Starshade Sub-scale Testing + Model Validation

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Collaboration

- Princeton
  - Jeremy Kasdin (PI)
  - Yunjong Kim
  - Michael Galvin

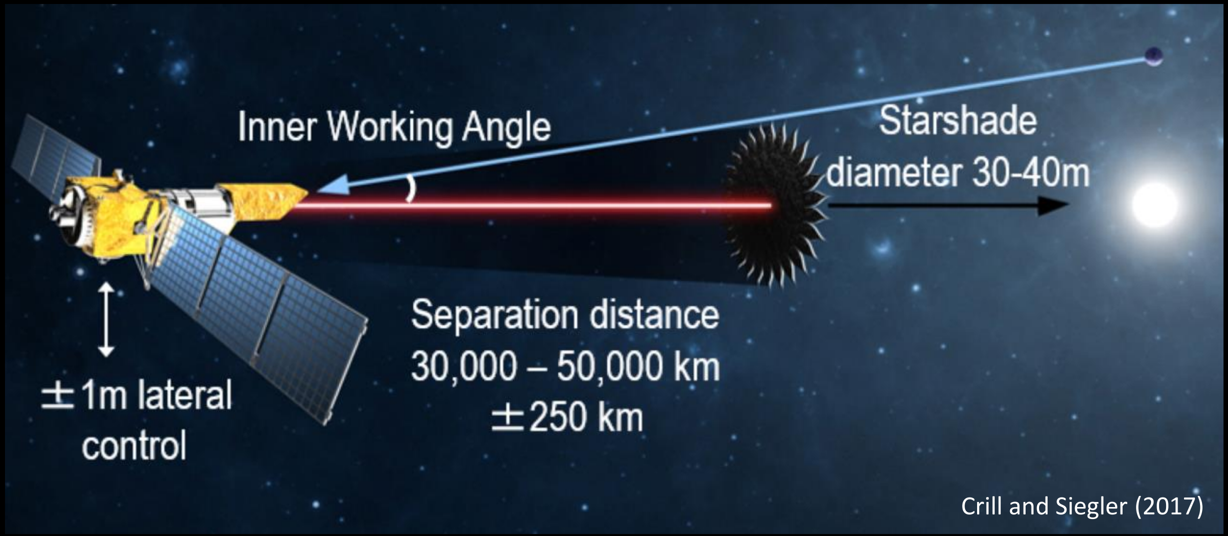
- JPL
  - Stuart Shaklan
  - Philip Dumont
  - Bala Balasubramanian + MDL Team

- Work performed under NASA ExEP
  Technology Development for Exoplanet Missions (TDEM) grant

S-2 Technology

- **Starlight Suppression and Model Validation**
  - Key technology area in need of development
    - S-2 ExEP Technology Plan (Crill and Siegler, 2017)

- Lack of full-scale starshade test before launch places **strong** 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)

Validation through experimentation

- The starshade will *live and die* by the optical models

- Assumptions in need of validation through sub-scale testing:
  - Scalar Diffraction Theory is sufficient
  - Babinet's Principle (in scalar limit) is applied correctly

- Model validation + sub-scale testing must:
  - Exercise the gremlins
  - Provide confidence in designs and error budgets at an early stage
  - Convince the reasonable critic

Sub-scale testing

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

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

Fresnel Number

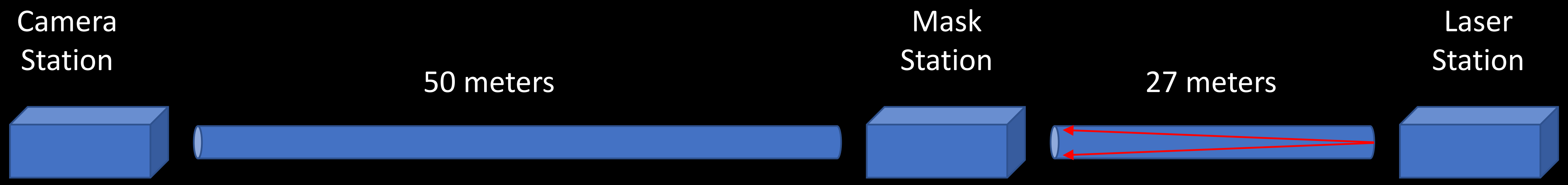
$$N = \frac{r^2}{\lambda z}$$

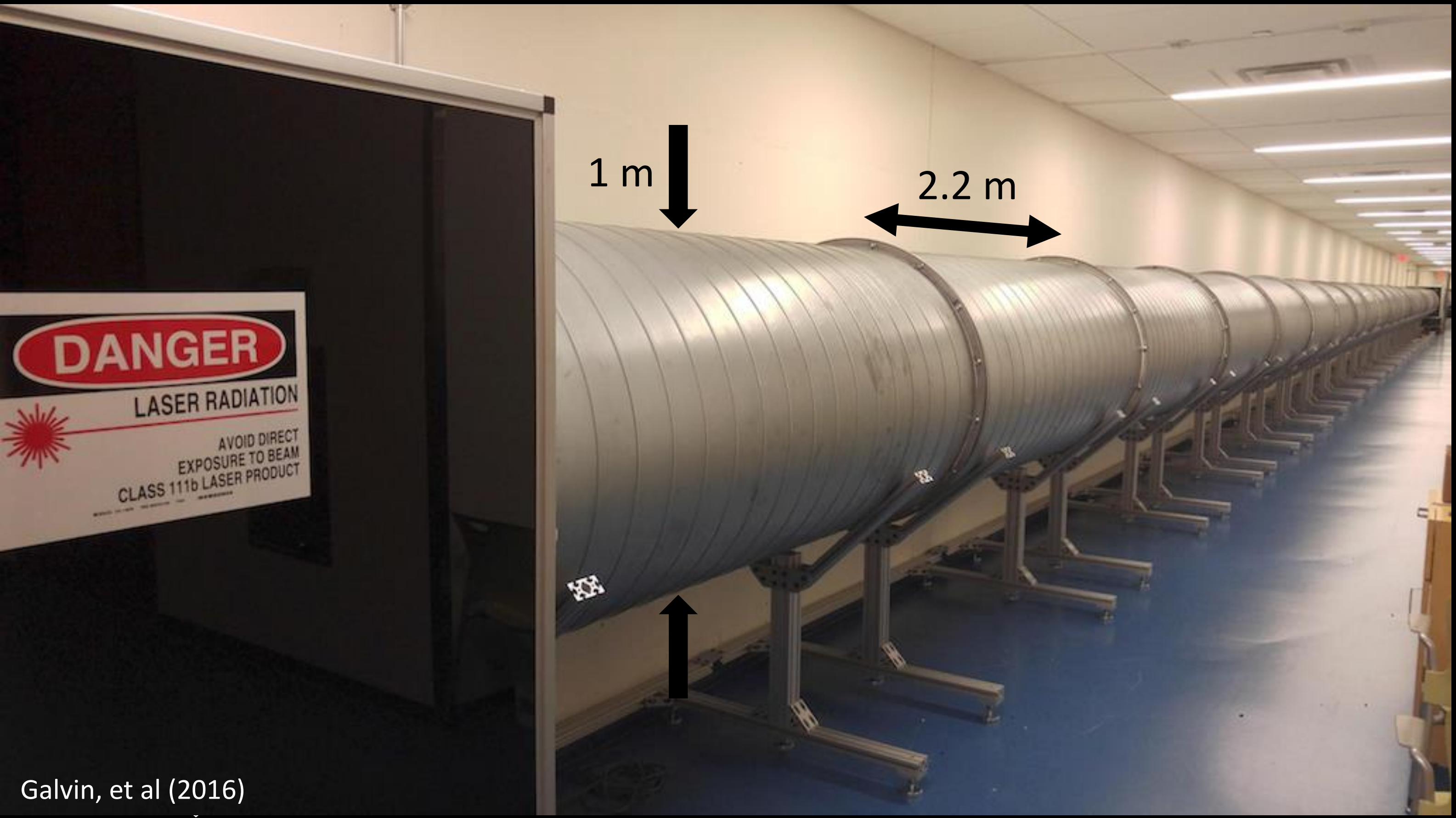
- Physics is identical for consistent Fresnel number
  - Under scalar diffraction + Fresnel approximations

	Starshade Radius (r)	Starshade Separation (z)	Wavelength (λ)	Fresnel Number (N)
Sub-scale lab	12 mm	17.5 m*	633 nm	13
Flight	17 m	35,000 km	633 nm	13

