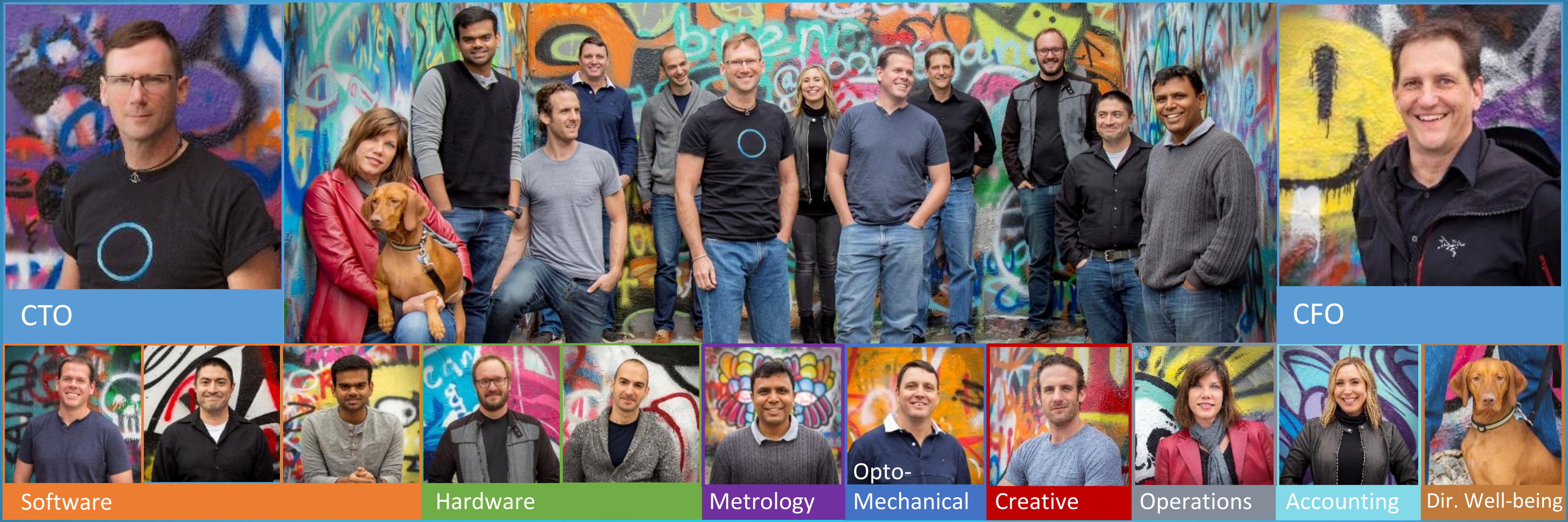
Light-field Display Technical Deep Dive

Howdy Texas A&M

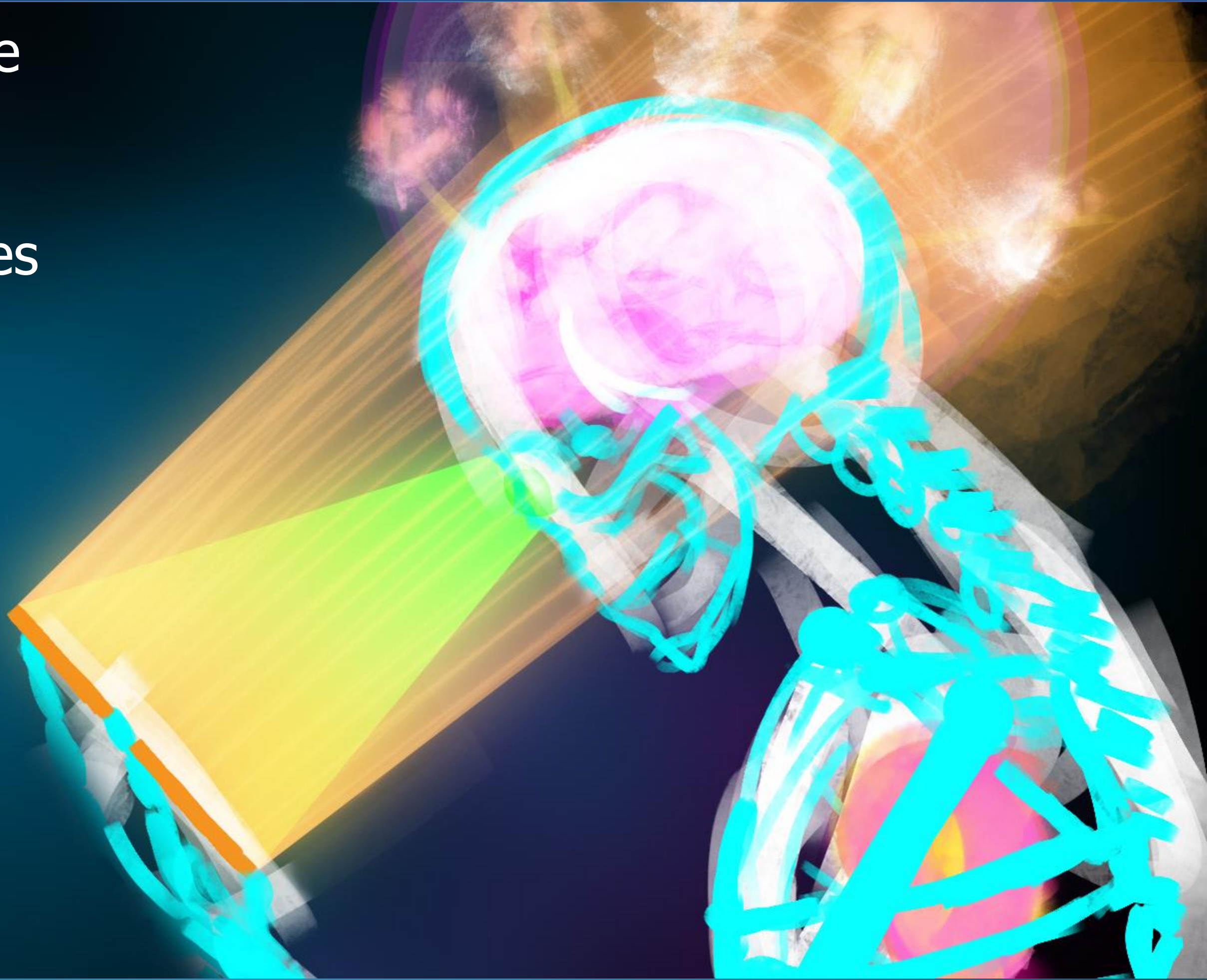
2019

Introduction to FoVI^{3D}

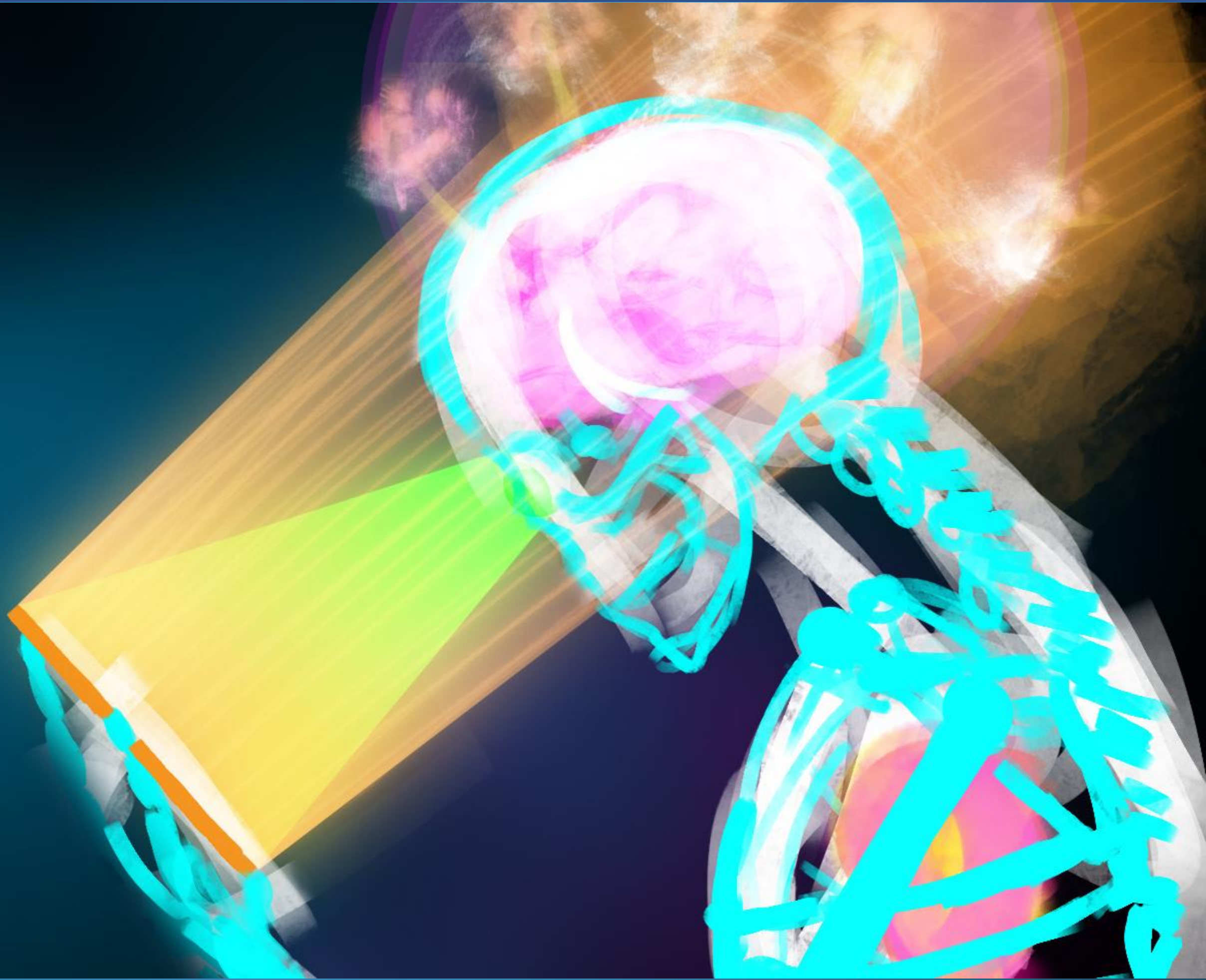


Strong technical team with deep experience in optical, mechanical, electrical, and software engineering.

- Definition and Significance of Light-field Displays
- Light-field Display Architecture and Properties
- Synthetic Light-field Rendering
- Heterogeneous Display Ecosystem
- Light-field Display Metrology
- Light-field Display Developer Kit



Definition and Significance of Light-field Displays

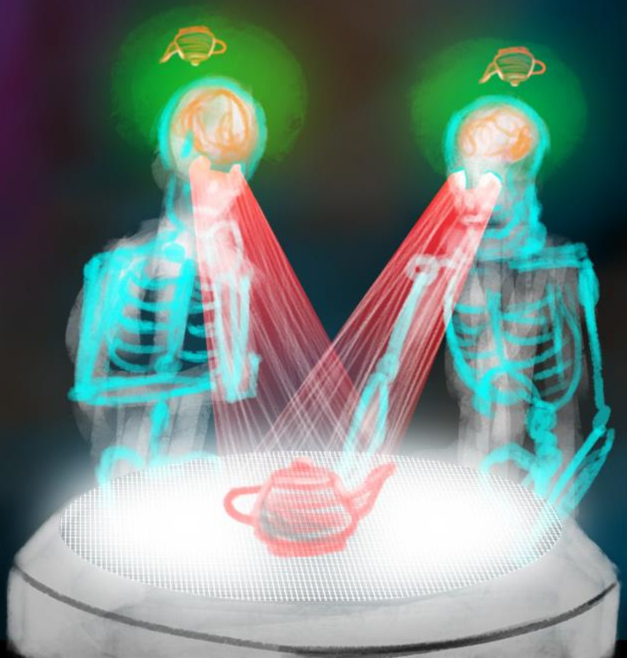


Light-field Displays in Popular Media

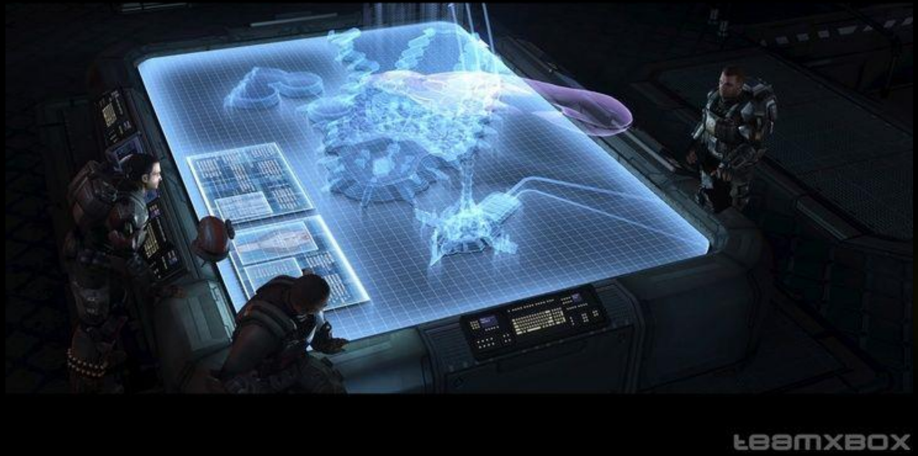
Natural vs Synthetic Light-fields

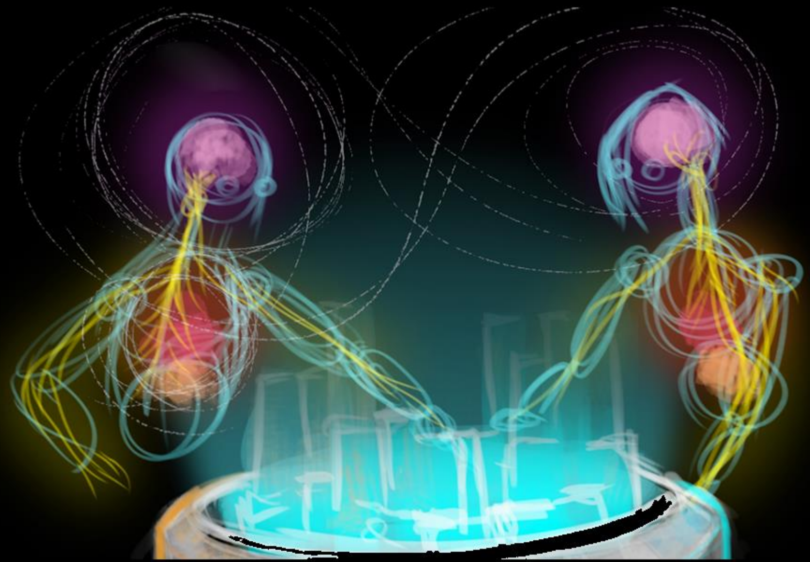
In a natural light-field we observe light reflected off objects, perceiving color and depth cues. An eye focuses a 3D scene on the retina as a 2D image, our brain reconstructs the 3D world.

In a synthetic light-field, we observe light projected from a surface that generates the same color and depth cues, thus we <u>see</u> the same object.



Light-field Display Definition

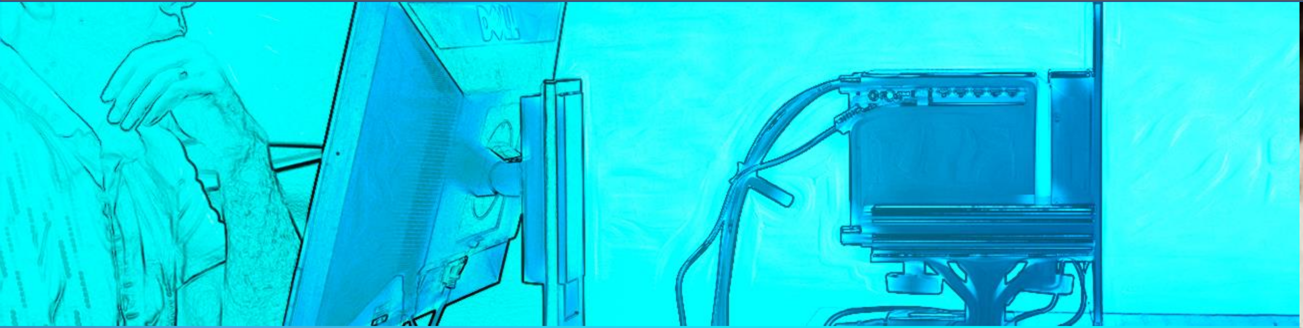




- Reproduces a 3D aerial image visible to the unaided eye without glasses or head tracking
- Binocular disparity, occlusion, specular highlights, and gradient shading and other expected depth cues must be correct from the viewer’s perspective as in the natural real-world light-field

Significance of Light-field Displays

- Human binocular vision and acuity, and the accompanying 3D retinal processing of the human eye and brain, are specifically designed to promote situational awareness and understanding in the natural 3D world.
- The ability to resolve depth within a scene, whether natural or artificial, improves our spatial understanding of the environment and as a result reduces the cognitive load accompanying the analysis and collaboration on complex tasks.



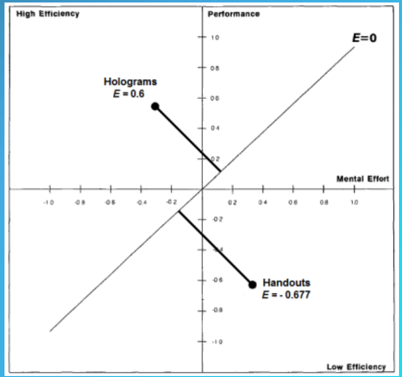
Background

- Originating with a DARPA *Urban Photonic Sand-table Display* challenge, core FoVI^{3D} team members participated in developing the initial Light-field Displays; Thomas was the computation architect on the program
- Core IP filed and the team continued to develop LfD technology
- Gen1 LfD systems built and installed in various research labs
- FoVI^{3D} formed to commercialize LfD technologies
- Extensive IP
  - Over 35 Issued and Pending Patents
  - LfD systems, Radiance Rendering Compute (MvPU), Distortion Correction Technologies, other
  - Proprietary Software

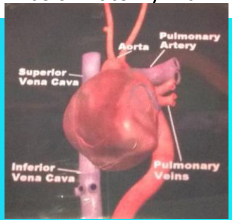
Light-field Display Developed by Zebra Imaging under the DARPA UPSD Program

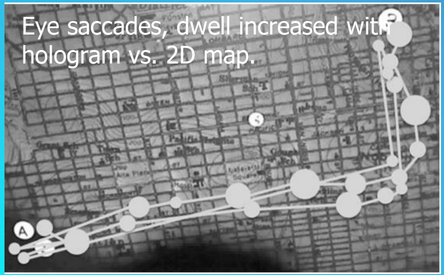
https://youtu.be/blb0TUBoZwA
https://youtu.be/b_CKQN1t-e8

Quantified Benefits of Light-field Displays



Holograms versus traditional 2D methods proved overwhelmingly to increase retention and reduce the cognitive load when used in recalling complex medical anatomy.
M. Hackett, Medical Holography for Basic Anatomy Training , 2013

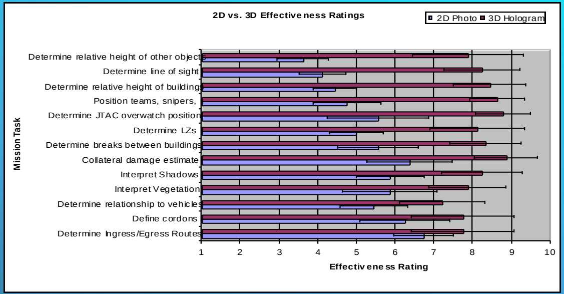




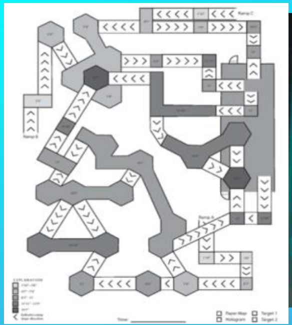
S. Fuhrmann, TSU Wayfinding Study, 2009

JTAC reported greater confidence determinations of CDE, relative height of buildings, lines of fire and sight, and JTAC over-watch positions.

