UNIVERSITY of ROCHESTER

THE INSTITUTE OF OPTICS

Digital Integral Cloaking [1]

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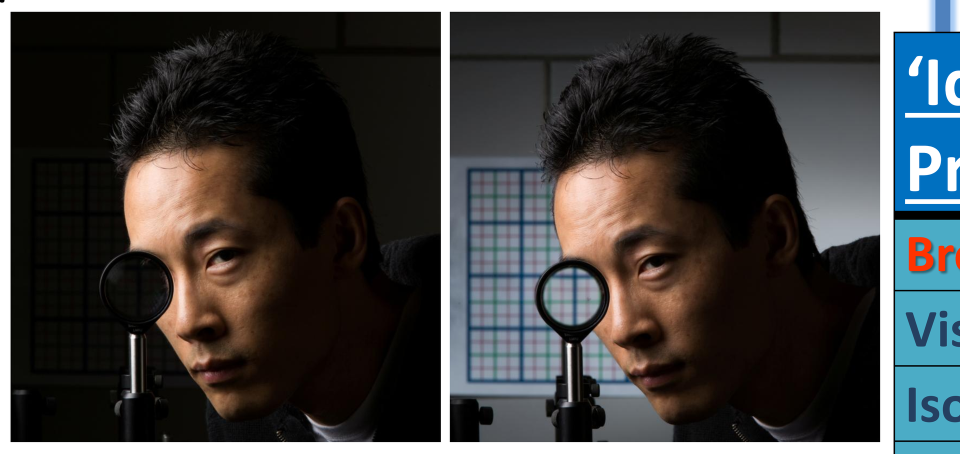
NORTHROP GRUMMAN

DARPA

A. Summary

To achieve broadband, omnidirectional invisibility, we propose "**digital cloaking**," where space, angle, spectrum, and phase are **discretized**. Experimentally, we demonstrate a 2D, planar, ray optics, digital cloak by using lenticular lenses. Theoretically, this can extend to a good approximation for an "ideal" cloak. As commercial digital technology improves, a **wearable cloak** is possible in the future [1].

B. "Cloaking"



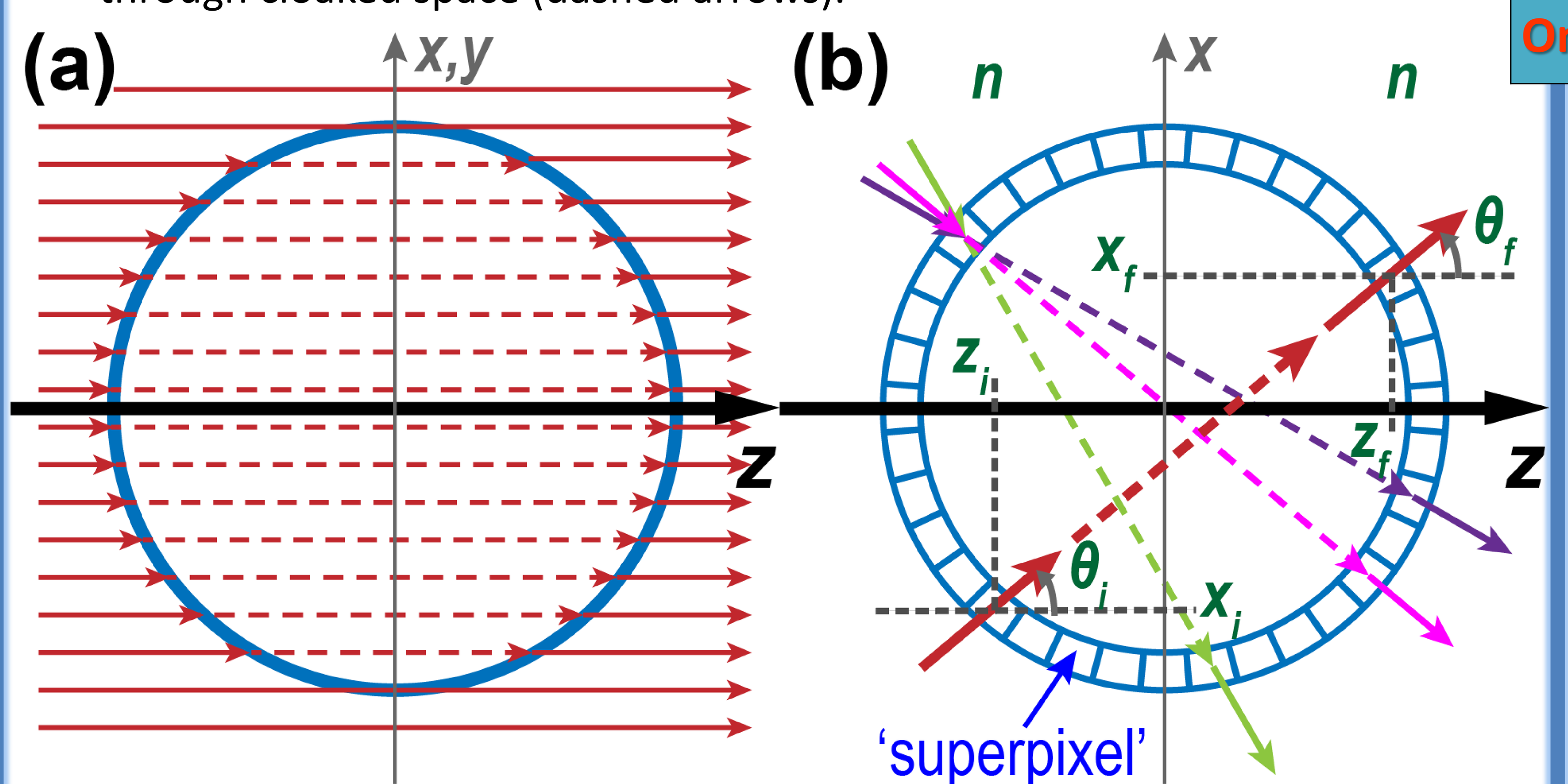
A **'perfect' cloak** should:

1) Hide a non-zero volume,

2) Make itself and the hidden object appear transparent.

C. 'Discretized' Cloaking [1]

- Consider an ideal spherical cloak (a). Light appears to travel in straight line through cloaked space (dashed arrows).



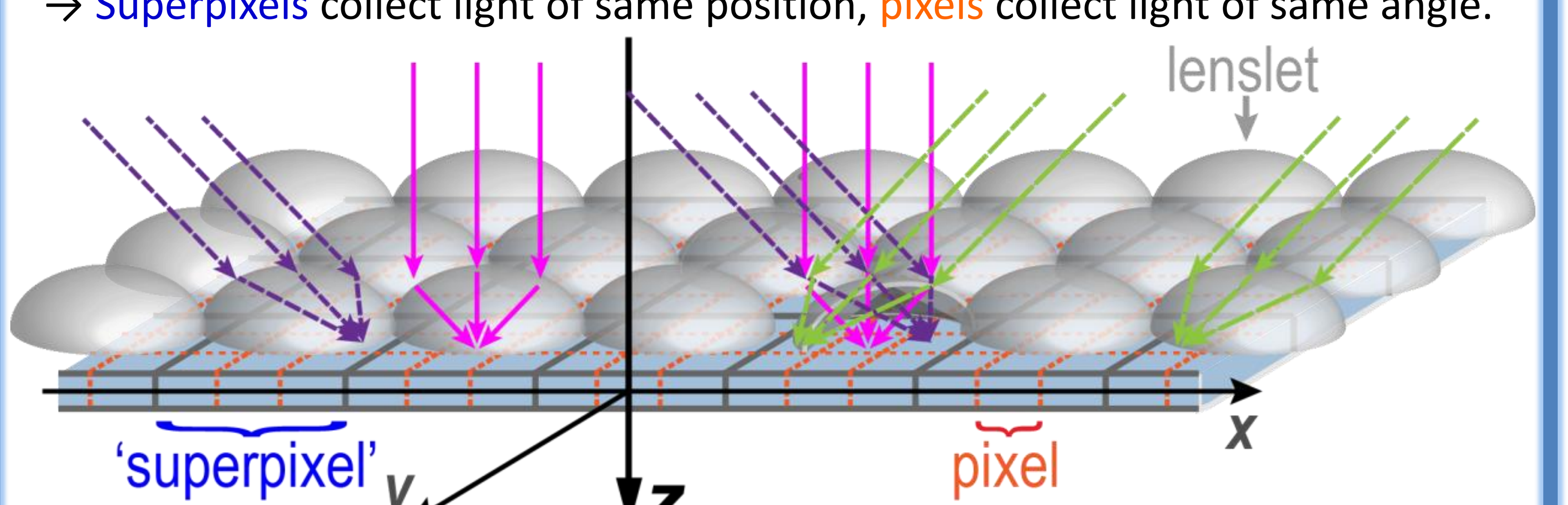
- Discretize cloak surface space into `superpixels' in (b):
  - Can approximate all ideal cloak properties.
  - Generalizable to arbitrary or dynamic shape.
  - Simplified to pixel-to-pixel light mapping:

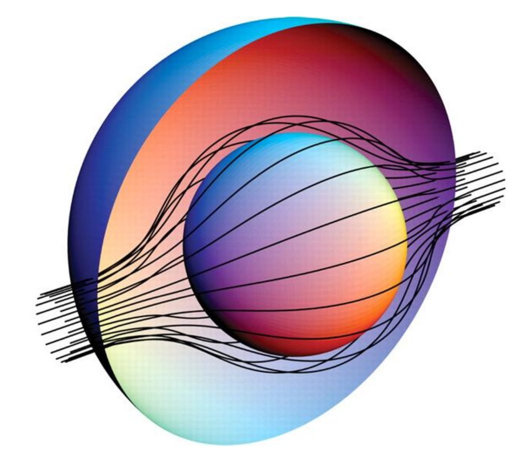
$$\begin{bmatrix} x_f \\ n\tan\theta_f \end{bmatrix}_{z=z_f} = \begin{bmatrix} 1 & (z_f - z_i)/n \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_i \\ n\tan\theta_i \end{bmatrix}_{z=z_i}$$

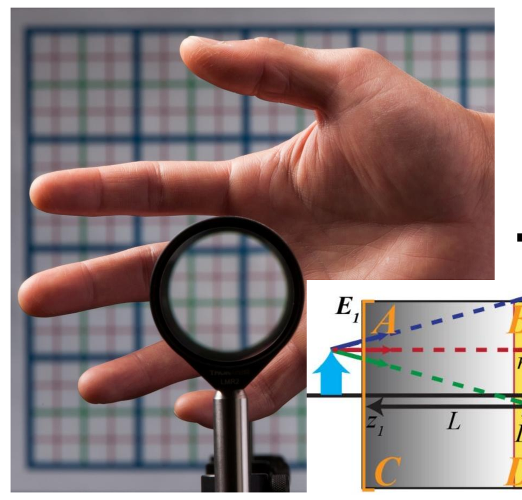
D. 'Digital Integral' Cloaking [1]

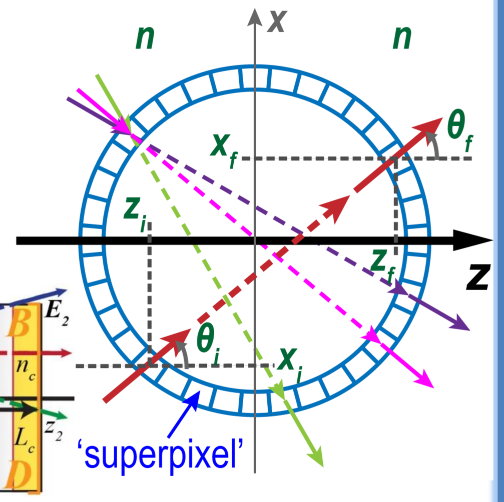
- Because surface discretized:
  - **Digital**: Add digital displays, detectors.
  - **Integral**: Use lenslet arrays ('Integral Imaging' [4]).

→ Superpixels collect light of same position, pixels collect light of same angle.





