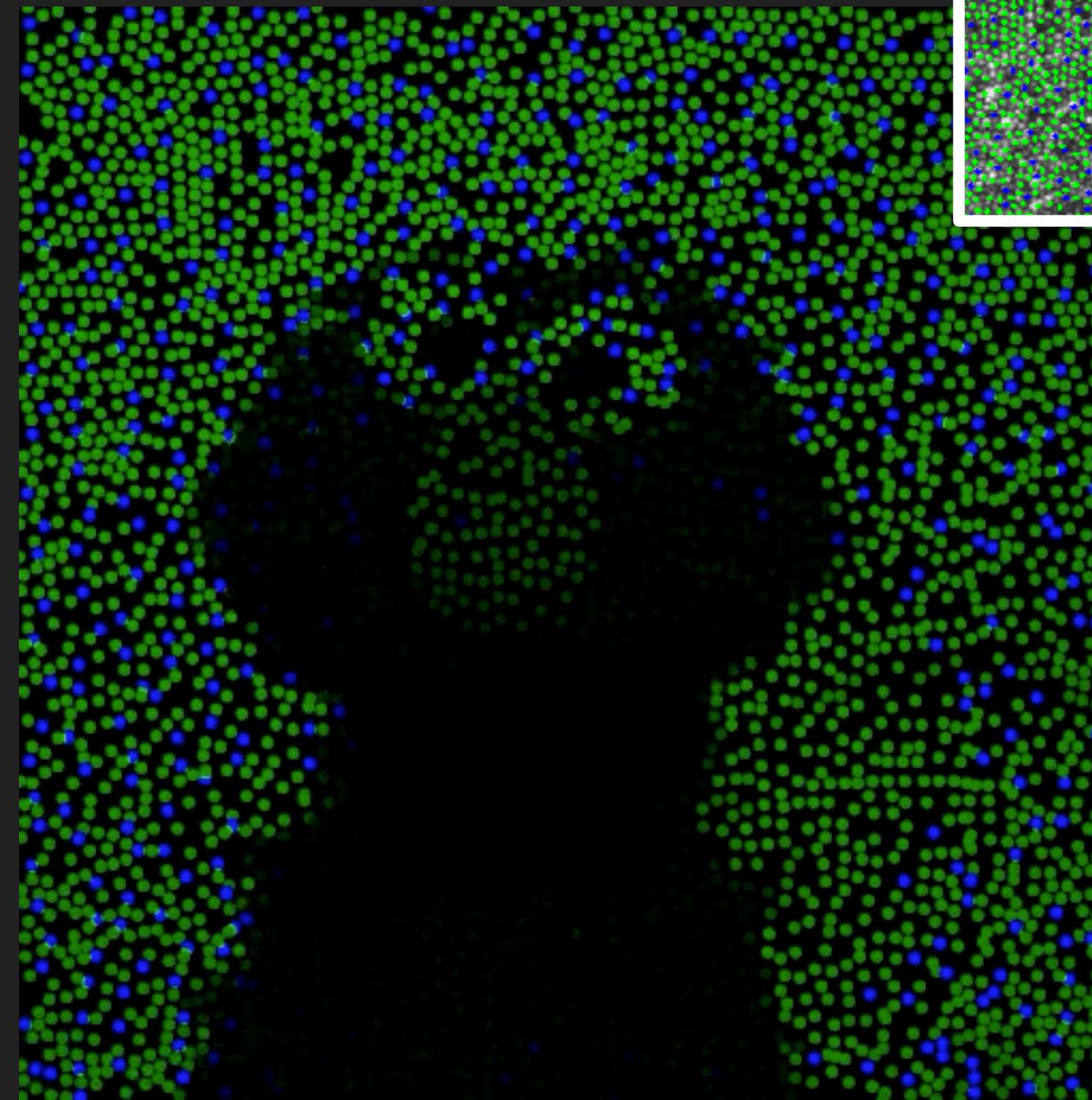
Regular Oz Vision: This Would Reproduce Color-Blind Percept