Evaluation of Holographic Technology in Close Air Support Mission Planning and Execution, John J. Martin AFRL, June 2008



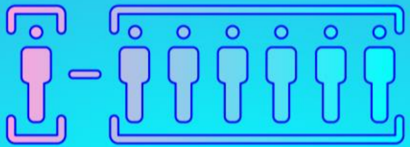
J. Martin, AFRL Human Performance Wing, 2008



The findings from these descriptive statistical comparisons indicate that the mean times from the search tasks performed by *the individuals using the hologram were approximately 23 percent faster for target one, and 54 percent faster for target two*.
N. Smith, SWAT Team Wayfinding in Laser Tag facility study, 2007

Light-field Display: Application Agnostic

Interaction



Collaboration

Visualization

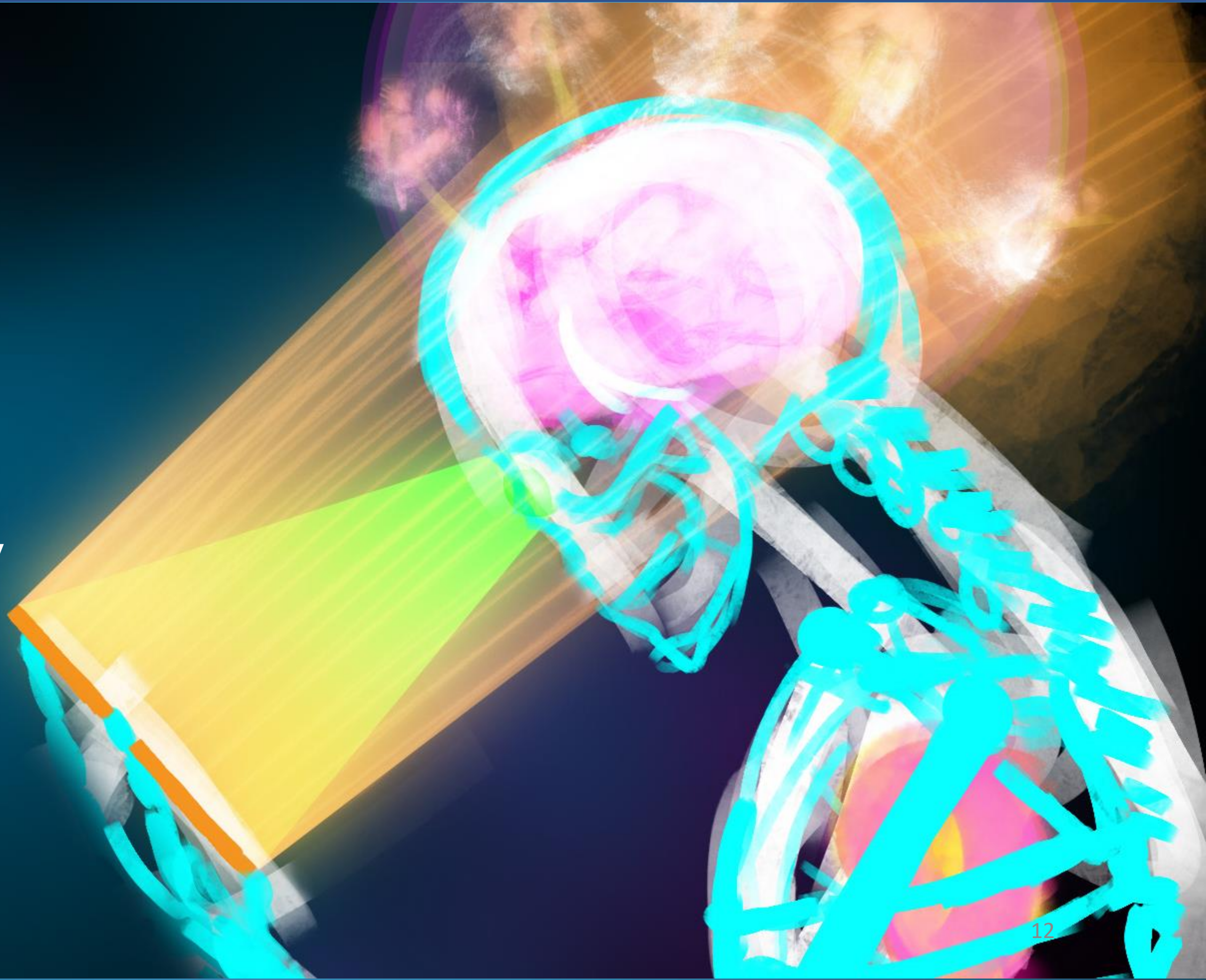
Defense:
- Command & Control
- Airspace Management
- Planning & Execution
- Sensor Coverage Analysis
- Multi-domain Situational Awareness

Entertainment:
- eSports (player and spectators)
- Casual gaming
- 3D internet exploration
- Supplemental display for traditional media consumption

Information Visualization:
- Automobile Navigation
- Engineering
- Architecture
- Design (film and game asset creation)
- Oil & Gas Exploration
- Population Data

Medical:
- Surgical Planning
- Concept Visualization for Patients
- Teaching
- Diagnostics

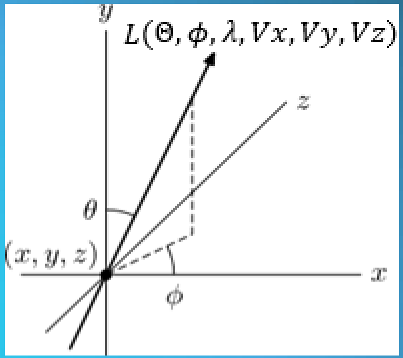
Light-field Display Architecture and Properties



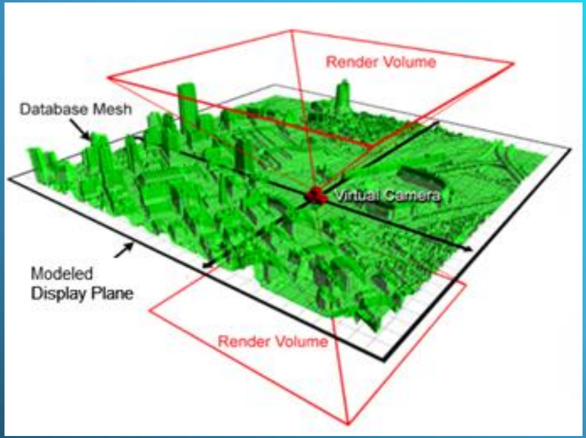
What is a Light-field Display

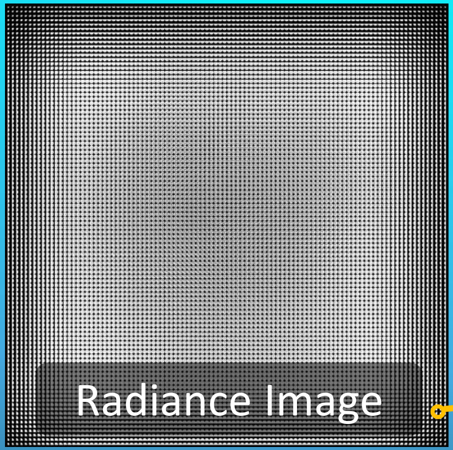
- A light-field is a set of rays that pass through a plane in space and is typically defined for computer vision by a plenoptic function:

$$L = P(\underbrace{\Theta, \phi,}_{\text{Direction}} \lambda, \underbrace{Vx, Vy, Vz}_{\text{Position}})$$

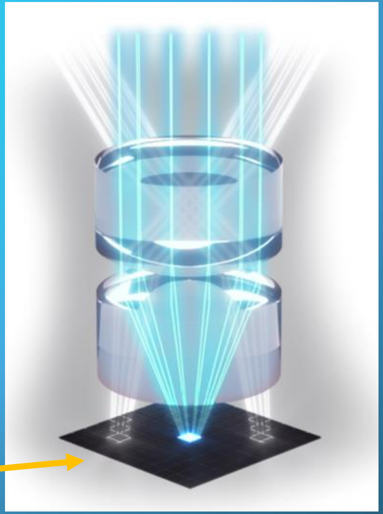


- Can be presented as a 2D raster image (Radiance Image) where each pixel represents the color, **position**, and **direction** of a ray within the light-field
- The synthetic light-field is computed from a 3D model and is projected through an array of micro-lenses to create a 3D aerial scene for all viewers with the displays projection frustum

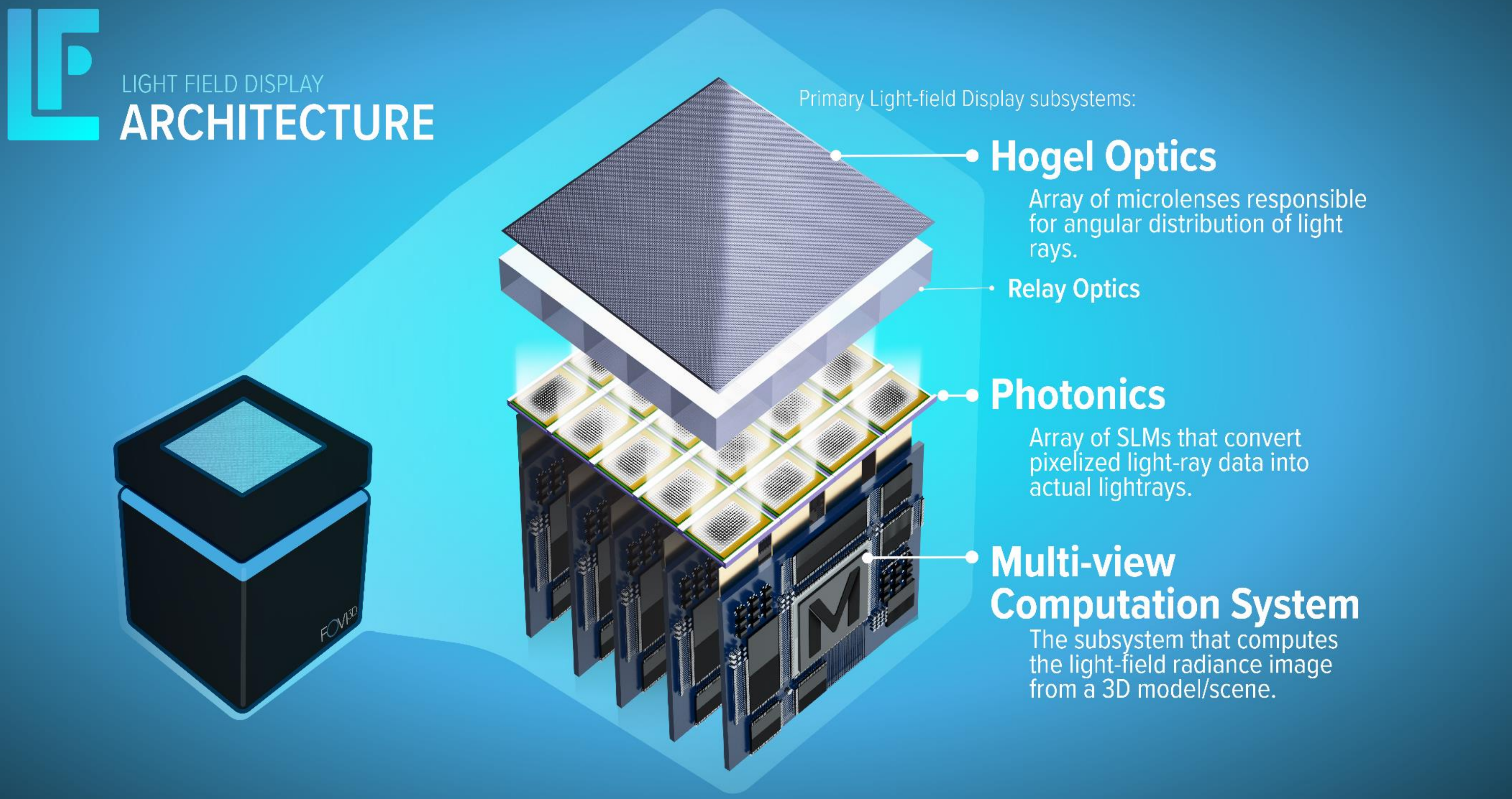




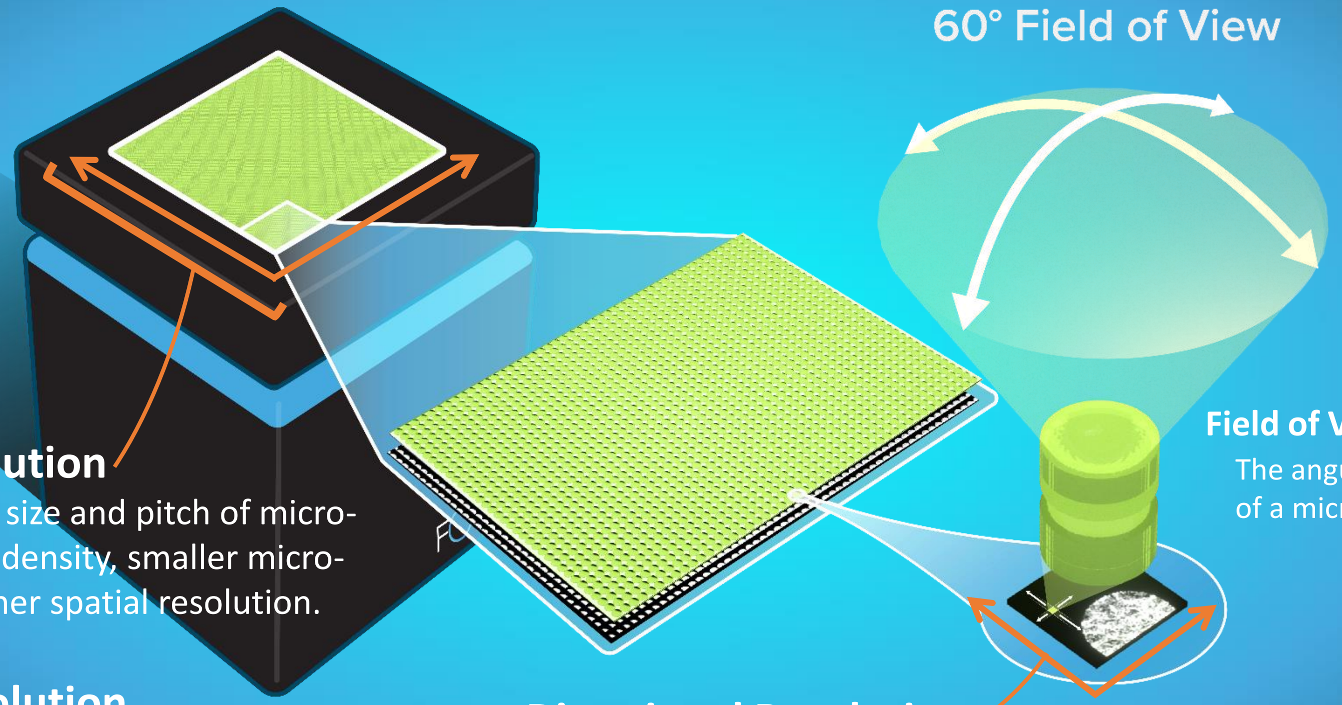
Hogel (Holographic element): The combination of micro-lens and micro-image. The micro-image colors rays emitting from a point spot on the image plane and the micro-lens angularly distributes the light-rays.



Light-field Display Architecture



Resolution in Light-field Displays



Spatial Resolution

Determined by size and pitch of micro-lenses. Higher density, smaller micro-lenses give higher spatial resolution.

Field of View (FoV)

The angular projection of a micro-lens.

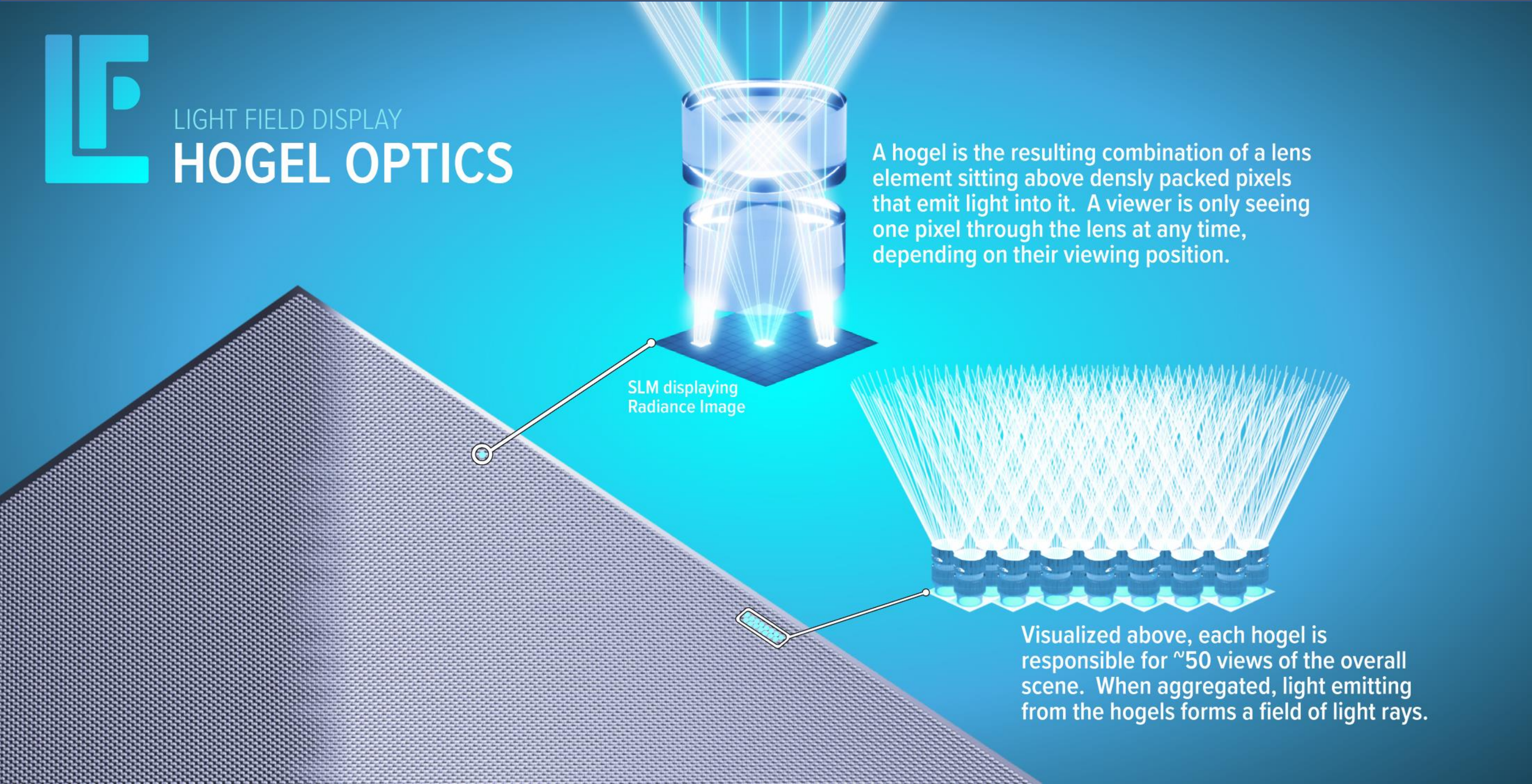
Angular Resolution

Pixels per degree (Dr/FoV) Gives an indication of potential projection height capability. More than one ray/pixel per degree is desirable. Angular pitch is FoV/Dr.

Directional Resolution

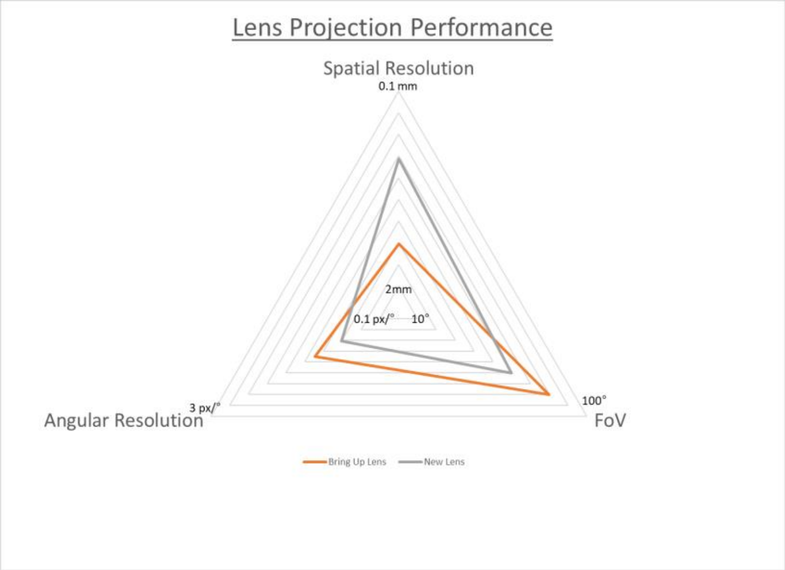
Determined by the dimensions of the hogel. Assuming a square hogel, Dr^2 is the number of rays per micro-lens. More is better.

