Update on Sub-scale Starshade Testing

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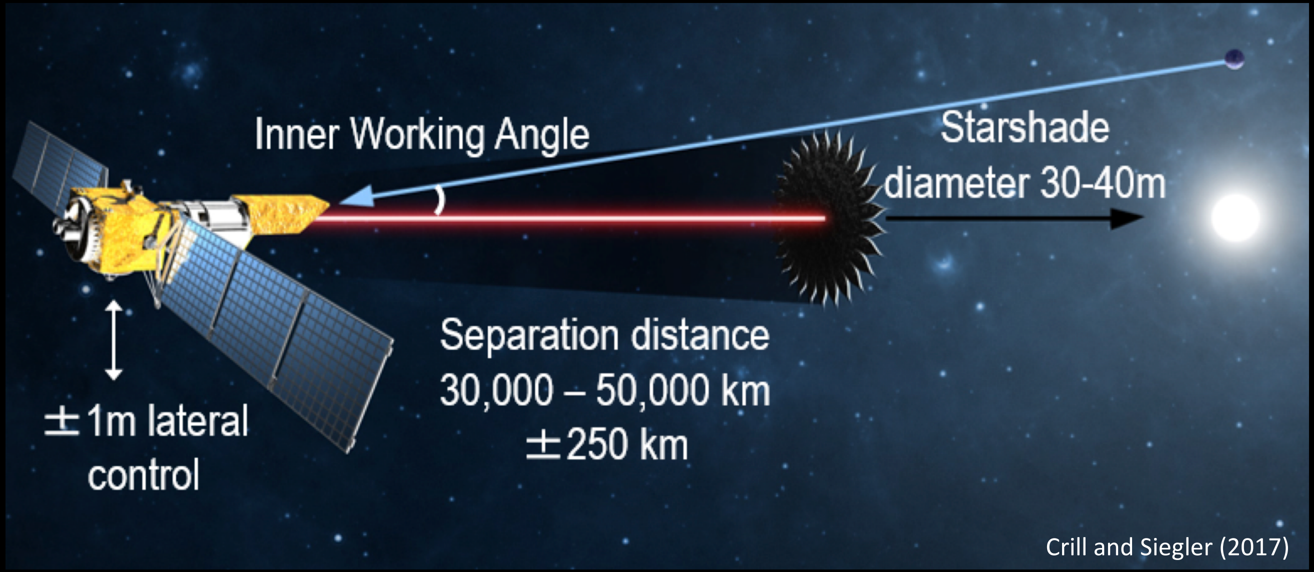
Optical Model Validation

Starlight Suppression and Model Validation

- Key technology area in need of development
  - S-2 ExEP Technology Plan (Crill and Siegler, 2018)

Lack of full-scale starshade test before launch places reliance on optical models to:

- set petal shape tolerance budgets
  - Deployment
  - Mechanical design
  - Materials
- set formation flying tolerances
- inform petal design
- estimate scientific yields



Crill and Siegler (2017)

Sub-scale testing

Physics is identical for consistent Fresnel number

- Under scalar diffraction + Fresnel approximations

$$U(p) \propto \frac{-i}{\lambda z} \iint e^{\frac{i\pi r^2}{\lambda z}}\, r dr\, d\theta$$

$$\propto \frac{-i}{2} \iint e^{i\pi n}\, dn\, d\theta$$

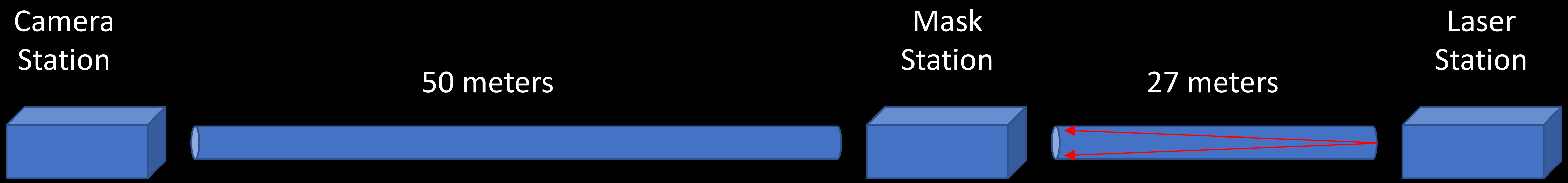
Fresnel Number

$$\boxed{n = \frac{r^2}{\lambda z}}$$

	Starshade Radius (R)	Starshade Separation (z)	Wavelength (λ)	Fresnel Number (N)
Sub-scale lab	12 mm	17.8 m*	633 nm	13
Flight	17 m	35,000 km	633 nm	13

*scaled for diverging beam

Princeton Frick Testbed


Camera Station

50 meters

Mask Station

27 meters

Laser Station

Primary Milestone:

- Demonstrate 10^{-10} contrast at flight-like Fresnel number

Starshade diameter:
- 24 mm

Effective distance:
- 18 m

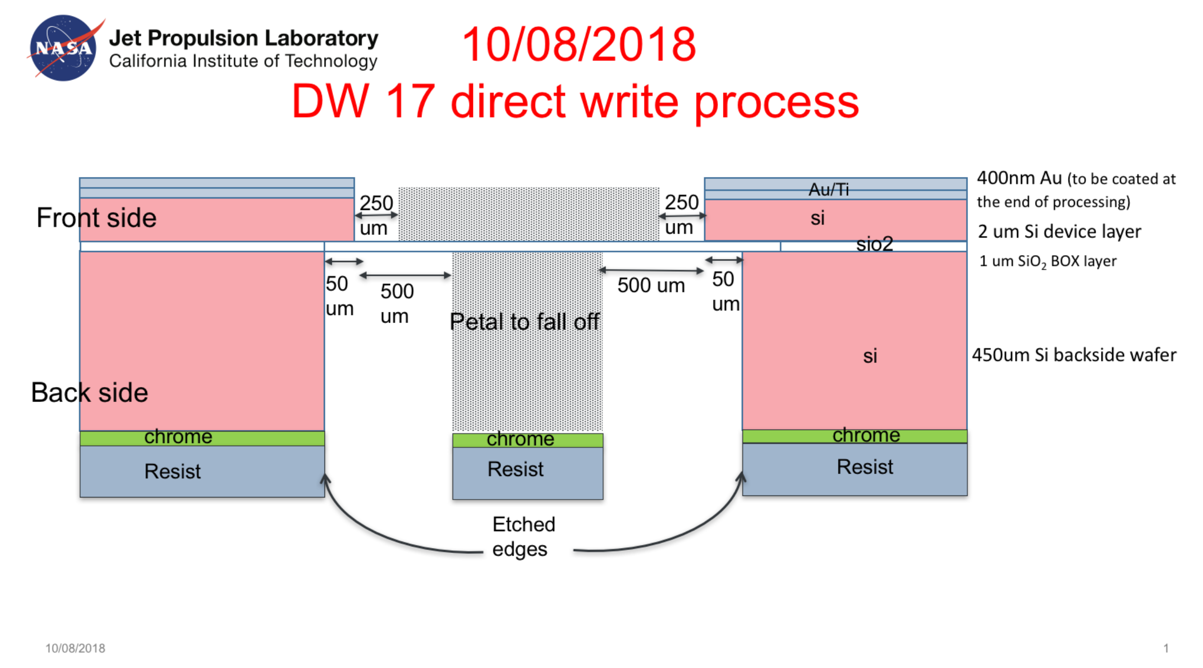
Wavelength:
- 638 nm

Aperture diameter:
- 5 mm
- ~4 resolution elements across SS

Fresnel Number:
- 13

Starshade Masks

- Made at Microdevices Lab (JPL)
- E-beam lithography (direct write)
- Deep Reactive Ion Etching process
- SOI Wafer with 2-7 µm thick device layer



Jet Propulsion Laboratory
California Institute of Technology

10/08/2018

DW 17 direct write process

Front side

250 um

250 um

Au/Ti

si

sio2

400nm Au (to be coated at the end of processing)