*scaled for diverging beam

Princeton Frick Testbed



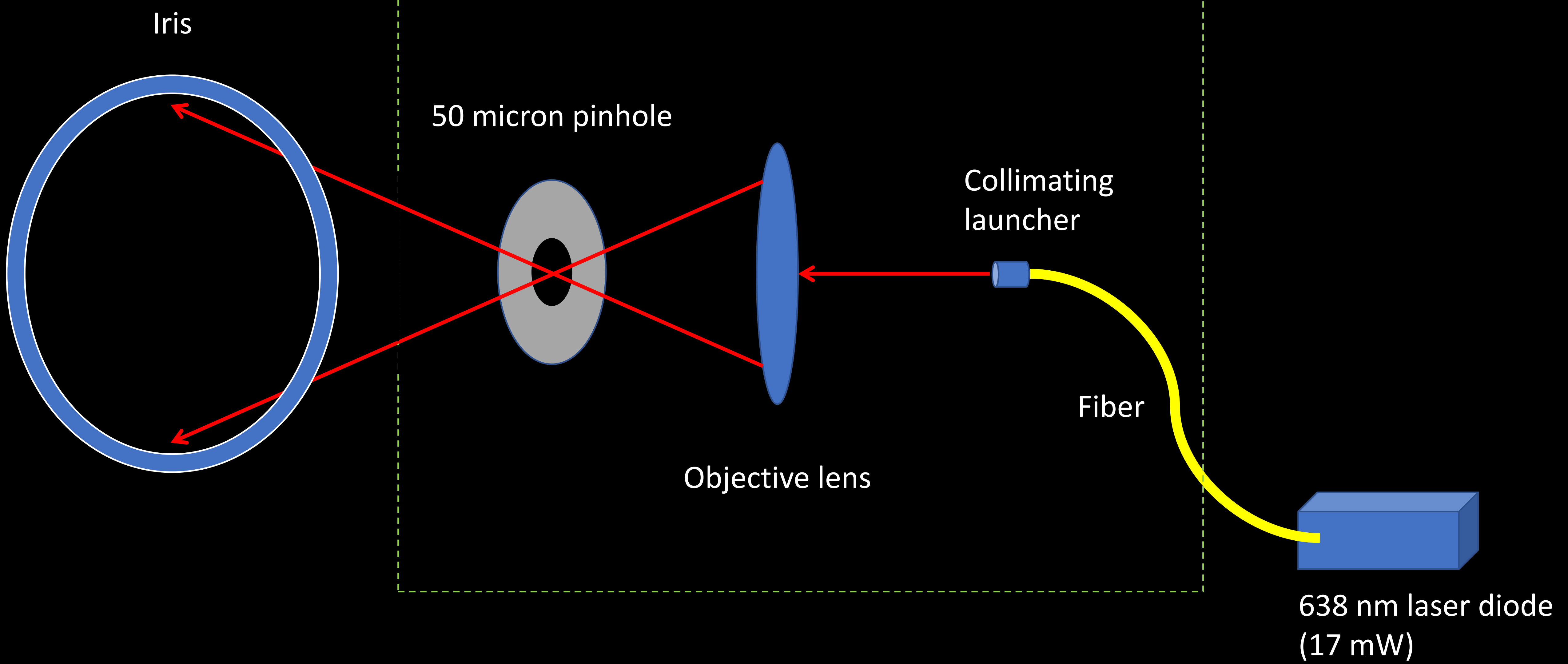


Galvin, et al (2016)

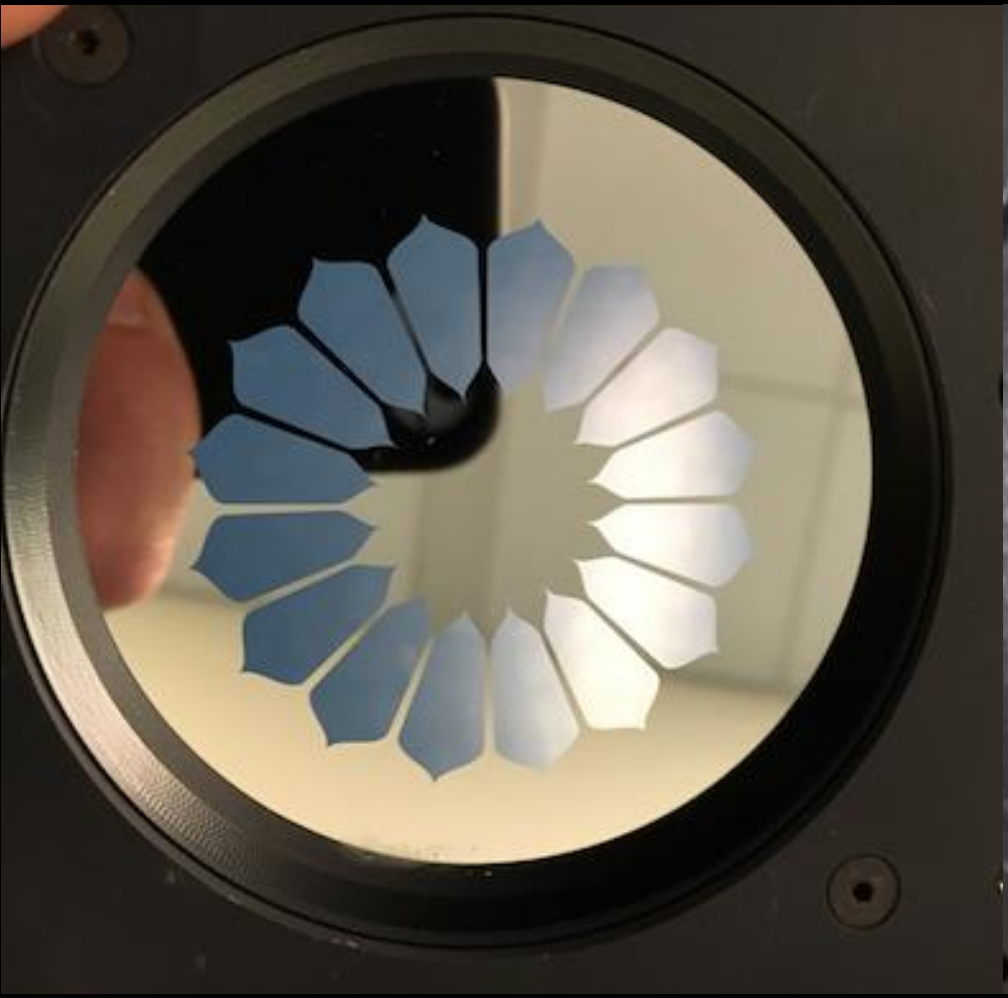
Primary Milestone:
- Demonstrate 10^{-9} suppression at flight-like Fresnel number

- Starshade diameter:
  - 34.7 mm (to peak apodization)
  - 50 mm (to outer starshade)
- Wavelength:
  - 633 (638) nm
- Aperture diameter:
  - 4 mm
  - ~4 resolution elements across SS
- Fresnel Number:
  - 27

Laser station



Mask station



Starshade mask

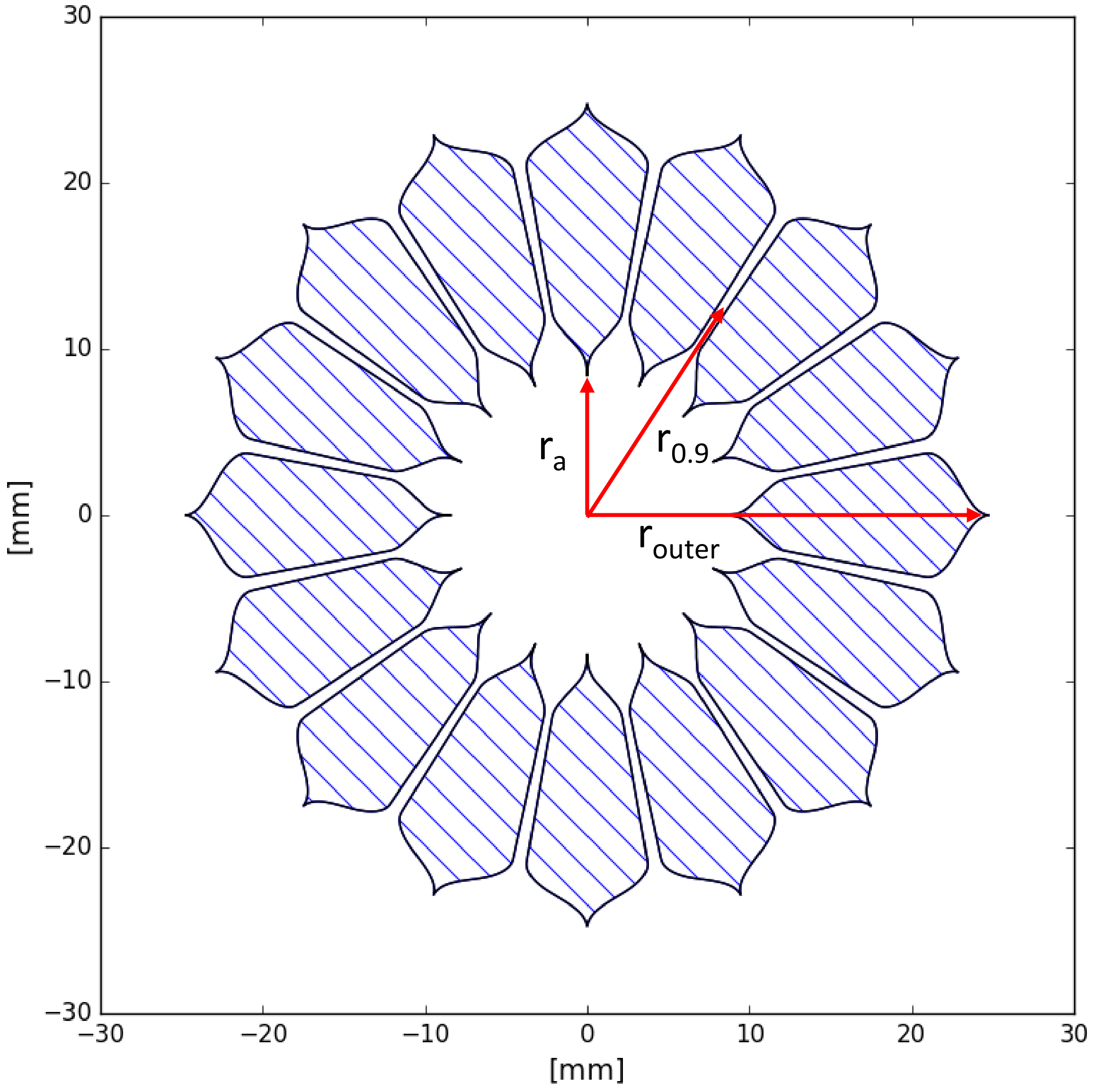
- Silicon mask etched by DRIE process
  - Made by Microdevices Lab at JPL