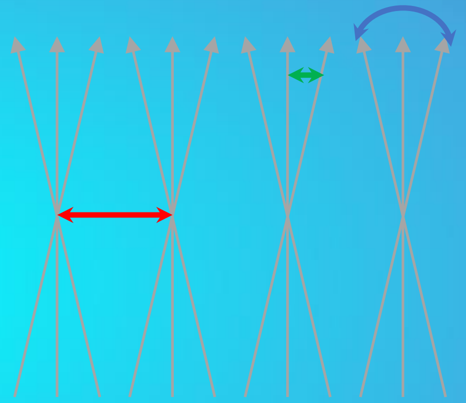
Hogel Optics



Hogel Lens Properties

A synthetic light field's 3D quality is driven by three properties (assuming perfect lenses):





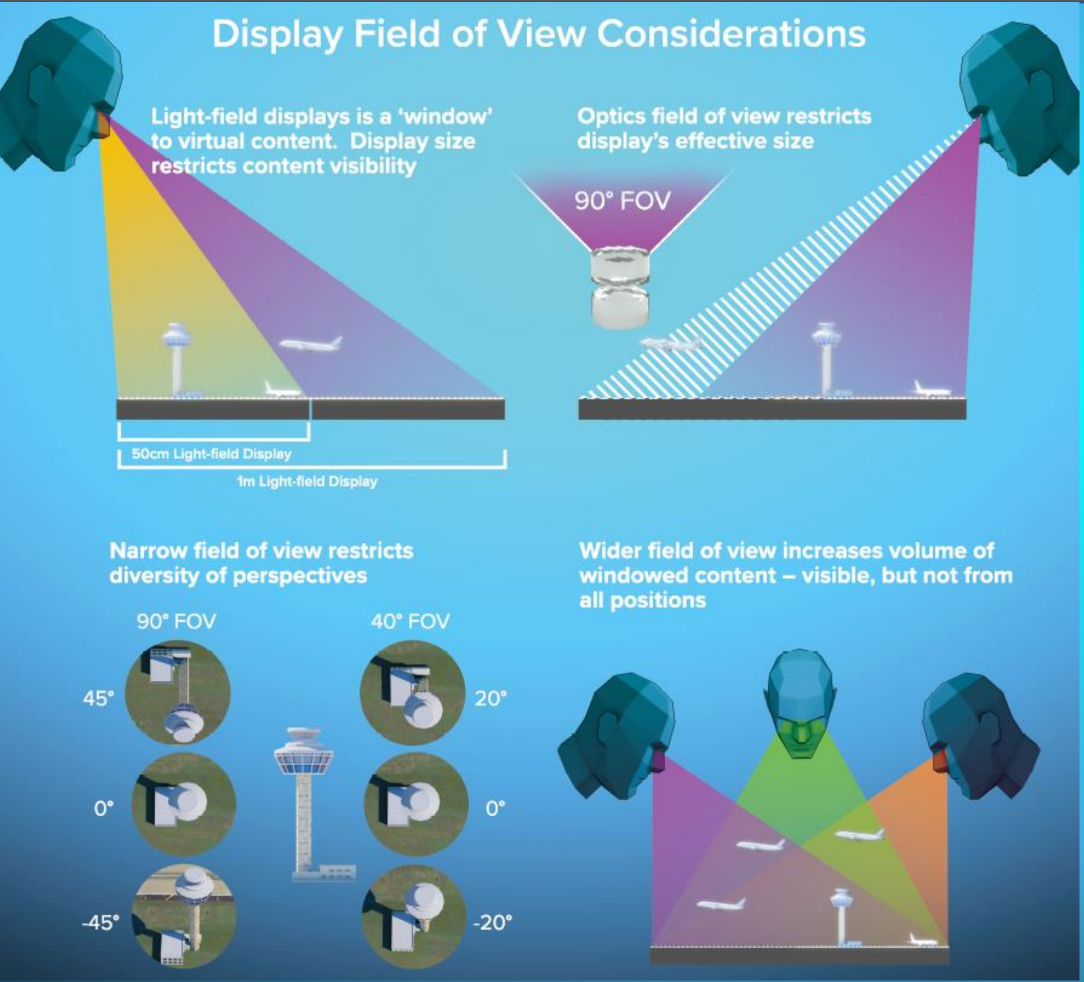
Why are the hogel optics so important

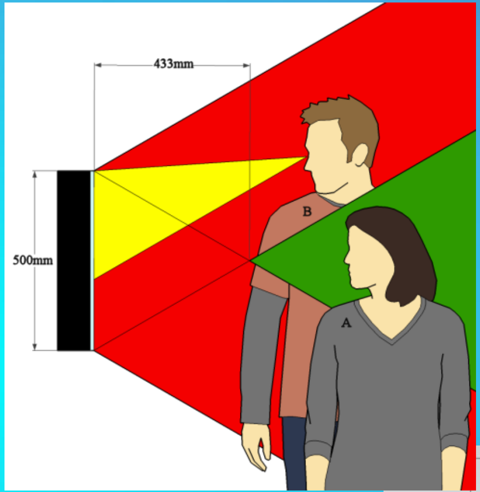
The maximum spatial resolution depends on size, spacing, and arrangement of the Micro-Lens Array

The higher the angular resolution, the better the opportunity to preserve detail as the light diverges from the hogel optics.

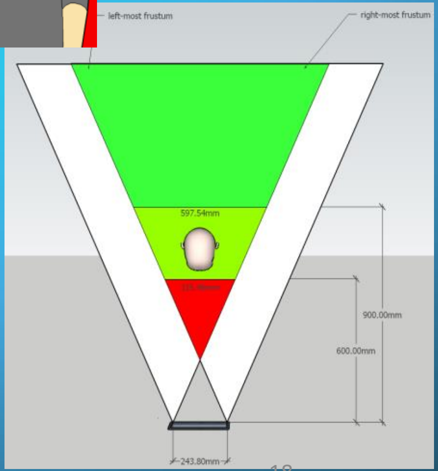
Field of view determines the display viewing space, and impacts the maximum display size

Field of View



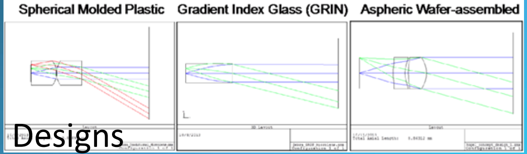


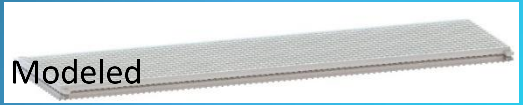
Vertically oriented display have the same challenge

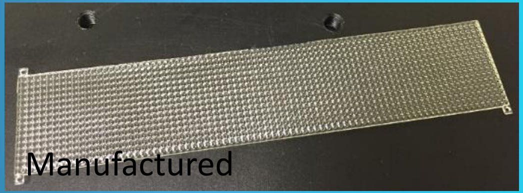


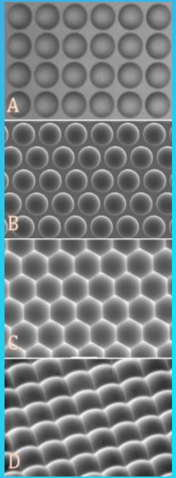
Personal displays can get away with tighter FoV

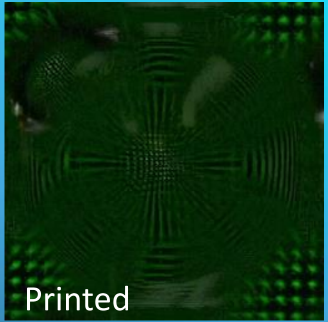
MicroLens Design and Manufacturing





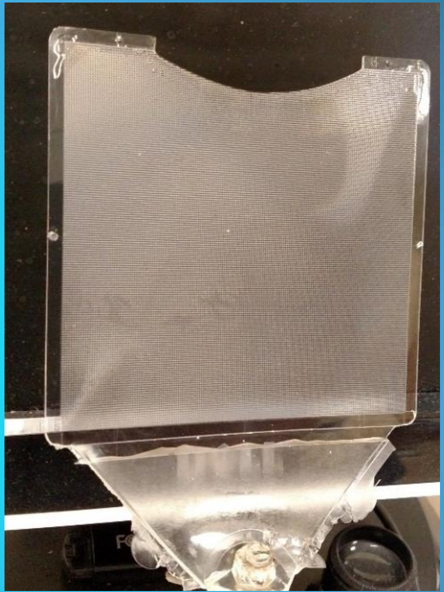


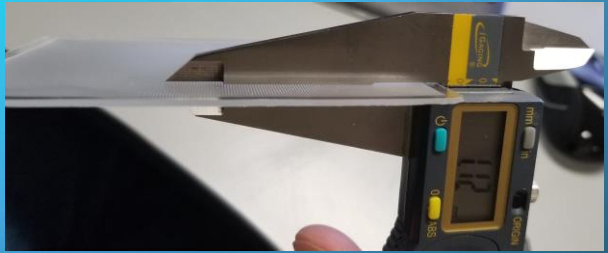




Challenge:

- Image blur decreases 3D aerial image fidelity
- MicroLens performance scales with design complexity:
  - Number of lens components
  - Number of curved surfaces
- Expensive to iterate on designs
  - Cost scales with complexity
  - Cost scales with size
- Hard to mold
- Lithographic processes are costly
- Current printed microlens array are of low quality – but there is progress
- SLM tiling introduces seams which inhibit the use of ‘hex’ package microlens arrays



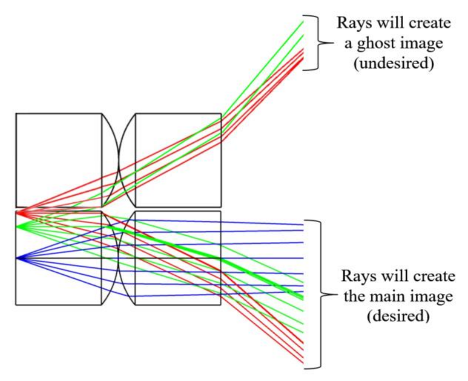


Micro-Lens Scatter and Cross-talk

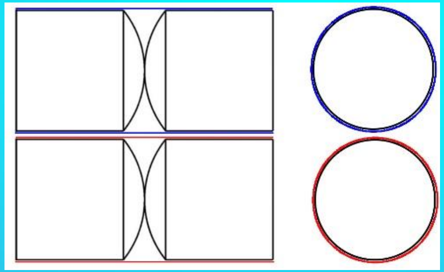
- A subcomponent of the microlens array are the baffles, which are design to block light emitted in undesired directions (often referred to as cross-talk as it typical crosses to neighboring hogels
  - This light is primary caused by the lambertian emission of the pixels from the OLED source, which can cause ghost images and gamma reduction
  - Baffles between individual lenslets absorb this stray light, reducing or eliminating the artifacts it causes

B

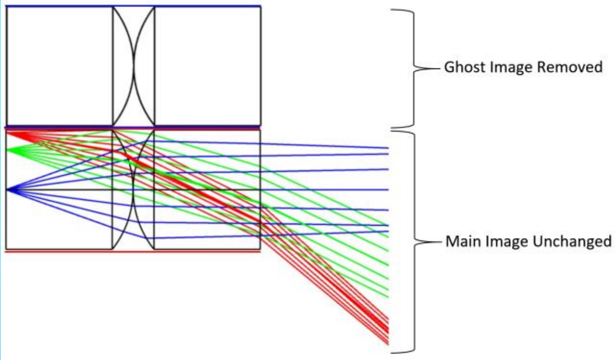
Unbaffled Pixels



Baffles (red and blue)

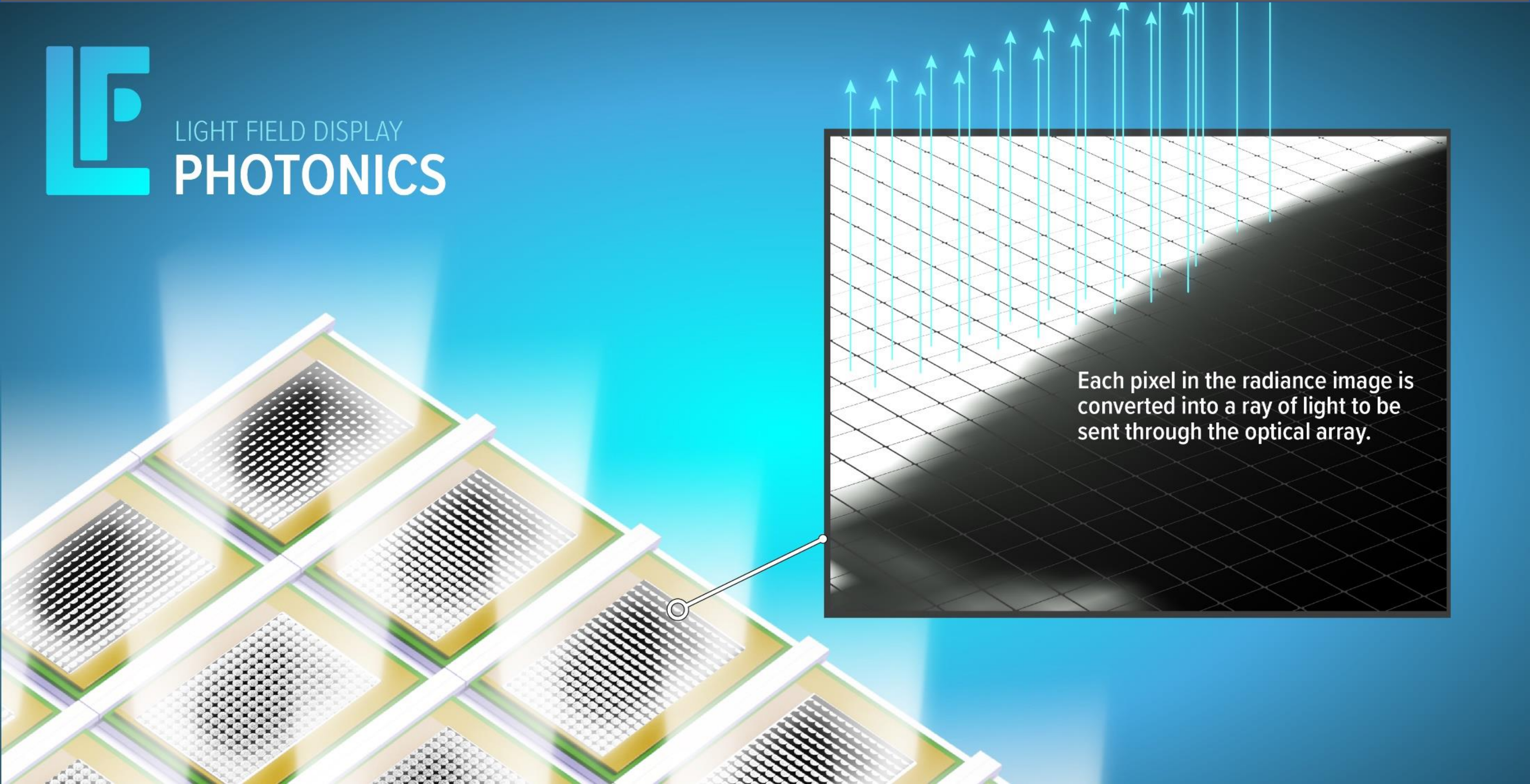


Baffled Pixels



- Baffles can be implemented as channels between lenslets, as stencils C inserted between the primary and secondary array or both

Photonics

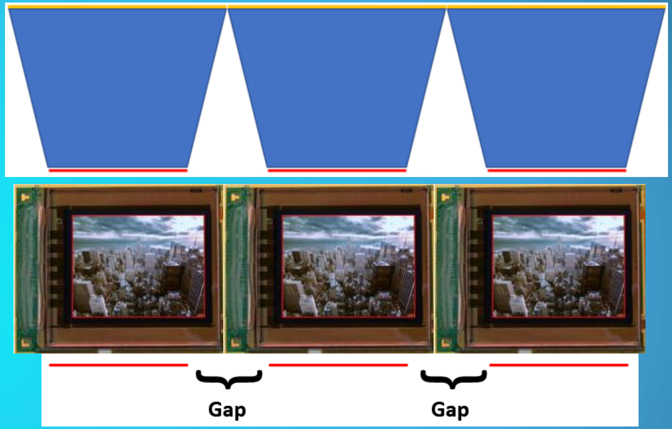

LIGHT FIELD DISPLAY
PHOTONICS
Each pixel in the radiance image is converted into a ray of light to be sent through the optical array.

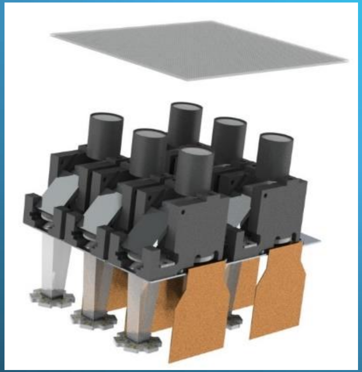
Large Area Photonics

To create large area photonics requires tiling of modulation devices (SLMs)

SLM technology imposes opto-mechanical constraints

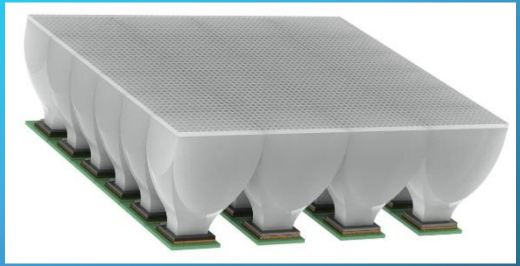
- Pixel Density: Directly drives the angular and spatial resolution of the display
- Luminance: Brightness loss through optical stack
- Display Package: Tiling micro-displays requires magnification to reduce seams created by packaging. Keep magnification to a minimal to maintain pixel density