2 um Si device layer

1 um SiO_2 BOX layer

50 um

500 um

Petal to fall off

500 um

50 um

si

450um Si backside wafer

Back side

chrome

Resist

chrome

Resist

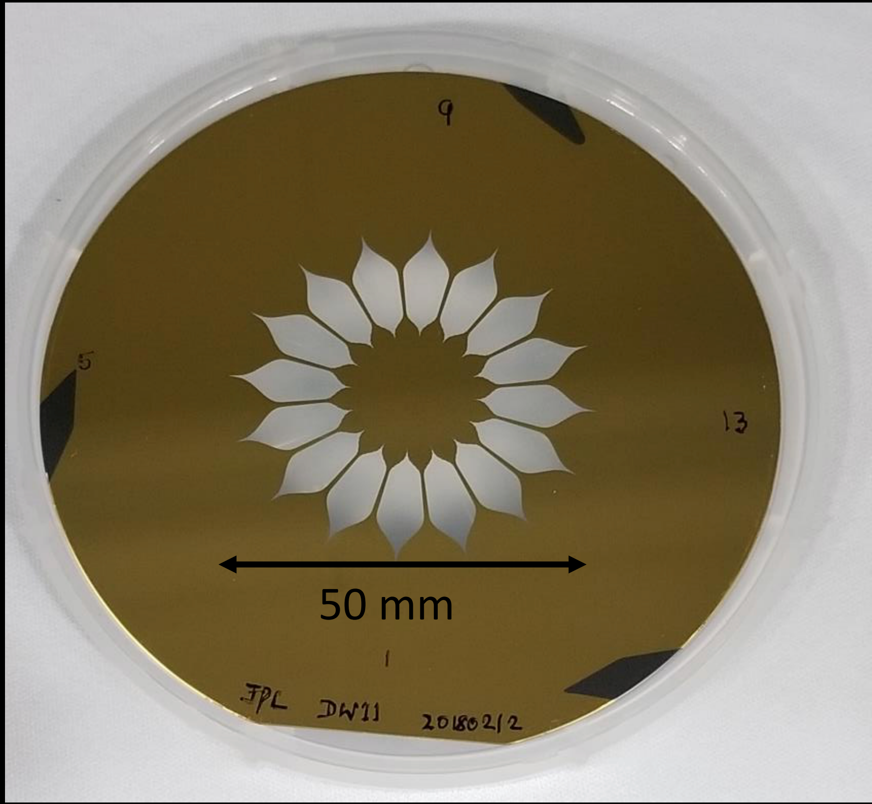
chrome

Resist

Etched edges

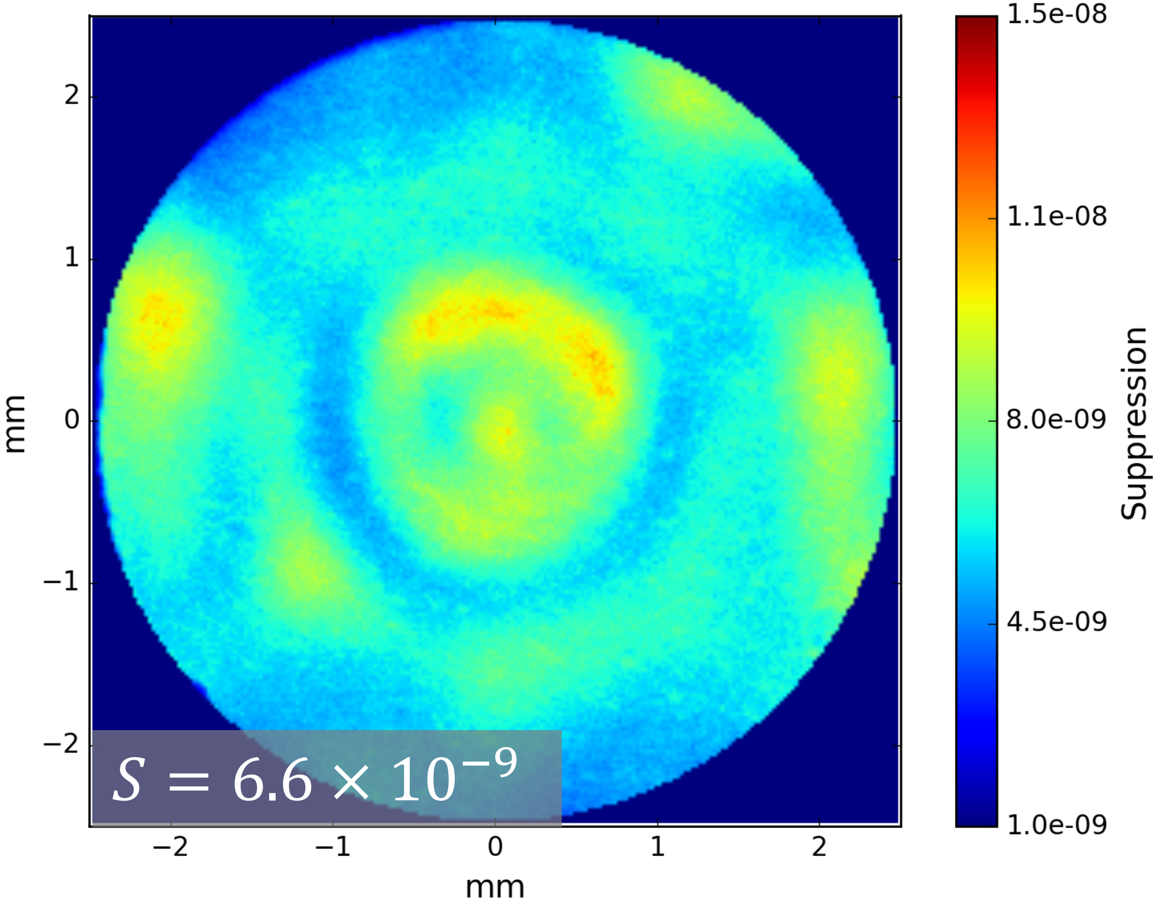
10/08/2018

1



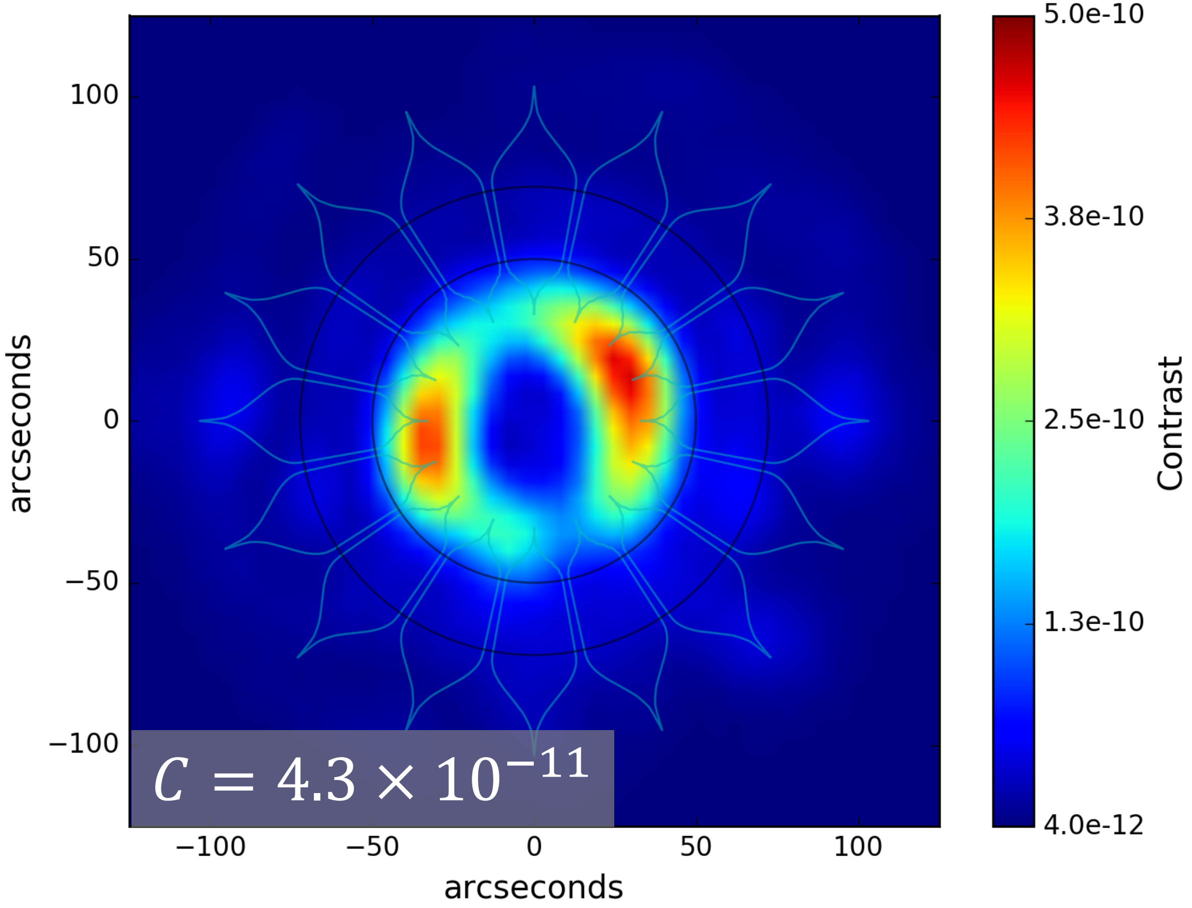
Best Results – DW17

Suppression (*pupil* plane)



$S = 6.6 \times 10^{-9}$

Contrast (*focal* plane)



