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Luke A. Johnson (MITRE);
Bahman Hafizi (Naval Research Laboratory)

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7515 Colshire Drive
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OUSD LUCI Program Review. 1. Mentored multiple students, outreach to optics community, and worked to fill expertise gap at NRL. 2. Learned that homogenous super-Gaussian coherence functions are impossible. 3. Developed visualization for complex fields. 4. Used genetic algorithm to generate partially coherent beams. 5. Developed adaptive, symmetric split-step laser propagation code. 6. Observed that hot spots from non-uniform coherence functions are maintained in Kerr medium. 7. Observed features of optical wave chaos in carbon disulfide.

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Statistical Formulation of Nonlinear Optics for Describing the Propagation of Partially Coherent, High Power Laser Beams

Principal Investigators: Luke A. Johnson (MITRE), Bahman Hafizi (Naval Research Laboratory)

Academic Advisor: Thomas Antonsen (University of Maryland)

LUCI Program Review 2023

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The NRL-MITRE-UMD Collaboration

Bahman Hafizi, Naval Research Labs, Washington, DC
Luke Johnson, MITRE, McLean, VA
Thomas Antonsen, Univ. of Maryland, College Park, MD

MITRE - Sean McDaniel, Siggy Scott
U. of Rochester - Dan Younis
UMD - Satvik Manjigani, Ben Schreyer

Org	FY22	FY23	FY24
NRL	$50k	$100k	$150k
MITRE	$150k	$100k	$50k

Scientific Motivation

- Nonlinear optics is largely focused on coherent fields.
- Statistical optics is largely focused on weak fields.
- Intense random fields occur in;
  - atmospheric turbulence,
  - refraction through the sea surface,
  - laser amplifiers, and more.
- Potential applications include;
  - directed energy or laser machining,
  - optical random number generators, and
  - high bandwidth multimode optical fibers.

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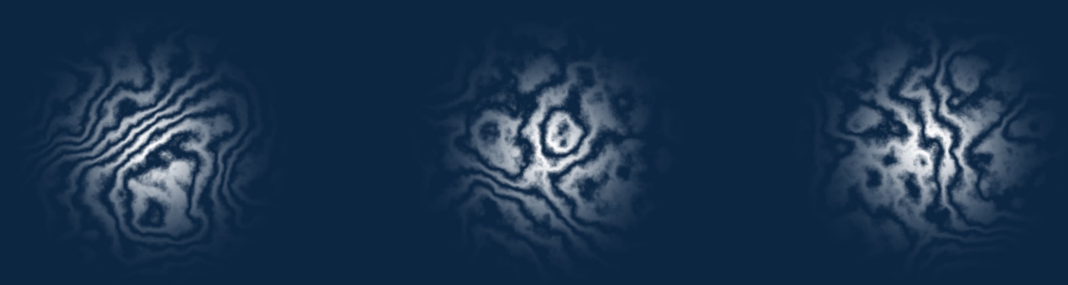
Scientific Objectives

(1) Study the role that **non-ideal, fluctuating laser beams** have on fundamental nonlinear optical phenomena.

(2) **Shape beams using spatial coherence** in nonlinear media.

Real part of a partially coherent laser beam



The field is a spatially-dependent, complex, **random** variable.

Background: Nonlinear Optics in Dielectrics

Nonlinear Schrodinger equation (NLSE) for the laser envelope A describes key dynamics relevant to high power laser propagation.

NLSE: $$2ik_0 \frac{\partial A}{\partial z} = [-\nabla_\perp^2 + V(\mathbf{r}, z, A)]A$$

Diffraction

Potential: $$V(\mathbf{r}, z, A) = \frac{4\pi e^2}{mc^2} n_e(\mathbf{r}, z) - \frac{\omega_0^2 n_0^2 n_2}{4\pi c} |A|^2$$

Plasma

Optical Kerr

Well established beam dynamics:

- Self-focusing and filament on-set
- Beam breakup (modulation instability)
- Laser filamentation
- Frequency generation (not shown)

Missing Physics: The field envelope A is a spatially-dependent, complex, **random** variable.