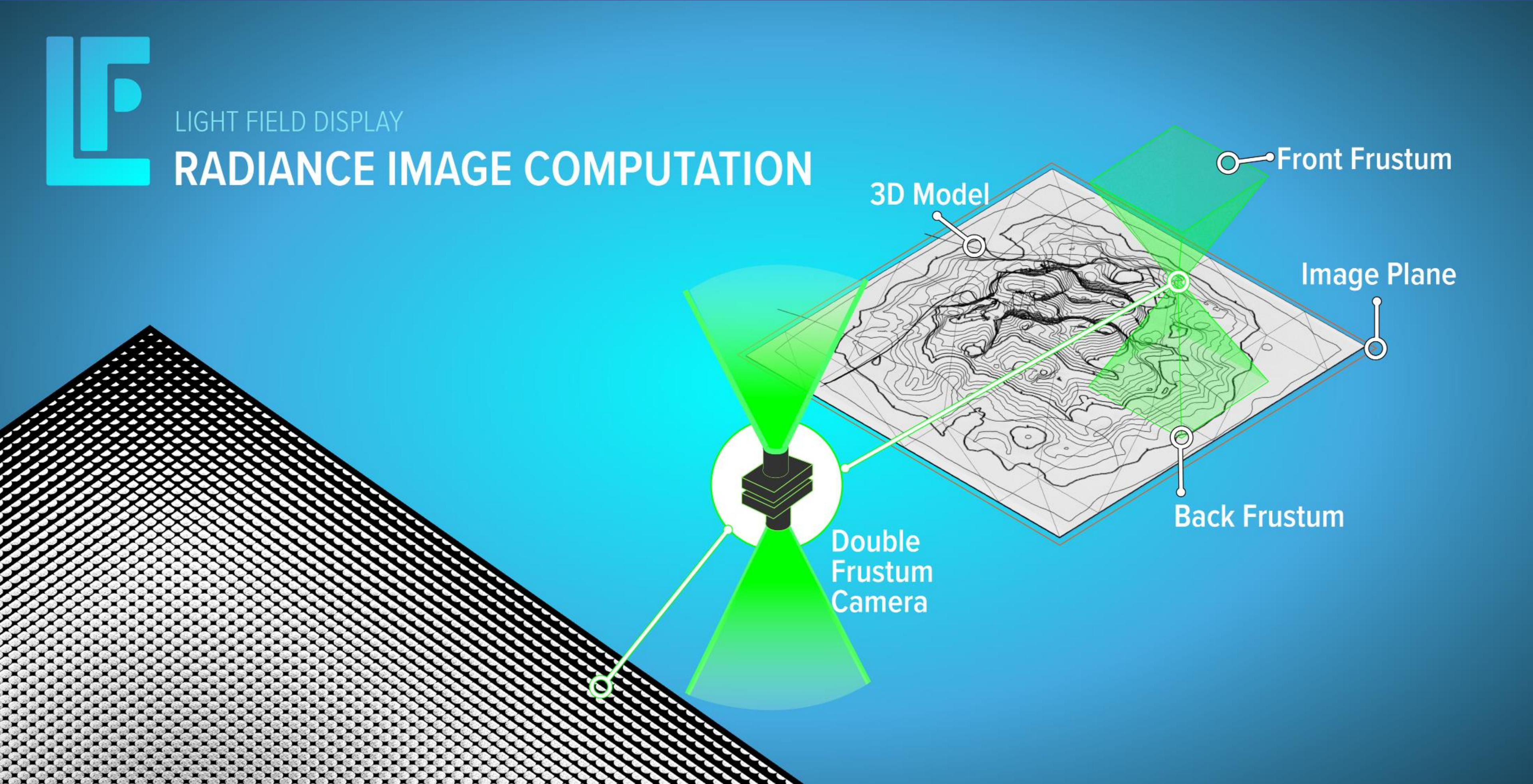
3x2 LCoS

9x4 Pico Projector

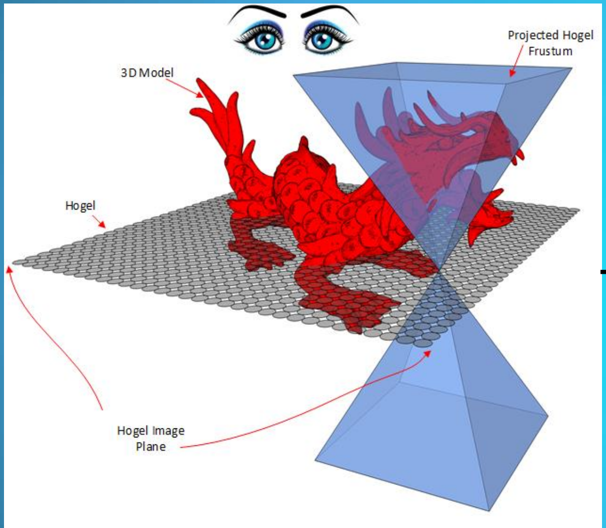


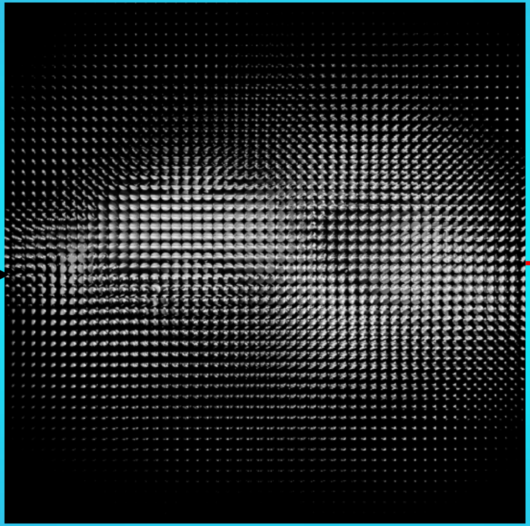
5x4 OLED

Radiance Image Computation



Synthetic Light-field Radiance Image



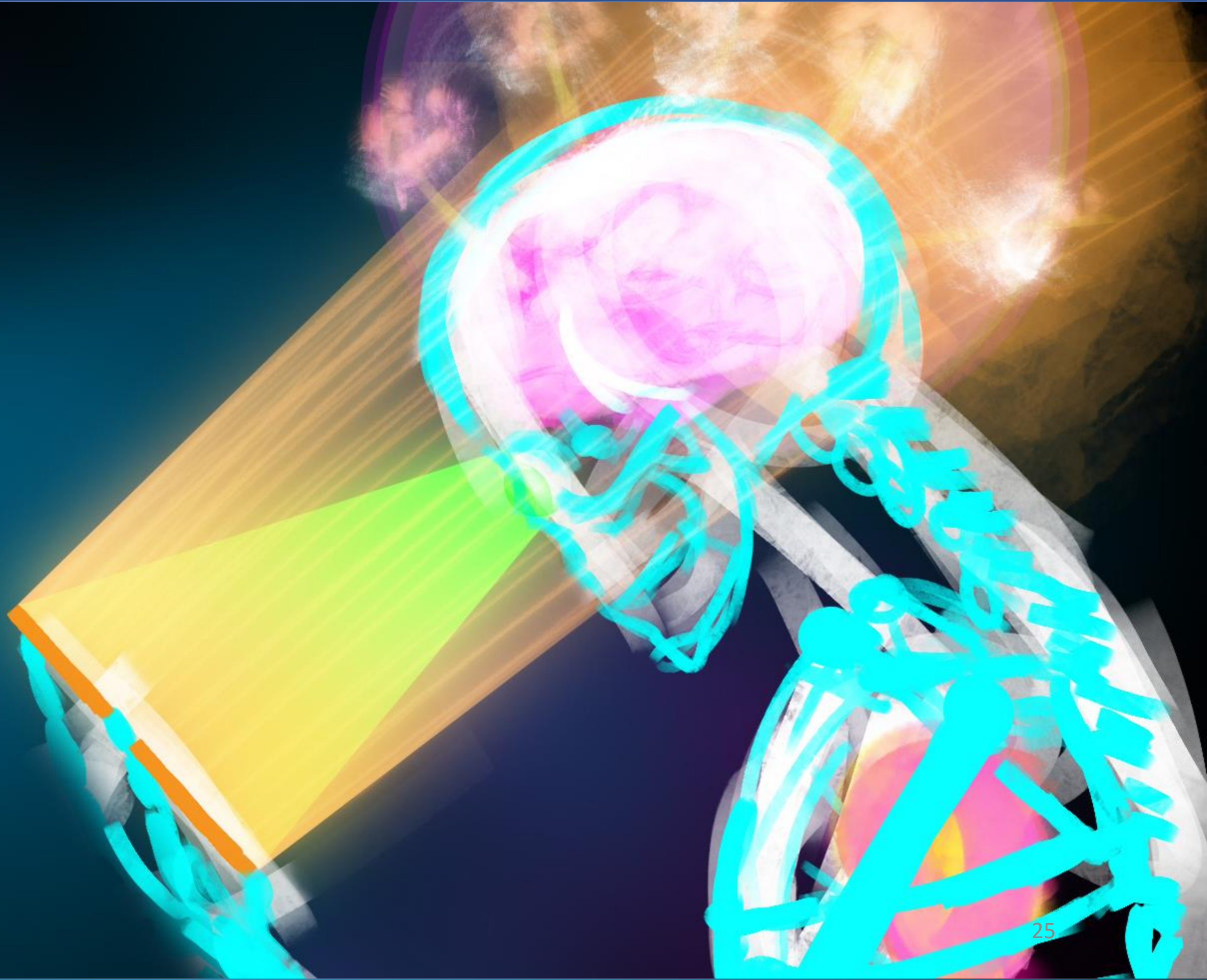


3D Model with Hogel Image Plane

Radiance Image
50^2 Hogels – 40^2 Pixels ("Rays") per Hogel

Resultant 3D Aerial LfD Projection

Radiance Image Rendering



Radiance Image Rendering

Two traditional approaches to computing the radiance image

Spatial x Directional

Double Frustum

- Calculate each hogel independently

Directional x Spatial

Oblique Slice and Dice

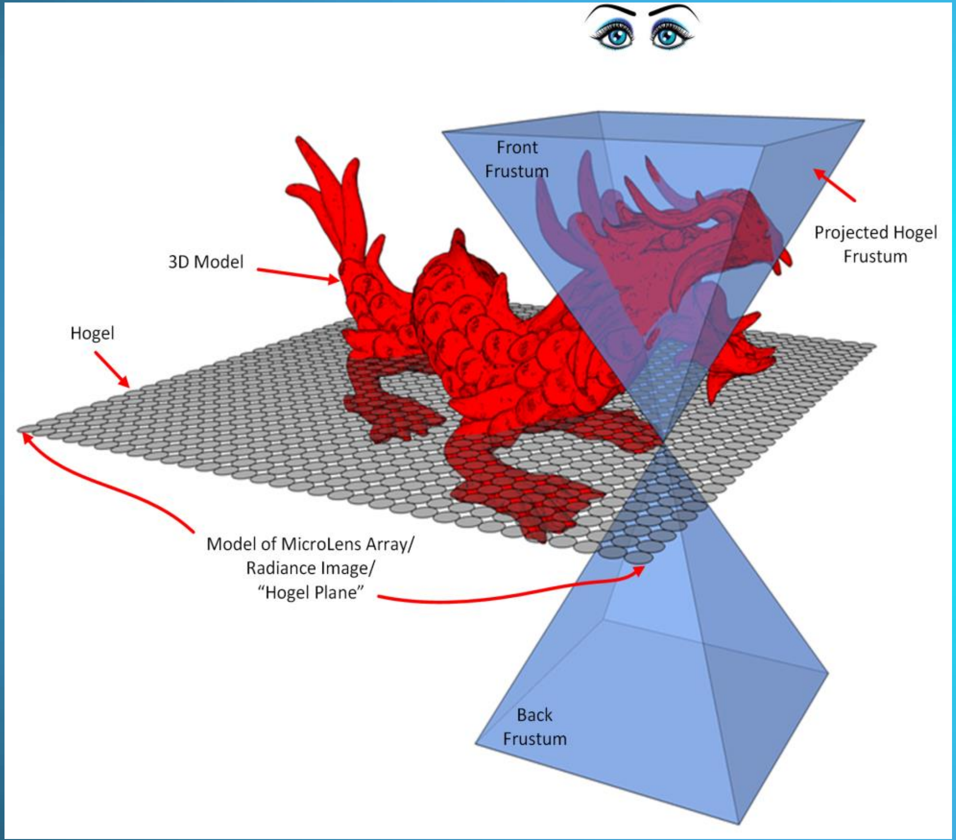
- Calculate each direction across entire display and divide into hogels

Actually…, a third FoVIAN approach

Bowtie Rasterizer

- *Rasterize all hogels in parallel*
- *Custom bowtie frustum*
- *Single dispatch from host PC*

Double Frustum Light-field Rendering



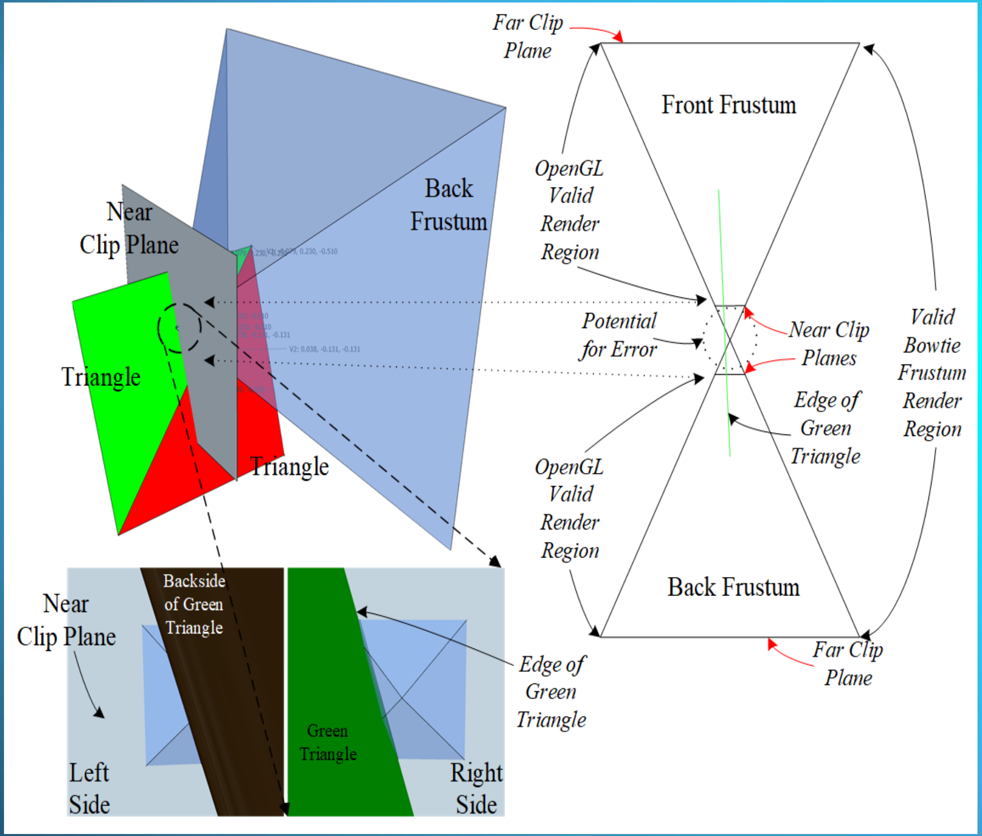
Render all rays passing through a single lens from above and below

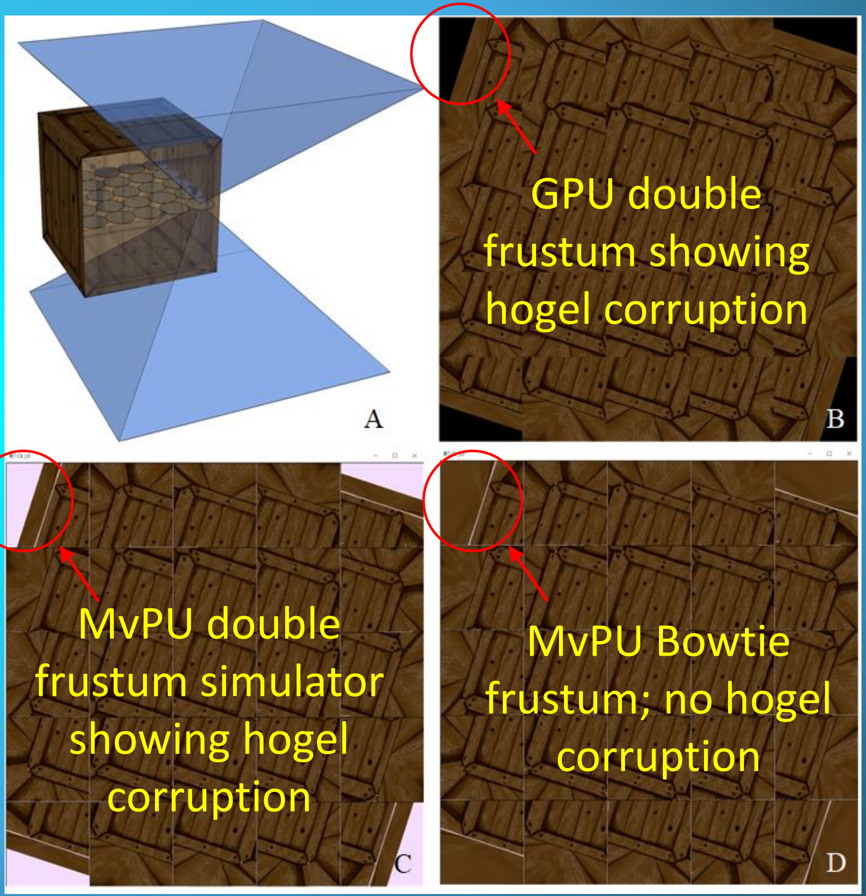
Pros
- Advantage of rendering a hogel natively
- Very parallelizable: each hogel is independent
- Large benefits from frustum culling

Cons
- Many (thousands) of render passes must be dispatched (OpenGL)
- Requires two passes of the geometry to create the 'double frustum'
- Very small viewport
- Camera matrix must have a non-zero near plane (OpenGL), creating stitching singularity artifact

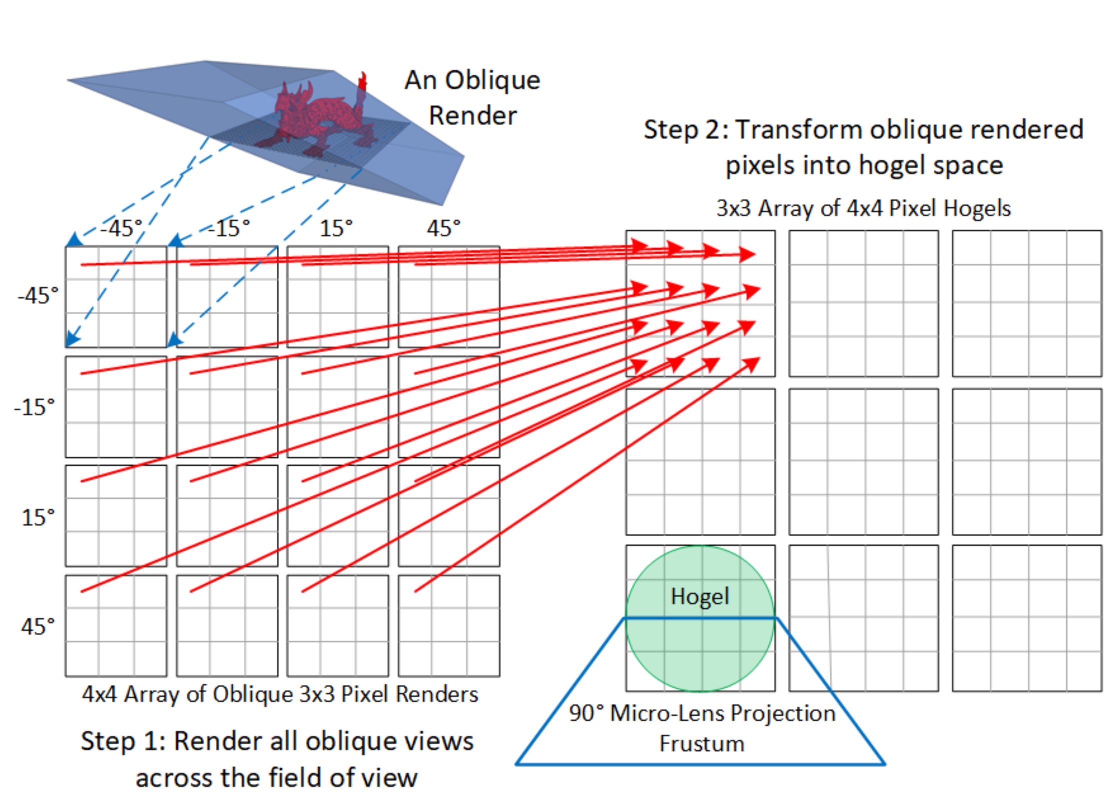
Halle, Michael W. "Fast Computer Graphics Rendering for Full Parallax Spatial Displays." *International Society for Optics and Photonics*.