- r_a : opaque radius
  = 8.4 mm

- $r_{0.9}$: radius to peak apodization
  = 17.4 mm

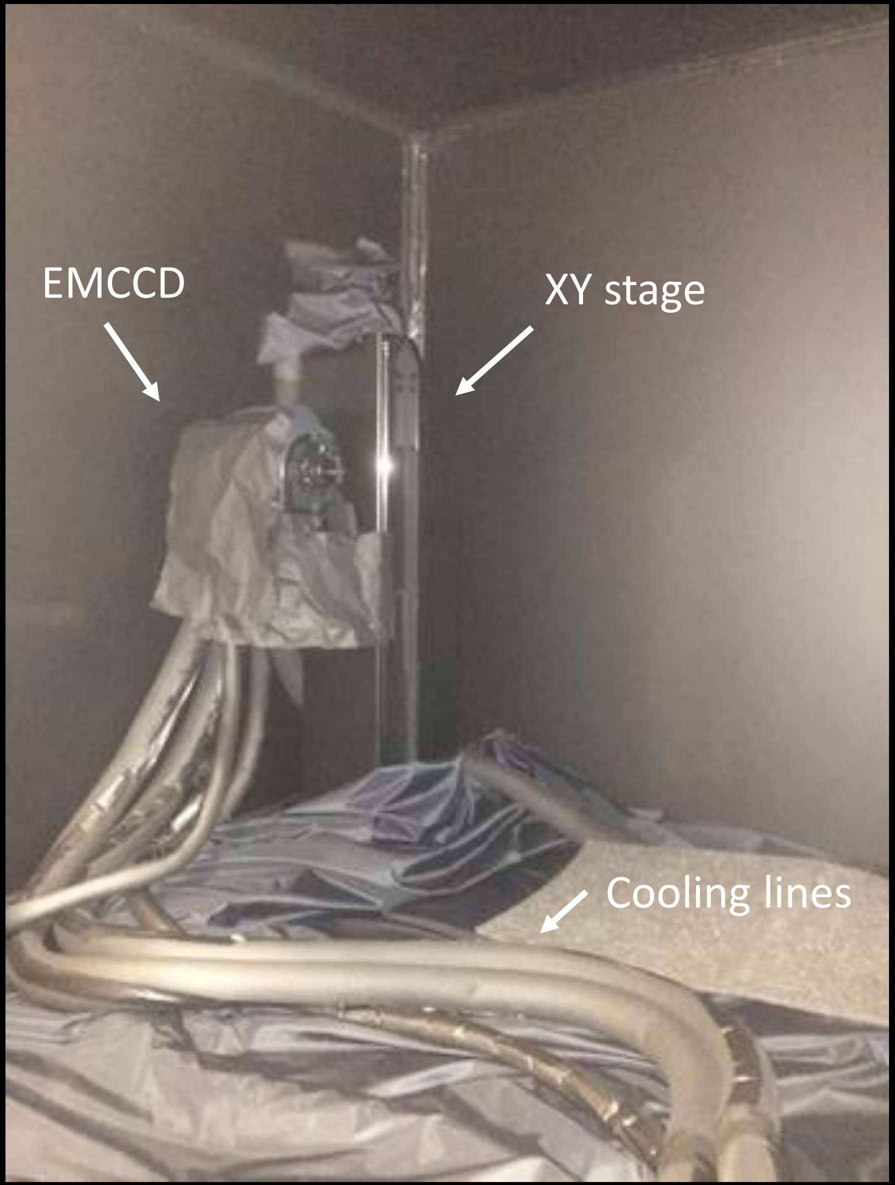
- r_{outer} : maximum radius
  = 25 mm

- $N_{0.9}$ = 27



Camera station

- EMCCD
  - Liquid cooled
  - 13 μm pitch pixels
  - 1024 x 1024
  - EM gain: 100x
- 4 mm aperture



Recent additions

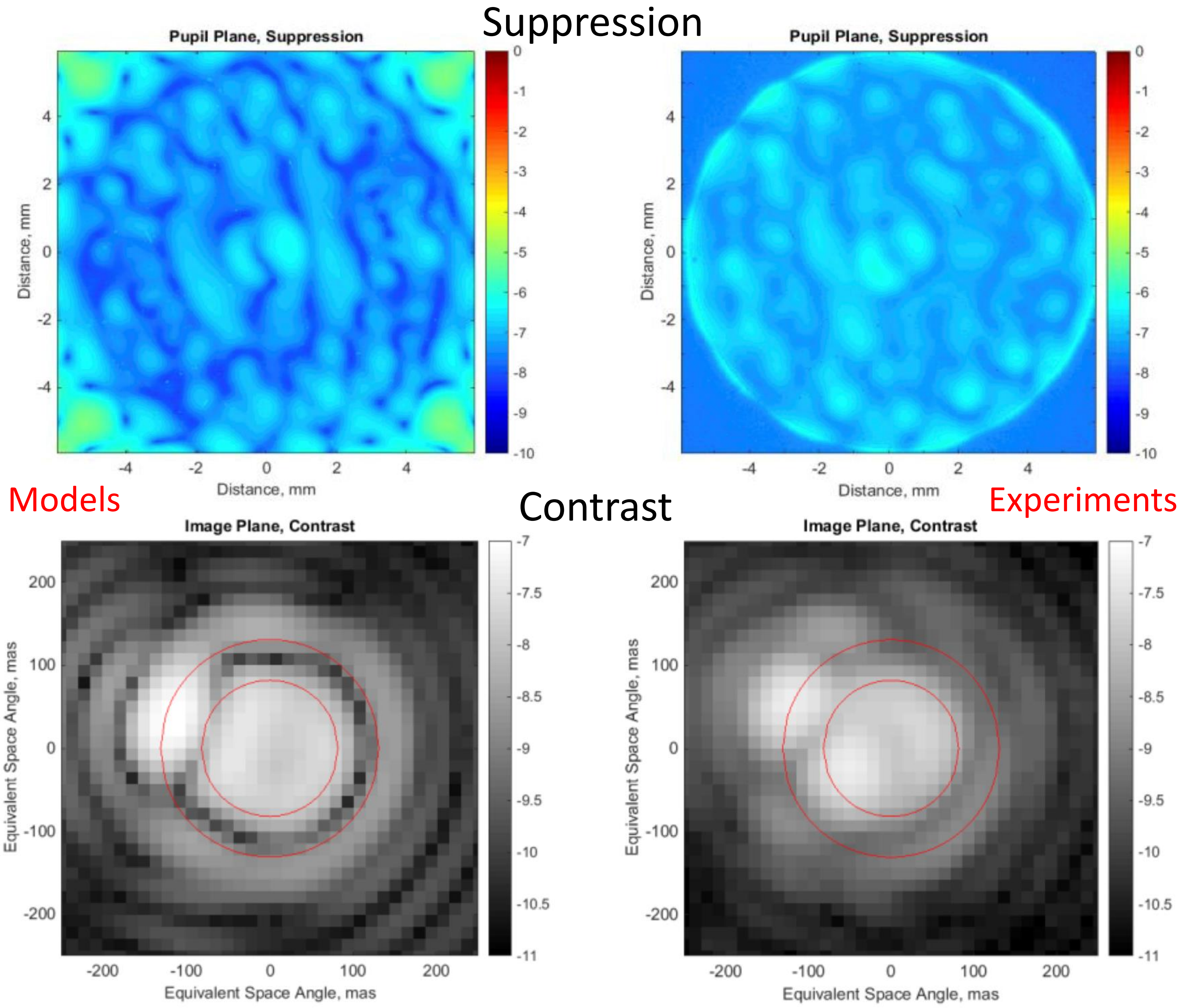
- Eliminated stray light from laser
  - Removed obstructions in front of laser (served as sources of diffraction)
- Using larger pinhole (50 micron) for cleaner wavefront
- Made boxes and tube light-tight
- Removed heat sources (camera, laser) from enclosure
  - Soon to install insulation around tube

Mask 1

*Work by Yunjong Kim

$S_{4.9} = 1.5 \times 10^{-7}$

Avg contrast: 5.2×10^{-8}



Est. 1.8 μm under-etch

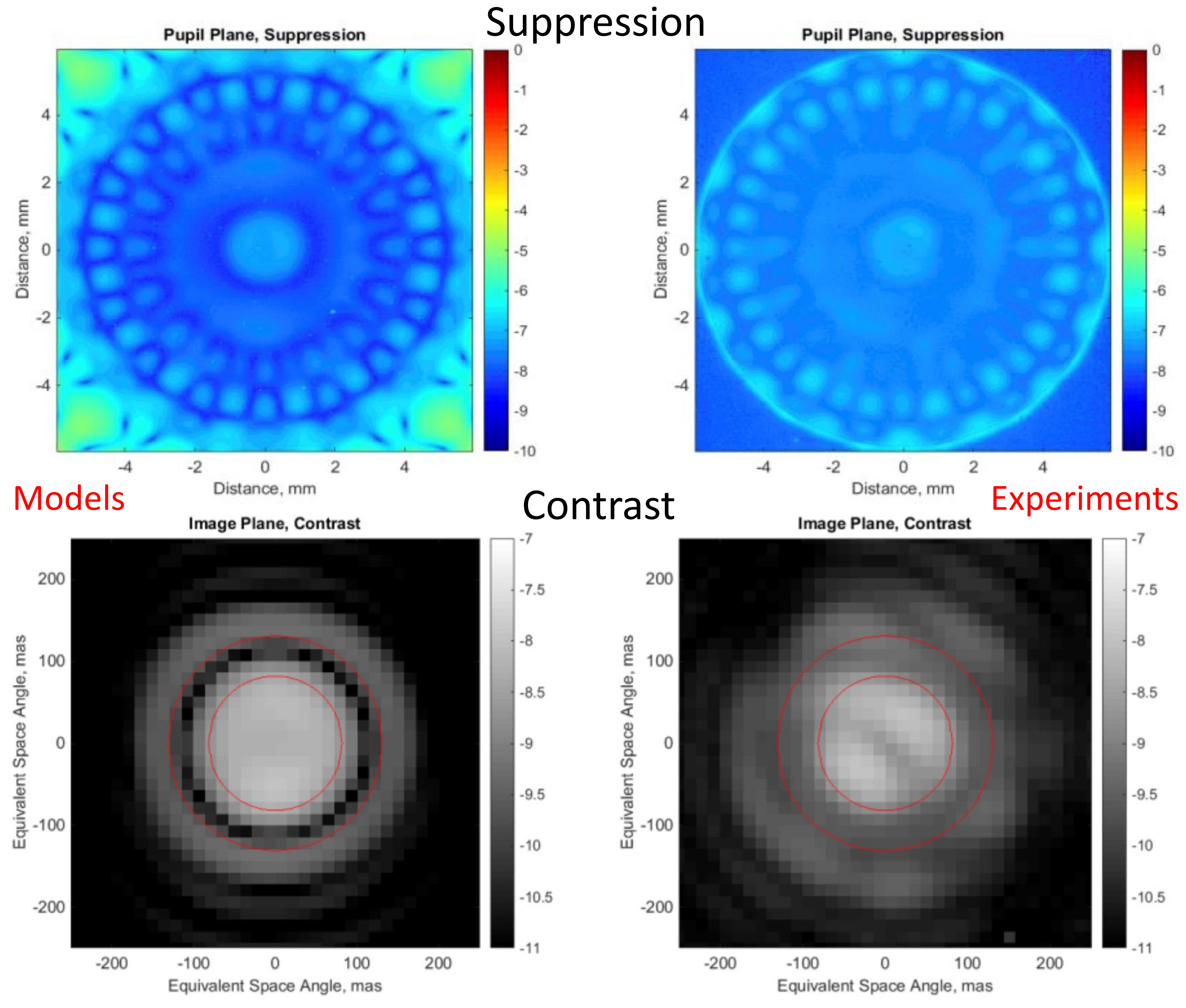
Kim, et al (2017)

