Paraxial Cloaking- A "Rochester Cloak" [1]

Is an Ideal, Broadband and Omnidirectional Cloak Possible? [2]

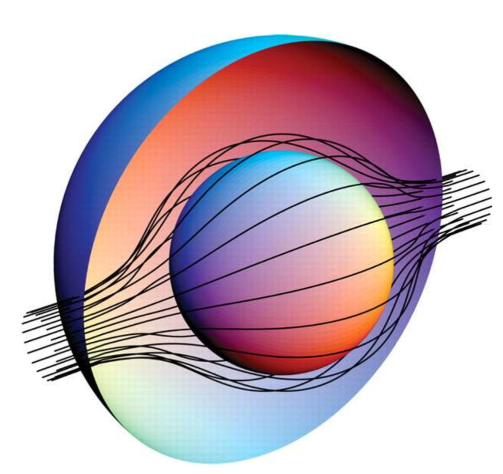
UNIVERSITY of ROCHESTER
THE INSTITUTE OF OPTICS

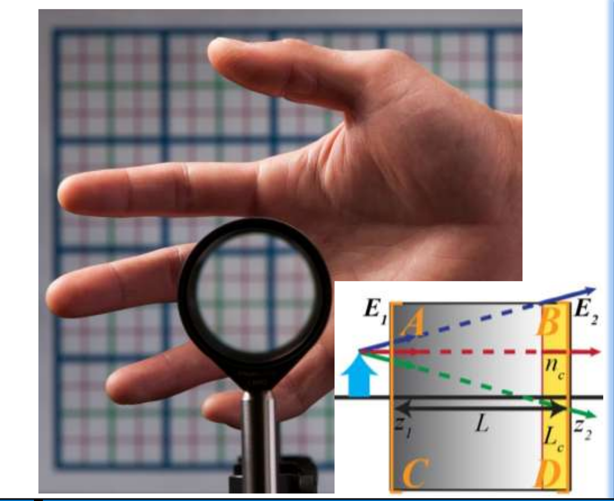
Joseph S. Choi*, John C. Howell**
*The Institute of Optics, University of Rochester, NY, USA (joseph.choi@rochester.edu)
**Department of Physics and Astronomy, University of Rochester, NY, USA (howell@pas.rochester.edu)

ARL DARPA

A. Summary

We use 'paraxial' (small-angle) geometric optics to demonstrate a ray optics cloak, after defining invisibility cloaking quantitatively [1]. To our knowledge, our 4 lens design was the first 3D, transmitting cloak that worked for a continuous range of viewing angles, while being broadband for the visible spectrum. We follow with broadband, full-field (phase + amplitude) matching [2].



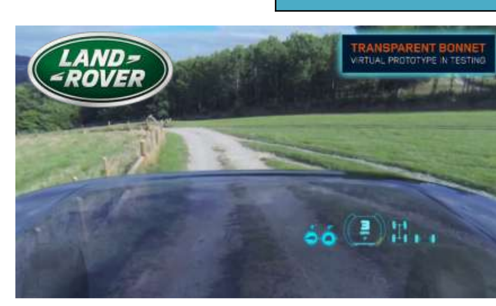


'Ideal' Cloak Properties	Transformation Optics	Initial Ray Optics Cloaking	Paraxial Cloaking
Broadband	Difficult	Excellent	Excellent
Visible spectrum			
Isotropic			
Macroscopic			
3D	Some challenges		
Full-field (+phase)	Excellent	~No (1 or discrete freq.)	Broadband (theory)
Omnidirectional		1 or discrete directions	Continuous multidirection