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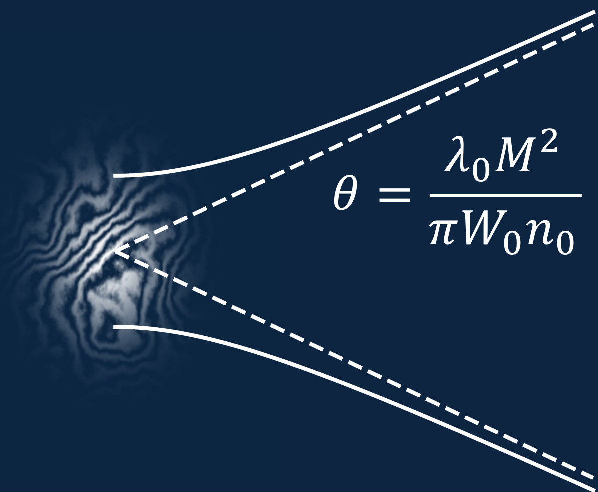
Key Accomplishments of 2022

1. Mentored multiple students, outreach to optics community, and worked to fill expertise gap at NRL.
2. Learned that homogenous super-Gaussian coherence functions are impossible.
3. Developed visualization for complex fields.
4. Used genetic algorithm to generate partially coherent beams.
5. Developed adaptive, symmetric split-step laser propagation code.
6. Observed that hot spots from non-uniform coherence functions are maintained in Kerr medium.
7. Observed features of optical wave chaos in carbon disulfide.

2. Super Gaussian Coherence Function is Impossible



$$\theta = \frac{\lambda_0 M^2}{\pi W_0 n_0}$$

We predicted that super Gaussian coherence functions do not increase beam divergence.

$$M^4 = 1 + \frac{W_0^2}{2\rho_c^2} - \frac{P}{P_{\mathrm{crit}}}$$

0

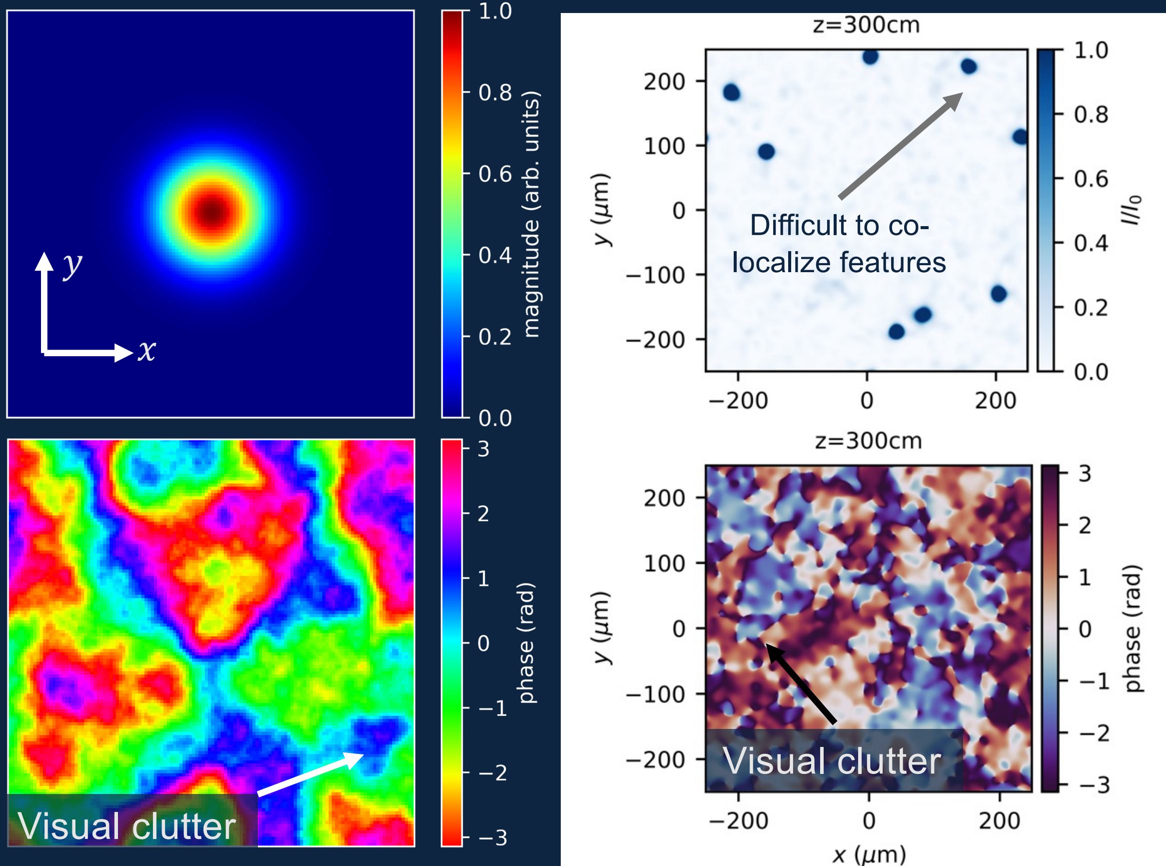
Speckle control w/o high divergence!