Double Frustum Near Plane Singularity





Oblique Slice and Dice Light-field Rendering



Pros

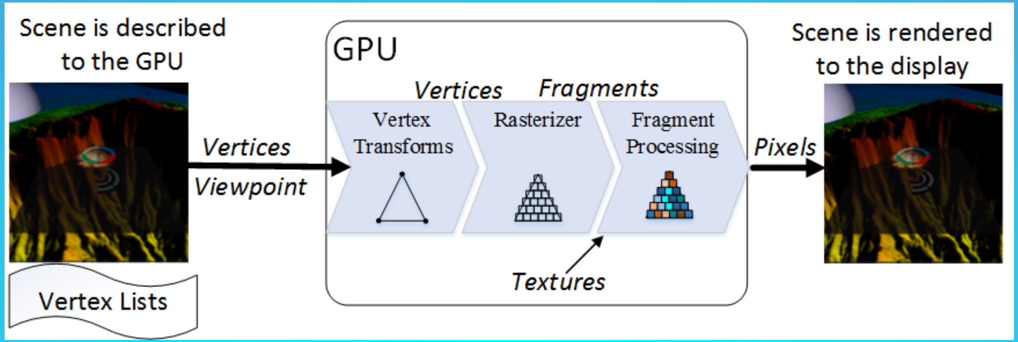
- Large framebuffer size sometimes makes better use of GPU memory architecture
- Requires many fewer passes of the geometry, still hundreds to thousands of passes depending on directional resolution

Cons

- Adding more GPUs doesn't reduce number of render passes
- Rendered pixels are not in a spatial form that can be projected through a portion of the micro-lens array
- Limited benefit from frustum culling, whole display oblique frustum is likely to intersect all objects
- May require resampling if the hogel arrangement is not a rectilinear grid
    - Inhibits on-the-fly transform
    - Resampling not cheap

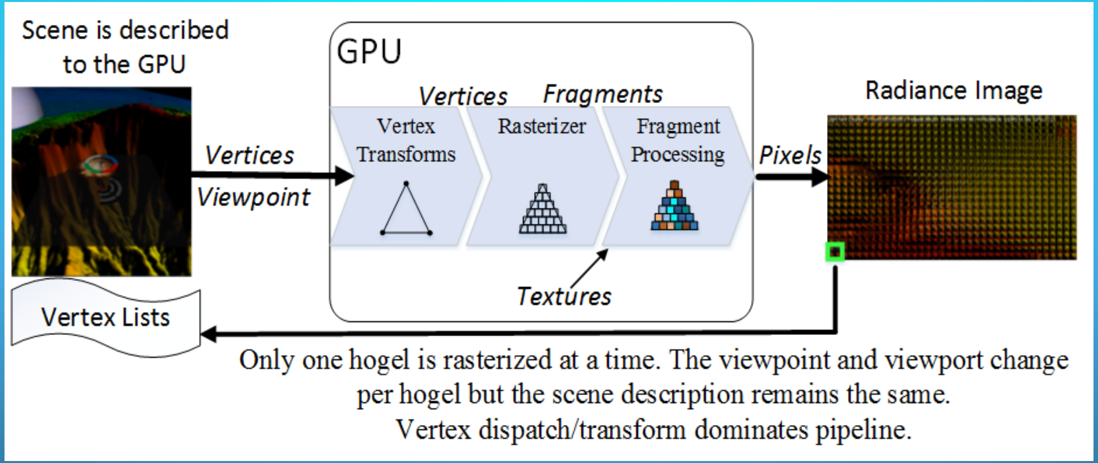
Traditional Render Pipeline for Multi-view Systems

2D Displays



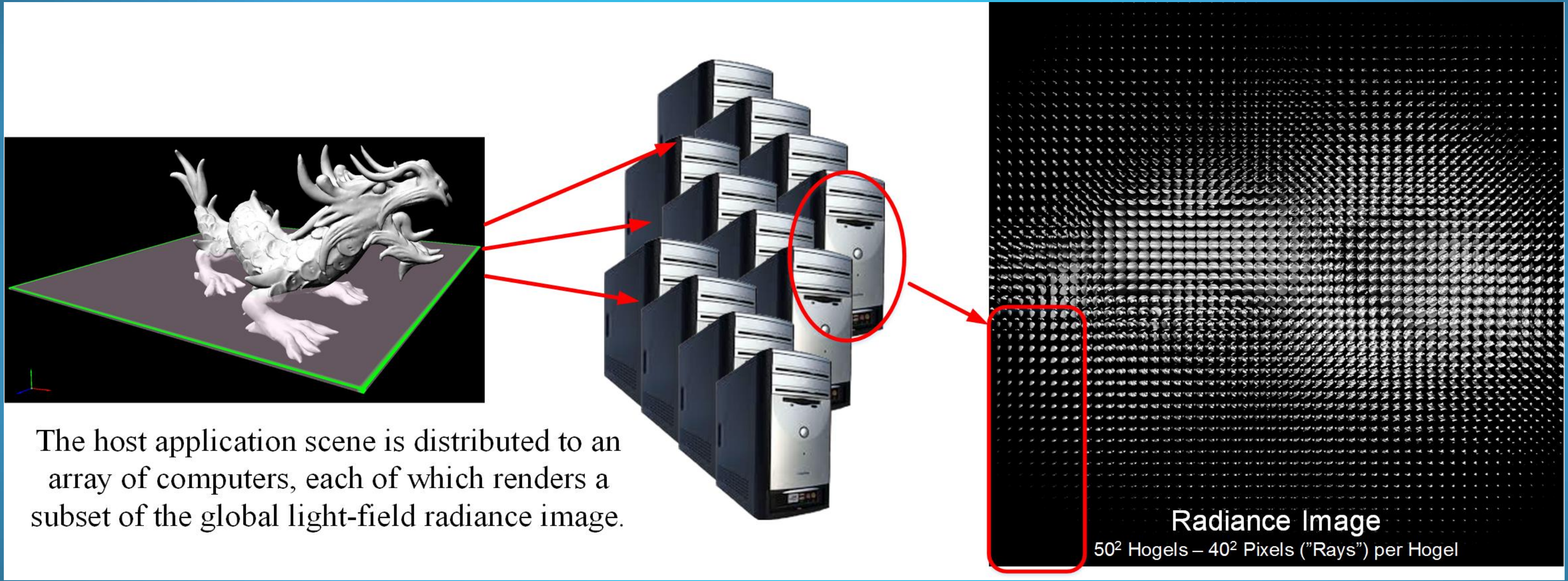
Large Viewport

Light-field Displays



1000s of very small viewports

Multi-view Update Rate and Interactivity



Light-field Display interactivity and update rate are proportional to the complexity of the scene/model, the power/configuration of the rendering cluster and the size of the light-field display radiance image.

Magnitude of the Light-field Radiance Image

Size of Radiance Image - Examples

1m x 0.75m (90° FoV) Static Light-fields

- 1.0mm hogels, Dr = 256, ~300mm (1ft) usable depth

1,000 hogels x 750 hogels x 256 rays x 256 rays x 3 RGB bytes per pixel = **~150 Gigabytes per frame**

- 0.7mm hogels, Dr = 512, ~600mm (2ft) usable depth

1,429 hogels x 1,071 hogels x 512 rays x 512 rays x 3 RGB bytes per pixel = **~1.2 Terabytes per frame**

1m x 0.75m (90° FoV) Dynamic, Real Time, Light-field Display

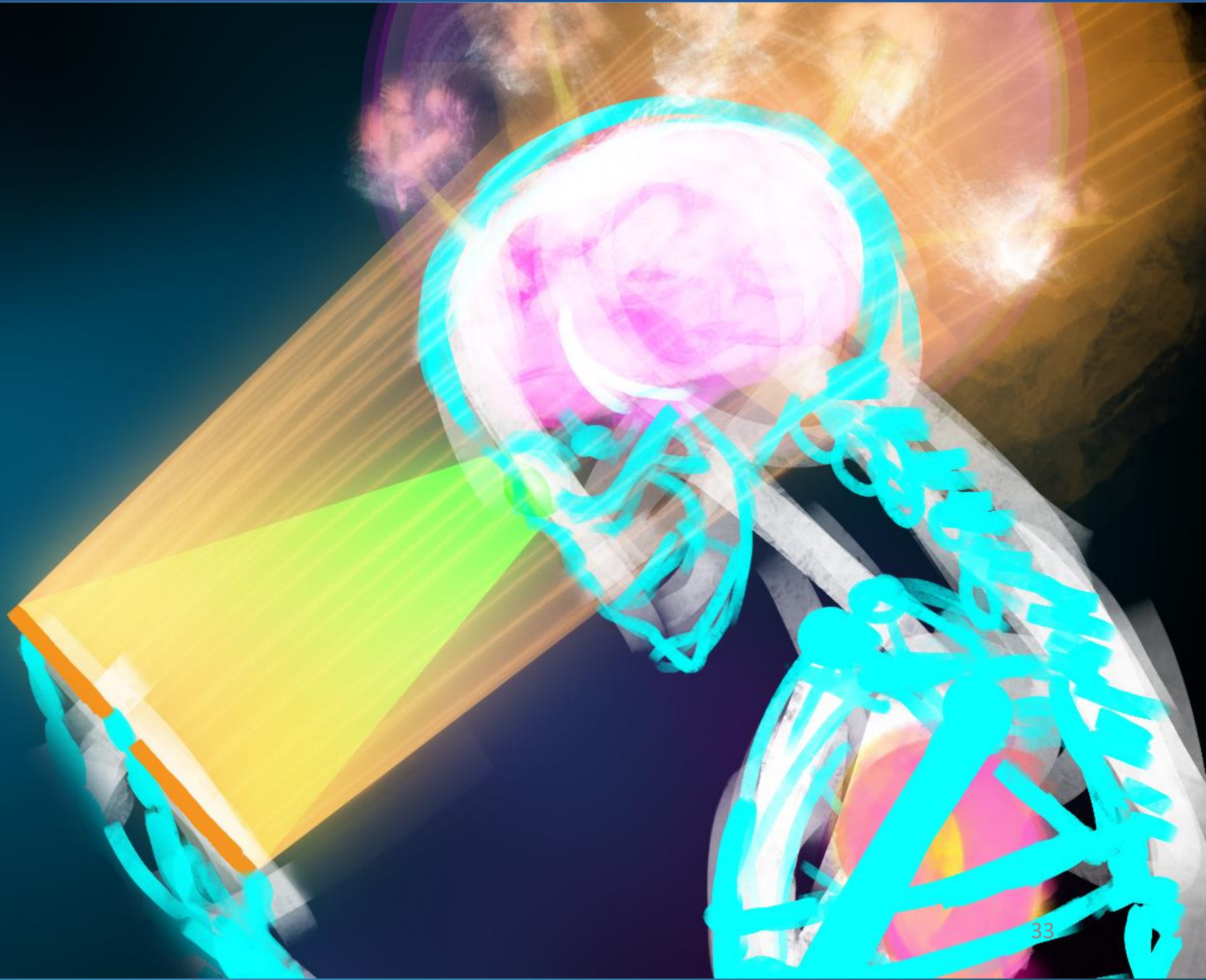
- 0.5mm hogels, Dr = 128, ~150mm (6”-8”) usable depth – real time 30 fps rendering

2,000 hogels x 1,500 hogels x 128 rays x 128 rays x 3 RGB bytes per pixel = **~150 Gigabytes per frame**

x 30 fps = **~4.4 Terabytes per second**

Conclusion: DO NOT MOVE PIXELS, don’t transport them, don’t store them.
Render in hardware at the display instead.

Heterogeneous Display Ecosystem



Field of Light-Displays (FoLDs)

HPO Lenticular

Swept Volume Volumetric

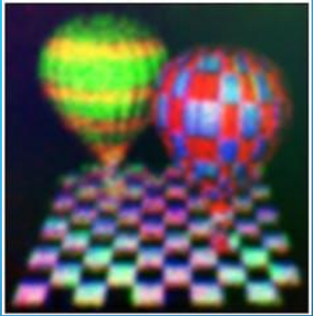
Light-field *Micro-Lens*

Light-field *Tensor*

HPO Multi-view Zone

Multi-depth Plane Volumetric

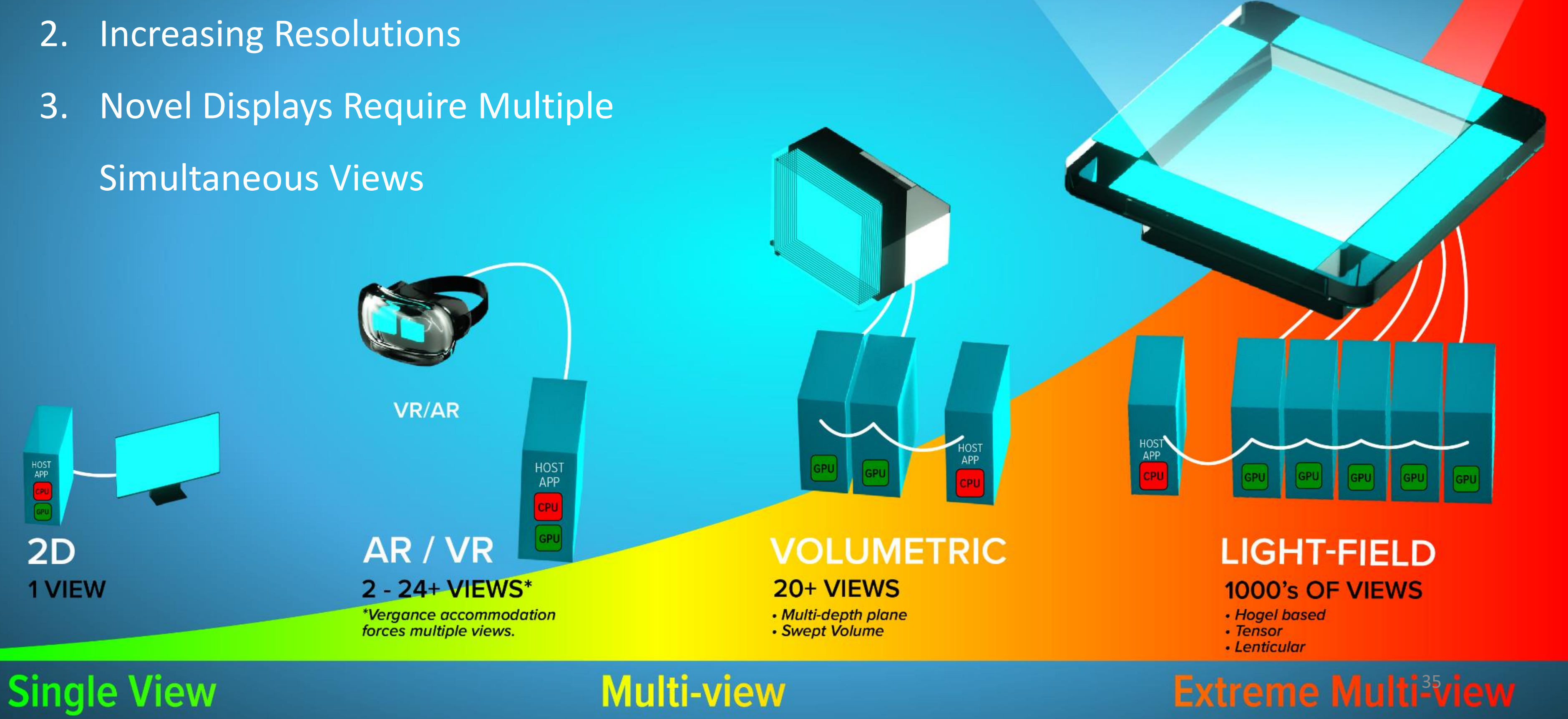
Multi-view Zone (LF?)



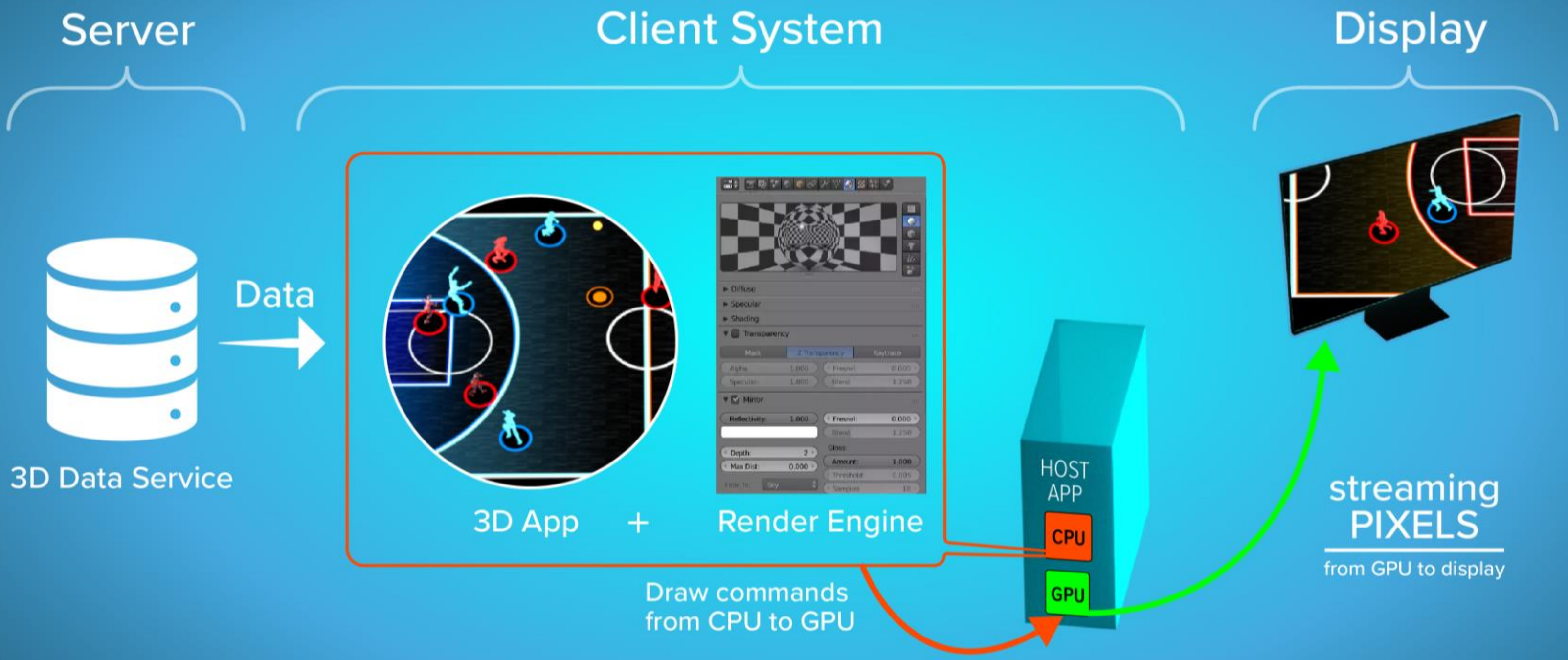
Hologram
Phase (Wavefront)