B. Background

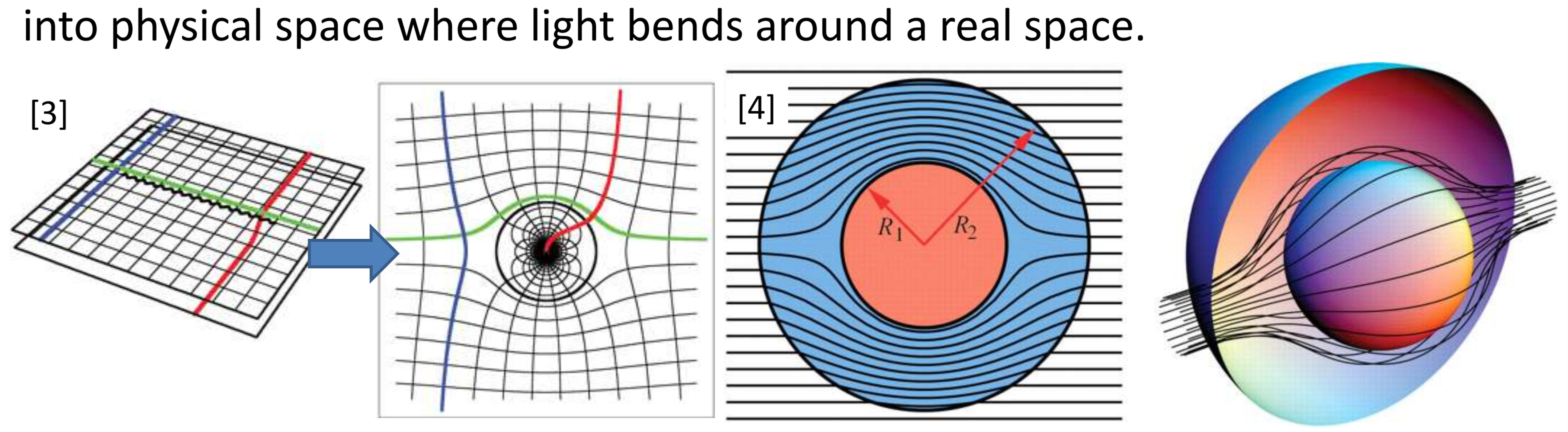
1) **Fiction**: Harry Potter, Star Trek, games, Invisible Man.

2) **Active invisibility**: Tachi Lab (Japan, 2003), Mercedes-Benz (2012), Land Rover (2014).



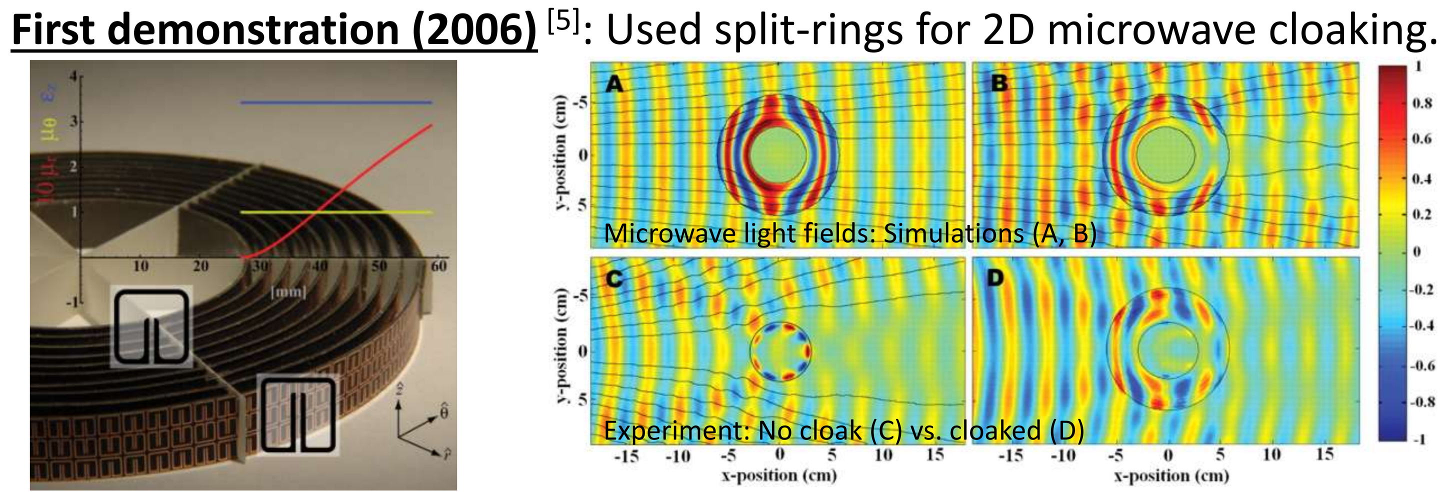
C. Transformation Optics [3,4]

Use coordinate transformations to map a virtual space where no light enters, into physical space where light bends around a real space.