$C = 4.3 \times 10^{-11}$

Previous Results – CL3

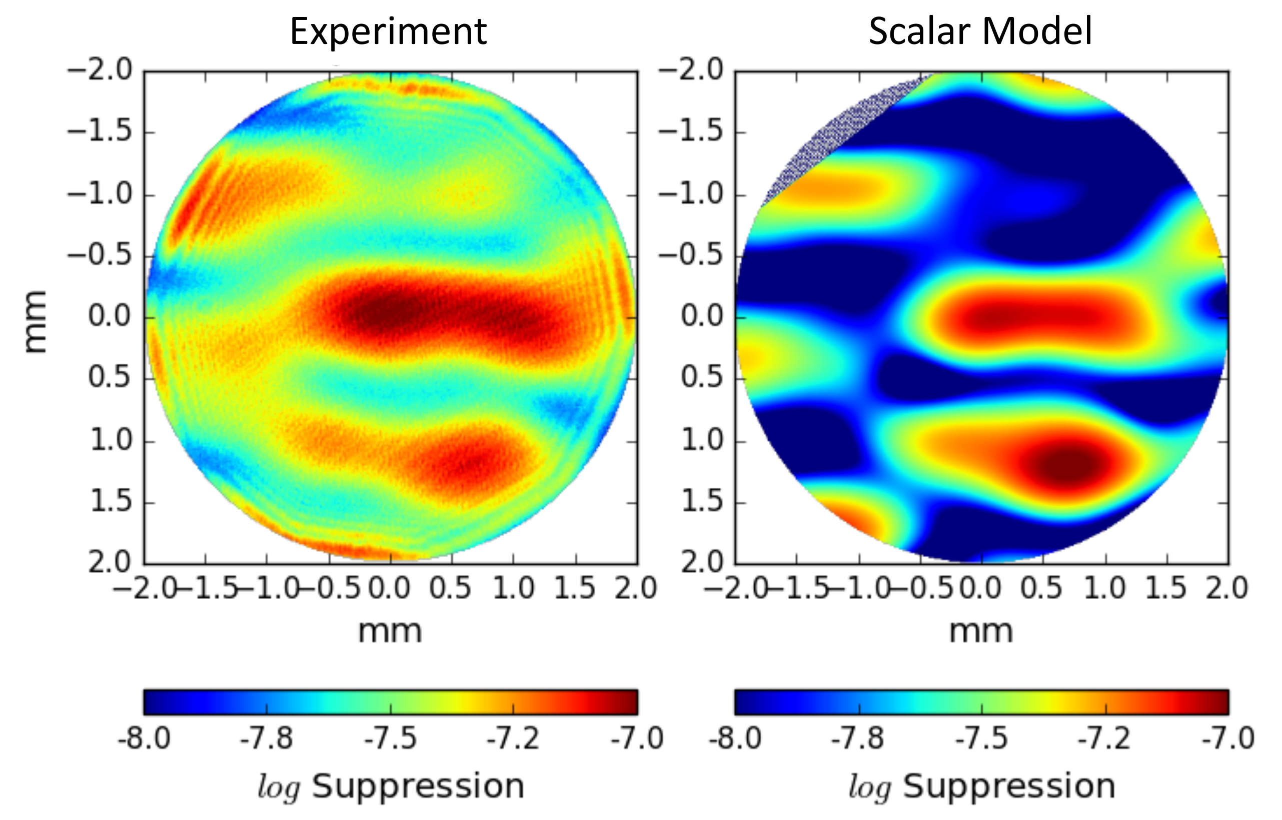
Presented at Mirror Tech Days 2017

Limited to 4×10^{-8} suppression

Mask was over-etched by 400 nm

- 1 µm thin Si_3N_4 device layer

Data/Model agreement



Direct Write Mask – DW9

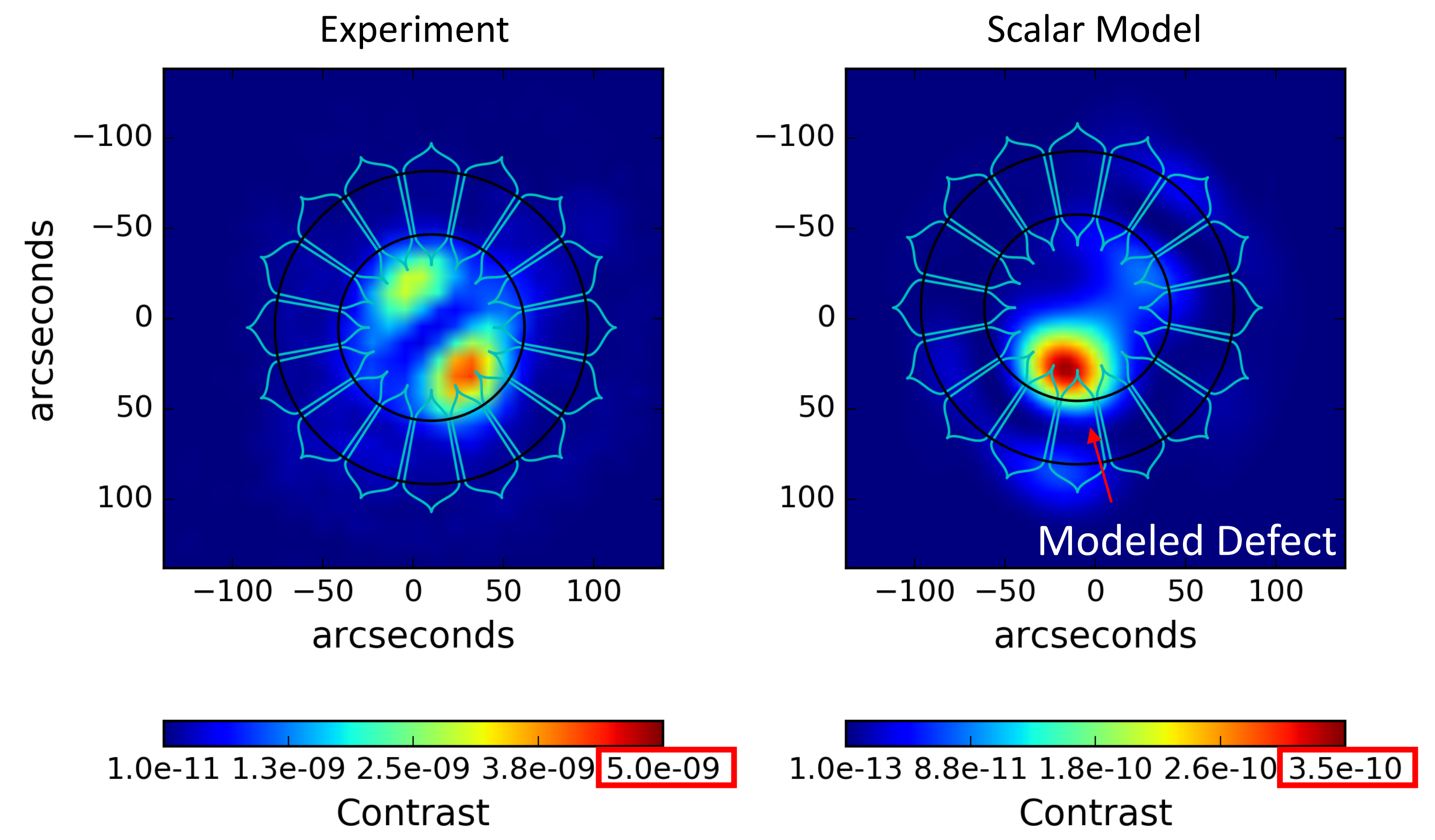
7 µm device layer

- No Si_3N_4 layer

Direct write + no Si_3N_4 layer lessened over-etching problem

- 150 nm overetch
  - Best at that time

Data showed 10x higher contrast than scalar model

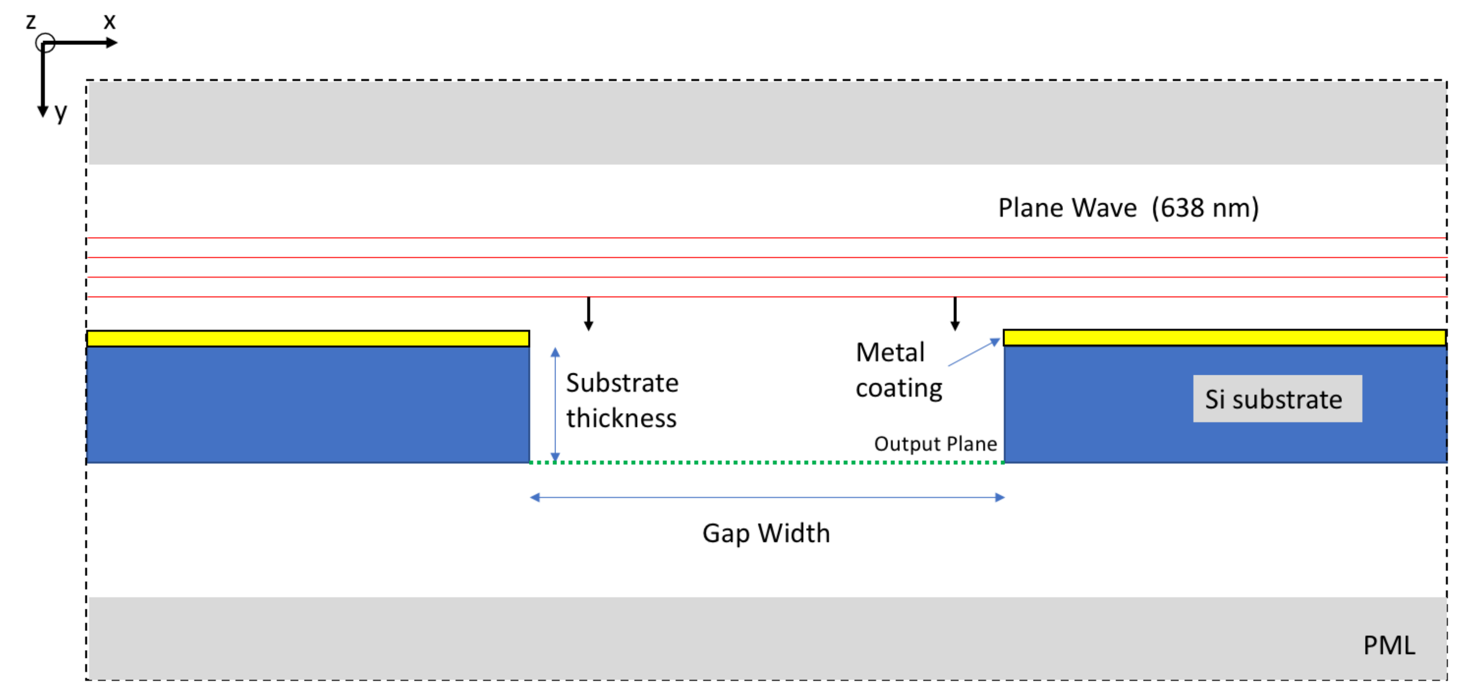


Vector Diffraction Code

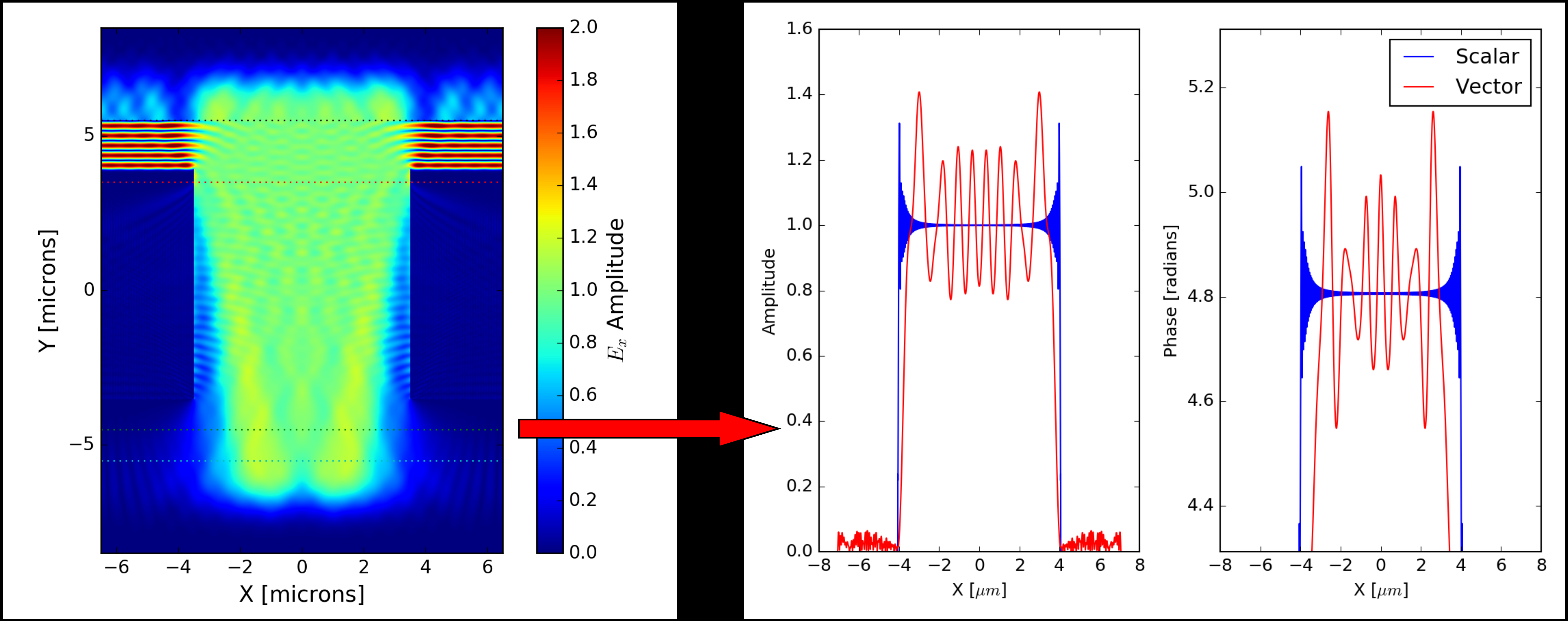
Meep (MIT Electromagentic Equation Propagation)