Mask 2

*Work by Yunjong Kim

$S_{4.9} = 4.6 \times 10^{-8}$

Avg contrast: 3.5×10^{-10}



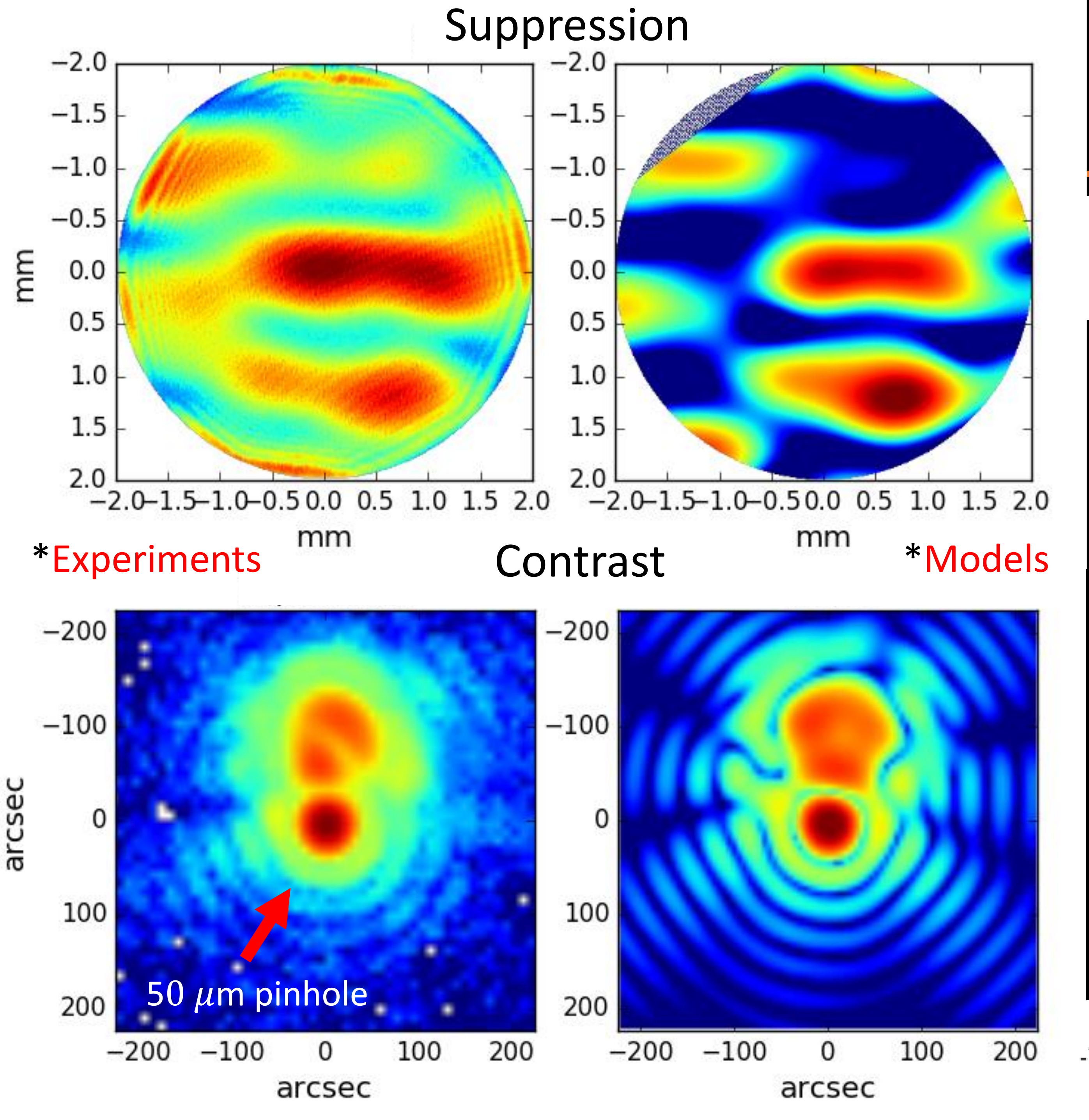
Est. 0.5 μm over-etch

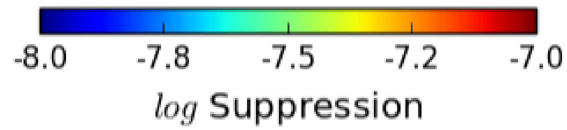
Kim, et al (2017)