To accomplish this, make 'metamaterials' (artificial materials), that have patterns and electromagnetic properties (ε, μ) dictated by the transform.

- **First demonstration (2006)** [5]: Used split-rings for 2D microwave cloaking.



- Great interest in scientific cloaking followed: Temporal event cloaking, thin radio wave canceling cloak, seismic cloaking, 'carpet' cloaking, etc.

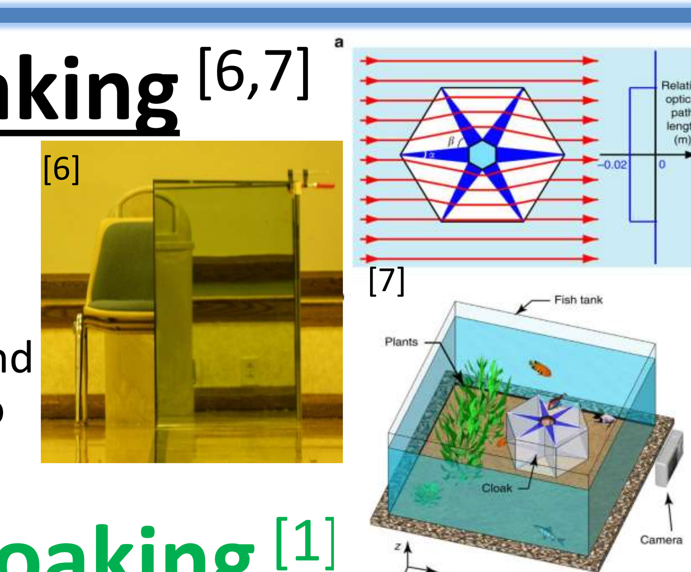
D. Define a "Cloak"

- We use the definition "**to hide**," instead of a wearable clothing.
- A '**perfect' cloak** should:

1) A non-zero volume,
2) Make itself and the hidden object appear transparent.

E. Initial Ray Optics Cloaking [6,7]

- Drop phase-matching of light fields to build macroscopic cloaks for visible light.
- Limited to 1 direction, or discrete directions.
- Issues: For change in viewing angles, background shifts, or cloaking region revealed. Also, some do not match magnification with object.

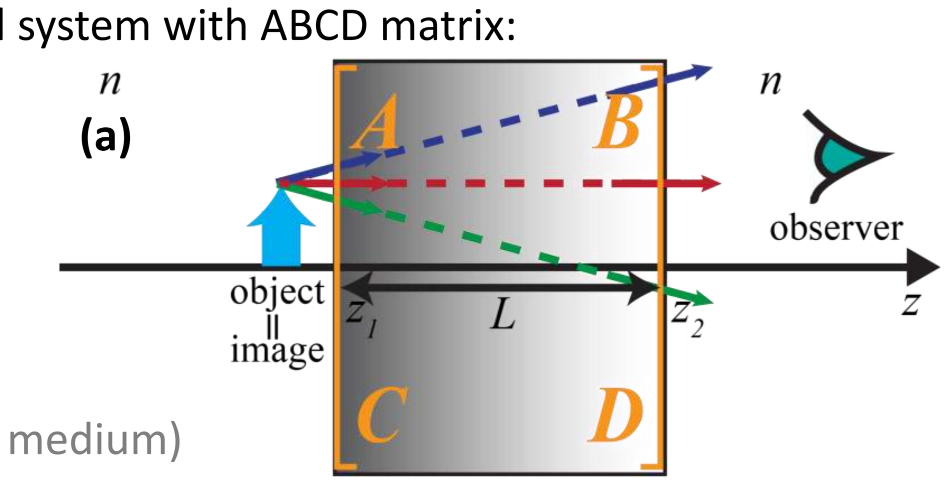


F. Paraxial *Ray Optics* Cloaking [1]

- **Quantitatively define "cloaking"**: Using geometric optics, in the small-angle ('paraxial') limit, a cloak is an optical system with ABCD matrix:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{perfect\ cloak} = \begin{bmatrix} 1 & L/n \\ 0 & 1 \end{bmatrix}$$