Physically realizable ⇔ Fourier transform of coherence is non-negative

Open Questions:

- Inhomogeneous coherence functions?
- Fourier composition of novel realizable coherences?

3. Visualization of Complex Field A



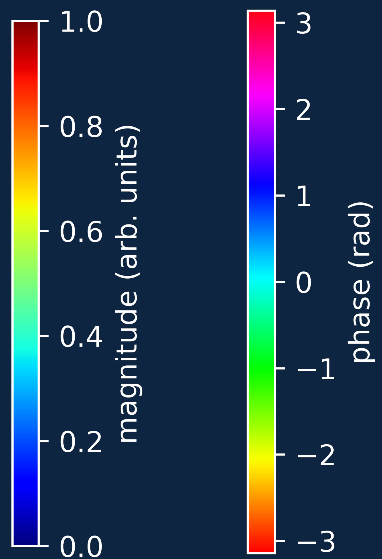
$$A(\mathbf{r}) = S(\mathbf{r})e^{i\phi(\mathbf{r})}$$

Magnitude

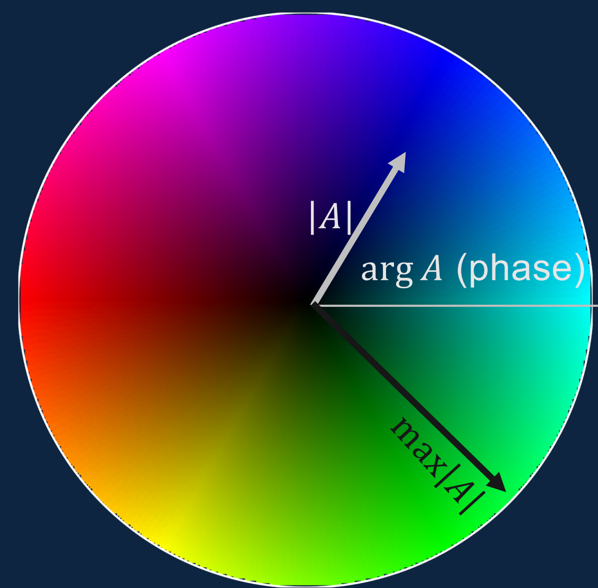
Phase

3. Solution: Replace 2 Colorbars with 1 Colordisk

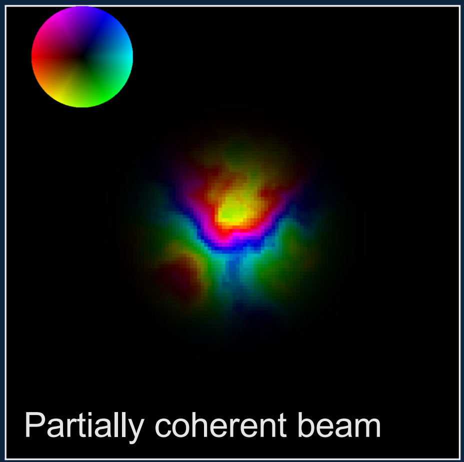
Two 1D Colormaps
$(|A|) \rightarrow (r, g, b)$
$(\arg A) \rightarrow (r, g, b)$