- A.F. Oskooi, et al., *Computer Physics Communications*, 181, 687 (2010)

- Finite-Difference Time-Domain solver of Maxwell's equations

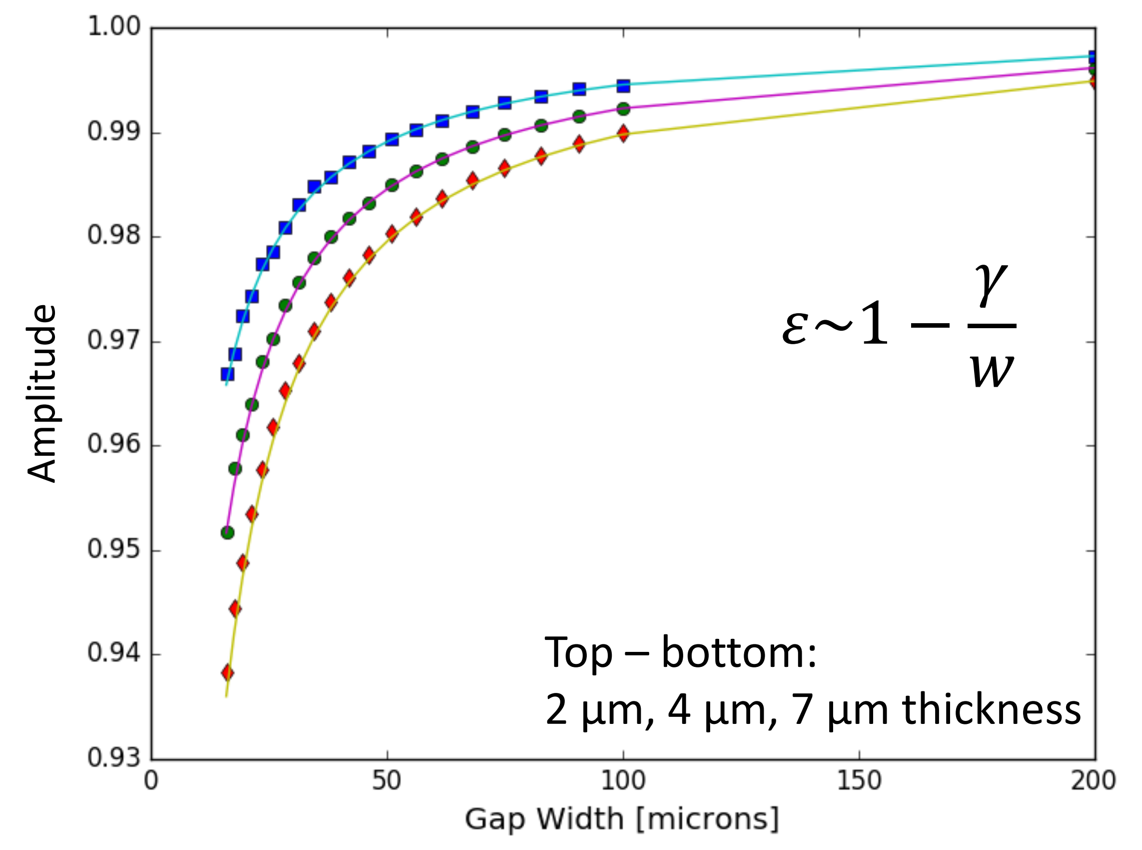


Meep Output



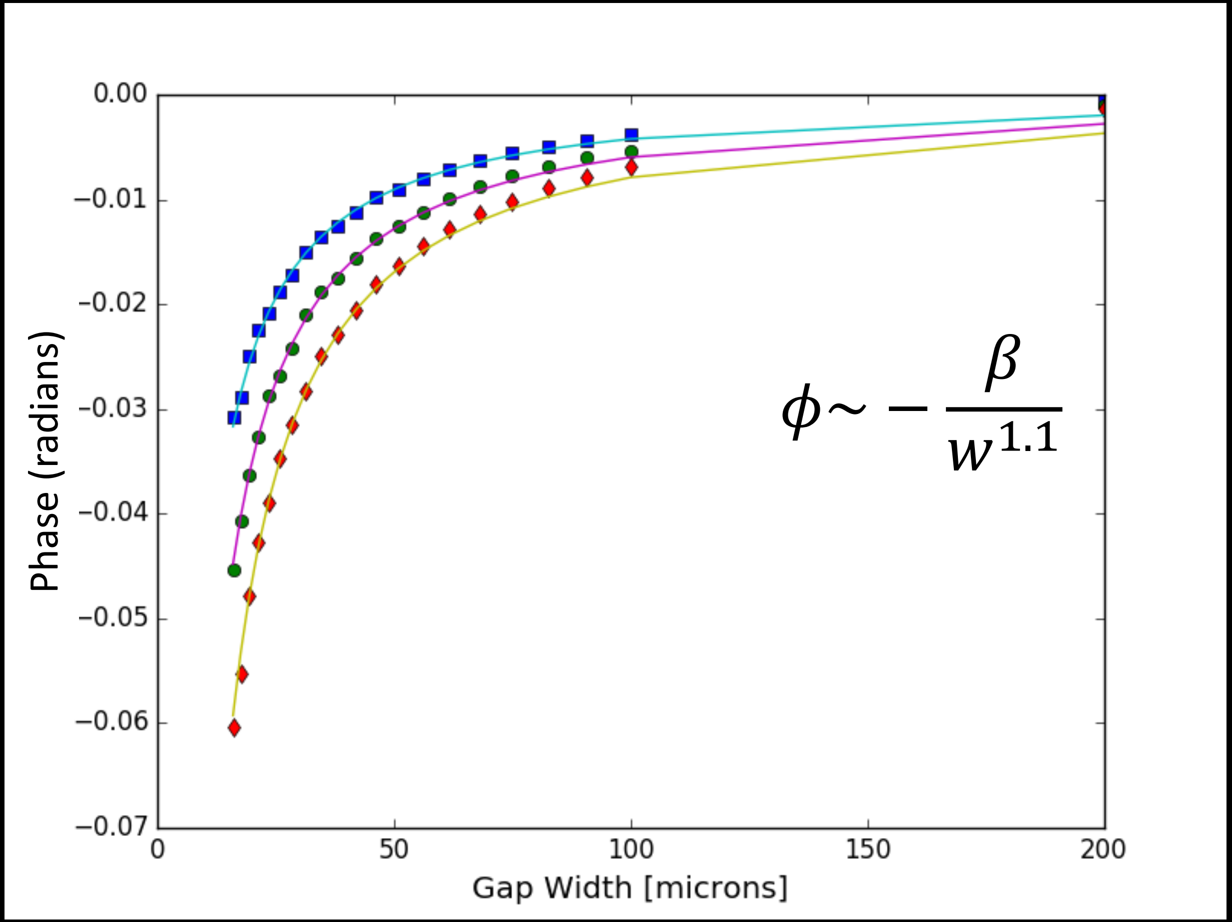
- Gap width = 8 µm
- ’p’ polarization

Field vs Gap Width



$$\varepsilon \sim 1 - \frac{\gamma}{w}$$

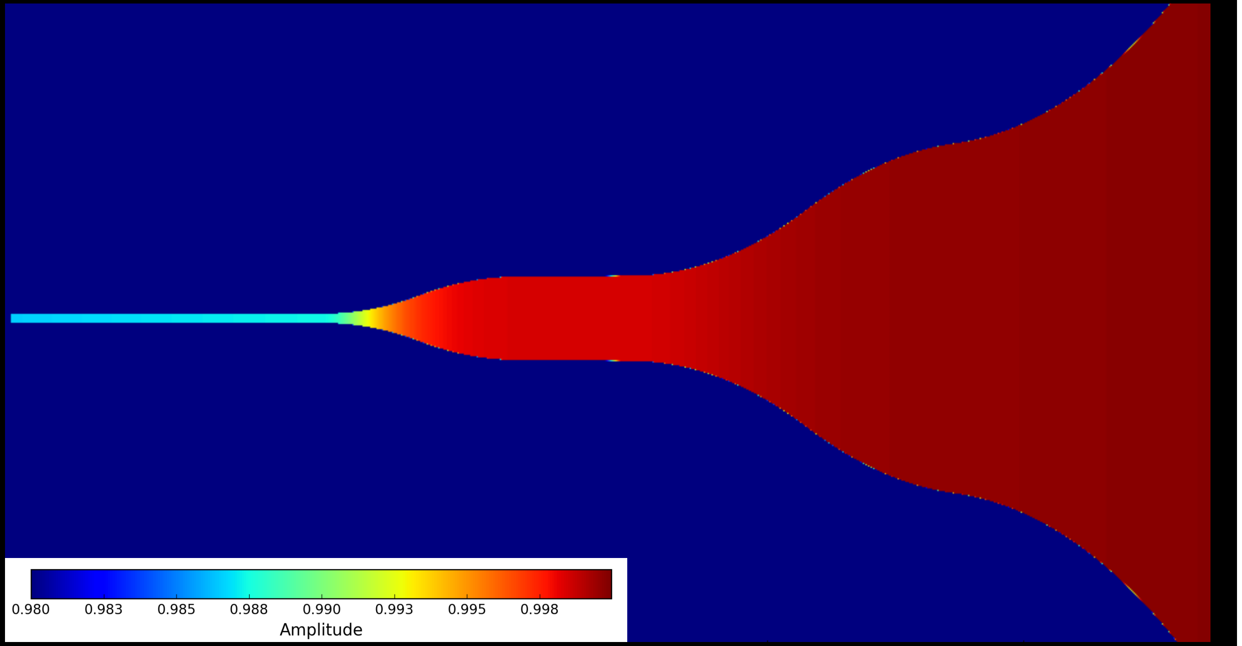
Top – bottom:
2 µm, 4 µm, 7 µm thickness