Today’s Display Environment: A Growing Problem

1. Multiple Display Types
2. Increasing Resolutions
3. Novel Displays Require Multiple Simultaneous Views

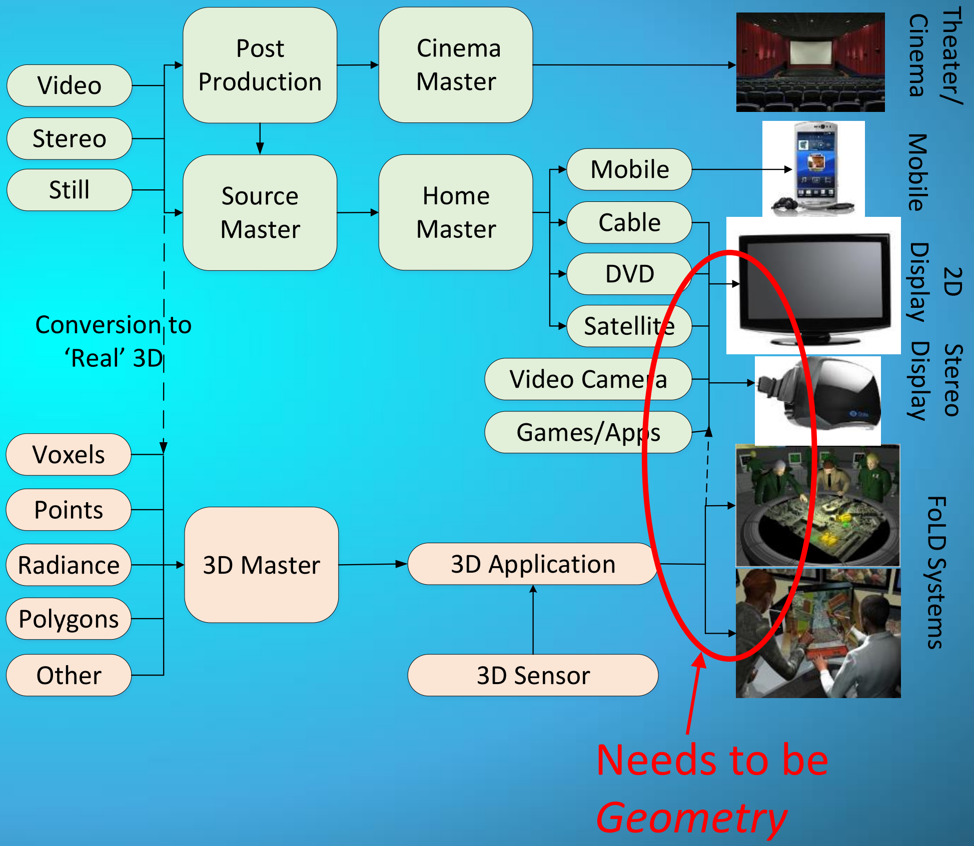


FOVI3D Current Graphics Rendering: **The Tightly Bound Display**

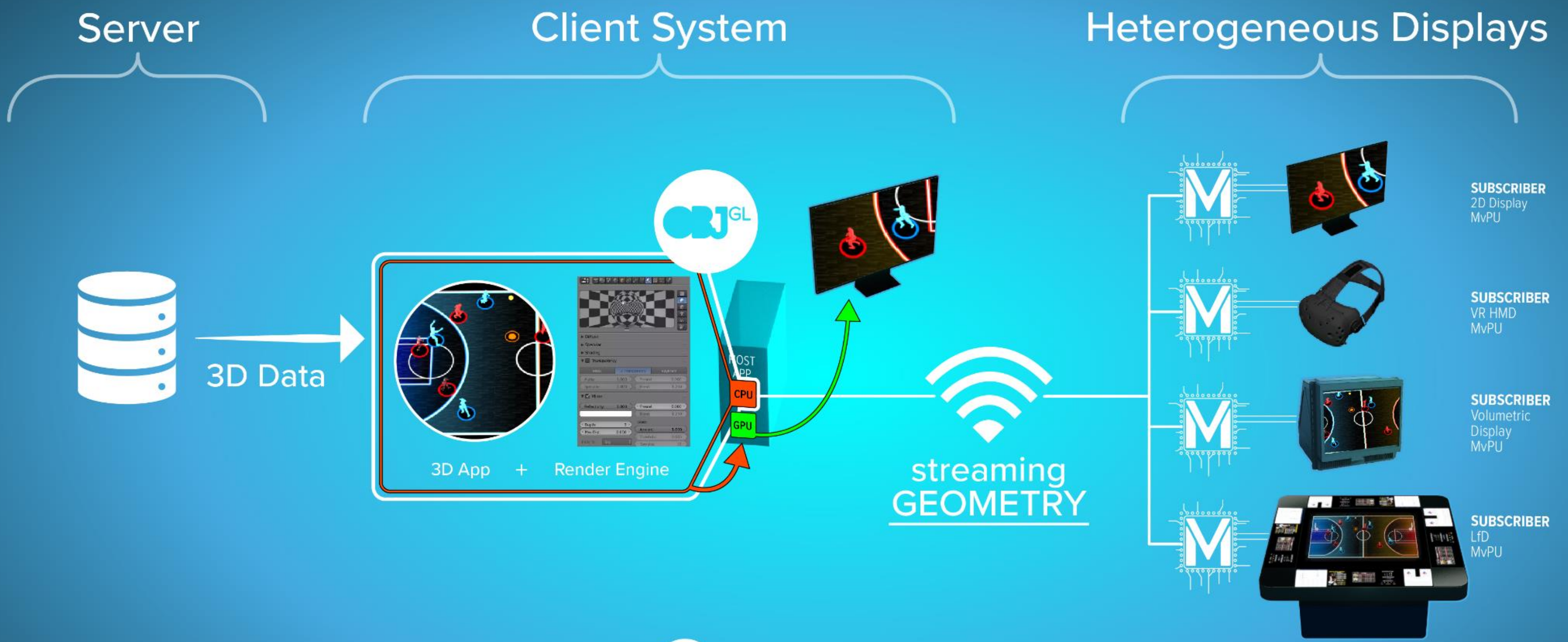


Source Master and the FoLD Ecoystem

1. 2D video is captured with the expectation that the downstream display offers a single point of view.
2. 3D visualization requires actual 3D real-world coordinates in three-dimensional space.



Tomorrow's Heterogeneous Display Ecosystem



1. 3D Data Service sends data to any device initiating a request.

2. CPU

PUBLISHER
3D App running on any single device issues ObgGL commands agnostically.

3. M

SUBSCRIBERS
Rendering occurs at the display via MvPU allowing unique rendering requirements to be met.

HDE: Sport Visualization

Beer

HMD
PoV 2

Flat Panel
PoV 4

Flat Panel:
PoV 0

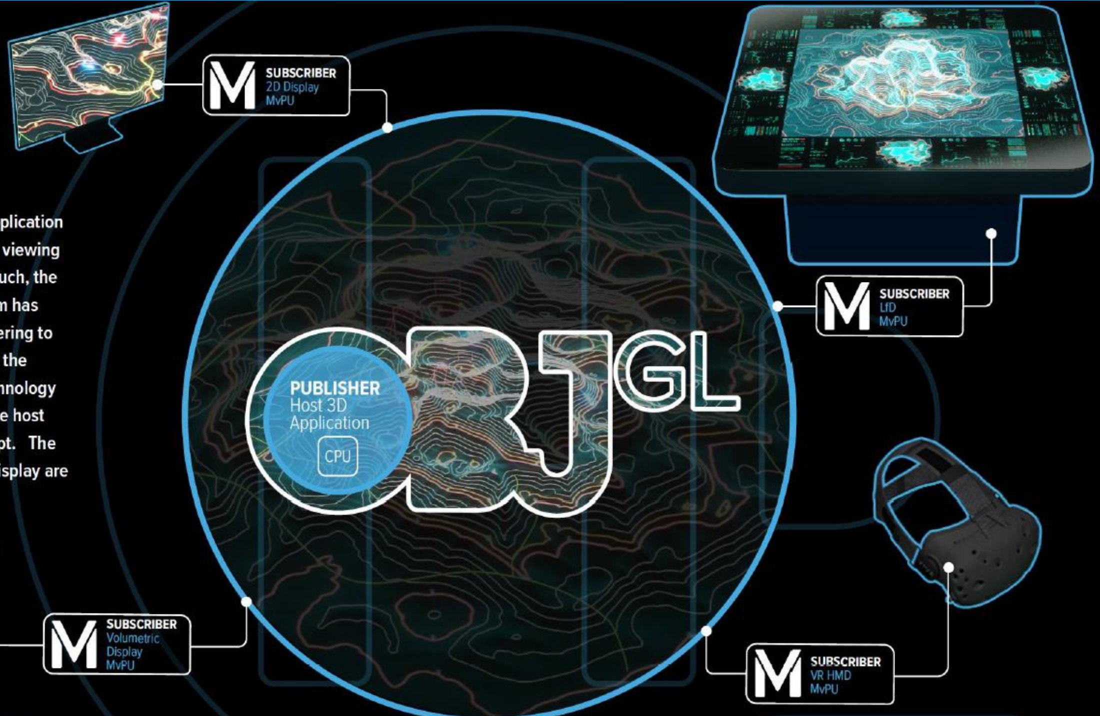
Light-field Display:
Bird's Eye View 0

Flat Panel:
PoV Stat 0

Object Graphics Library (ObjGL)

TODAY

Traditionally, a host application creates a 3D scene for viewing on a 2D monitor. As such, the host application system has responsibility for rendering to that display device. If the underlying display technology changes or evolves, the host application has to adapt. The host application and display are tightly bound.

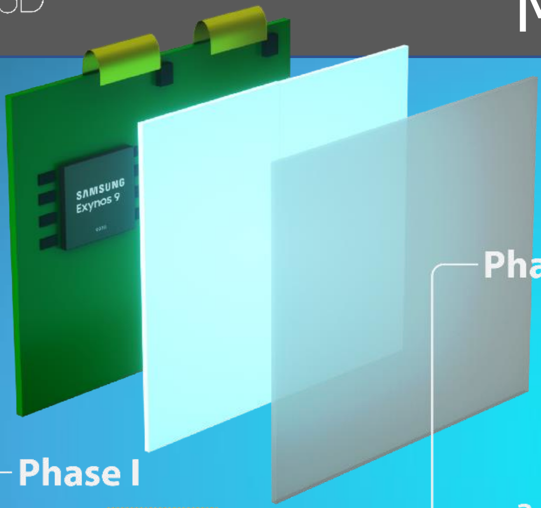


FUTURE WITH HDE

Within the Heterogeneous Display Ecosystem, the host application that creates a 3D scene is loosely bound to the display environment. Responsibility for rendering is placed with the display. The host application broadcasts its 3D scene data in a display agnostic manner via ObjGL; the display receives the scene data and renders the views required by its architecture and projection system internally via the MvPU.

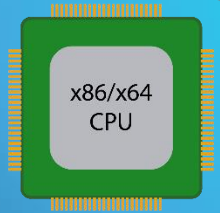
Consider, for example, an eSports application/game broadcast from a Netflix-like server. The game is streamed without regard to the types of visualization devices present within the ecosystem. Whether a viewer wants to wear a head mounted display (HMD) for a first-person perspective at ground level or a group of viewers surrounds a Light-field Display (LfD) for a bird's-eye view of the entire scene, the host application is unaware. The host application and the display technology are free to evolve independently.

MvPU Development



If the Phase II framerate goals can be obtained with OTS GPUs, then custom Phase III MvPU may only be necessary to reduce SWaP.

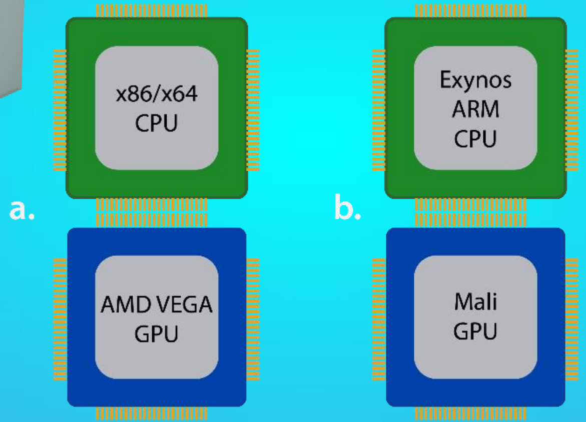
Phase I



MvPU reference algorithm developed in C/C++

- FoVI3D currently has a working reference simulator for Bowtie rendering a LfD radiance image

Phase II



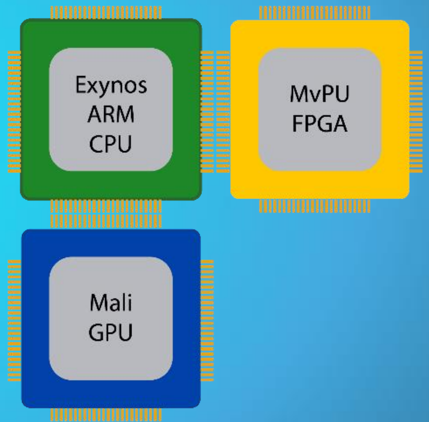
a. MvPU OpenCL port of reference to desktop GPU

- Focus on extreme multi-view rendering for collaborative display

b. MvPU OpenCL port of reference to mobile GPU

- Focus on shallow multi-view rendering for personal/mobile display

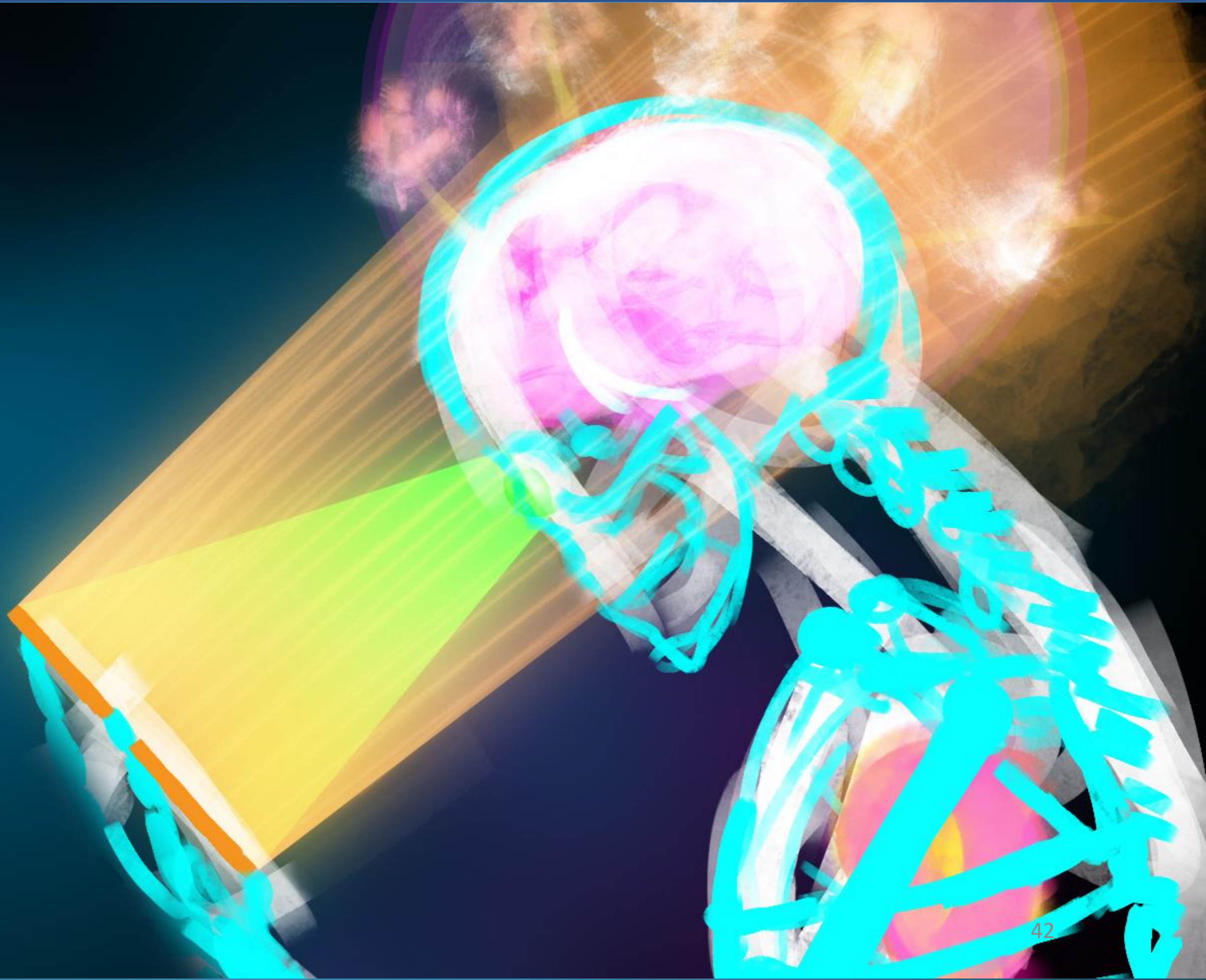
Phase III



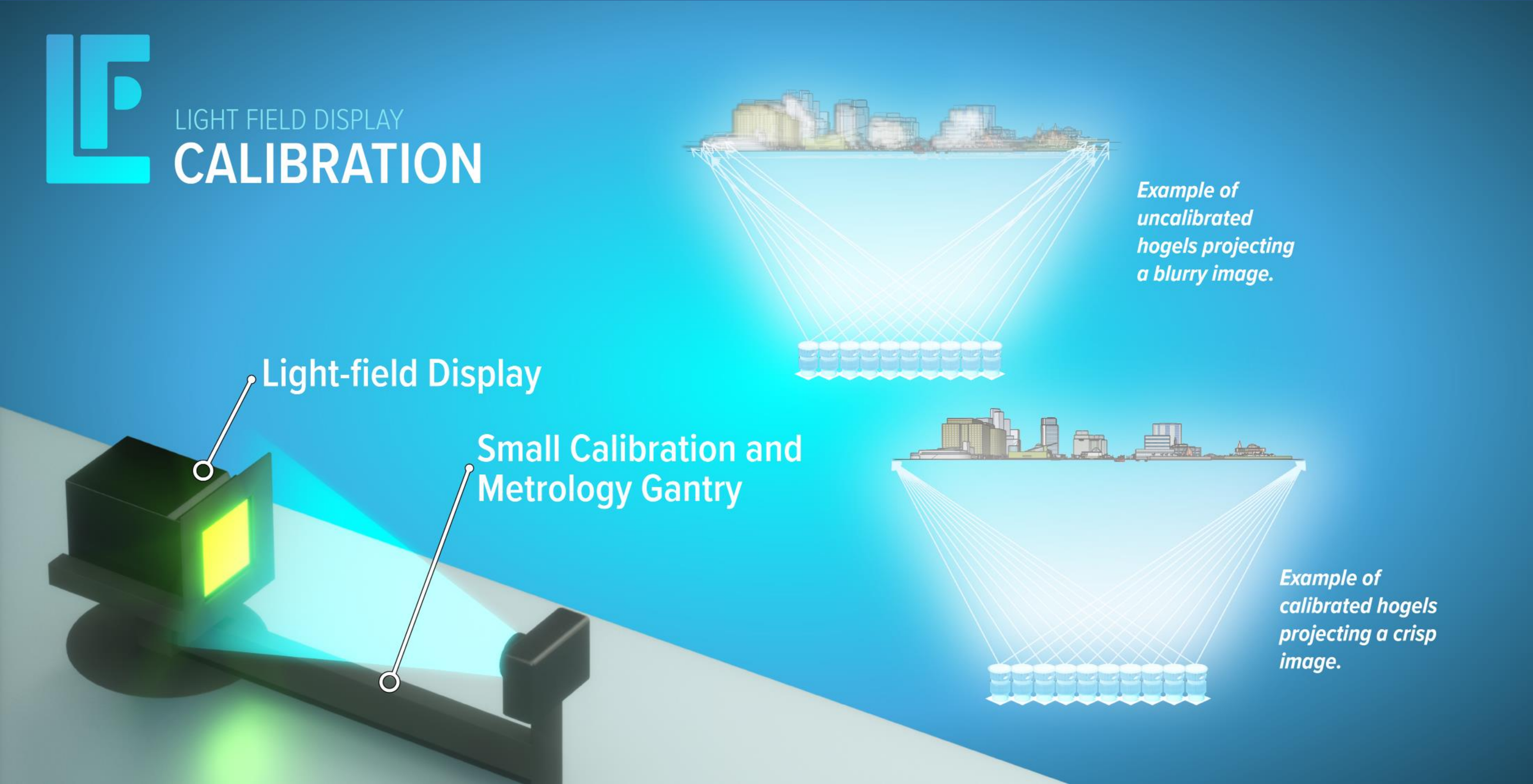
MvPU FPGA Accelerator

- Preserves GPU for normal rendering
- MvPU is responsible for multi-view rendering for 3D displays

Calibration and Metrology



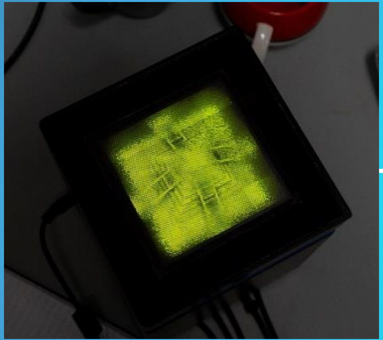
Calibration

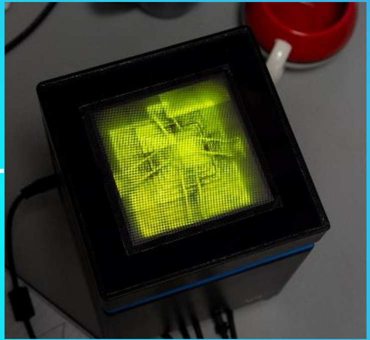


Calibration

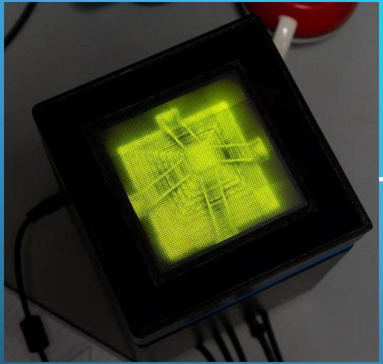
Spatial Calibration:
Maximize clarity of projected content