Reproducing Protanope Vision, Cone-by-Cone



Target Video

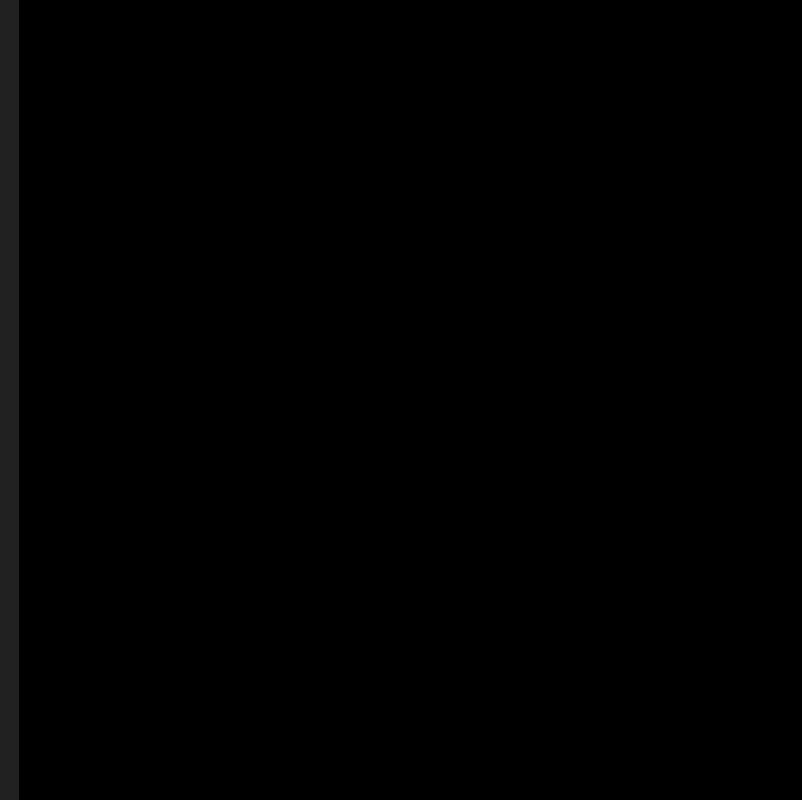


Regular Oz Vision - LMS Activations

Reproducing Protanope Vision, Cone-by-Cone



Target Video

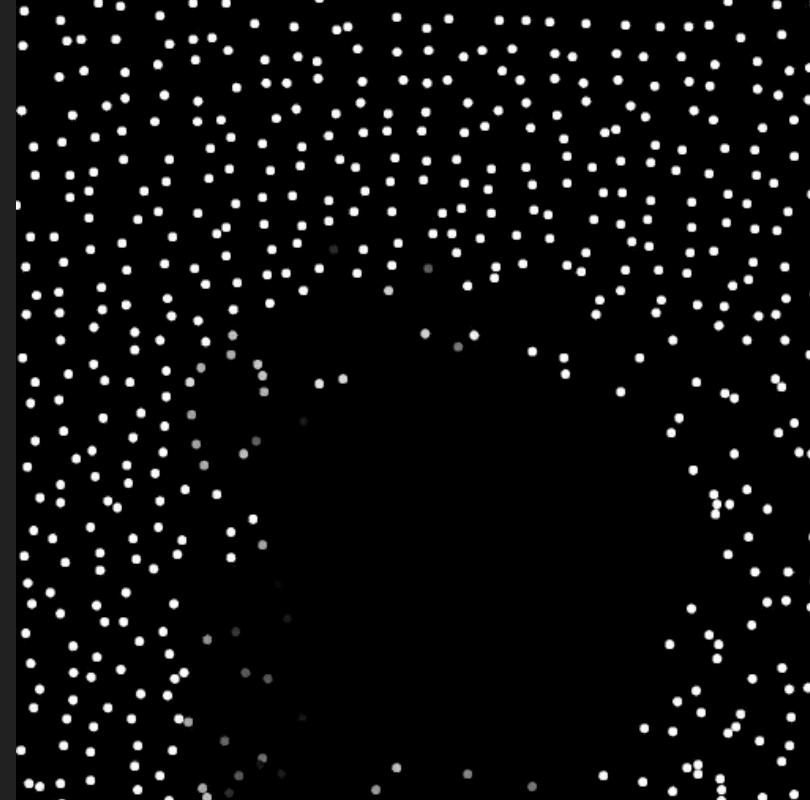


L-Cones

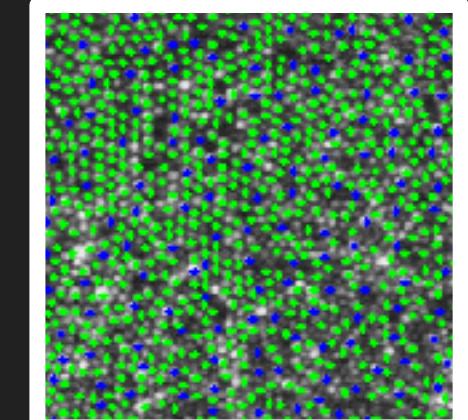


M-Cones

Laser Microdoses (500 nm)