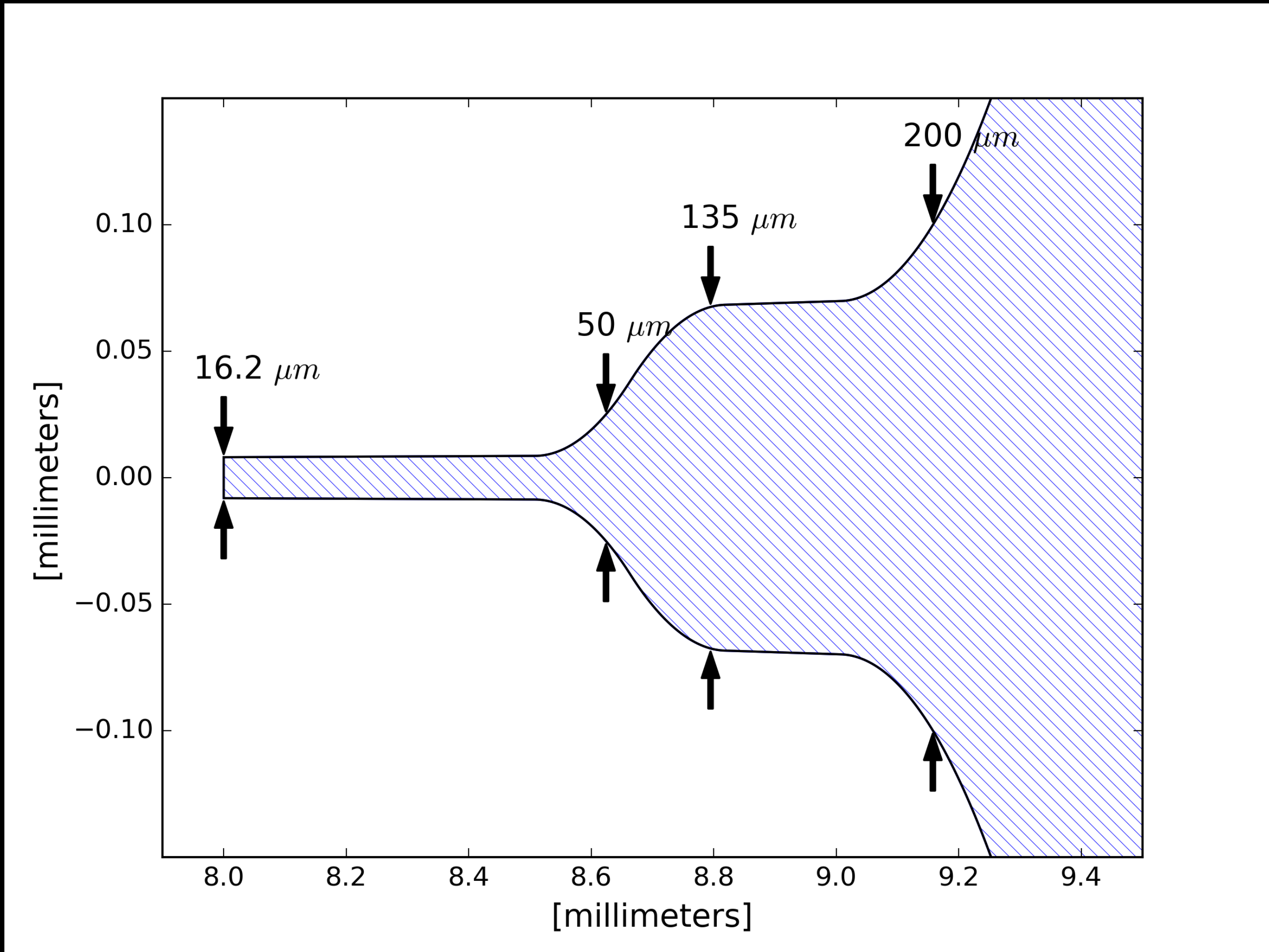


$$\phi \sim -\frac{\beta}{w^{1.1}}$$

Implementation in scalar model

$$E \propto FFT\left\{E_0 \varepsilon(w) e^{i\phi(w)}\right\}$$





Est. Vector Effect

Decrease in amplitude from vector effect independent of width

- Effective gap width γ smaller
- γ < 1 µm

Phase has slight dependence on width

$$Vector\ Effect \propto \left(\frac{\gamma \times perimeter}{area}\right)^2 \propto \left(\frac{\gamma}{radius}\right)^2$$

Effect $\sim 10^6 \times$ lower for space case

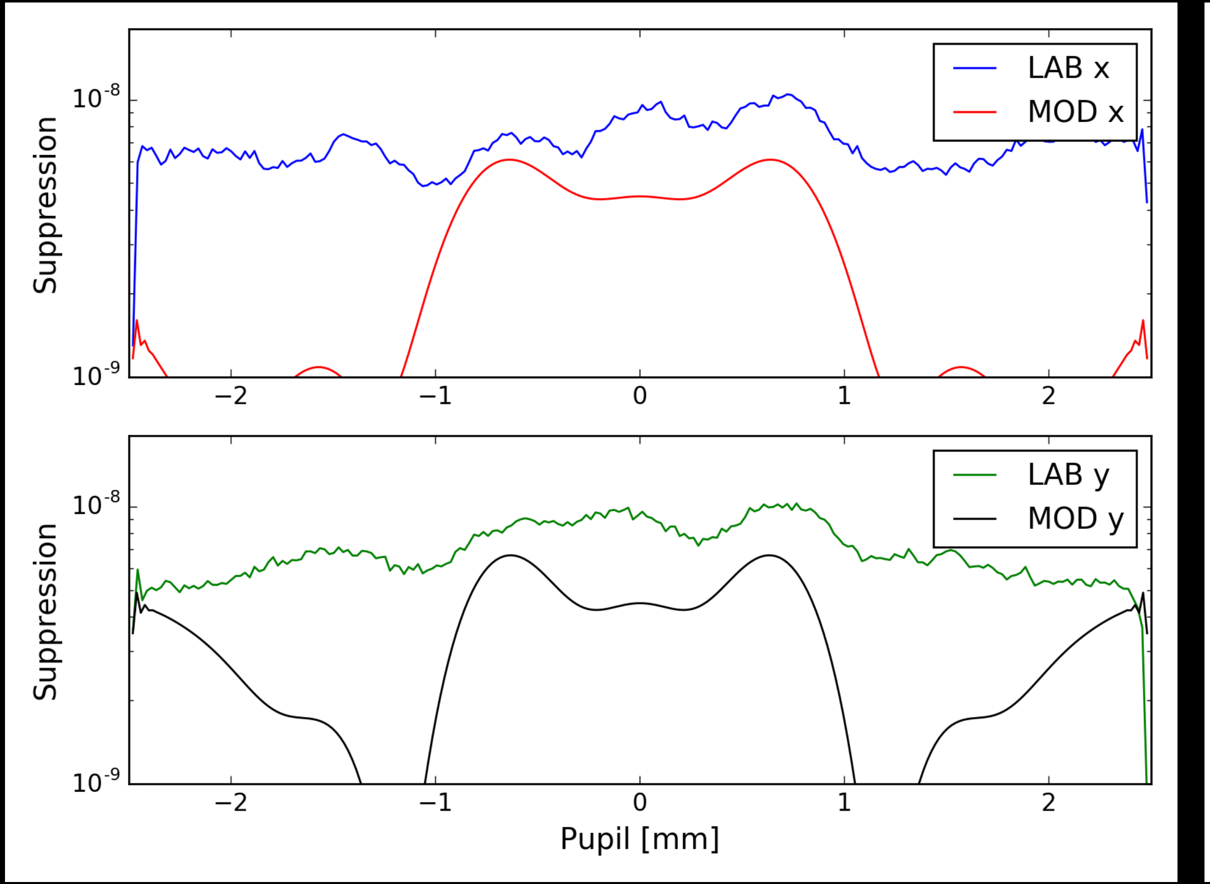
Mask Production

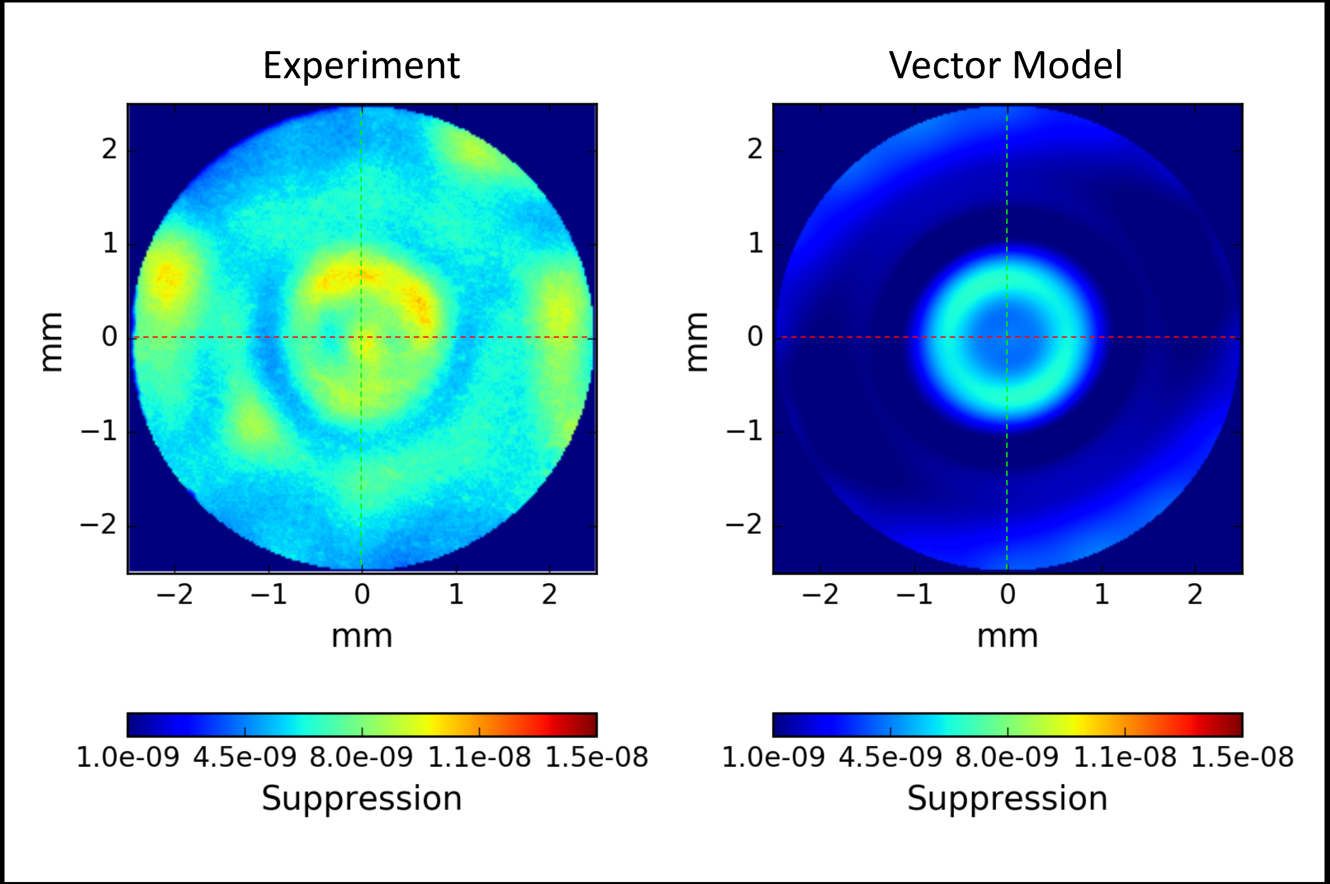
Mask Name	Completion Date	Lithography Process	Device Layer Thickness	Si_3N_4 Membrane?	Etching Error	Suppression
CL3	Jan 2017	Contact Lith.	1 µm	Yes	400 nm	4×10^{-8}
DW3	Nov 2017	Direct Write	1 µm	Yes	150 nm	Broke at PU!
DW9	Jan 2018	Direct Write	7 µm	No	150 nm	6×10^{-8}
DW11	Feb 2018	Direct Write	7 µm	No	150 nm	1.5×10^{-8}
DW13	Jun 2018	Direct Write	4 µm	No	275 nm	1.2×10^{-8}
DW14	Jun 2018	Direct Write	2 µm	No	300 nm	1.3×10^{-8}
DW16	Aug 2018	DW - biased	2 µm	No	30 nm	7.4×10^{-9}
DW17	Sep 2018	DW - biased	2 µm	No	30 nm	6.6×10^{-9}