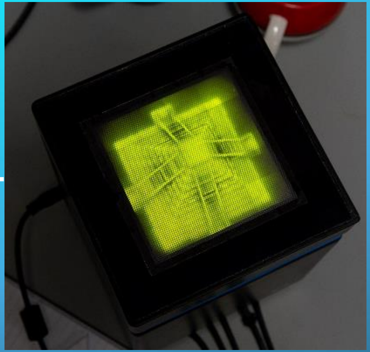
Color / Brightness Calibration:
Minimize visibility of distracting tiling artifacts





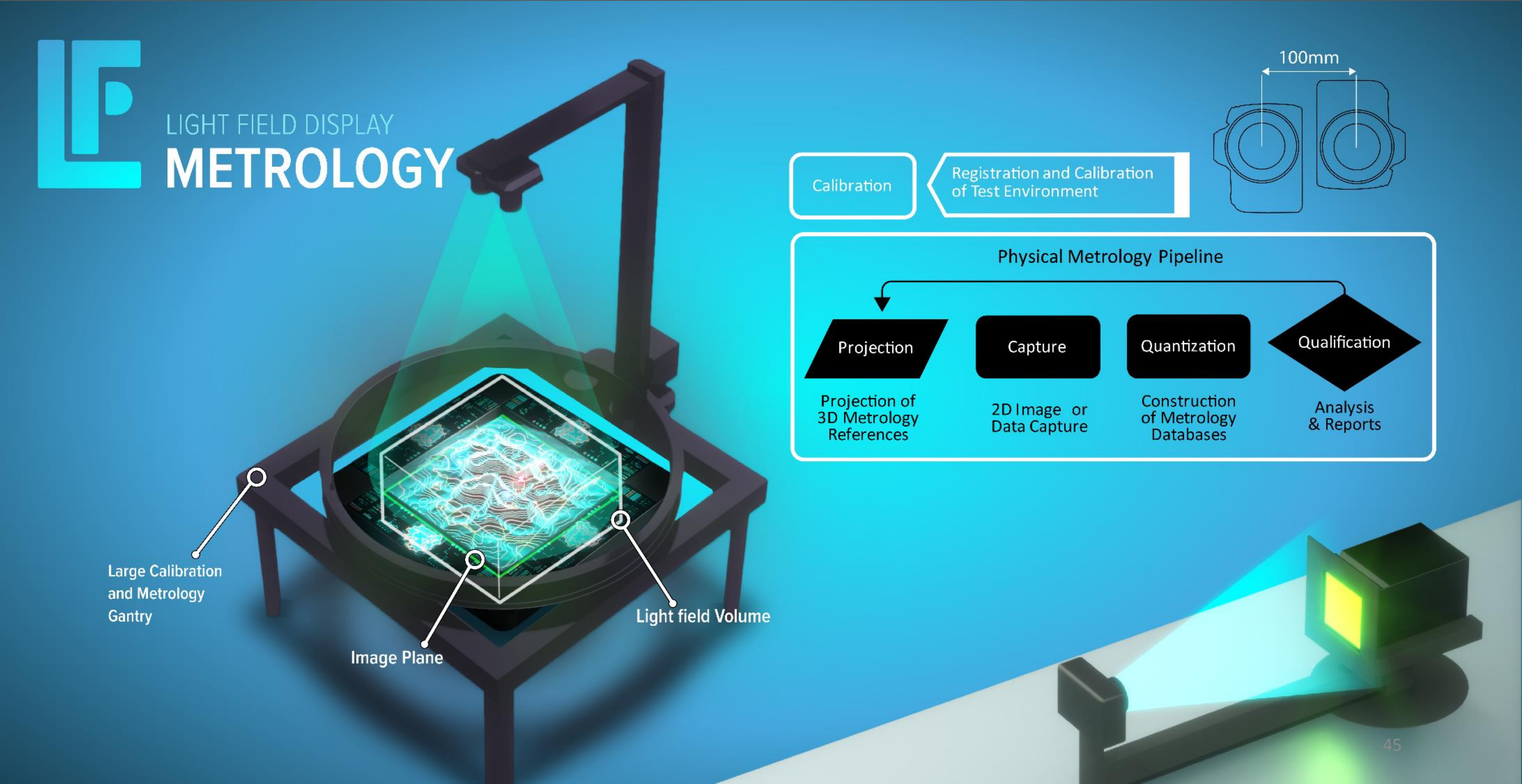
Before



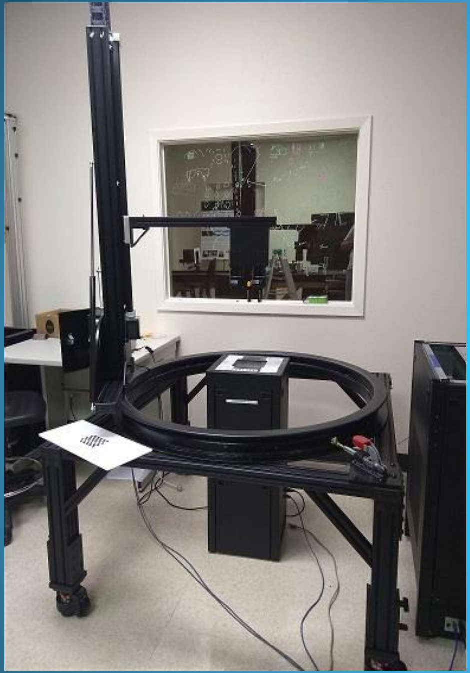


After

Light-field Display Metrology

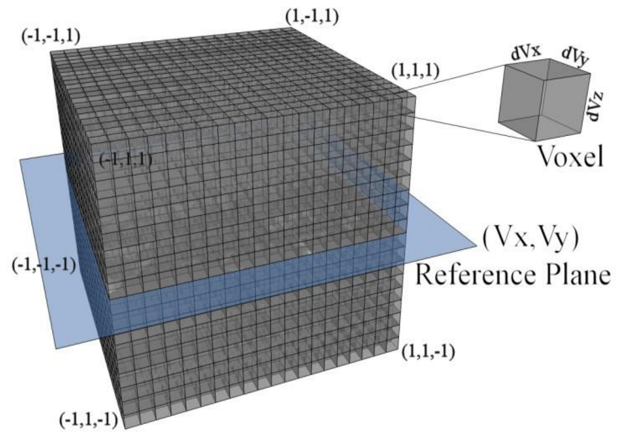


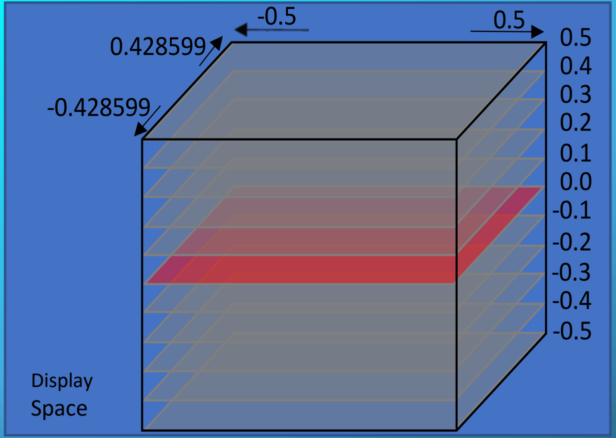
Camera Gantry



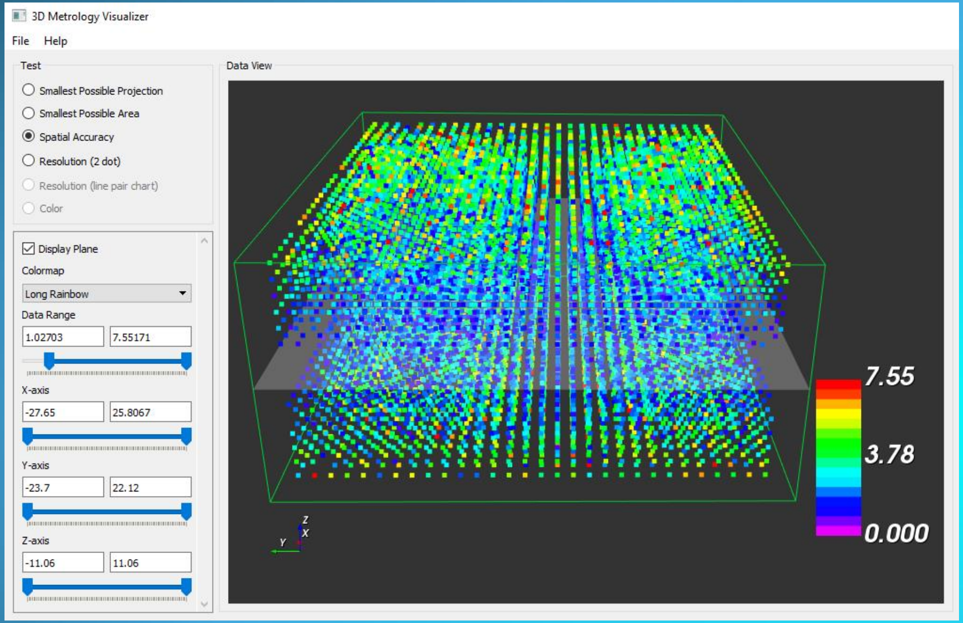
Defining the Volume

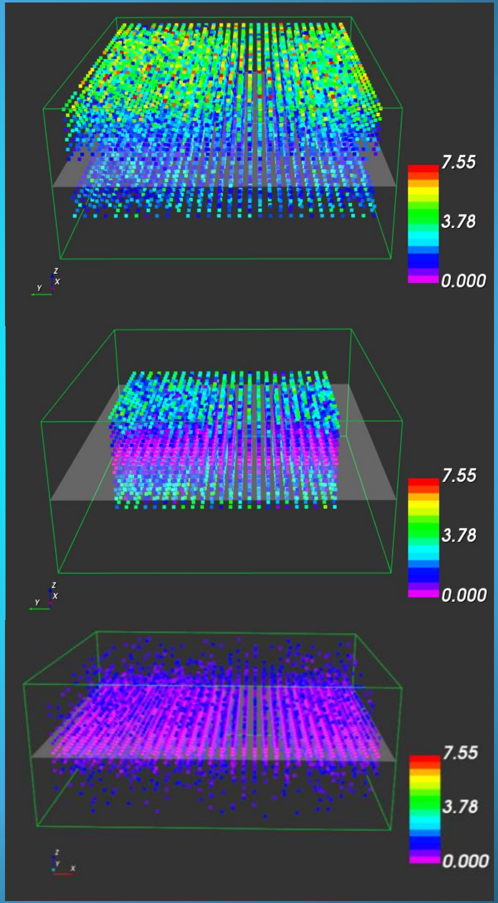
- Normalized voxel database of metrology
- Of some pre-defined resolution – number of hogels along an axis?
- Populated from multiple perspectives
- Each voxel has a plurality of metrics
- Database stores measurements collected from multiple viewing angles





Spatial Accuracy

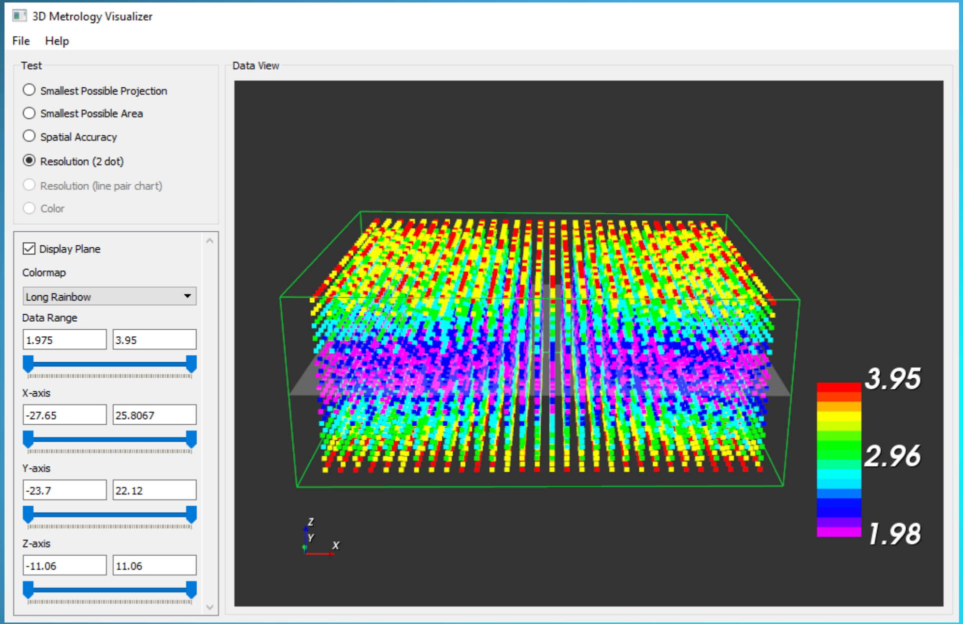


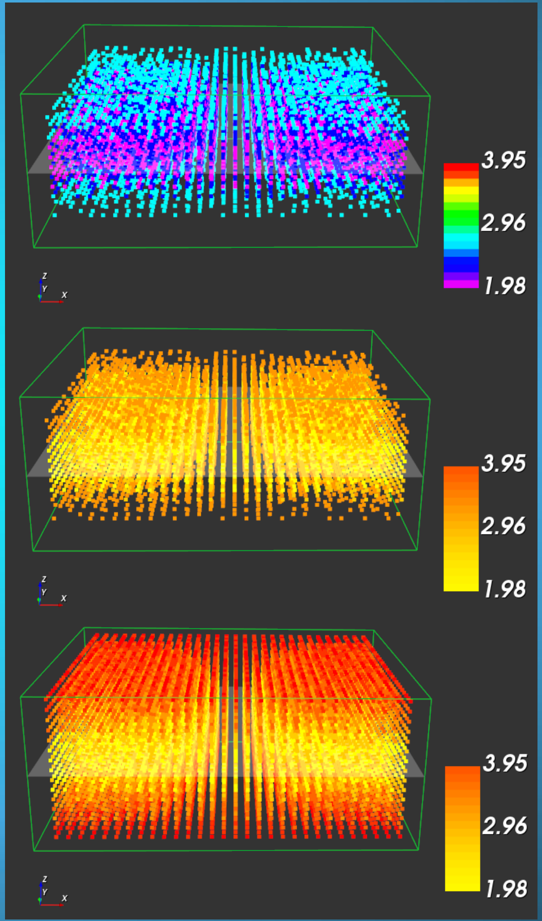


Measurement of the 3D positional precision of geometric primitives in the projected 3D volume

$$Abs.\ Error = \sqrt{(x_e - x_m)^2 + (y_e - y_m)^2 + (z_e - z_m)^2}$$

Spatial Resolution

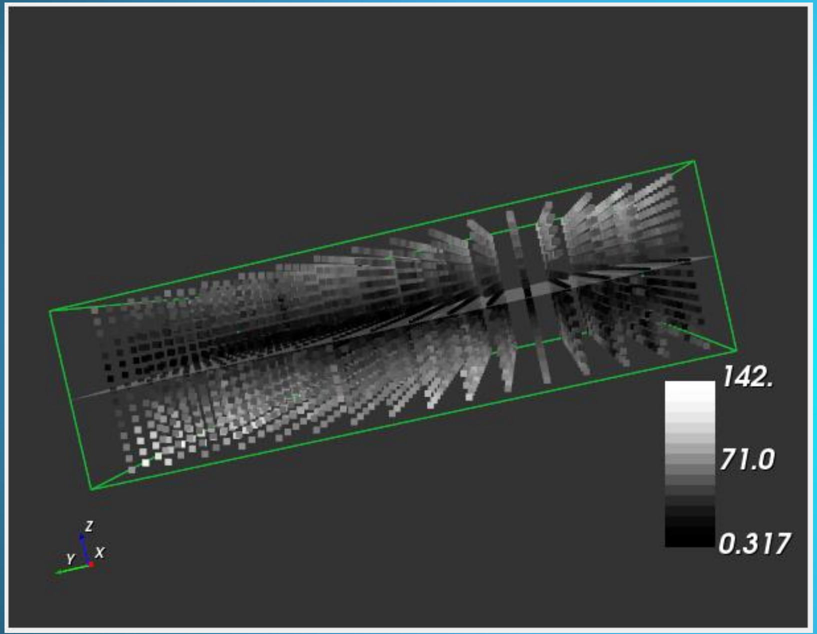


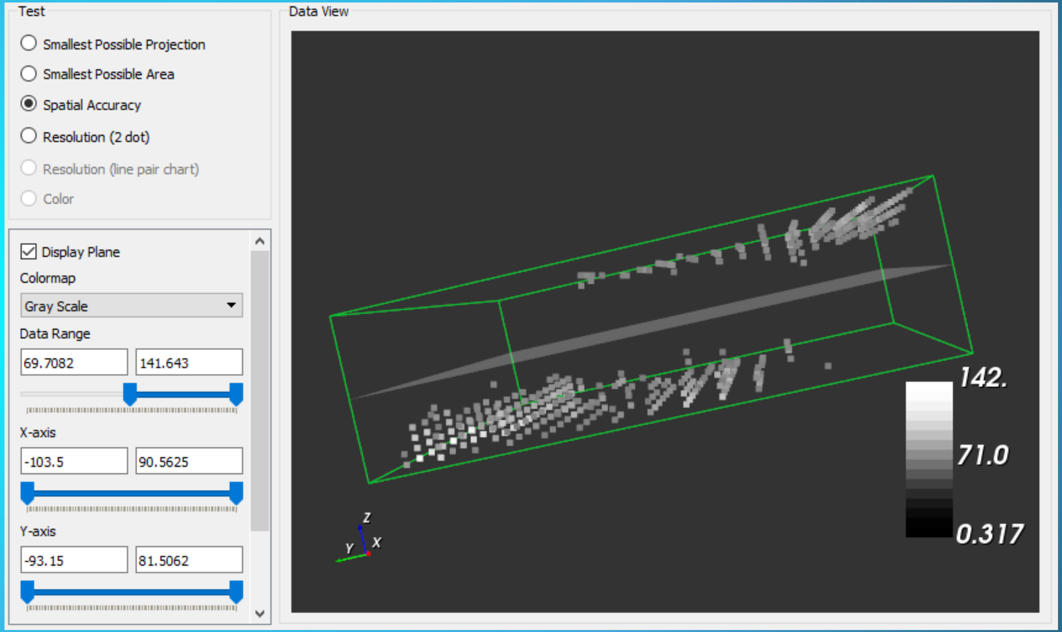


Measurement of the spatial detail in the 3D FoLD projection volume and a partial qualification of the FoLD's plenoptic description.