Mask 3

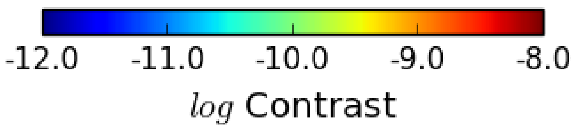
$S_{12.0} = 4.2 \times 10^{-8}$

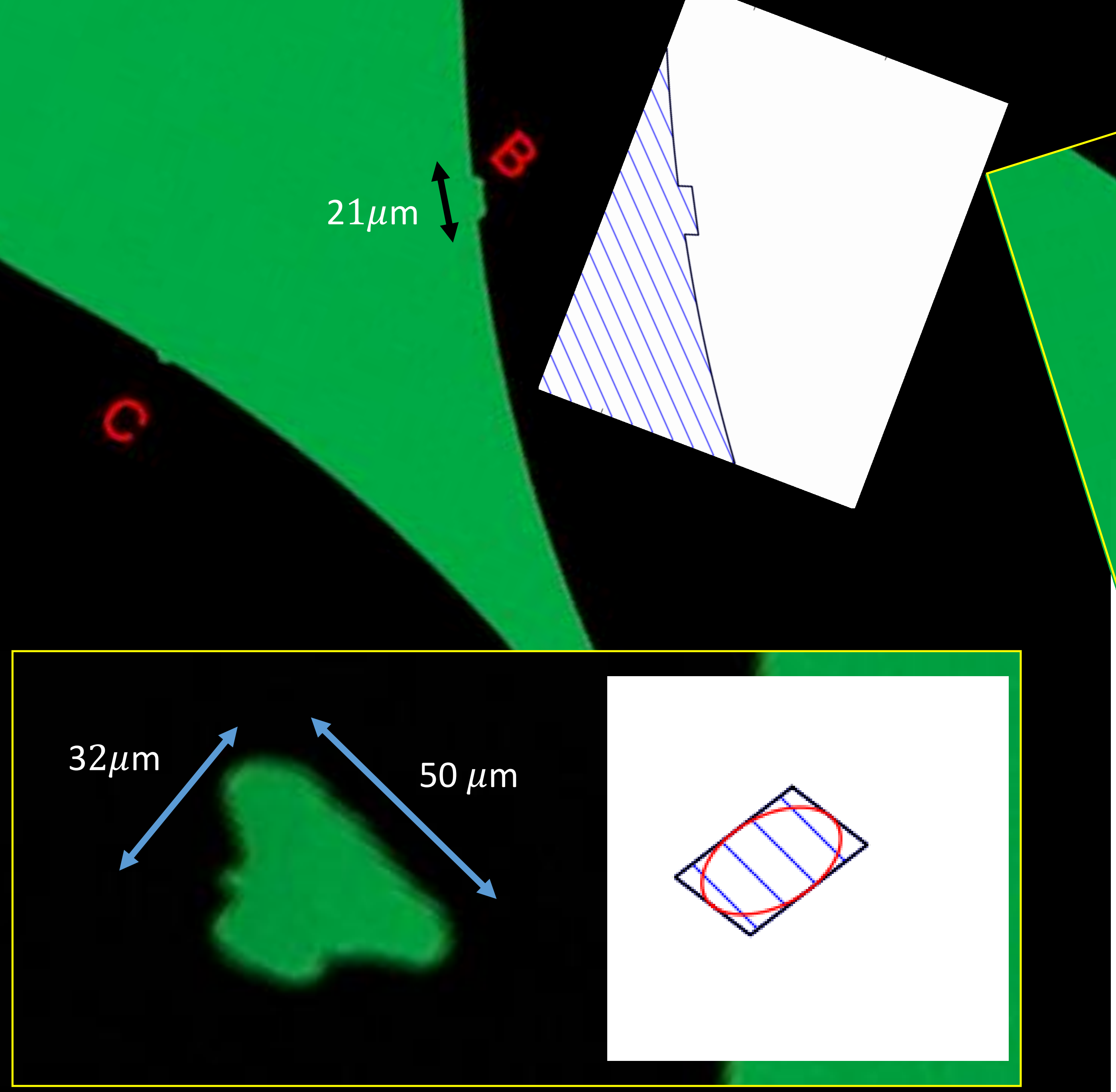
Peak contrast:
1.1×10^{-8}

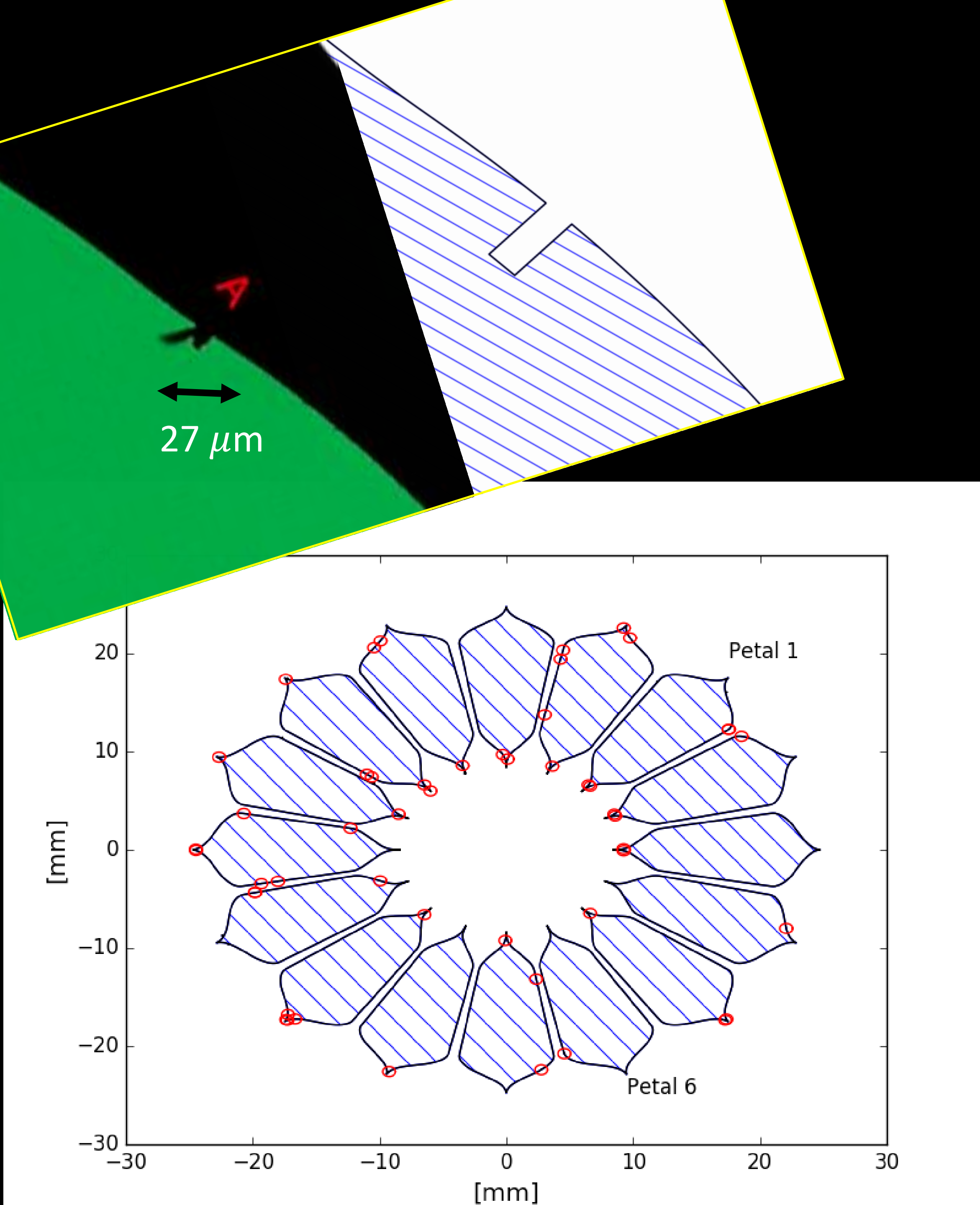




Est. 0.4 μm over-etch (verified by SEM measurements)