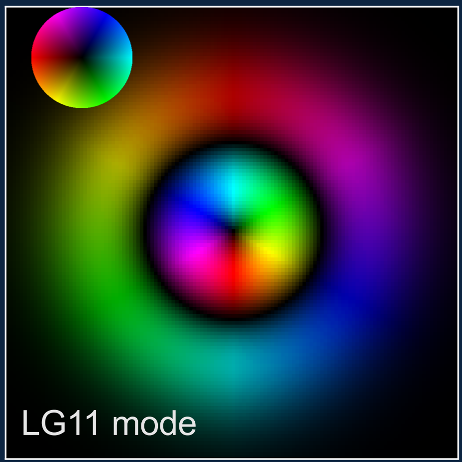


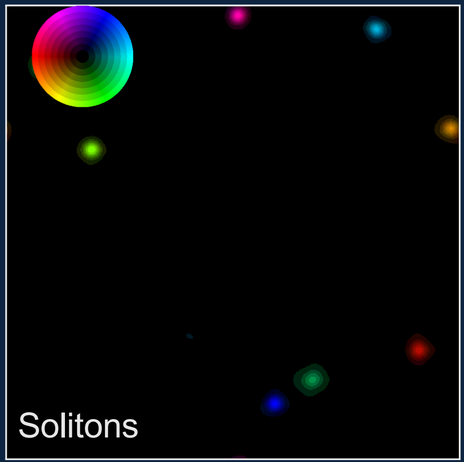
One 2D Colormap
$(|A|, \arg A) \rightarrow (r, g, b)$



3. Example Visualizations of Complex Fields







Valuable for exploratory data visualization in optics.

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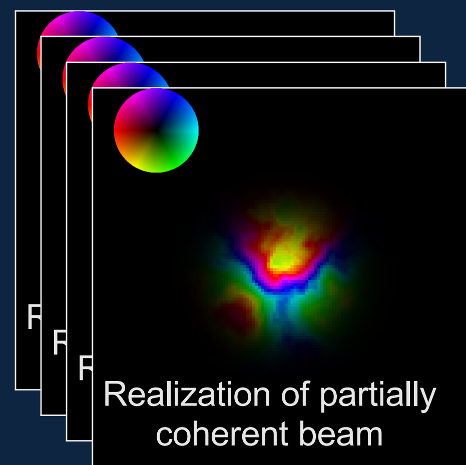
4. AI Generation of Partially Coherent Beams

random number seeds

parameters

function
f



Evolutionary Algorithm (LEAP)
1. Compare ensemble statistics with target functions
2. Update f

Goal: Generate beams with controllable 1st and 2nd order statistics.

LEAP, https://github.com/AureumChaos/LEAP/, co-maintained by Siggy Scott

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4. Baby Steps: Brute Force Generation

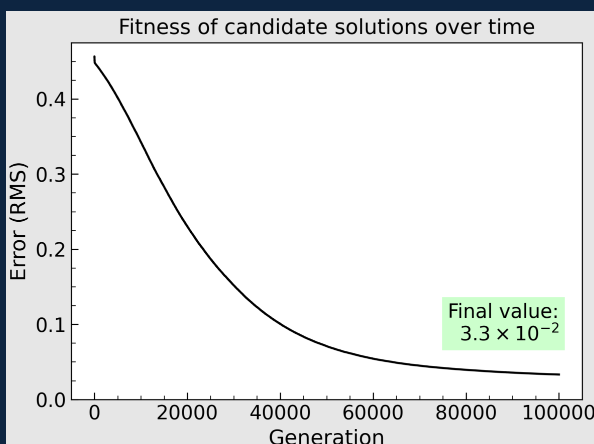
Goal: Generate an ensemble of phase fields $\phi(\boldsymbol{r})$ that are spatially coherent:

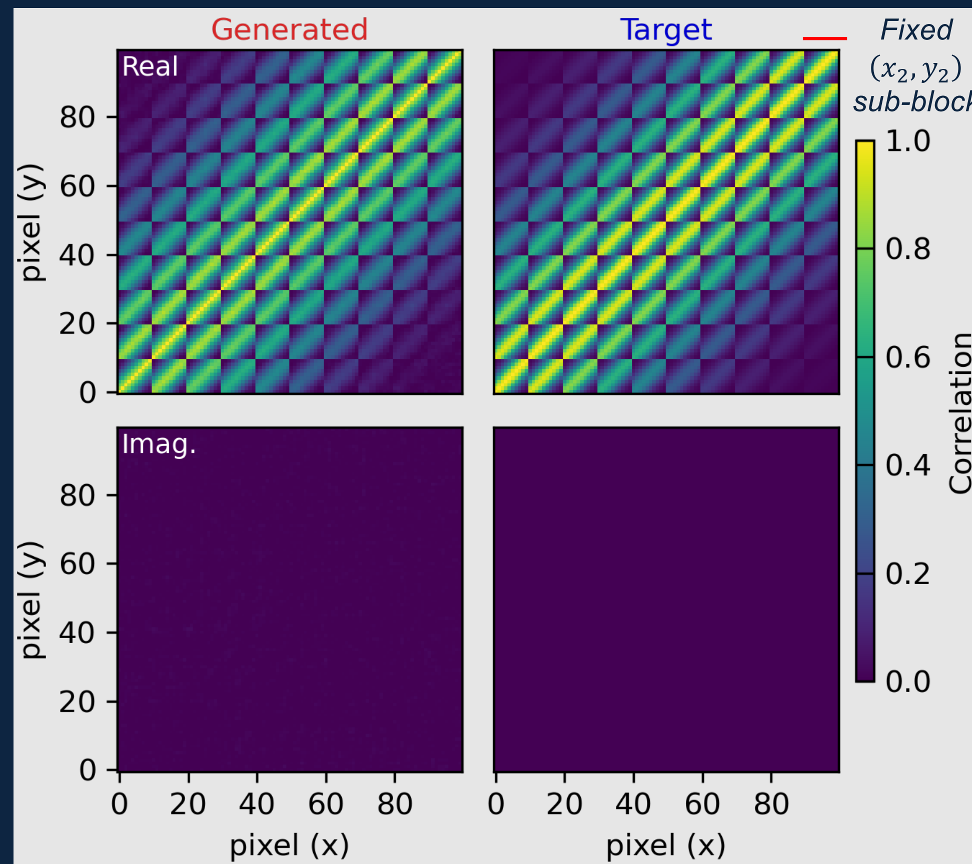
$$\langle \exp i[\phi(\boldsymbol{r}_2) - \phi(\boldsymbol{r}_1)] \rangle = \mu(\boldsymbol{r}_1, \boldsymbol{r}_2),$$

where $\mu(\boldsymbol{r}_1, \boldsymbol{r}_2) = \exp[(-|\boldsymbol{r}_2 - \boldsymbol{r}_1|^2)/\rho_c^2]$ for instance.

Approach: Use an evolutionary algorithm – LEAP (Python)

Example: 250 realizations, $\phi(\boldsymbol{r})$: $10{\times}10$ px





4. Next Steps: Linear Functions

Goal: Generate an ensemble of phase fields $\phi(\boldsymbol{r})$ that are spatially coherent:

$$\langle \exp i[\phi(\boldsymbol{r}_2) - \phi(\boldsymbol{r}_1)] \rangle = \mu(\boldsymbol{r}_1, \boldsymbol{r}_2),$$

where $\mu(\boldsymbol{r}_1, \boldsymbol{r}_2) = \exp[(-|\boldsymbol{r}_2 - \boldsymbol{r}_1|^2)/\rho_c^2]$ for instance.

Approach: Find linear transformation from uncorrelated noise to correlated.

Goal: Using multi-objective fitness functions to control 1st and 2nd order statistics.

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5. nlse2d – A python code for statistical nonlinear optics

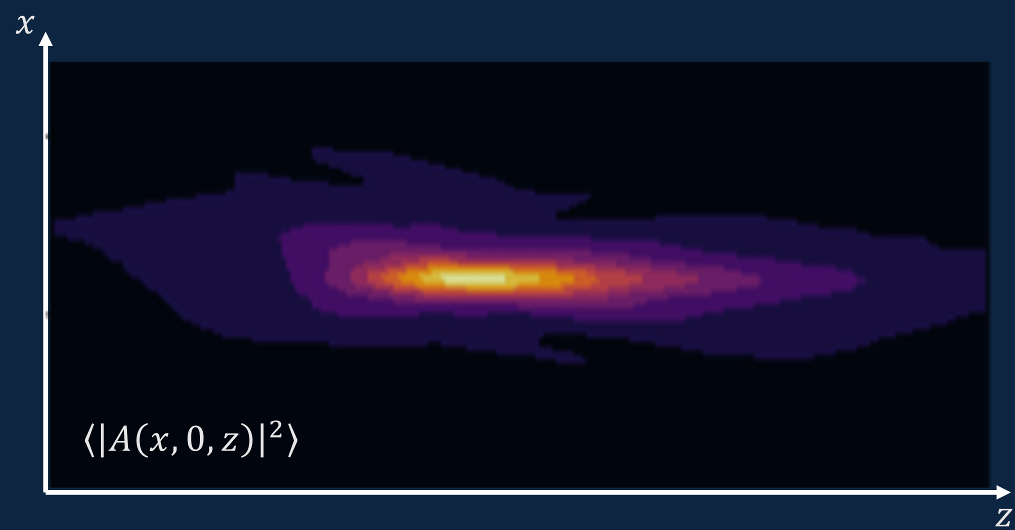
- Solves 2D nonlinear Schrodinger equation