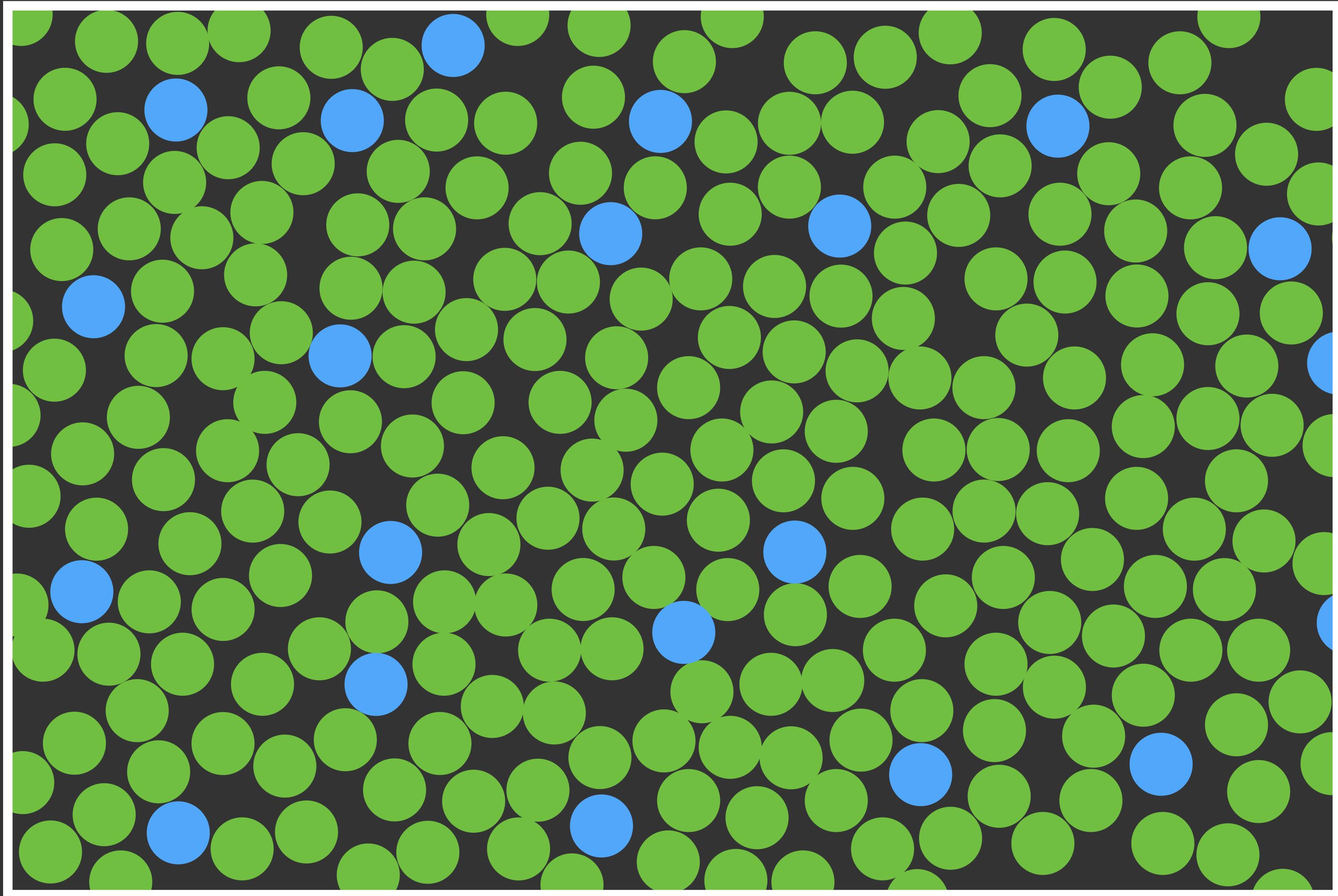


S-
Cones



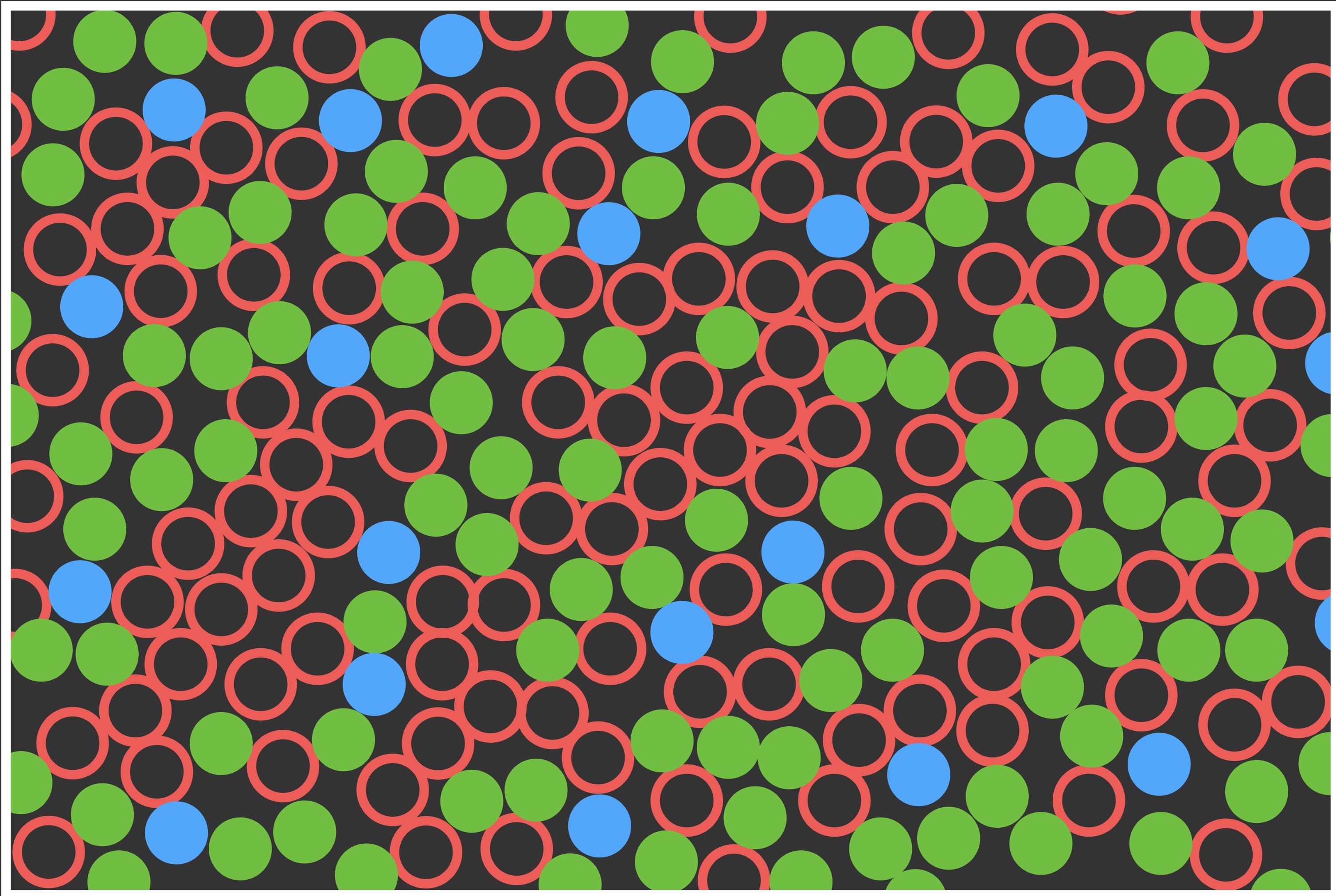
Regular Oz Vision

Real Retina Cone Map (Protanope)



Real Cones: ● M-type ● S-type (Missing L cones)

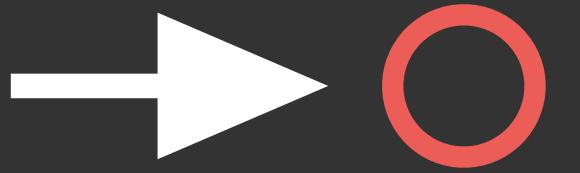
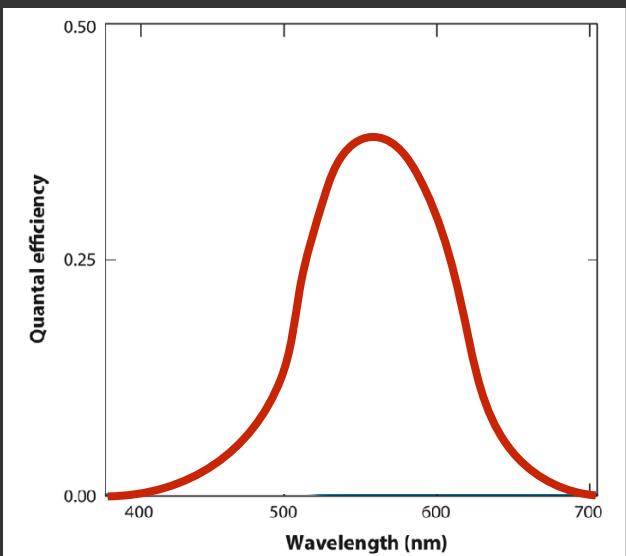
Coretsumo Retina Cone Map (Protanope)



Real Cones: ● M-type ● S-type ○ "Mutant"

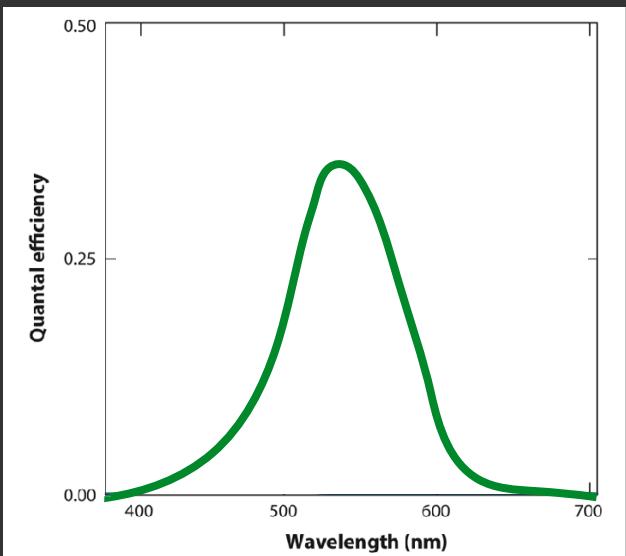
Coretsumo: Deliver LMS Values to "Mutant" Mosaic

L



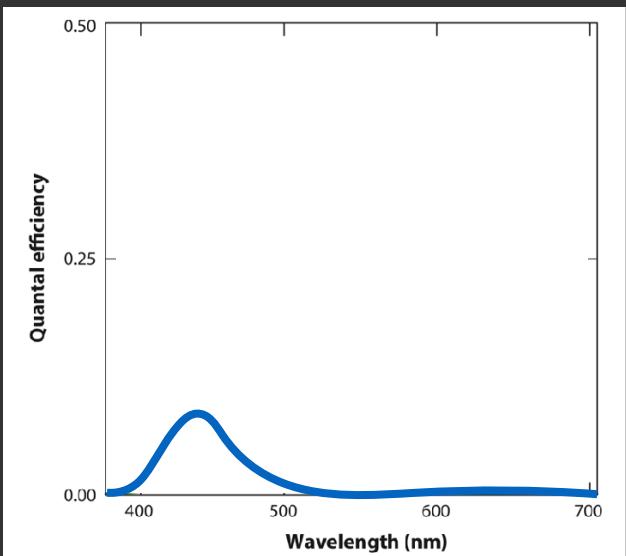
"Mutant"