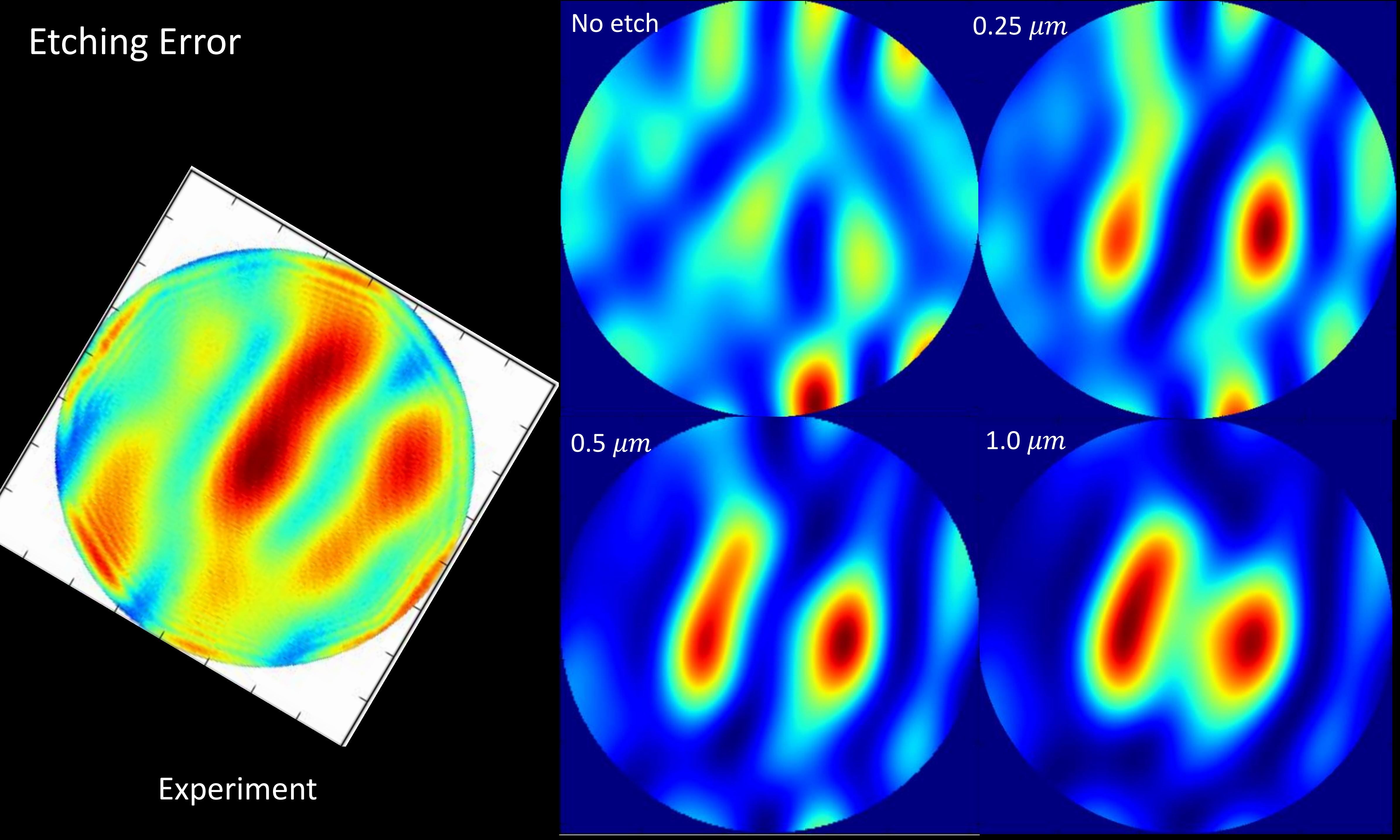






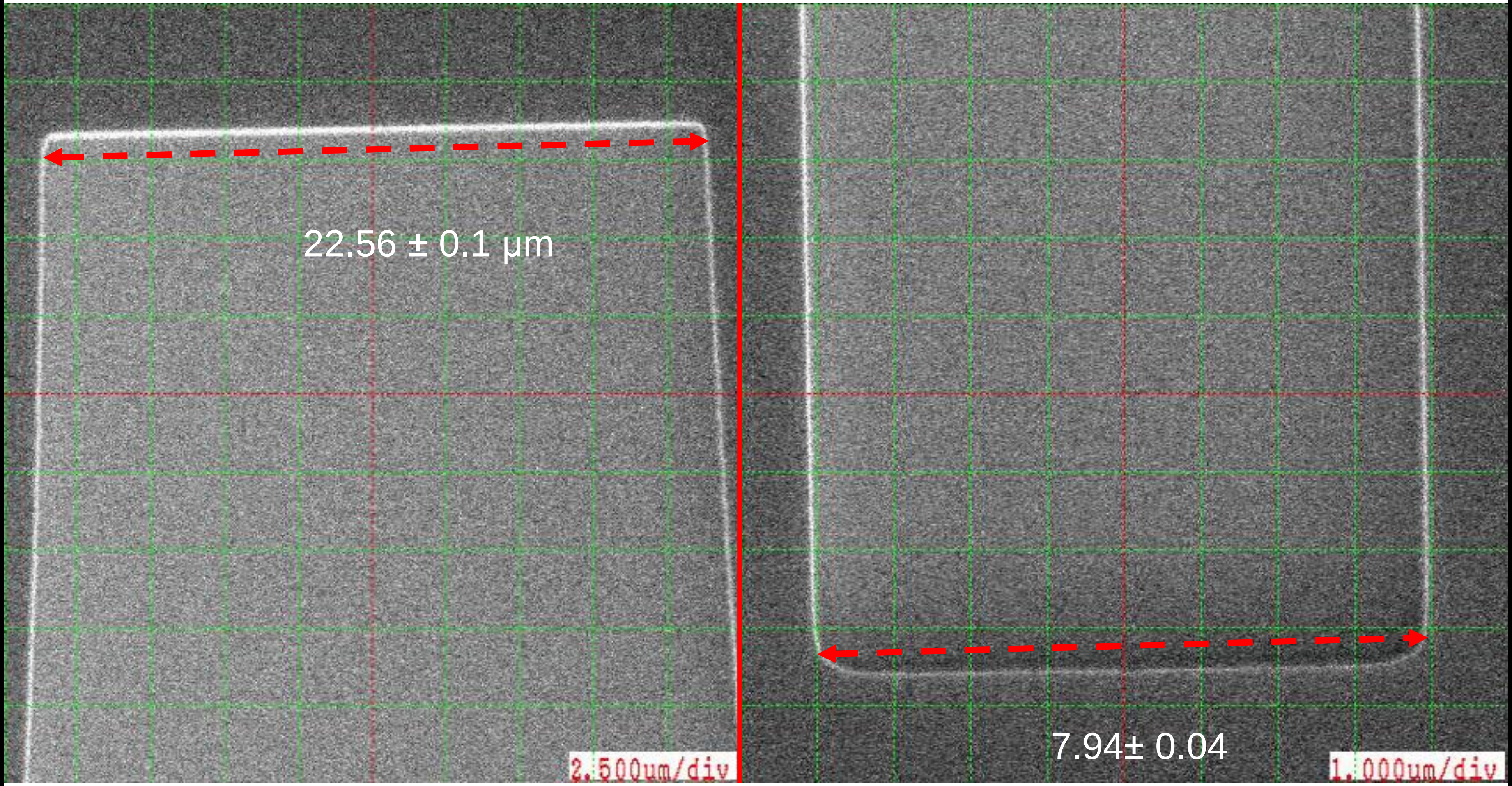
Images: B. Balasubramanian

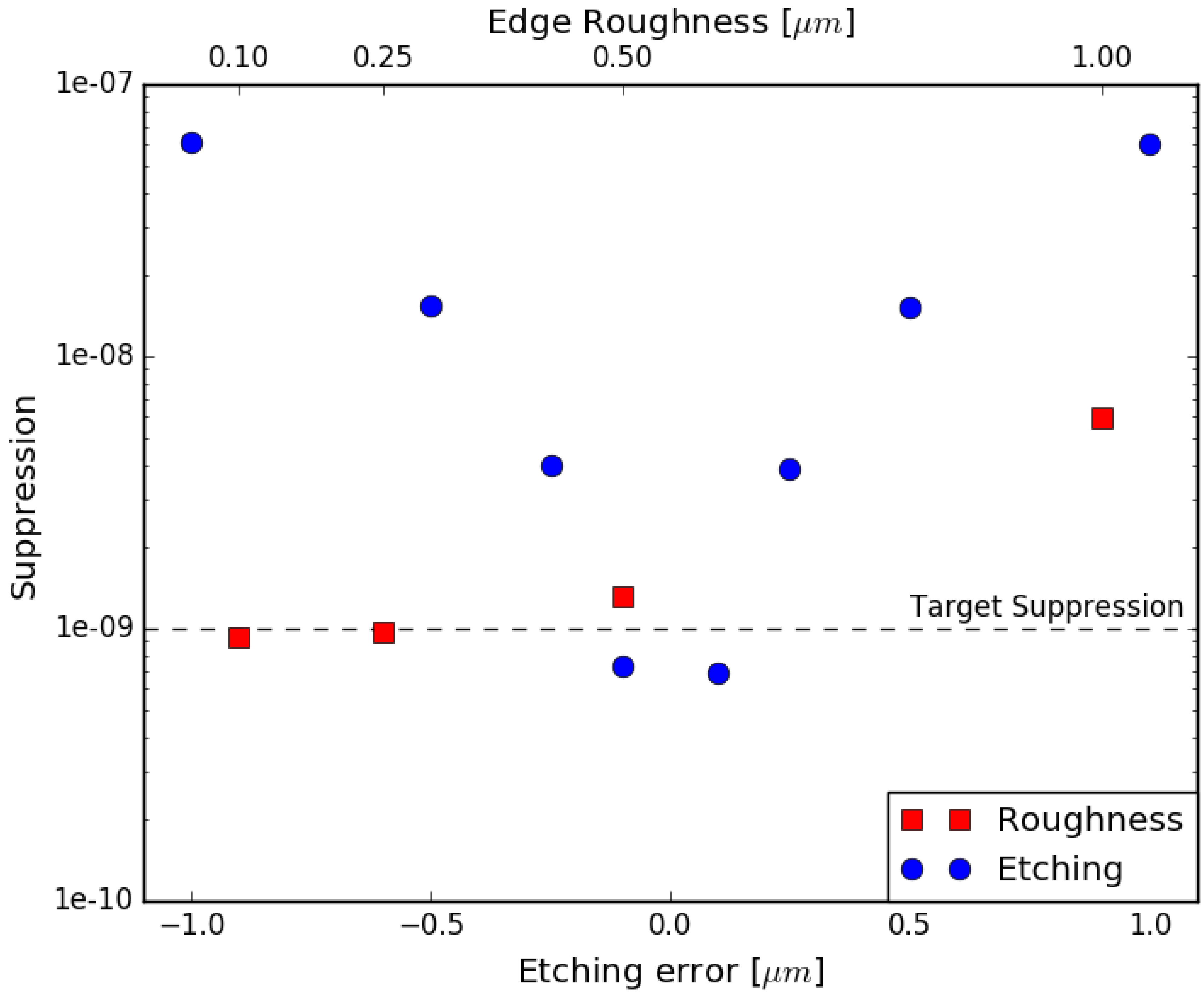
Etching Error



Petal 1

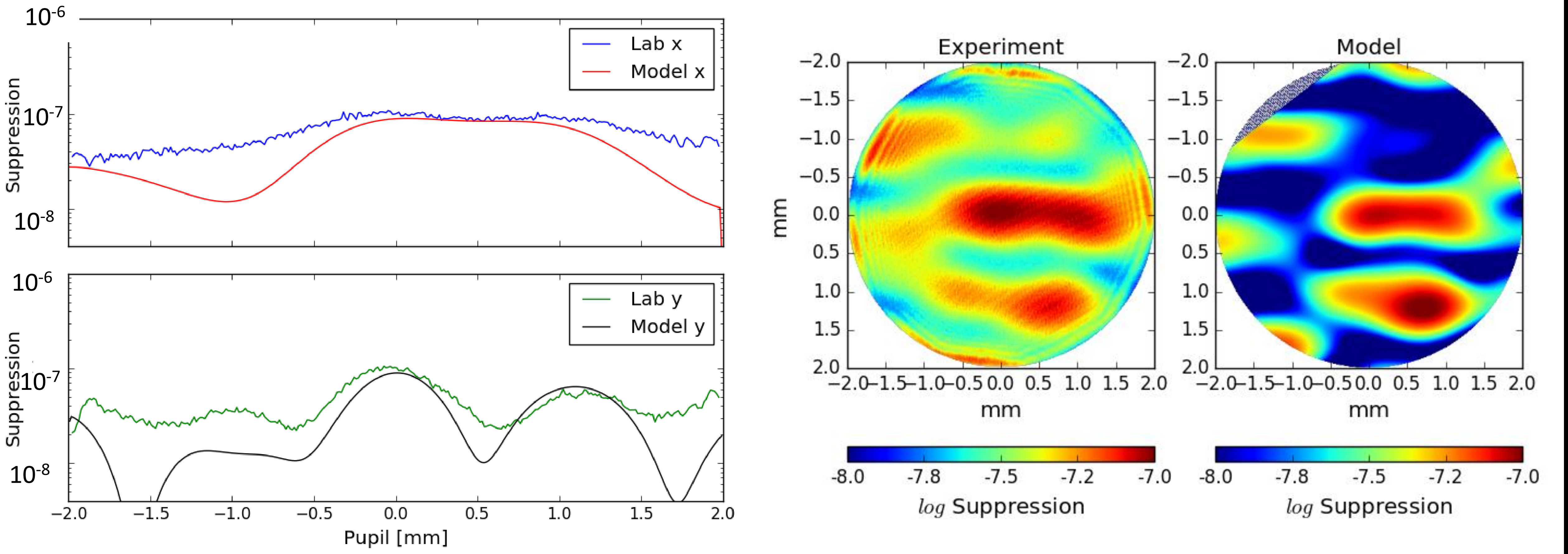
- Inner Tip – SEM 7.94μm *(spec. 7.54μm)*
- Outer Tip – SEM 22.56μm *(spec. 22.06μm)*