(L = Length of the cloaking system,
n = Refractive index of the ambient medium)



G. Solve Cloaking ABCD Matrix

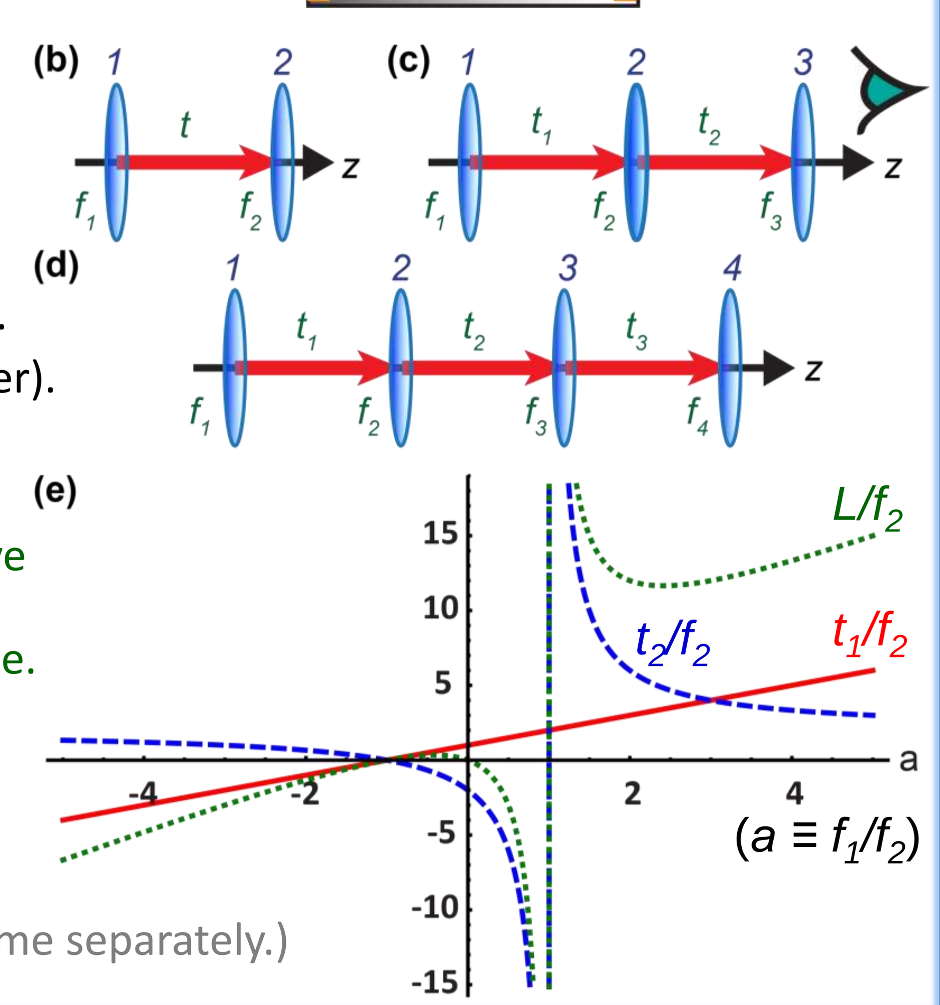
(a) Find **simplest** ABCD solution: Use rotationally symmetric thin lenses.

(b) **1 or 2 lens(es)**: $f_1=f_2=\pm\infty$ (no power).

(c) **3 lenses**: Can asymptotically approach 'perfect' cloak for $L\to0$.

(d) **4 lenses**: At least 4 needed to solve 'perfect' cloak ABCD with lenses *and* have non-zero cloaking volume.