$$\frac{\partial A}{\partial z} = \frac{i}{2}\nabla_\perp^2 A + iV(|A|^2)A$$

where

$$V(|A|^2) = \delta n(|A|^2)/n_0$$

- Normalized
- Symmetric split-step
- Adaptive z-step to resolve nonlinear phase



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6. Propagation Results

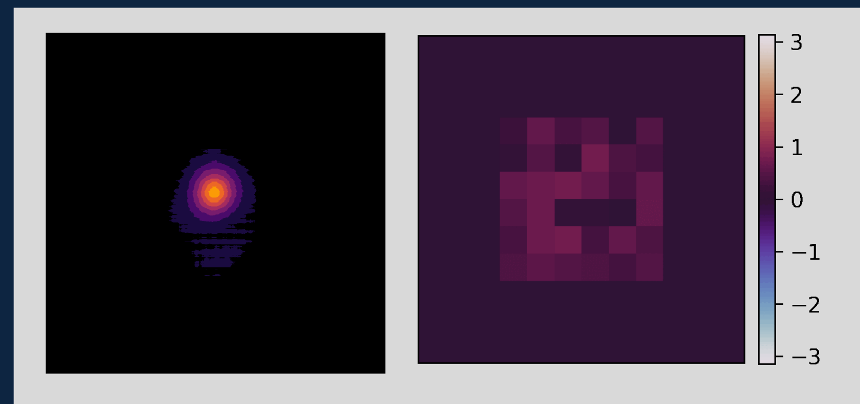
Grid: 512×512
Length: $8192 k_0^{-1}$
Distance: $Z_R = 3.2 \times 10^5 k_0^{-1}$
Beam radius : $800 k_0^{-1}$
Power: $P = 0\ ,1.1 P_{\text{crit}}$

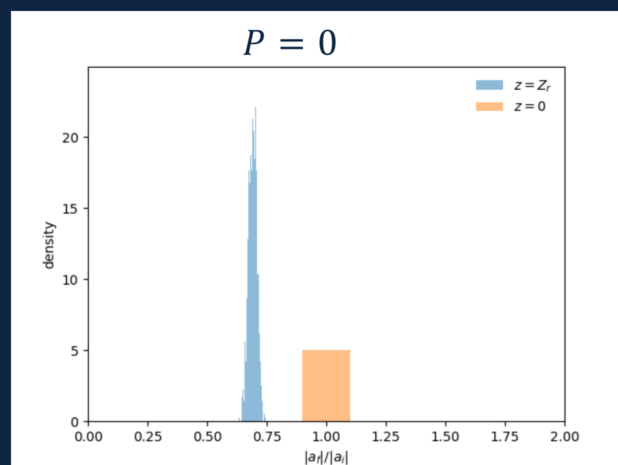
6x6 Deformable Mirror

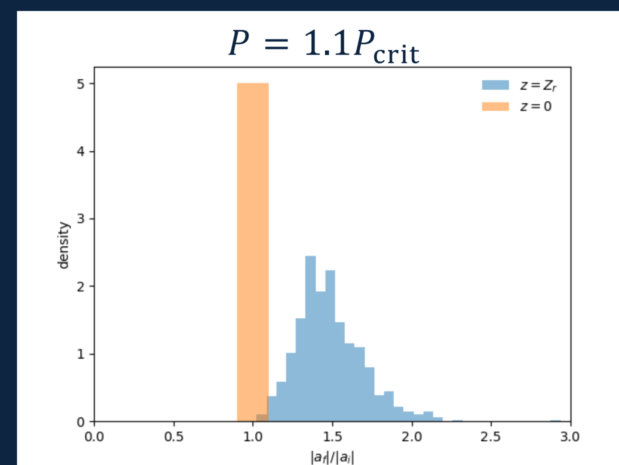
- 6x6 segmented actuators
- Size: $4096 k_0^{-1} \times 4096 k_0^{-1}$

For 6.28micron wavelength these distances are in microns.

nlse2d library: “dm_example.ipynb”