DW17 - Suppression

Experiment: 6.6×10^{-9}
Vector Model: 2.2×10^{-9}

Thickness
Mask: 2 μm
Model: 0.9 μm

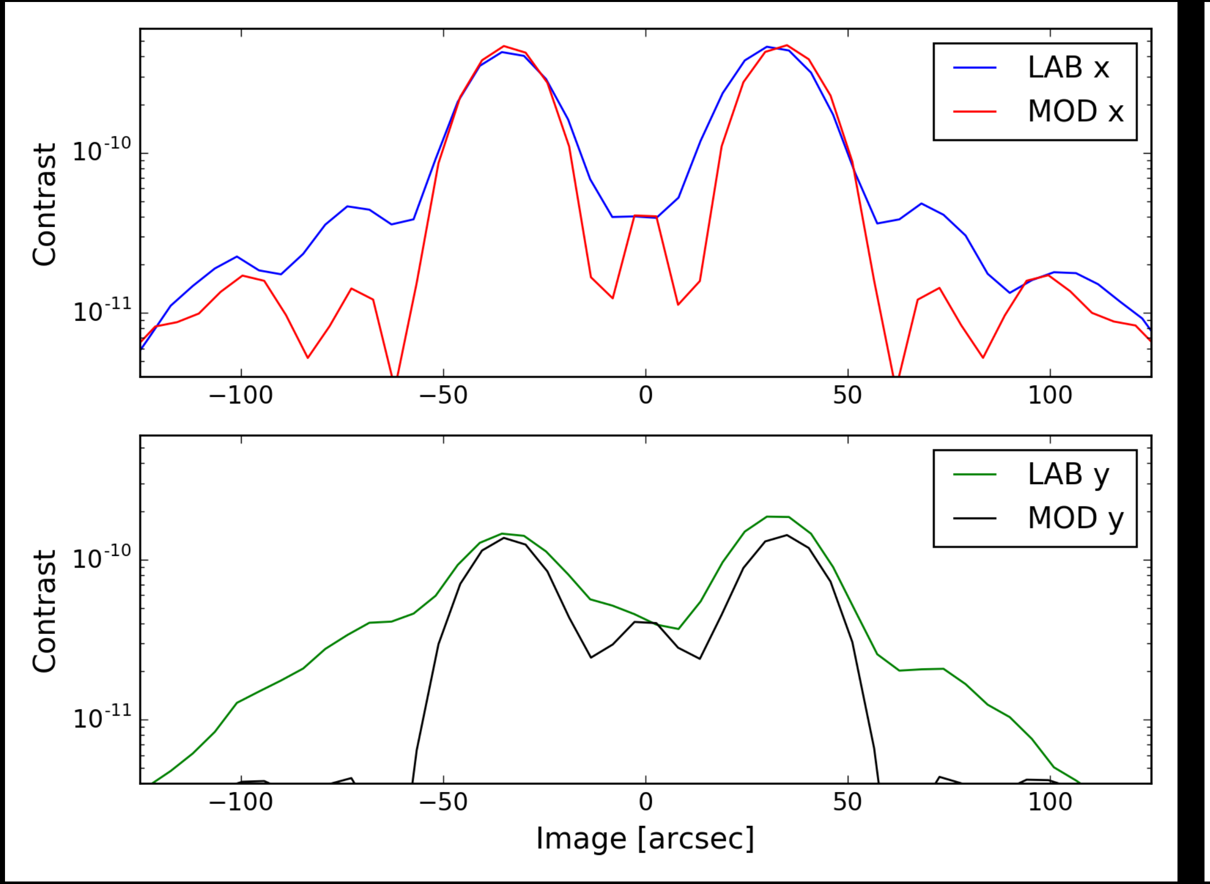


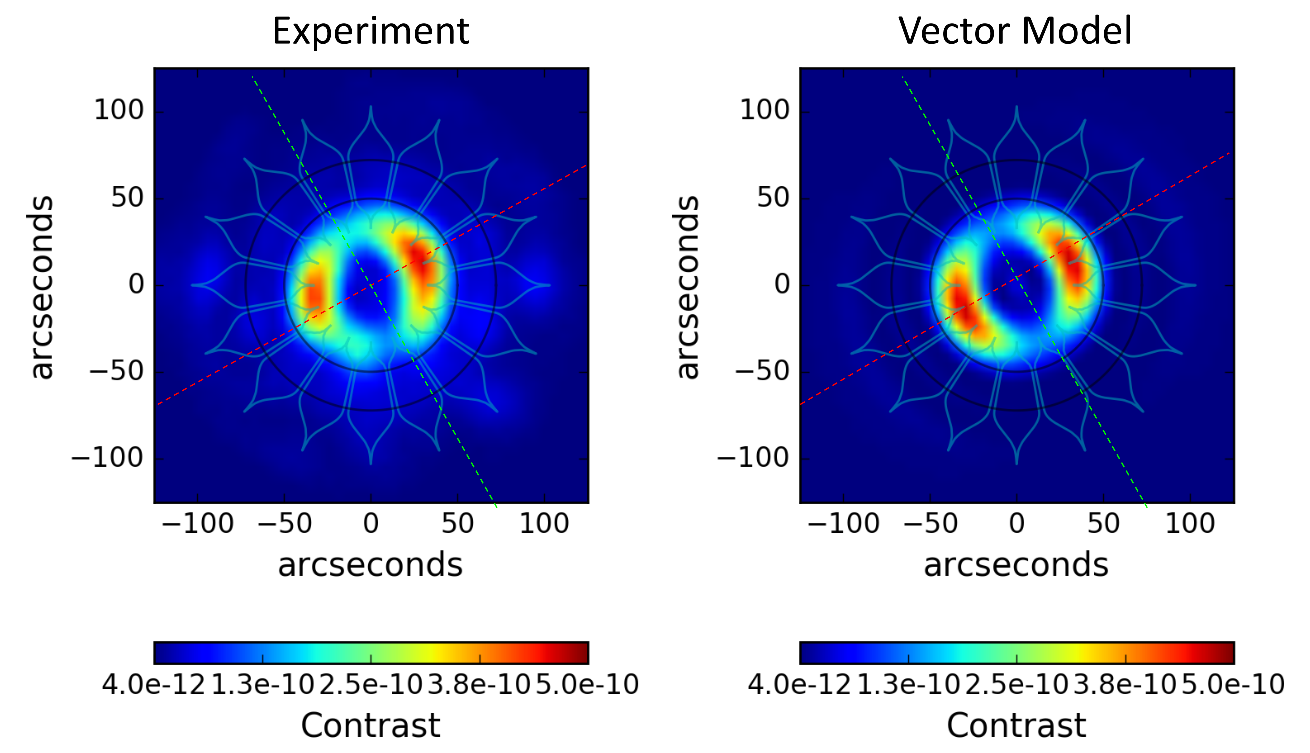


DW17 - Contrast

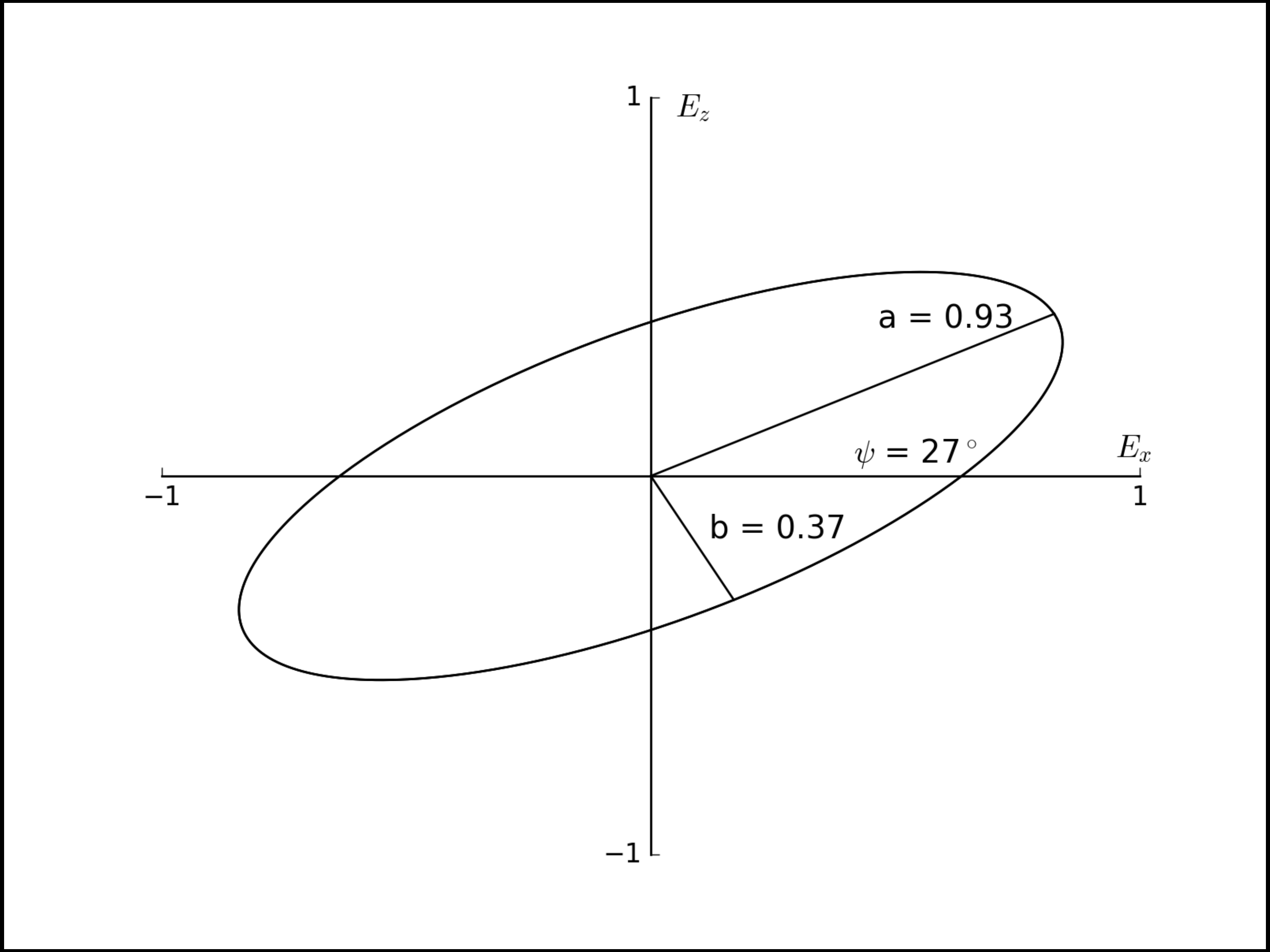
Experiment: 4.3×10^{-11}
Vector Model: 1.5×10^{-11}