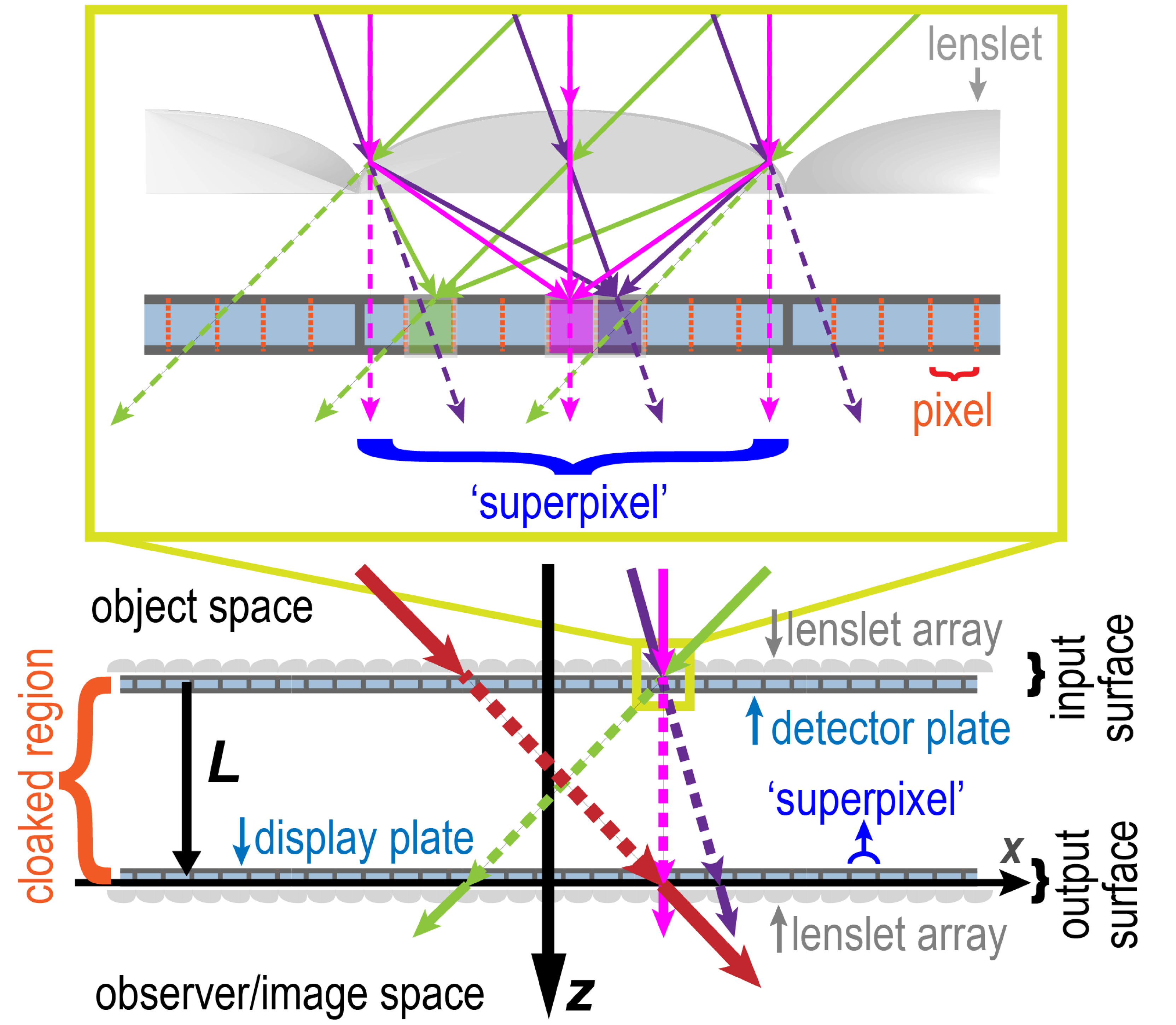




<table>
<tr><th>'Ideal' Cloak Properties</th><th>Transformation Optics[2]</th><th>Paraxial Cloaking [3]</th><th>Discretized Cloaking[1]</th></tr>
<tr><td>Broadband</td><td rowspan="4">Difficult</td><td rowspan="5">Excellent</td><td rowspan="7">Good</td></tr>
<tr><td>Visible spectrum</td></tr>
<tr><td>Isotropic</td></tr>
<tr><td>Macroscopic</td></tr>
<tr><td>3D</td><td>Some challenges</td></tr>
<tr><td>Full-field (+phase)</td><td rowspan="2">Excellent</td><td>Broadband (theory)</td></tr>
<tr><td>Omnidirectional</td><td>Continuous multidirection</td></tr>
</table>