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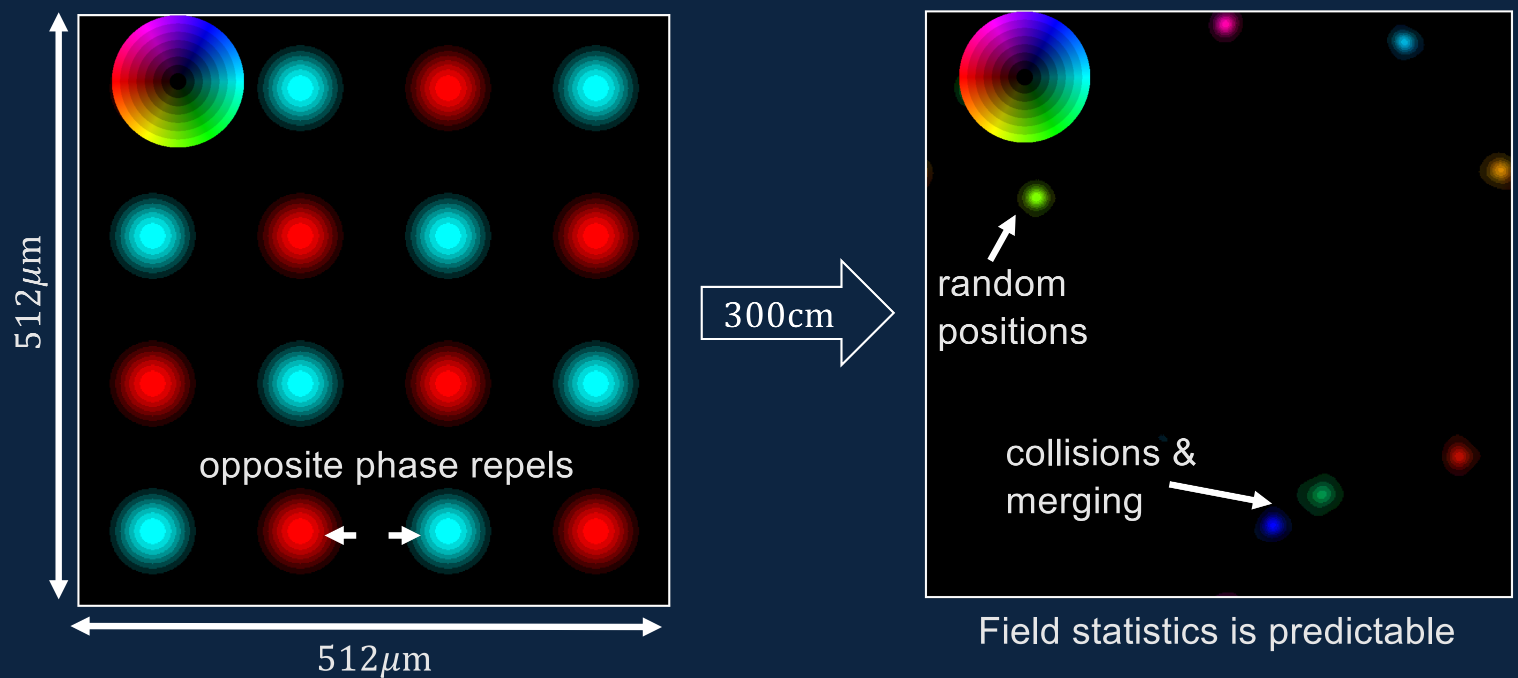
7. Wave Chaos in Carbon Disulfide Optical Soliton Arrays

Carbon disulfide is liquid with huge nonlinear index that can by modeled using $n = n_0 + n_2 I - n_4 I^2$.



Applications: extreme optical filamentation, nonlinear beam merging

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Conclusions

Key Accomplishments:

1. Mentored multiple students, outreach to optics community, and worked to fill expertise gap at NRL.
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Future Work:

- Use multi-objective genetic approach for control of 1st and 2nd order statistics
- Publish comparison between theory and simulation of nonlinear beam divergence.
- Continue mentoring and community outreach.

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Backup

Exotic Partially Coherent Field

- Generation of partially coherent beams is non-trivial.
- Statistical optics literature covers field shaping using coherence function.
- What happens in nonlinear medium?
- Sean ported code for generating twisted anisotropic Gaussian Schell model beams.
- One of only a handful of model beams for spatial coherence.

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