M

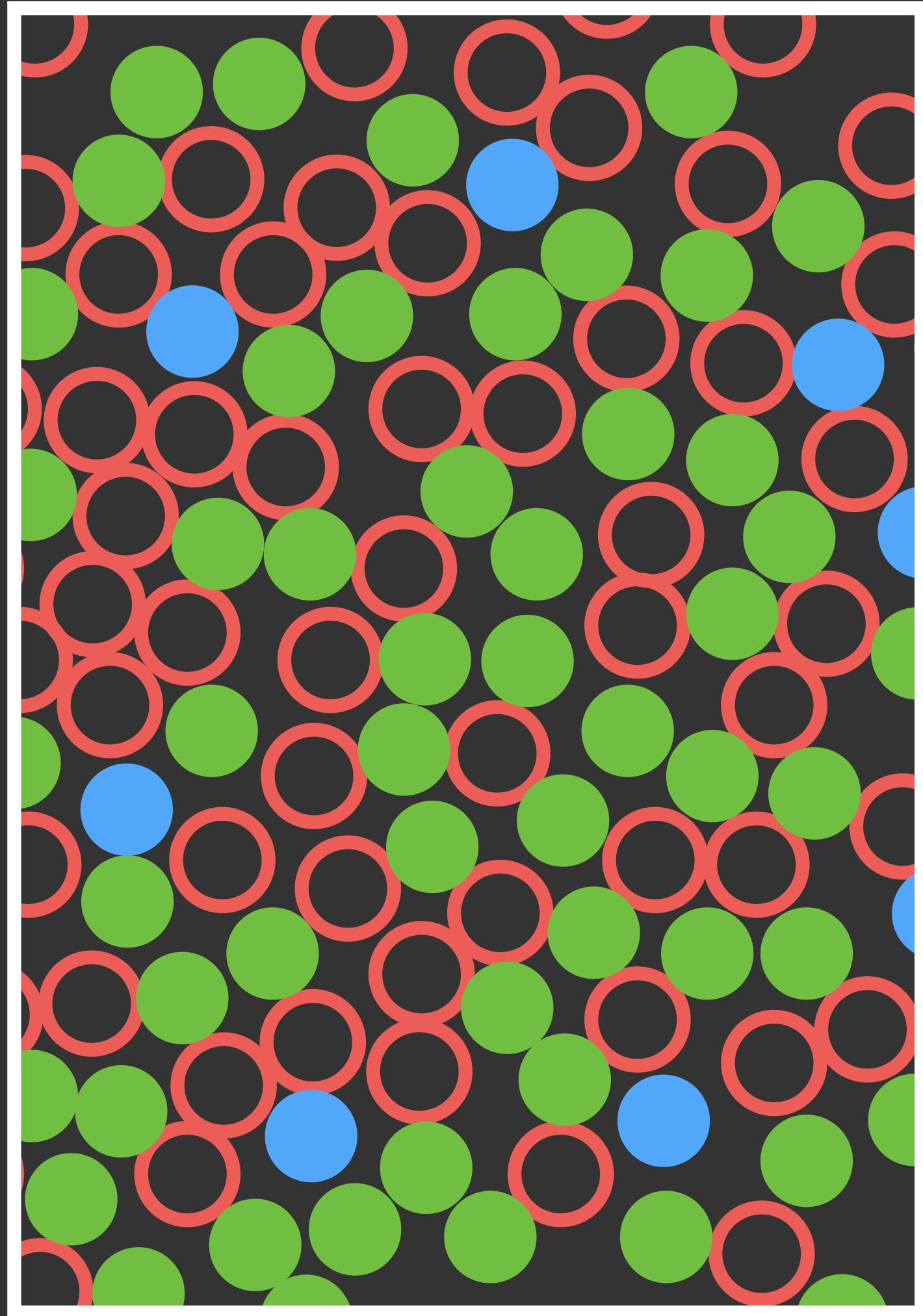


M

S



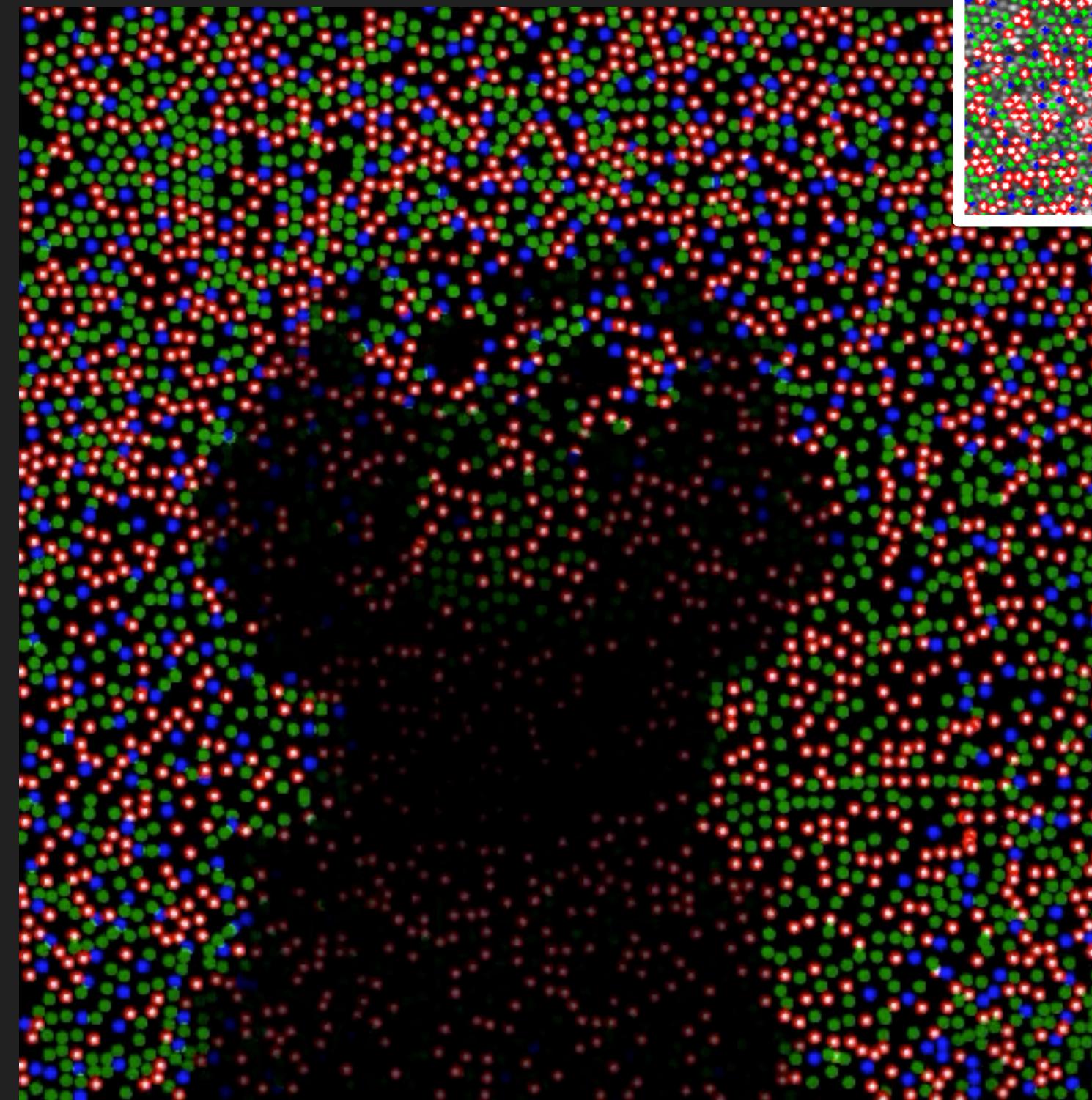
S



Attempting to Elicit Trichromacy in a Protanope



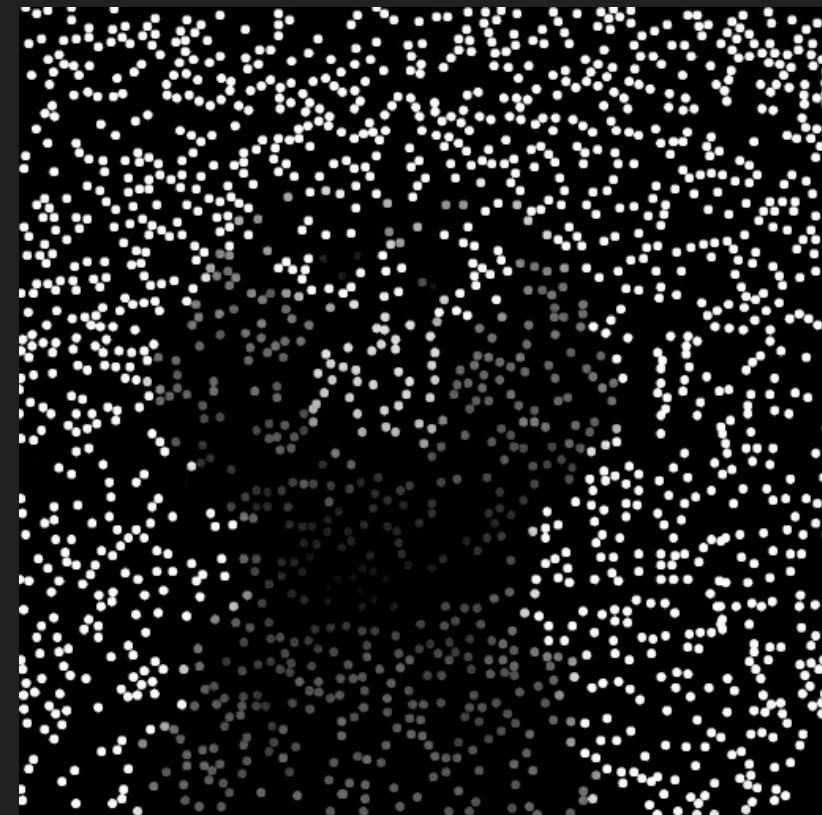
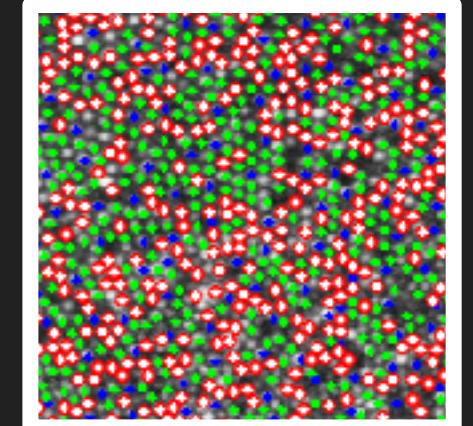
Target Video