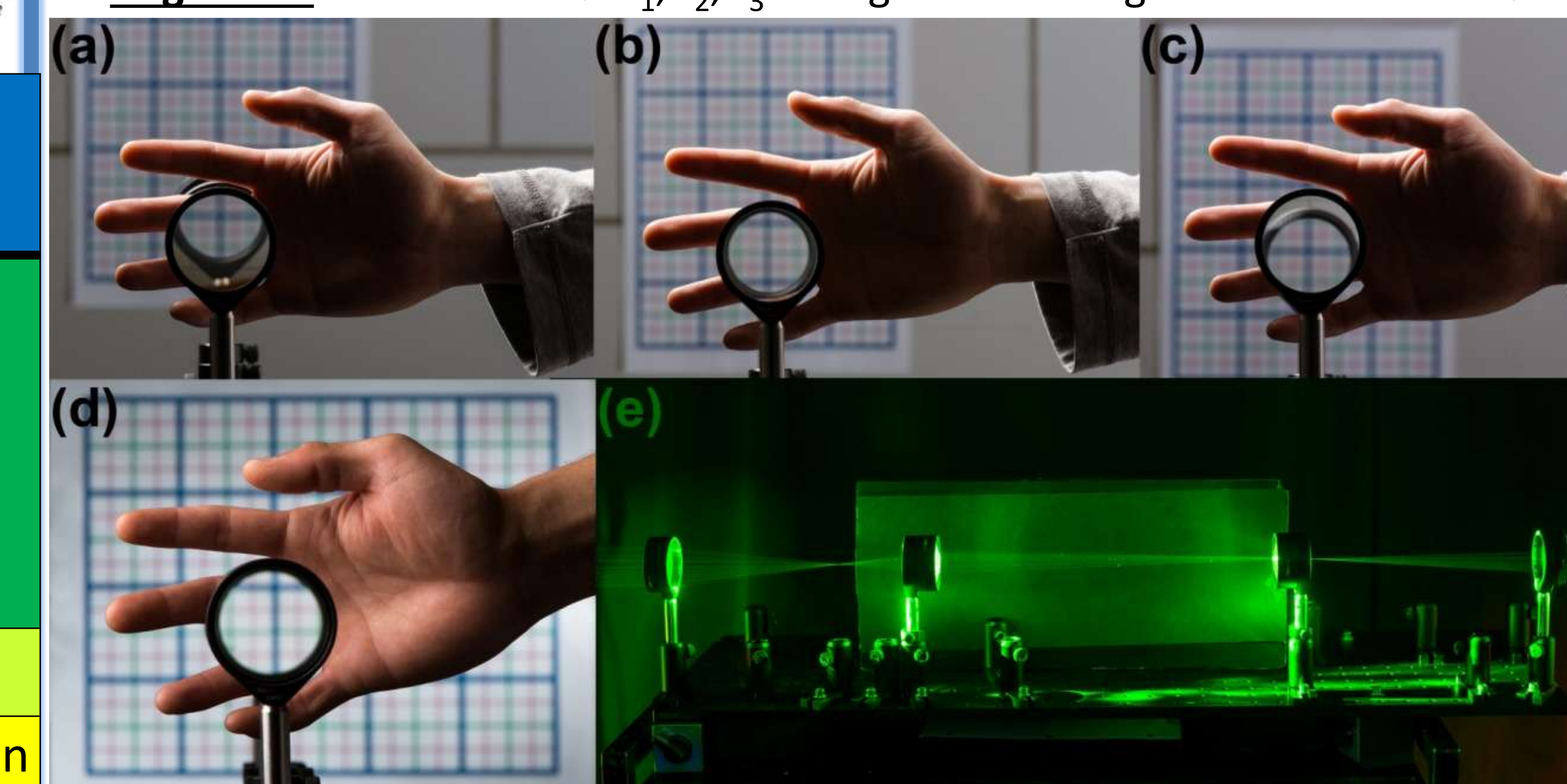
(e) Figure **(e)** shows all left-right symmetric ($f_1=f_4$, $f_2=f_3$, $t_1=t_3$) 4 lens cloaking solutions *.