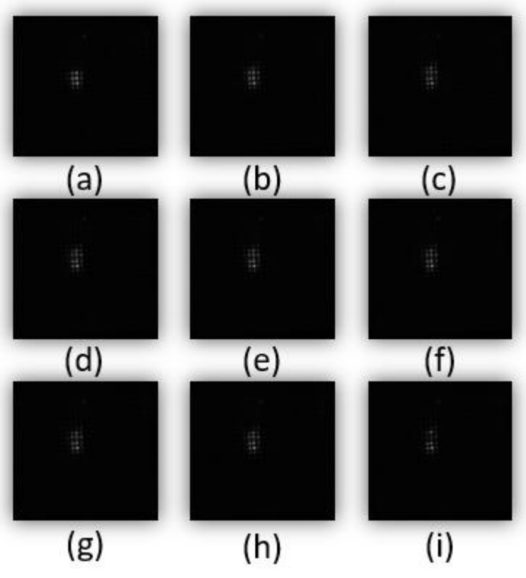
$$L = P\left(\Theta, \phi, V_x, V_y\right)$$

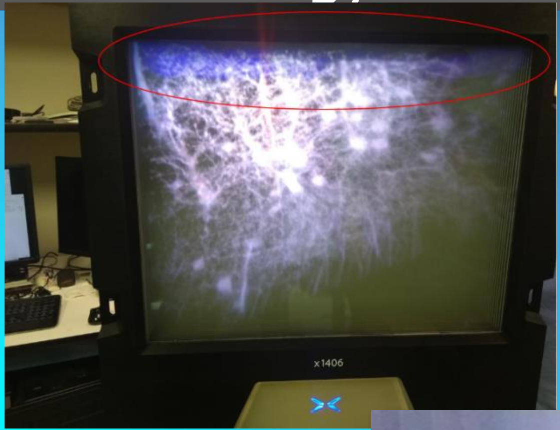
9-Tile ZMD Spatial Accuracy

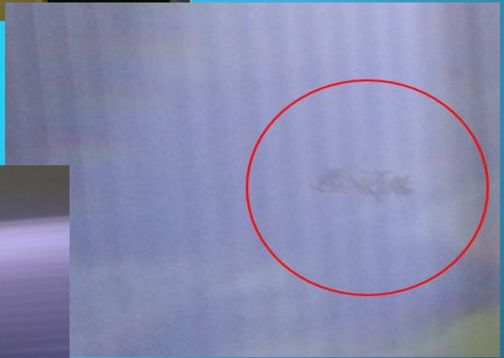




Display Artifacts Make 3D Metrology Hard



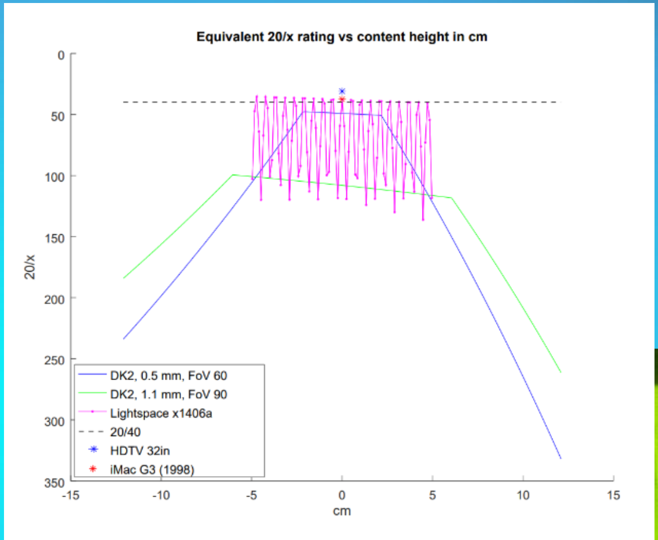


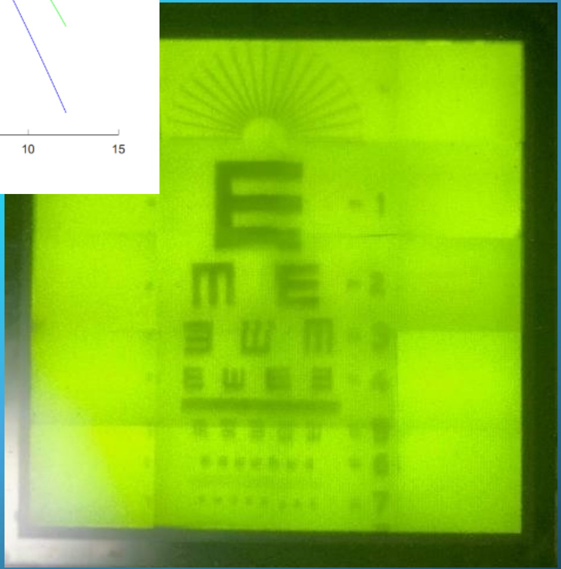


Snellen Volume

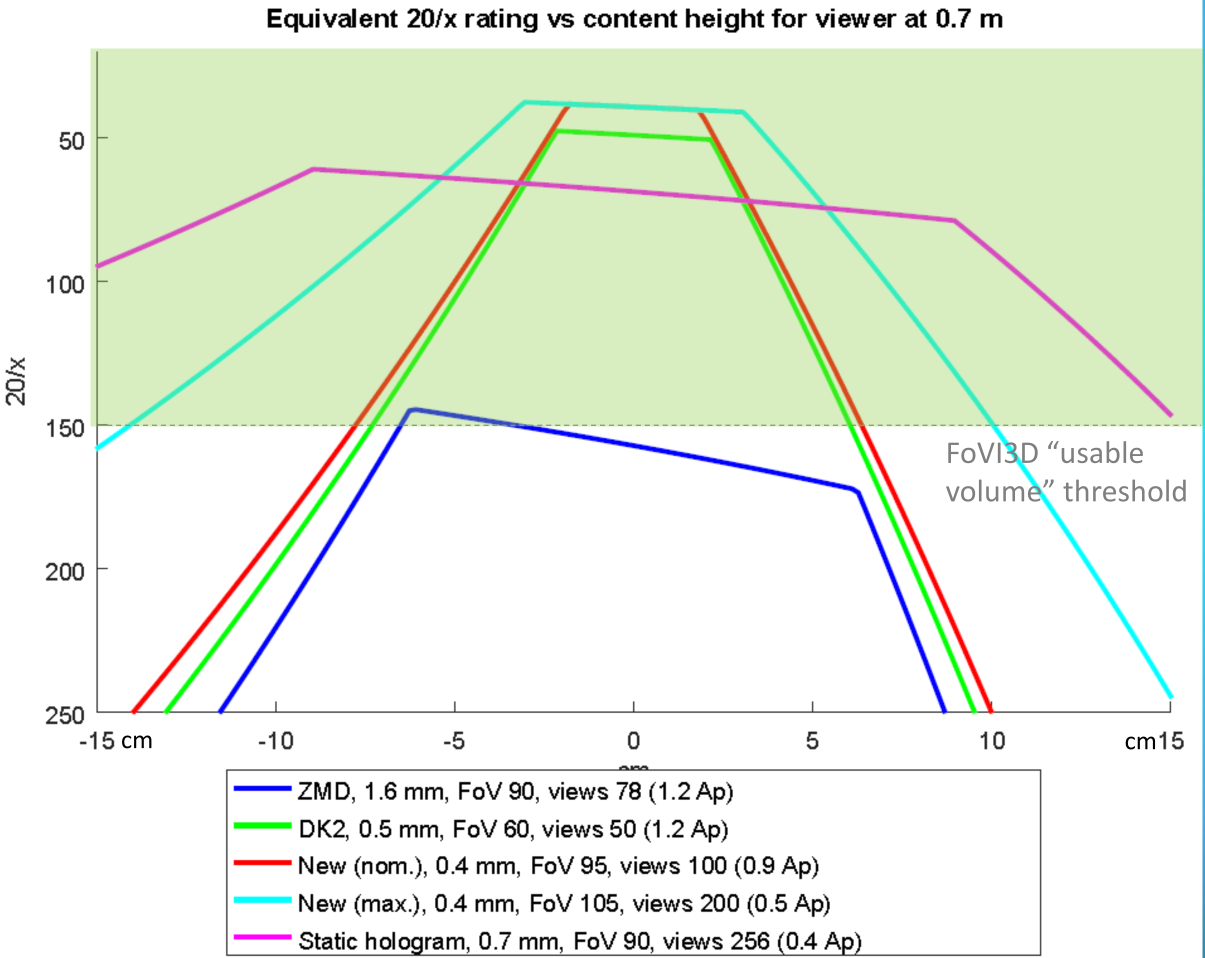
- Display resolution requirements depend on viewer's distance: angular sub tense of features
- Snellen scale – widely familiar measure of angular acuity:

  20/20 = 6/6 = 1 arc minute feature
- Snellen volume: a 3D display's projection volume in which a typical user can resolve a target level of detail
- Similar evaluation of VR headsets being performed by Oliver Kreylos (doc-ok.org)





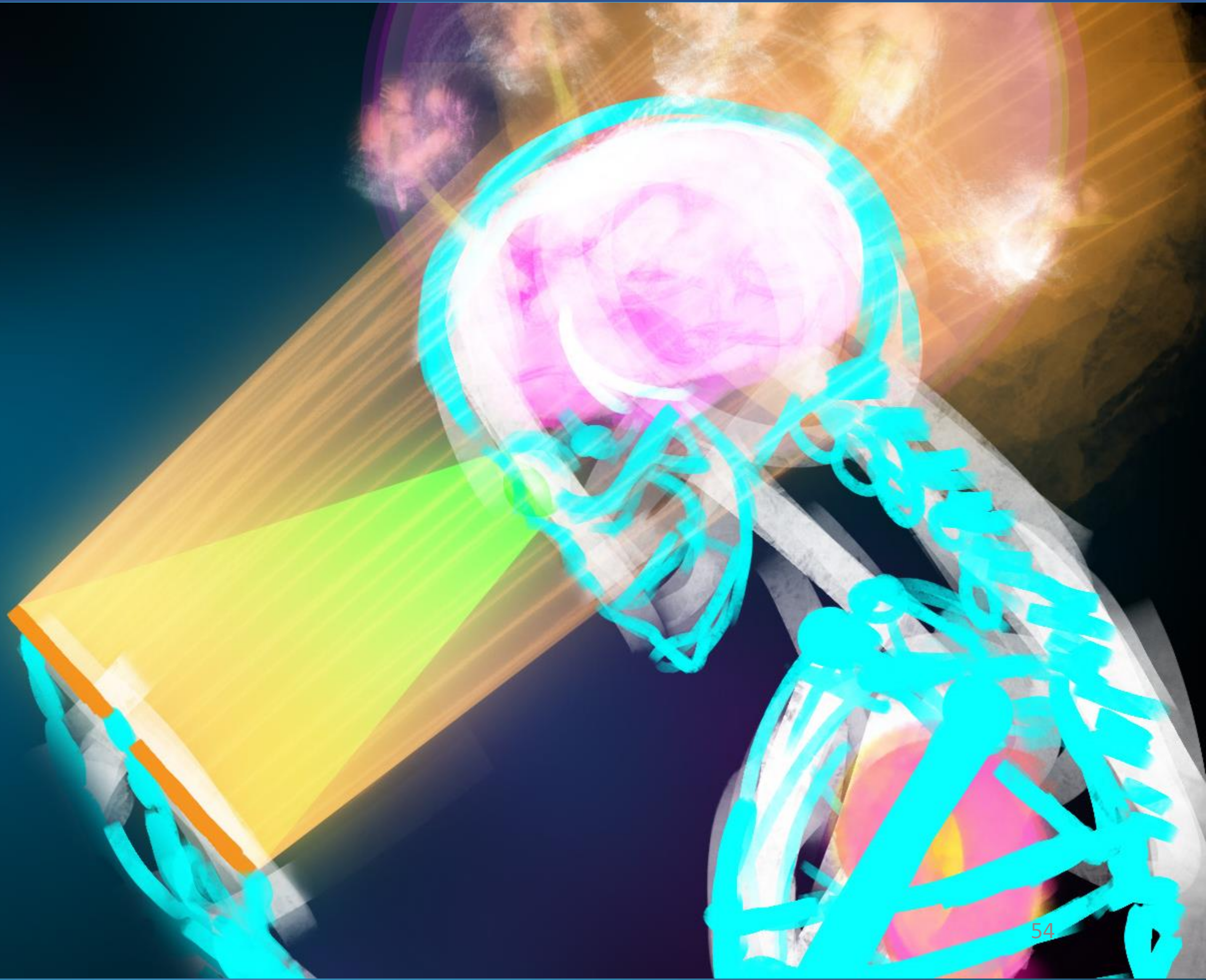
Snellen Volume



	Display	Usable Volume	Interstitial Pixel Grid Feature Size
	ZMD	---	0.8mm*
	DK2 (Wilcox)	+/- 7cm	.05mm
	New (min. spec.)	+/- 8cm	.05mm
	New (max. spec.)	+/- 13cm	.05mm
	Static Hologram	+/- 20cm	.03mm

*will detract focus from displayed virtual object

Light-field Display Developer Kit



Today's Demo: DK2

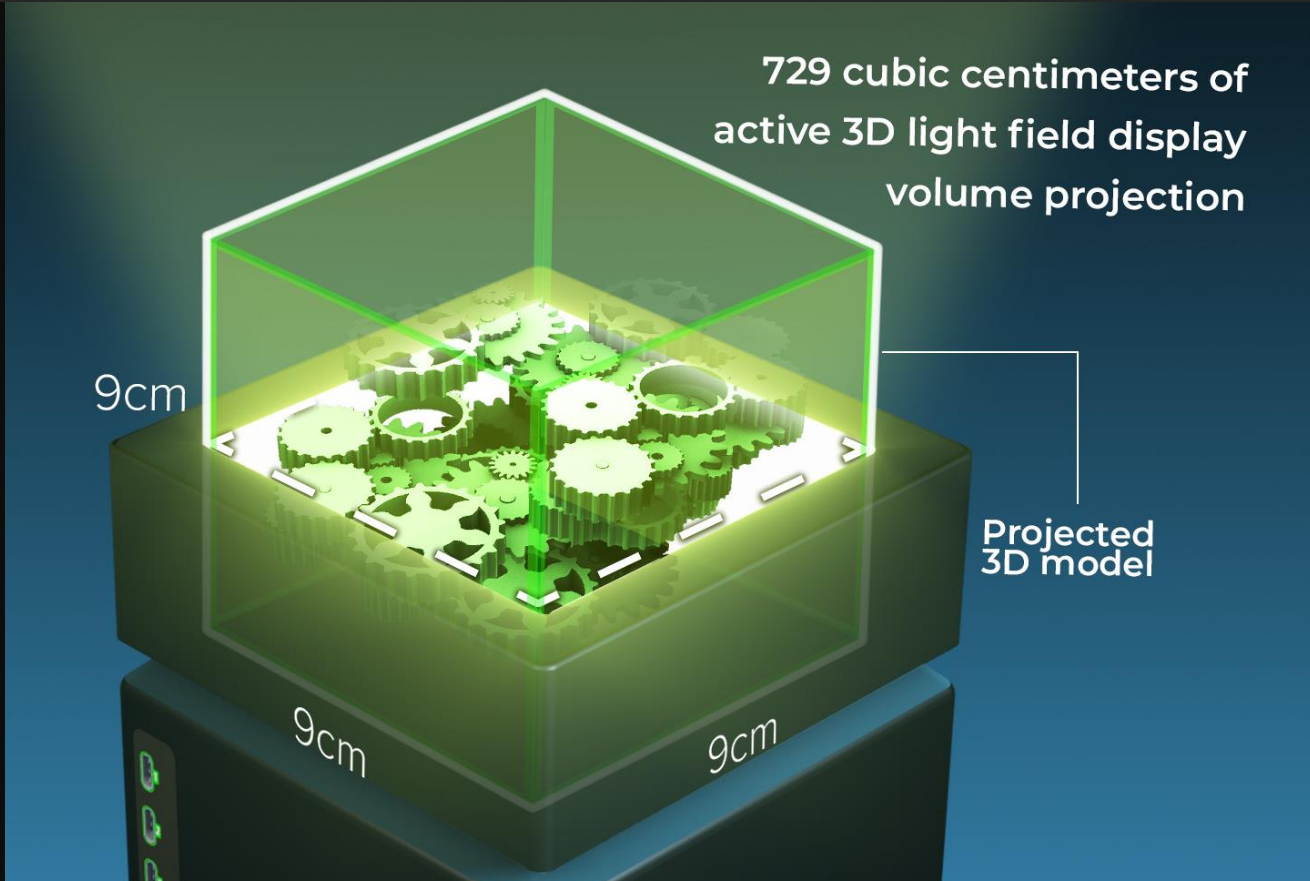
Light-field Display

Object Graphics Library

Multi-view Processing Unit

Heterogeneous Display Ecosystem

DK2: Light-field Display



DK2 Evolution

Demonstrating:

Lucas - The highest resolution light-field display yet created.

GEN 1

- 90° field of view
- 1.6 mm hogel diameter
- 80 x 70 hogel display
- 76 x 76 views per hogel

DK2 Wilcox

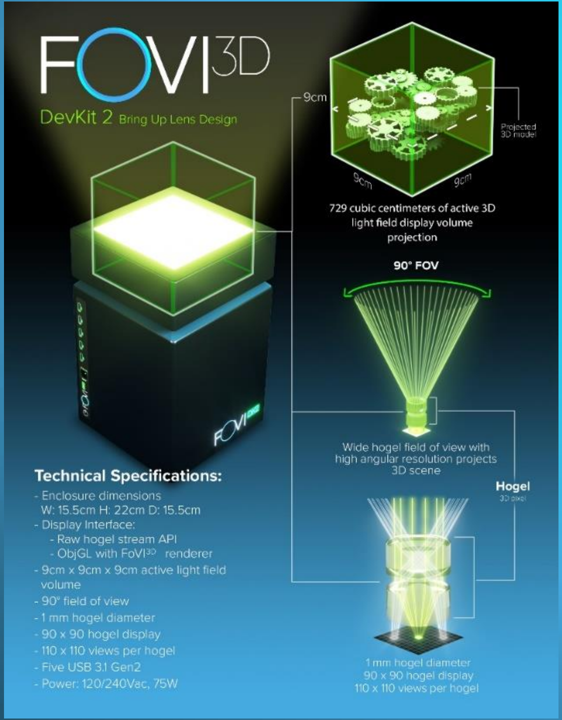
- 90° field of view
- 1.0 mm hogel diameter
- 80 x 80 hogel display
- 110 x 110 views per hogel

DK2 Lucas

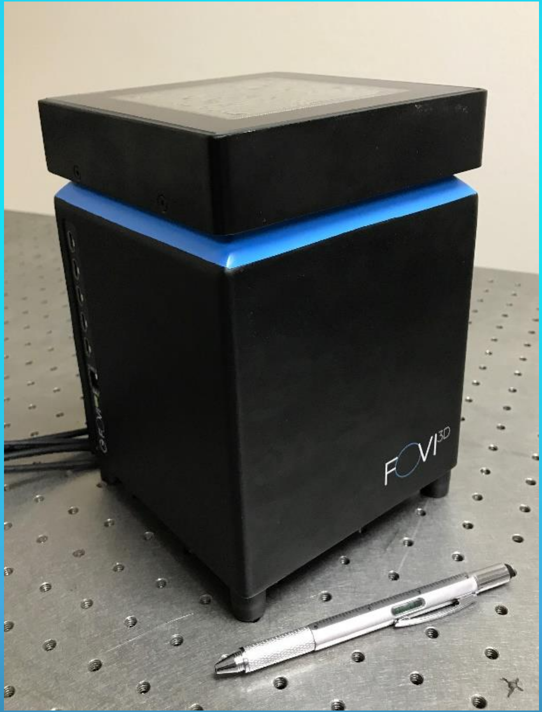
- 60° field of view
- 0.5 mm hogel diameter
- 168 x 168 hogel display
- 55 x 55 views per hogel

Light-field Display Developer Kit

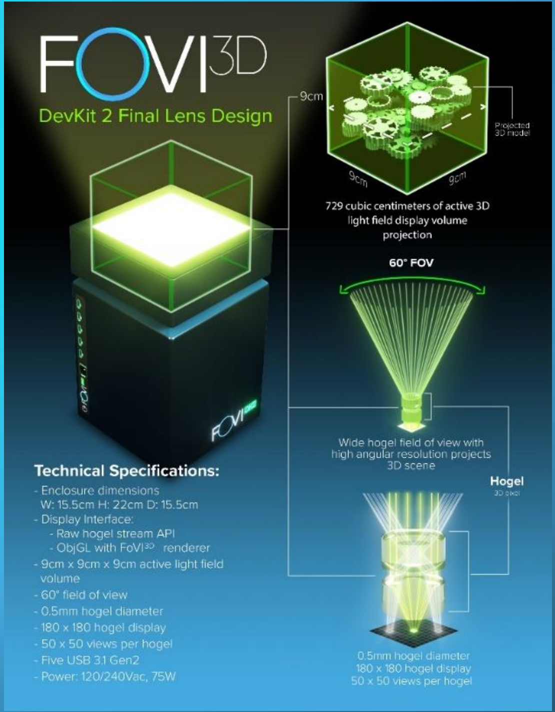
Lab Prototype Display With ~1.0mm Plastic Micro-Lens



LfD DK2



LFD Developer Kit with ~0.5mm Glass Lens Solution First Quarter 2018



Technical Challenges

- Pixel Density
  - Need very high pixel density to achieve spatial angular requirements
- Optical Manufacturing
  - High precision optics to preserve ray detail
- Light-field Computation
  - Ginormous number of samples/rays/pixels
- Display Agnostic Format
  - Future proof for novel display architectures
- Metrology
  - Capture, quantification, standardization

Thank you

Socialize the significance of light-field display technology and what FoVI^{3D} is doing about it.

Thank you

Questions?