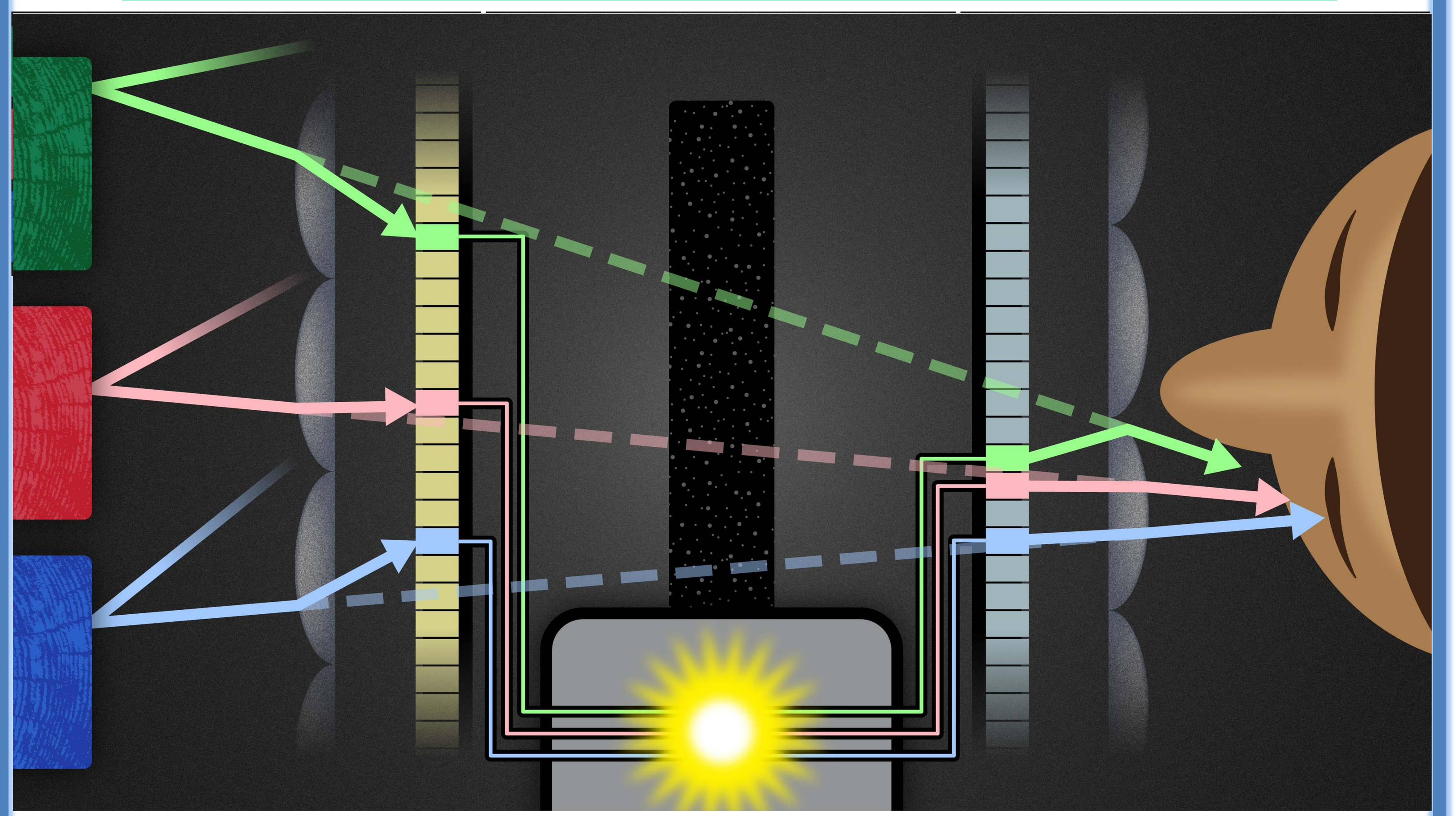
E. Example Digital Integral Cloak

- Simplify to 2D, planar, ray optics:



- **To extend to discretized ideal cloak**
  - **3D**: Use spherical lenslet array (fly's eye lens array).
  - **Phase-matching**: Use corrective plate or spatial light modulator [3].
  - **Arbitrary shape**: (z_f-z_i) depends on input and output pixel pairs positions.
  - **Omnidirectional**: Place emitters and detectors together on closed surface.
  - **Wearable cloak**: Sensors and processor can be used for dynamic shapes.