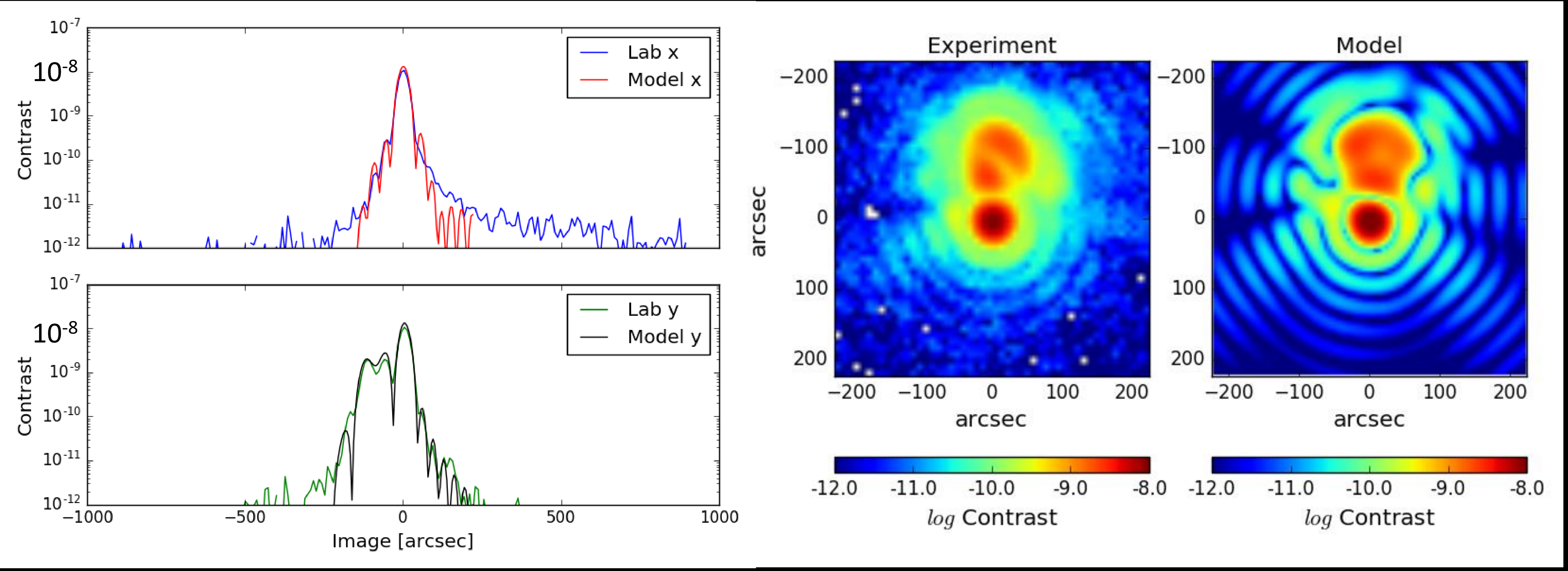


Edge Roughness [μm]
0.10
0.25
0.50
1.00
1e-07
1e-08
1e-09
1e-10
Suppression
Target Suppression
Roughness
Etching
−1.0
−0.5
0.0
0.5
1.0
Etching error [μm]