Thickness
Mask: 2 μm
Model: 0.9 μm





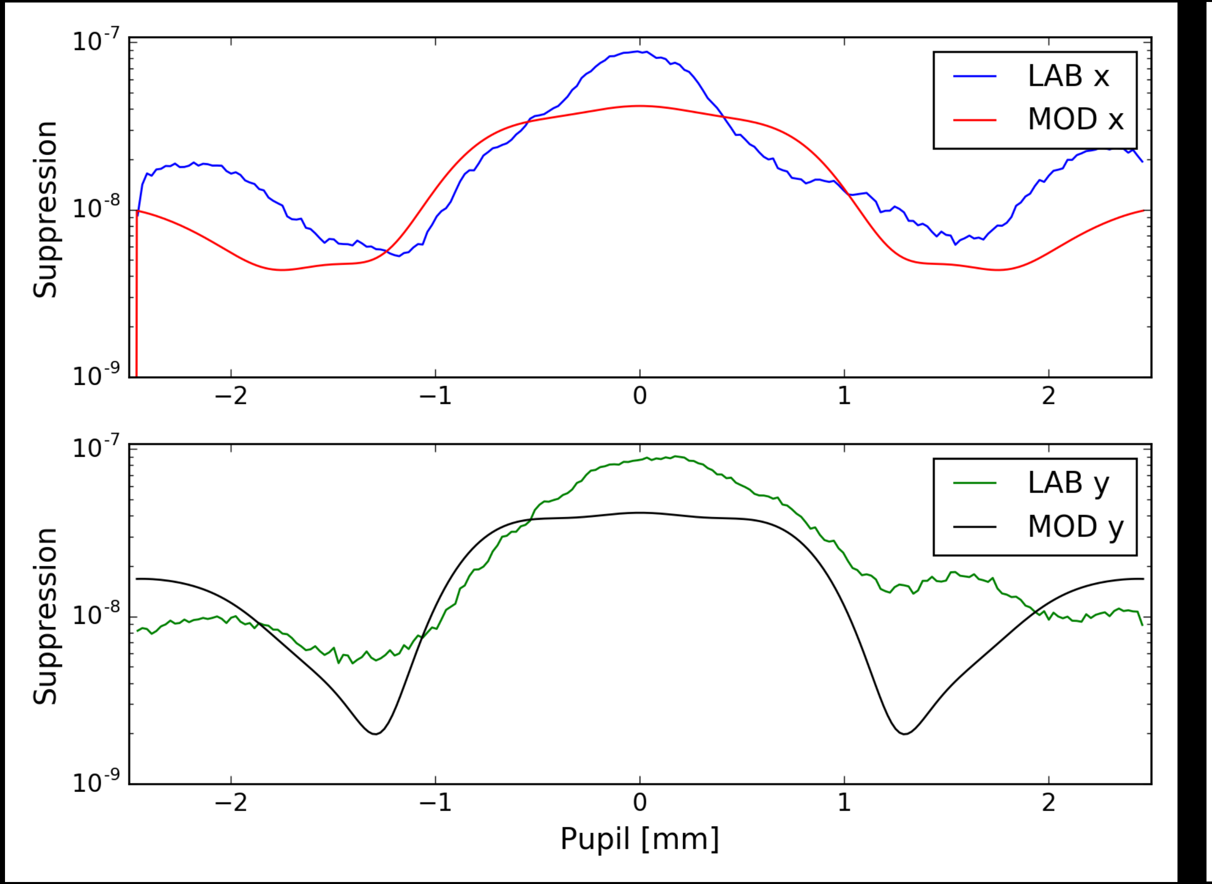
Polarization Ellipse

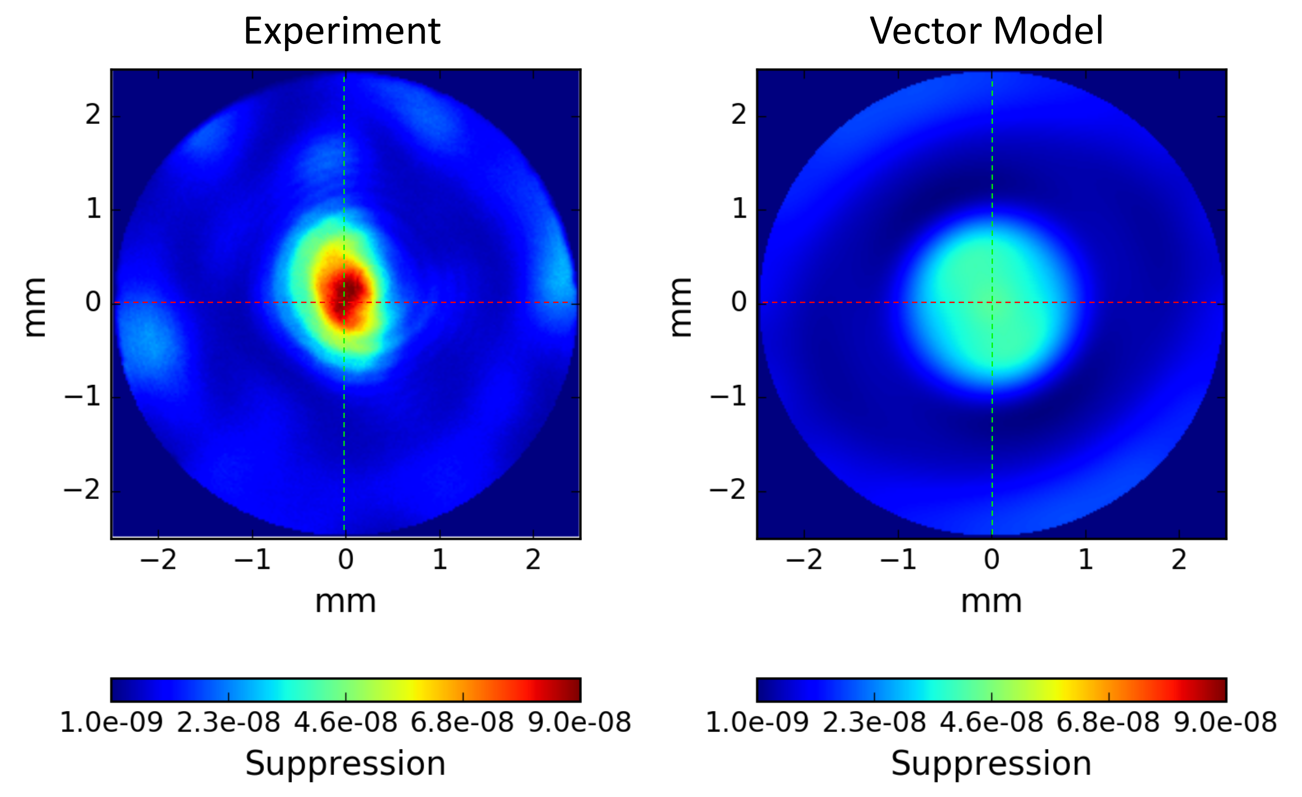


DW11 - Suppression

Experiment: 1.4×10^{-8}
Vector Model: 1.1×10^{-8}

Thickness
Mask: 7 µm
Model: 5 µm

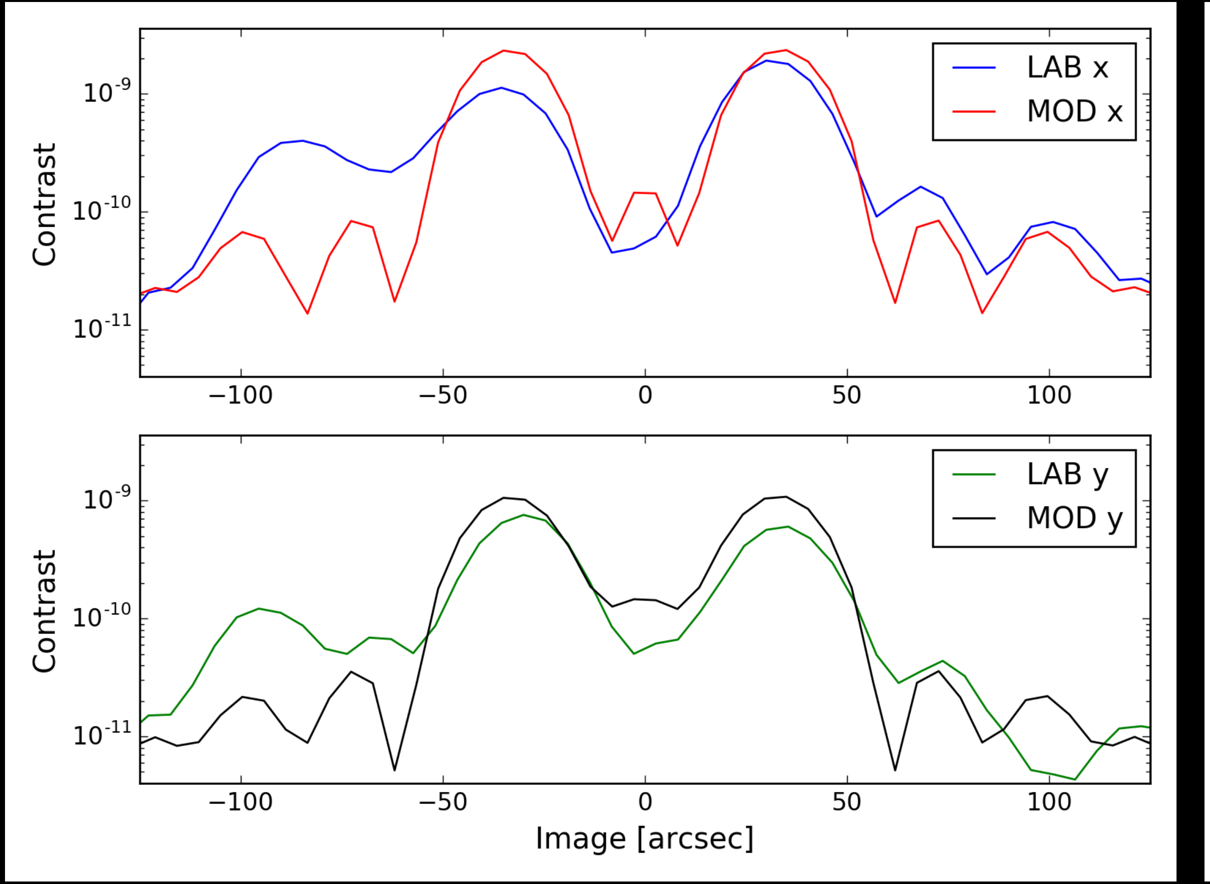


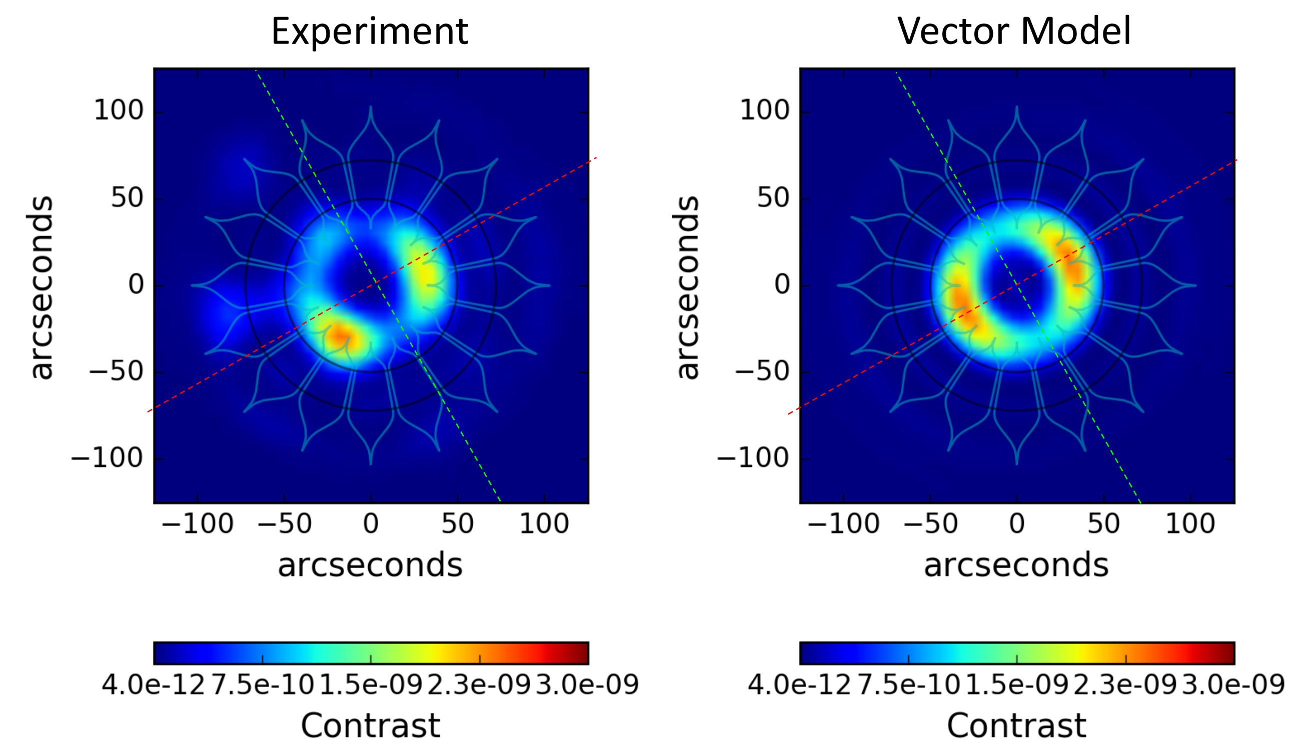


DW11 - Contrast

Experiment: 1.2×10^{-10}
Vector Model: 7.4×10^{-11}

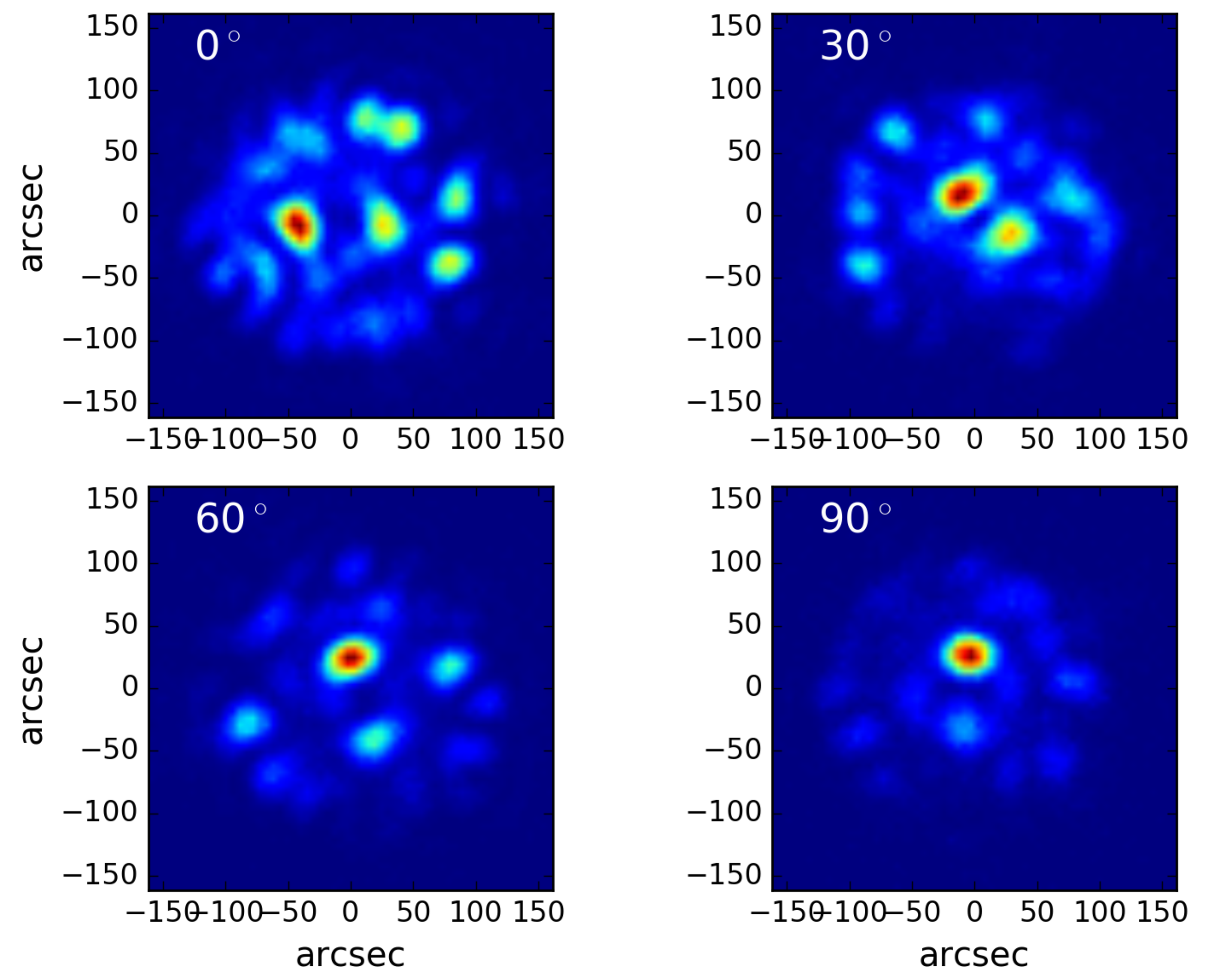
Thickness
Mask: 7 µm
Model: 5 µm





Rotating Polarizer

DW17



Conclusions

Best starshade performance to date at flight-like Fresnel number

- Suppression = 6.6×10^{-9}
- Contrast = 4.3×10^{-11}

Improved performance due to improved mask quality

- Bias + new process eliminated over-etching

Non-scalar diffraction effects arose at lower contrast levels

- Current limiting factor
- Problem due to small starshade size
- Built vector diffraction into optical models

Future Work

Align vector model with data

- Measure mask thickness

Identify source of background scatter

Design mask to mitigate vector effects?

Test across 100 nm bandpass

Introduce intentional flaws to mask

Thank You!

BACKUP
SLIDES

Mask Comparison