F. "Digital Rochester Cloak" Principle



(Mike Osadciw / University of Rochester)

G. Demonstrations

*** Horizontal (x) Demo:**

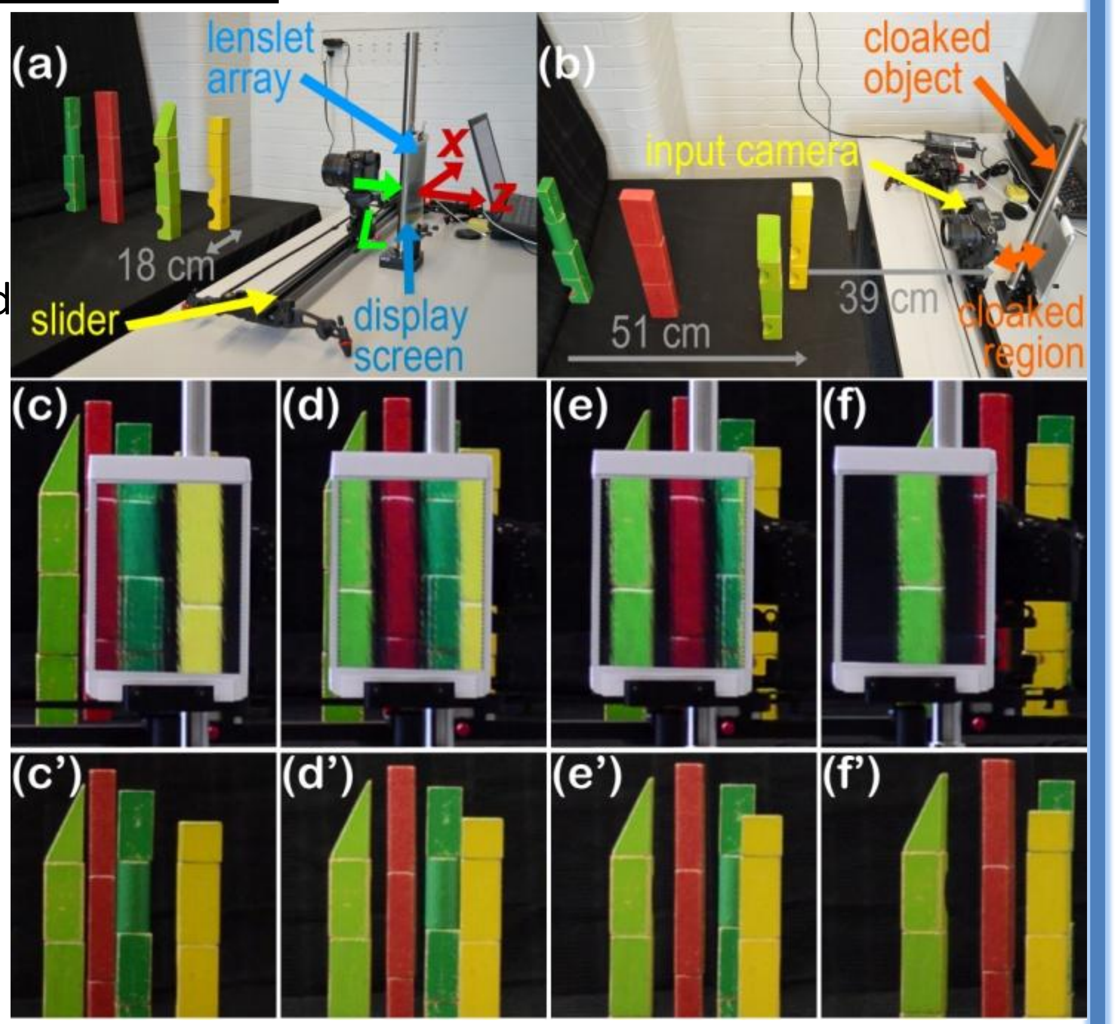
(a)-(b): Setup

(c)-(f): With cloak

(c')-(f'): Without cloak

- 60-90cm depth-of-field
- 29° field-of-view (11° shown)
- 51.5 total "views"
- Output resolution:
  - Angular: 0.56°
  - Spatial: 1.34mm