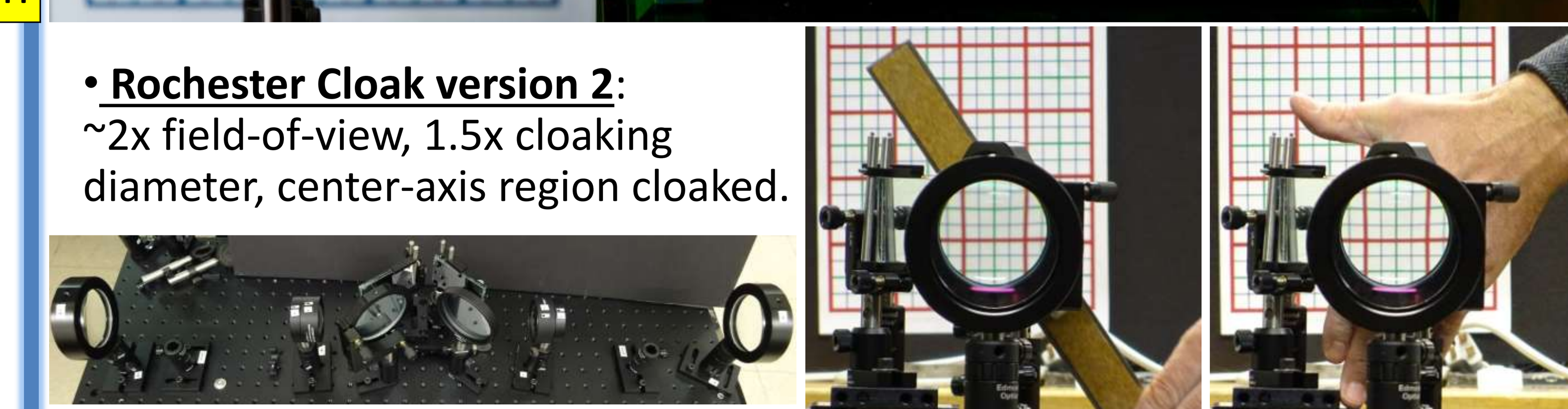
* (Need to check non-zero cloak volume separately.)

H. "Rochester Cloak"

- **4 lens cloak** that solves 'perfect' cloak ABCD matrix with cloakable volume.
- **Advantages**: Broadband for entire visible spectrum, 3D, isotropic, macroscopically scalable, and uses off-the-shelf optics.
- **Limitations**: Center *not* cloaked, ~3° field-of-view, edge effects, not full-field.
- **Alignment**: Sensitive. ~1% t_1, t_2, t_3 change causes magnification=1 to ~50%.



- **Rochester Cloak version 2**: ~2x field-of-view, 1.5x cloaking diameter, center-axis region cloaked.



I. Paraxial *Full-Field* Cloaking [2]

1) **Field propagation** (Huygens' integral in Fresnel (paraxial) approximation):

$$\tilde{E}_2 = i\frac{e^{-ik_0L_0}}{B\lambda_0}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\tilde{E}_1 \exp\{-i\frac{\pi}{B\lambda_0}[A(x_1^2+y_1^2)-2(x_1x_2+y_1y_2)+D(x_2^2+y_2^2)]\}dx_1dy_1$$

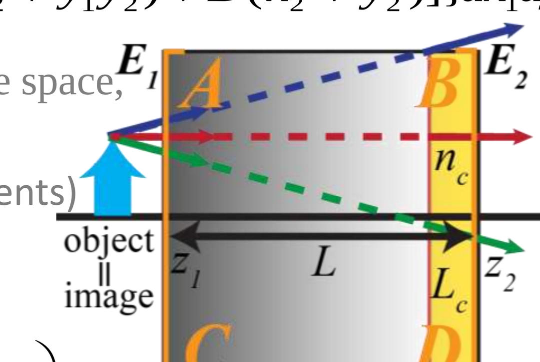
($L_0=\Sigma_i n_i L_i$ = On-axis optical path length, (x,y)= Transverse space,
λ_0, k_0 = Wavelength, wave vector ($2\pi/\lambda_0$) in vacuum,
$\tilde{E}$ = Complex field amplitude, (**A**,**B**,**C**,**D**) = Matrix coefficients)