Coretsumo Oz Vision - LMS Activations

Attempting to Elicit Trichromacy in a Protanope

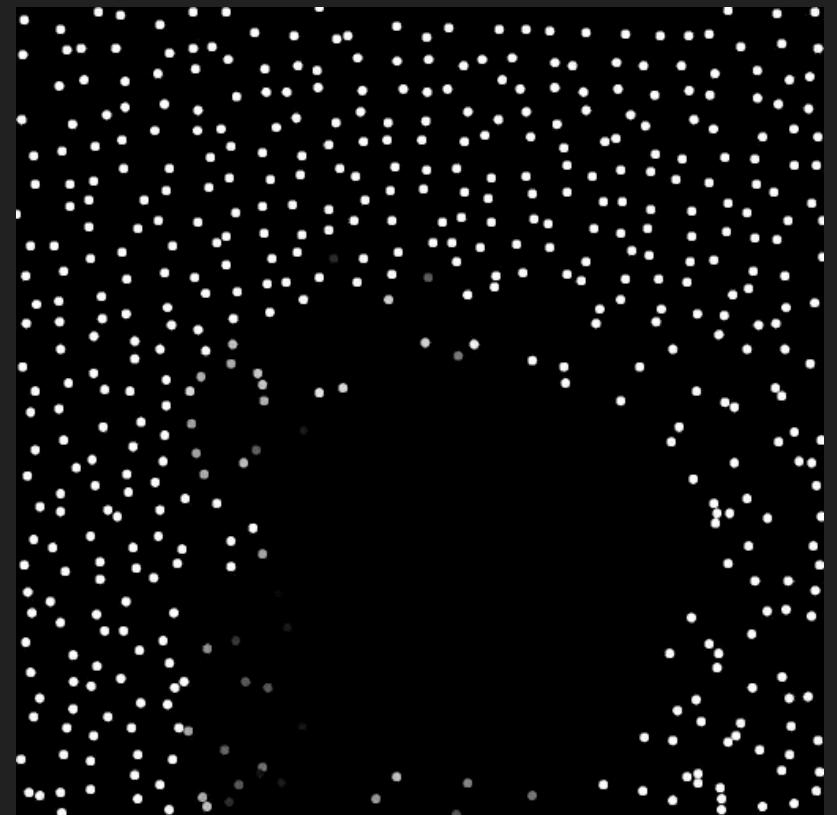
Coretsumo Oz Vision



“Mutant” M-Cones



Other M-Cones



S-Cones

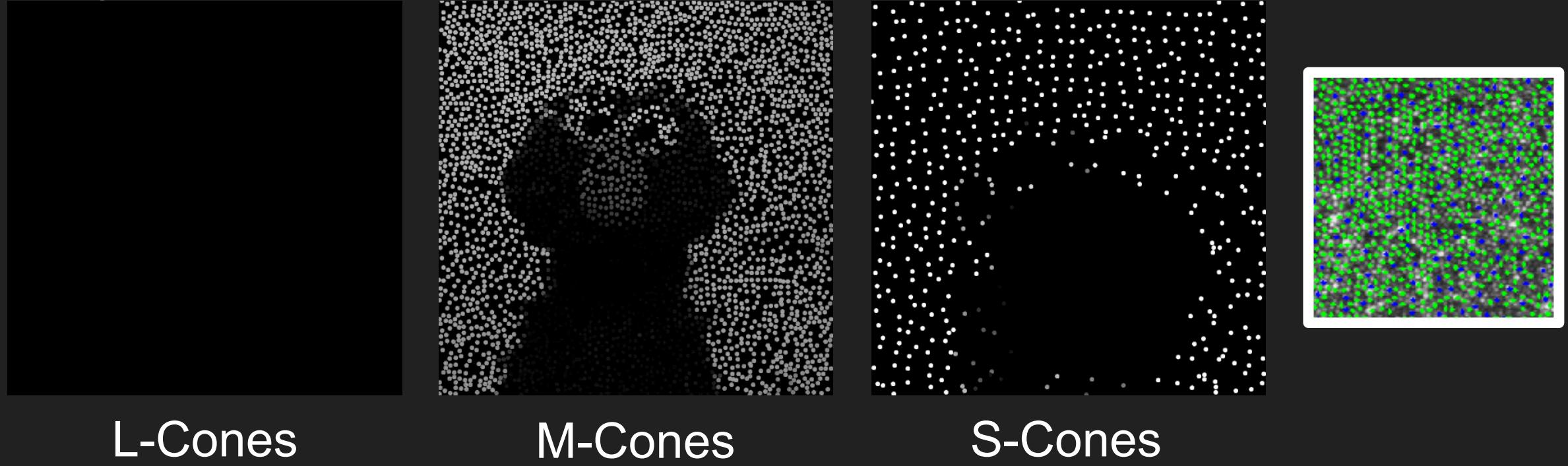
Target Video

Laser Microdoses (500 nm)

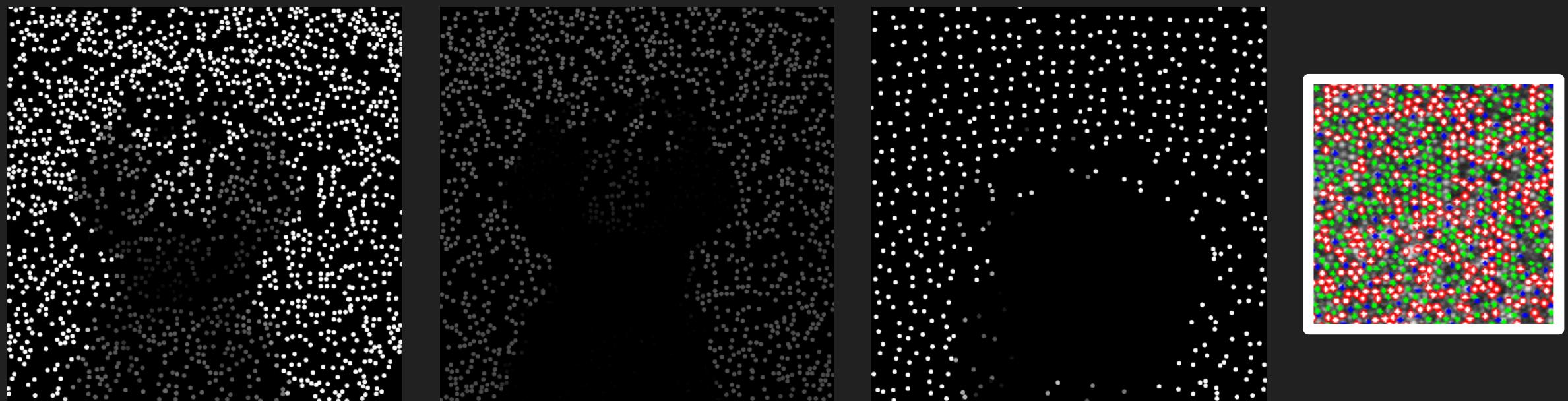
Attempting to Elicit Trichromacy in a Protanope