→ Alignment, parallax matched



*** Longitudinal(z) Demo:**

Distance/FOV from screen

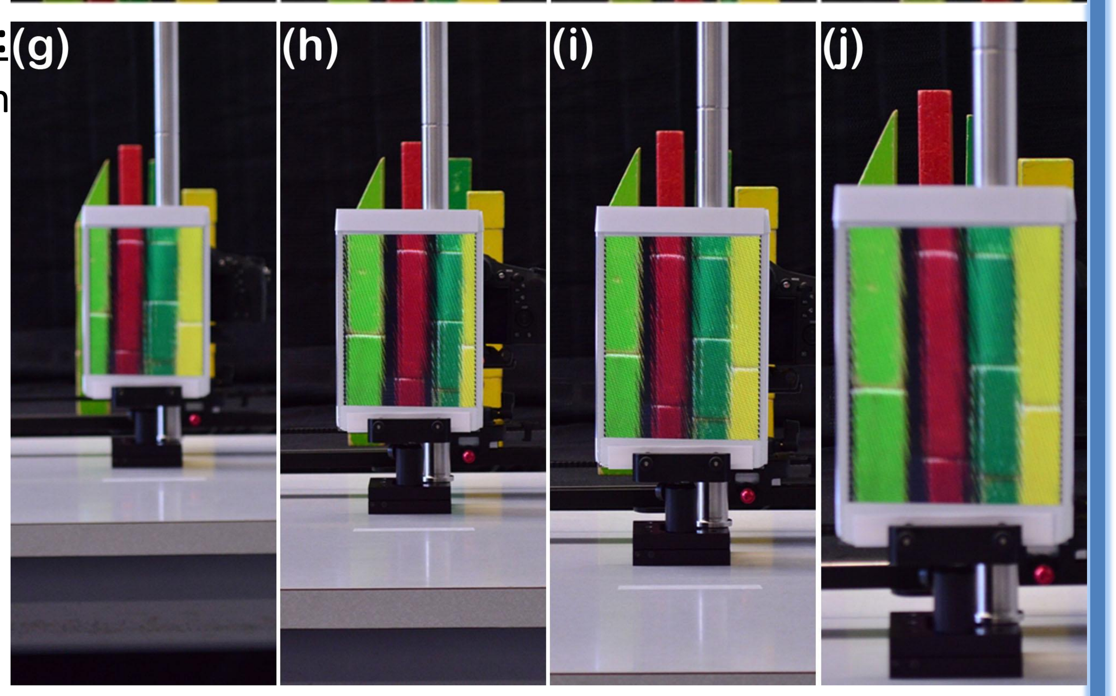
(g) 272 cm / 2.53°

(h) 235 cm / 2.93°

(i) 203 cm / 3.38°

(j) 150 cm / 4.59°

Closer → more seen



H. References

[1] J. Choi and J. Howell, *Optica* **Vol. 3**, Issue 5 (2016).

[2] J. Pendry, D. Schurig, and D. Smith, *Science* **312**, 1780 (2006); U. Leonhardt, *Science* **312**, 1777 (2006).

[3] J. Choi and J. Howell, *Opt. Express* **22**, 29465 (2014); *Opt. Express* **23**, 15857 (2015).

[4] G. Lippmann, *C. R. Acad. Sci.* 146, 446 (1908).

I. Acknowledgment

Aaron Bauer, Greg Schmidt, University of Rochester Communications (Larry Arbeiter, Matthew Mann, Leonor Sierra, Mike Osadciw, Adam Fenster), UR Ventures.

(Created by Joseph Choi; April, 2016) (Select photos by Adam Fenster, J. Choi, J. Howell / University of Rochester)