2) **Full-field phase-matching**:

Add a thin, flat plate with index n_c and length L_c.

$$n_c(\lambda_0) = n(\lambda_0) + \frac{1}{L_c}\left(m\lambda_0 + \sum_i[n(\lambda_0)-n_i(\lambda_0)]L_i\right)$$

(m = Integer multiple for 2π phase-matching,
n_i, L_i = Index, on-axis length of *original* elements)

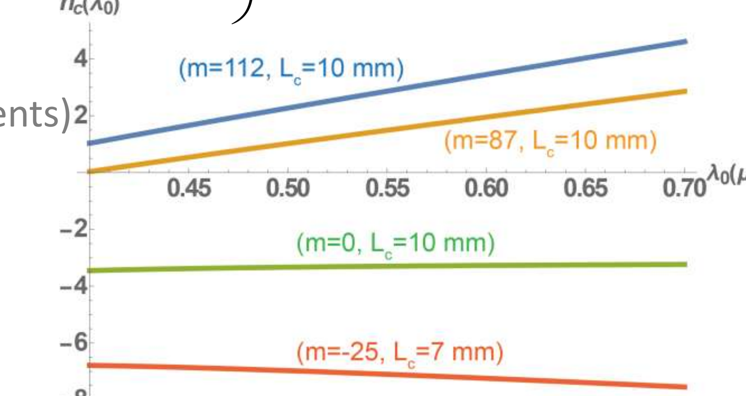


3) **Conclusions and Questions**:

* Paraxial full-field cloaking = Isotropic.
* **Broadband vs. Omnidirectionality**:

→ Cannot have both for cloaking…?

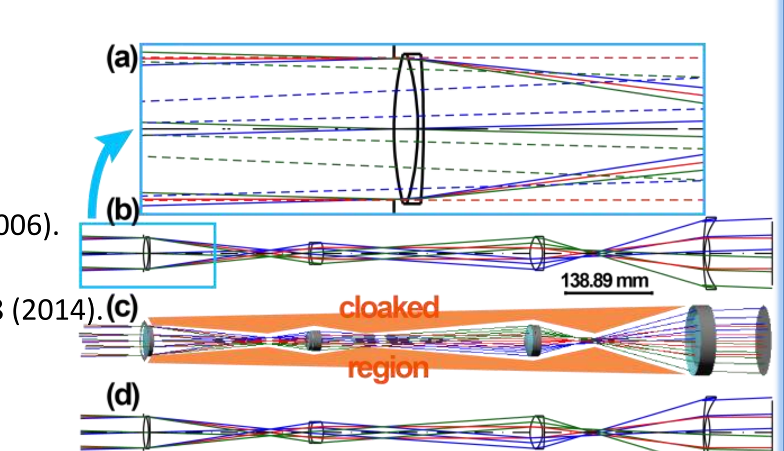
→ Can it be done with isotropic, ray optics?



(Dispersion of "Rochester Cloak" phase-correcting plates.)

J. References

[1] J. Choi and J. Howell, *Opt. Express* **22**, 29465 (2014).
[2] J. Choi and J. Howell, *Opt. Express* **23**, 15857 (2015).
[3] U. Leonhardt, *Science* **312**, 1777 (2006).
[4] J. Pendry, D. Schurig, and D. Smith, *Science* **312**, 1780 (2006).
[5] D. Schurig et al., *Science* **314**, 977 (2006).
[6] J. C. Howell, J. B. Howell, J. Choi, *Applied Optics* **53**, 1958 (2014).
[7] H. Chen et al., *Nature Communications* **4**, 2652 (2013).



K. Acknowledgment

- Funding: Army Research Office, DARPA DSO, Sproull Fellowship (University of Rochester).
- Discussions: Aaron Bauer, Robert Gray, Kyle Fuerschbach, Greg Howland, Prof. Allan Greenleaf, Prof. James Fienup.
- Material: NSF IGERT Fellowship, University of Rochester Communications (Larry Arbeiter, David Barnstone, Adam Fenster, Matthew Mann, Leonor Sierra), UR Ventures, Edmund Optics.