Regular Oz Vision



Coretsumo Oz Vision



Target Video

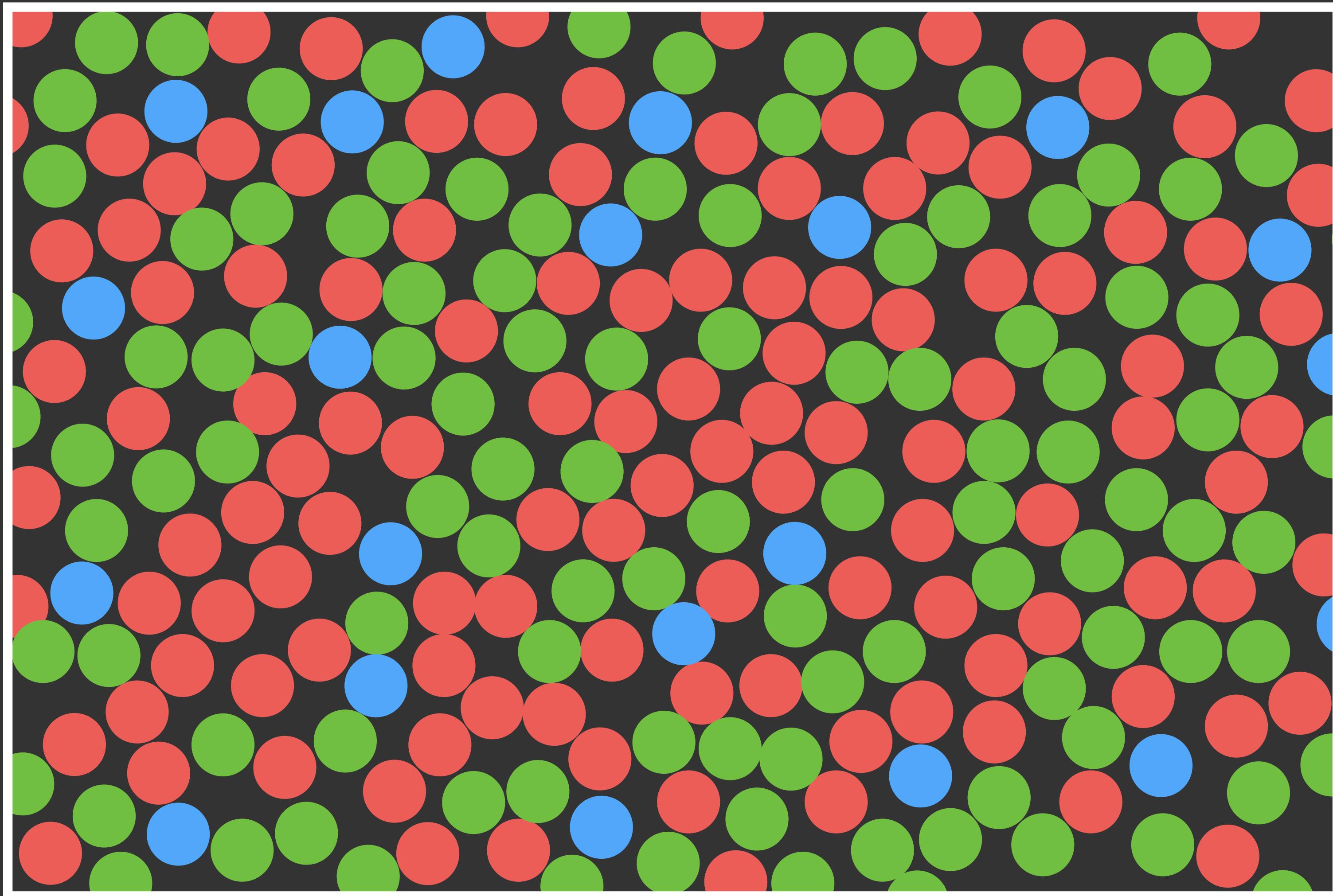
"Mutant" M-Cones Other M-Cones S-Cones

Laser Microdoses (500 nm)

Can use Coretsumo to add any number of virtual photoreceptor types with arbitrary spectral responses

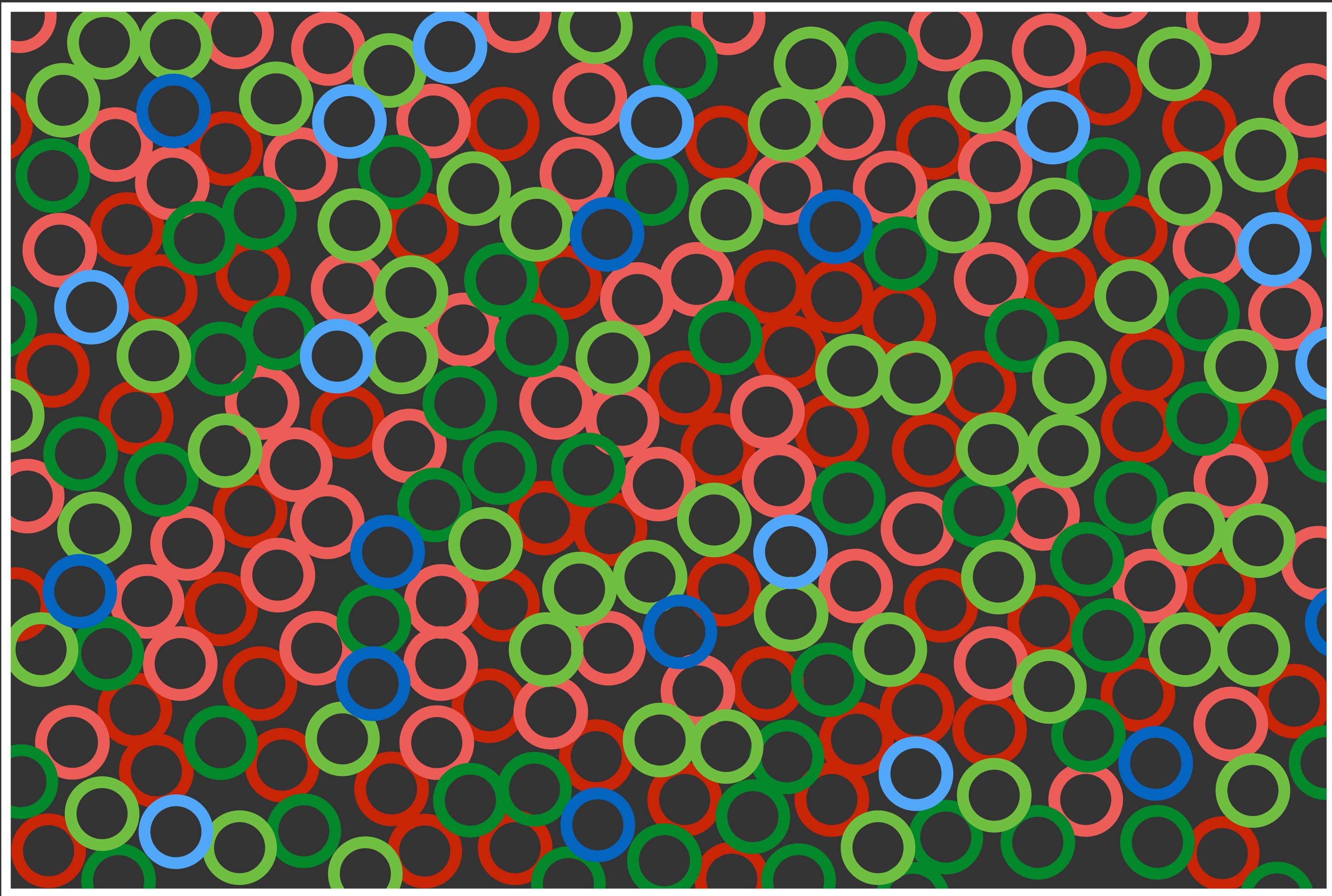
Example: Coretsumo 3D > 6D

Real Retinal Map of Cones (Normal Color)



Real Cones: ● L-type ● M-type ● S-type

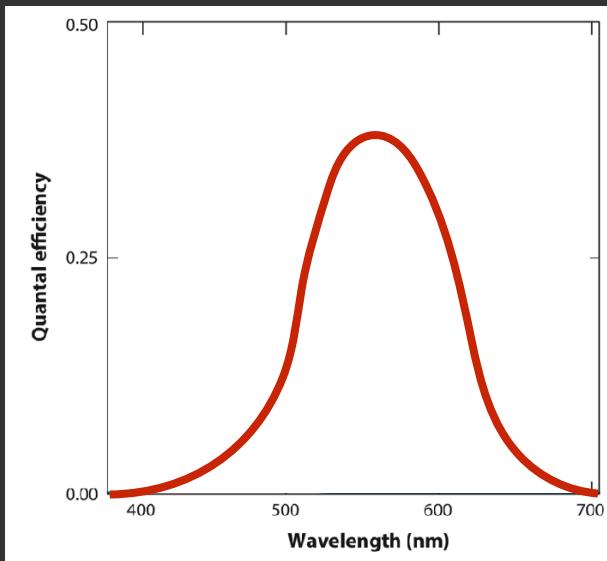
Coretsumo Cone Label Mosaic (6 Label Example)



Cone Labels: ○ L1 ○ L2 ○ M1 ○ M2 ○ S1 ○ S2

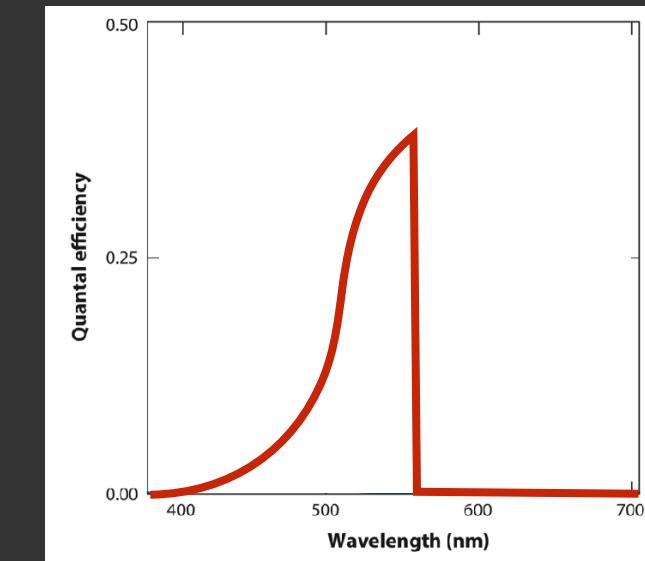
Create Six Virtual Response Functions: E.g. "LMS Half-Curves"

Real cones (3)

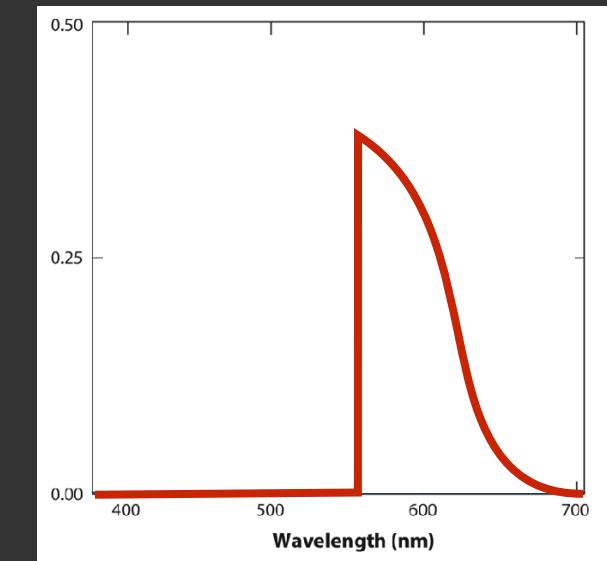


L

Virtual photoreceptors (6)

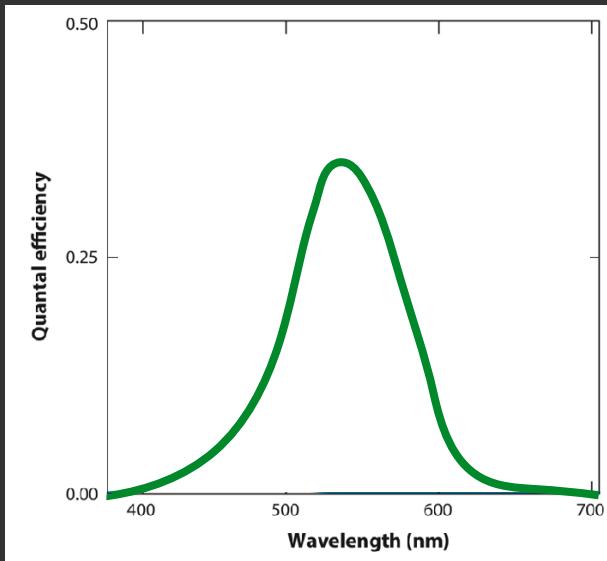


L1

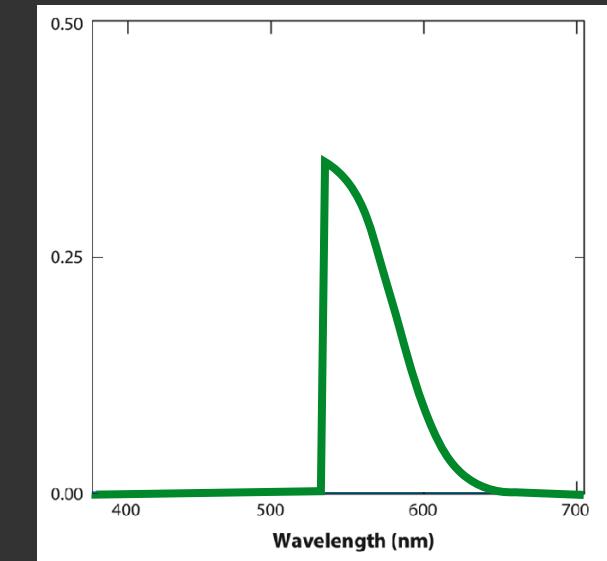


L2

M

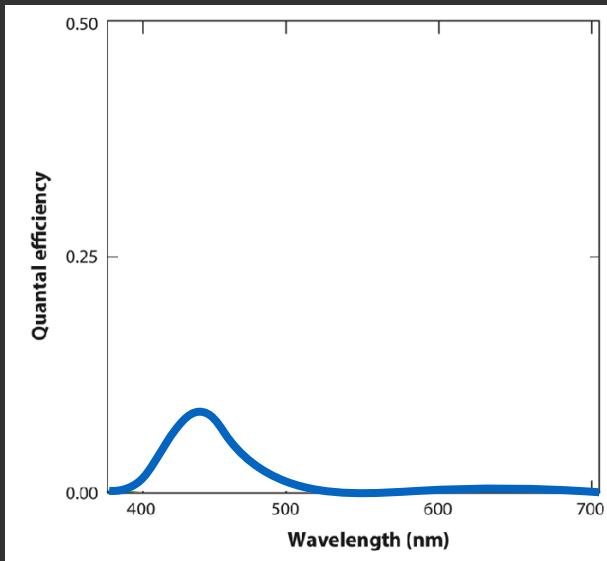


M1

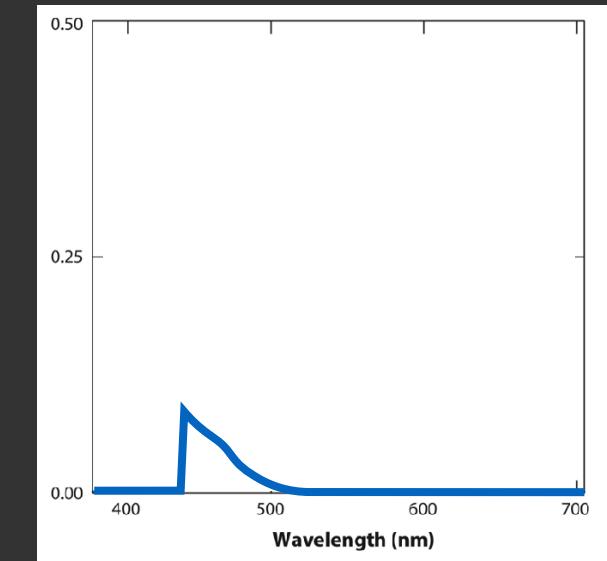


M2

S

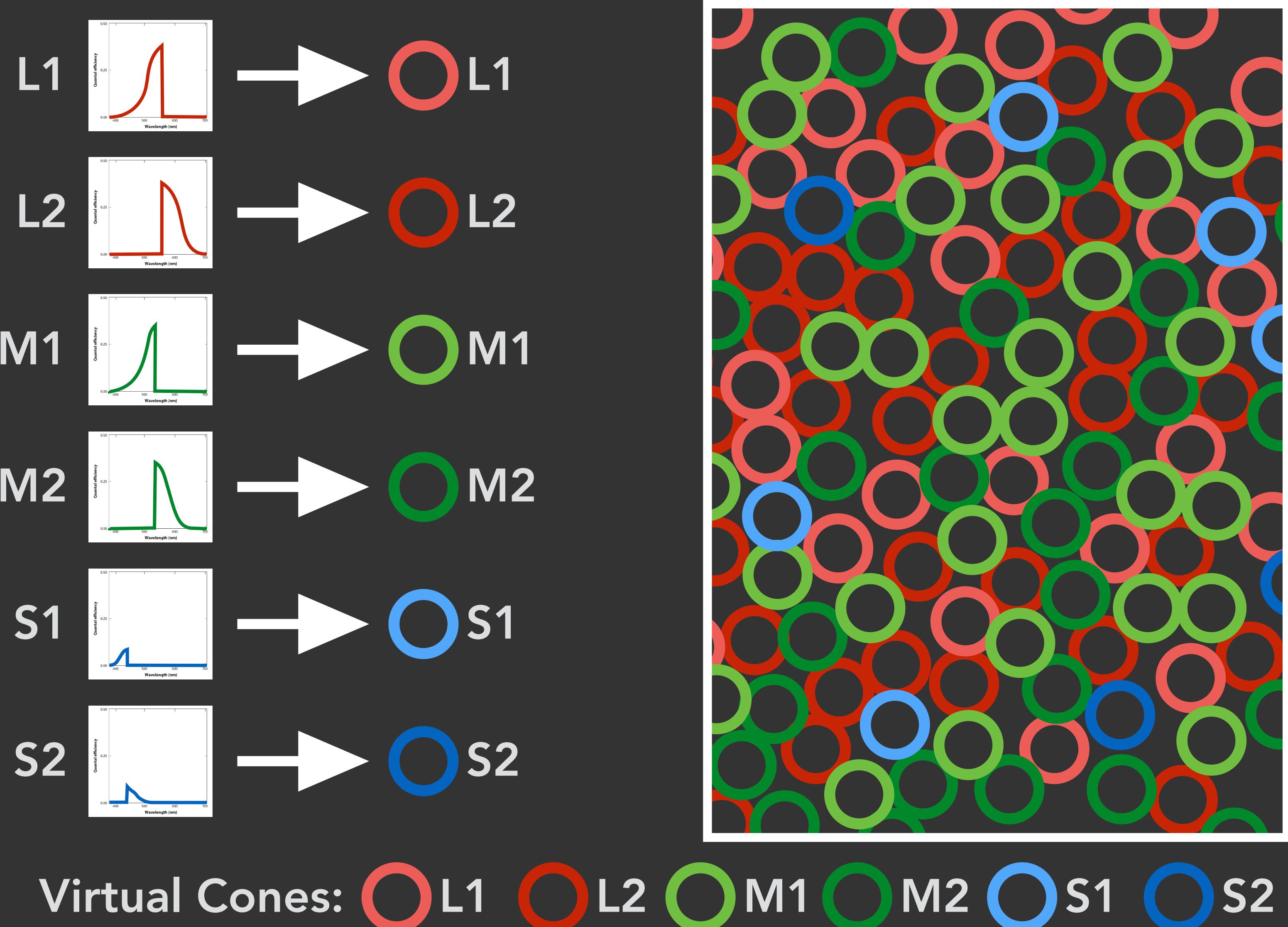


S1



S2

Coretsumo: Deliver "6D Color" to Labeled Cone Mosaic



Coretsumo 3D > 4D: RGB + IR?



Thermal camera output on right (note hot water pipes under wood floor).
In Oz, instead of false color as here, could insert thermal info as 4th color channel

Questions?

Discussion: How to Test Coretsumo?

Describe in detail what perceptual experiment you would run.

Discussion: What Info For 4th Channel?

Describe in detail what information you would inject into a 4th cone class, and what you imagine might happen. Hint: you may wish to consider possibilities beyond images.

Oz Vision - Recap

- Goal: program activity at every retinal photoreceptor at every point in time
- Colors beyond the human gamut?
- Treat color blindness?
- Perceive color in higher dimensions – 4D, 5D, 6D?
- Probe neural plasticity of human perception

Oz Vision - A New Principle for Color Display

Ren Ng, James Fong, Utkarsh Singhal, Peter Manohar,
Andrew Aikawa, Jay Shenoy, Yi Zong, Rishi Uphadhyay,
Hugh Johnson, Li Yang Kat, Jesse Ku, Arjun Sabnis,
Steven Sun, Jiaqi Zhang

Emma Alexander

Electrical Engineering & Computer Sciences

Alexandra Boehm, John Erik Vanston, Brian Schmidt,
Pavan Tiruveedhula, Will Tuten, Austin Roorda
Optometry / Vision Sciences

Berkeley
UNIVERSITY OF CALIFORNIA

L.F. Baum
W.W. Denslow