Model v Experiment: *Suppression*

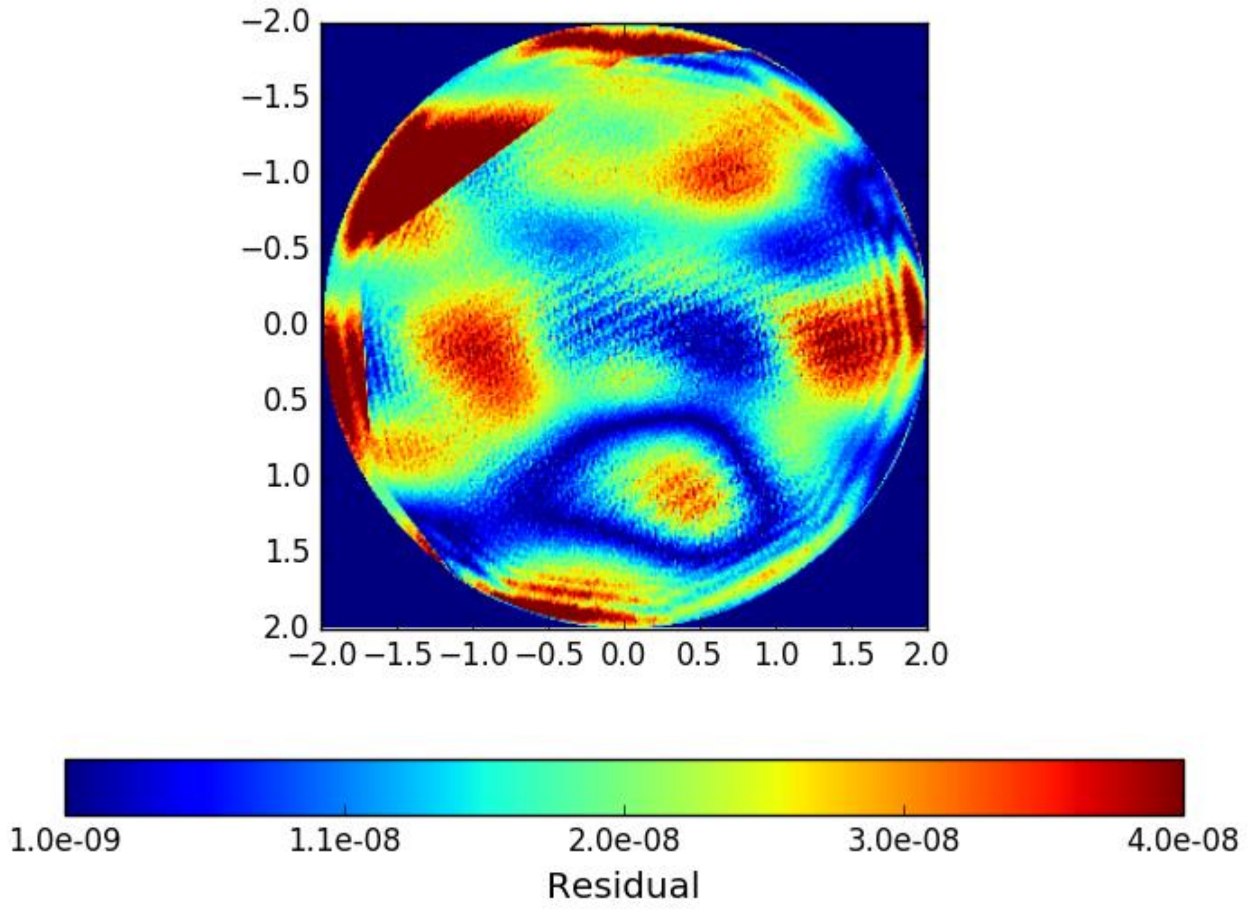


Model v Experiment: *Contrast*

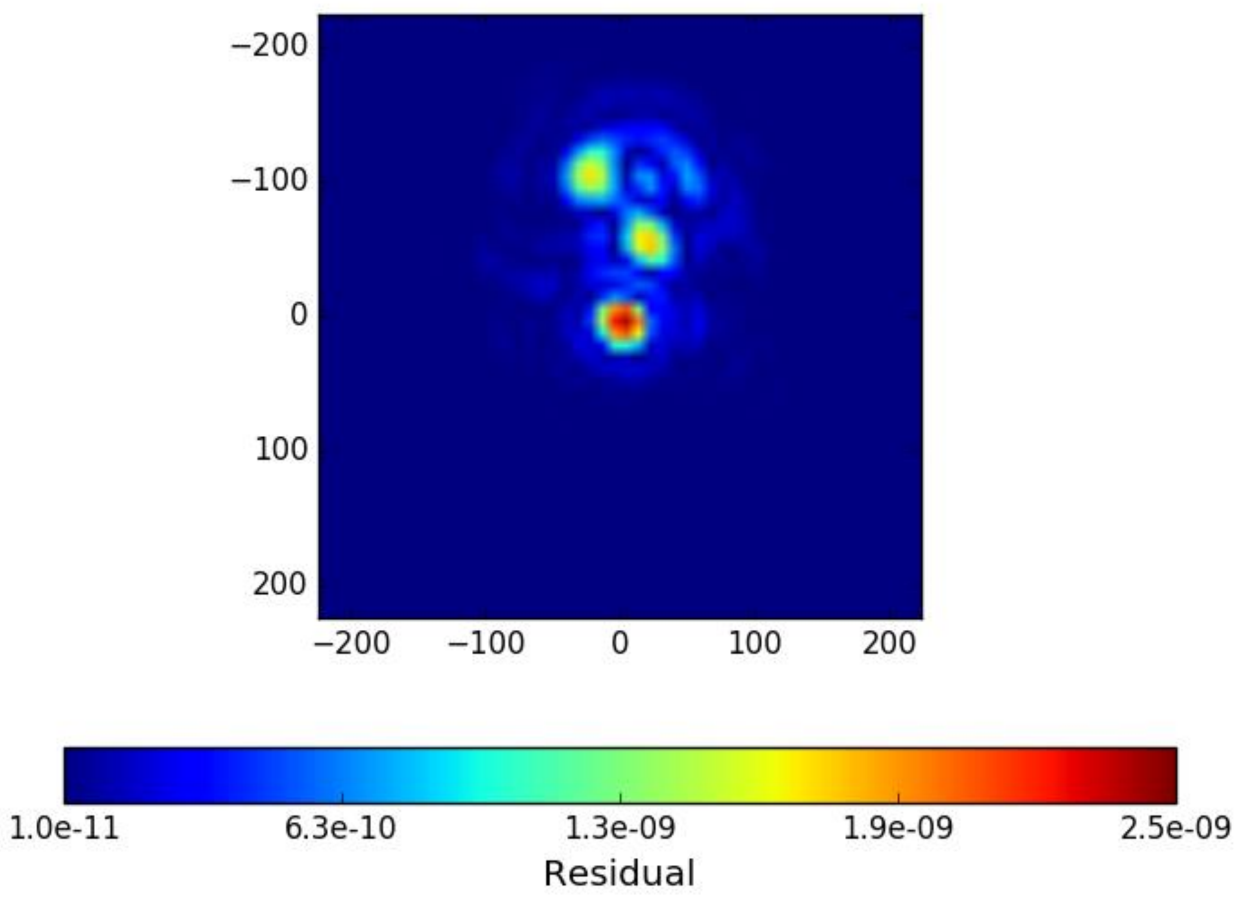


Residuals

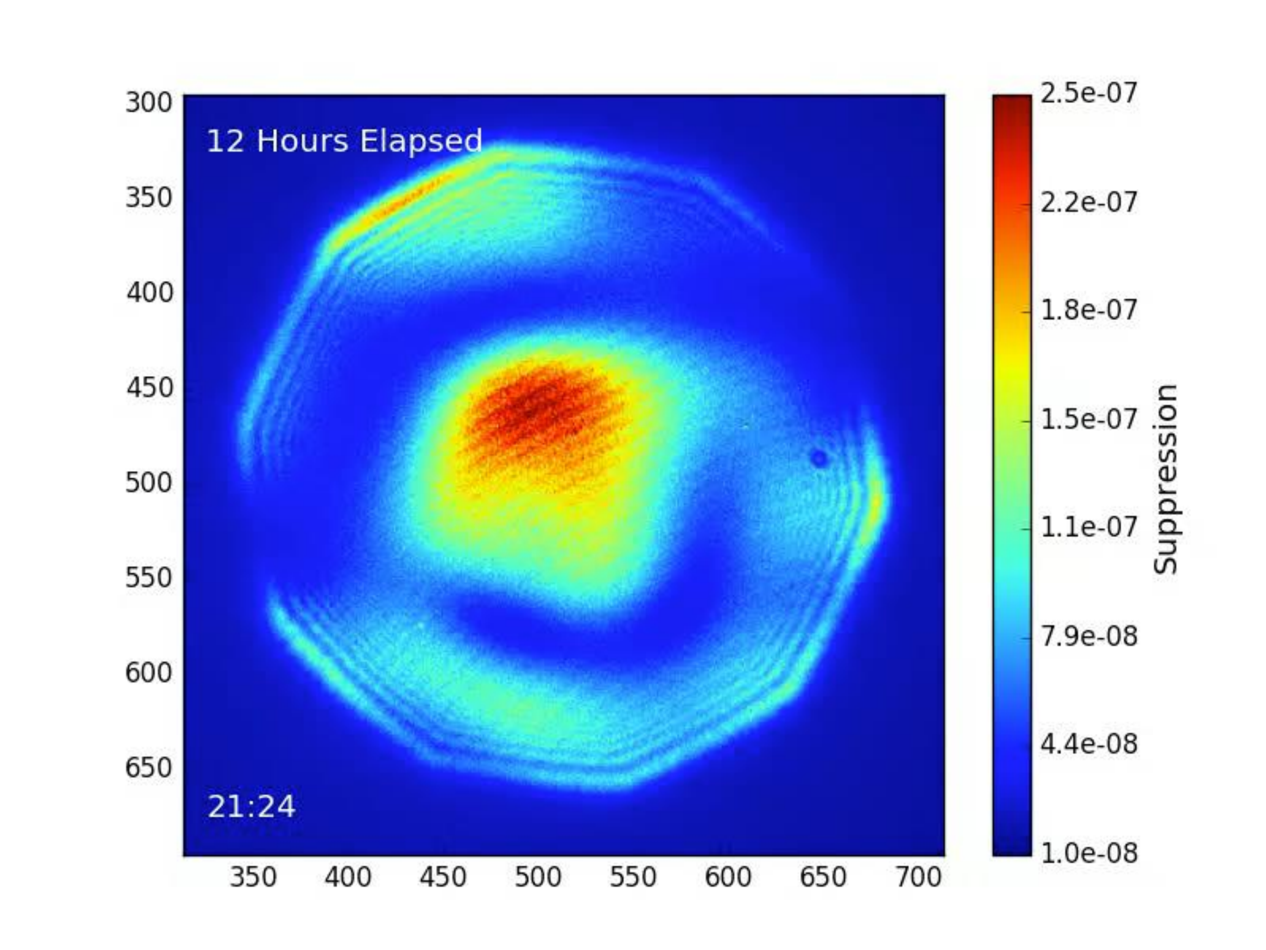
Suppression

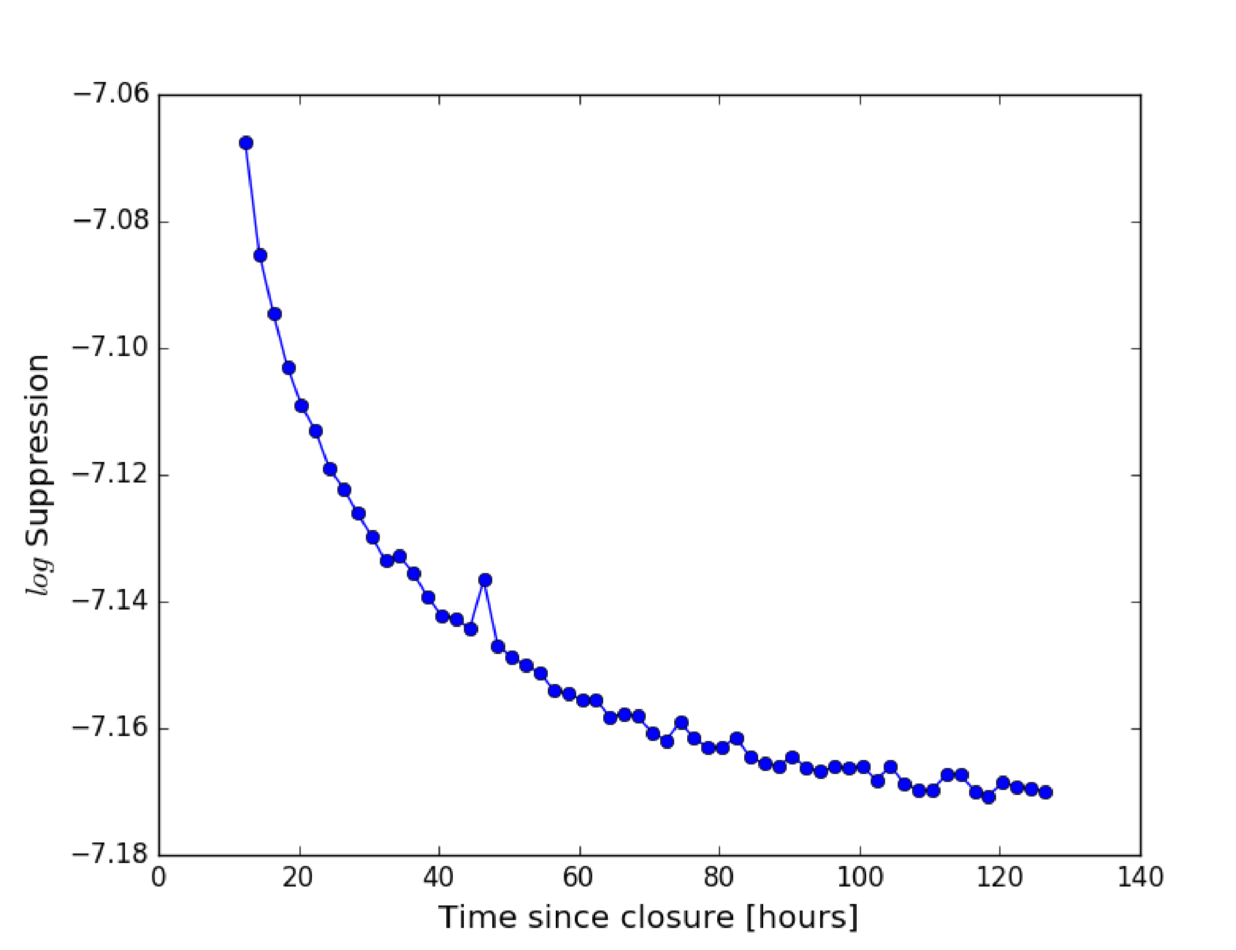


Contrast



Atmospheric turbulence





Reaching 10^{-9} Suppression

- Suppression is limited by manufacturing of mask
  - 400 nm uniform over-etch in Silicon etching process
  - Small features are difficult to manufacture on large wafer size
  - Working to eliminate (or pre-bias) over-etch
    - Direct-write process may help

- Next limitation: random defects on mask edge

- Not sure if atmosphere will be limitation at lower levels

Next steps at Frick

- Completing primary milestone:
  - Manufacture mask with $\sim 0.1\ \mu m$ etching error
- See if atmosphere will limit model validation at 10^{-9} contrast
- Improve agreement between models and lab data
  - Get better measurements of mask (< 100 nm resolution)
  - Reduce variation from atmosphere
    - Insulate tube
    - Decrease exposure time


Thank
You!

BACKUP
SLIDES

Technology Development

Road to TRL 5

- Reach TRL 5 before 2020 Astrophysics Decadal Survey
  - Looking for recommendation for a Starshade Rendezvous with WFIRST
- SSWG recommends ground demo is sufficient
- Models agree with experiments at $10^{-\Gamma}$ intensity level
  - $\Gamma \geq 9$
- Decompose Fresnel number
  - Validate in large swath of parameter space
- Test at similar **fit, form, function**
  - Fit: demonstrate we understand scalability
  - Form: looks like a starshade (tips, valleys, etc)
  - Function: works as a system (broadband light)

Fresnel Number

- r_x: radius to apodization value x
- z_0: source – starshade distance
- z_1: starshade – telescope distance
- λ: wavelength

$$N_x = \frac{r_x^2}{\lambda\, z_{eff}}$$

$$z_{eff} = \frac{z_1 z_0}{z_1 + z_0}$$

Contrast definition

$$C_{(i,j)} = \frac{b_{(i,j)}}{max\left\{u\right\}}$$

$b_{(i,j)}$ value of blocked image at off-axis position (i,j)

$max\left\{u\right\}$ peak value of unblocked image

Suppression definition

Suppression = $\dfrac{\text{Total light in aperture } \textbf{\textit{with}} \text{ starshade}}{\text{Total light in aperture } \textbf{\textit{without}} \text{ starshade}}$

$$S_\sigma = \frac{\sum_i^N b_i}{A \sum_j^N u_j}$$

Shadow parameter: $\sigma \equiv \frac{a}{r}\left(\frac{z_1 + z_0}{z_0}\right)$

$\sigma \rightarrow 1$: good
$\sigma >> 1$: bad

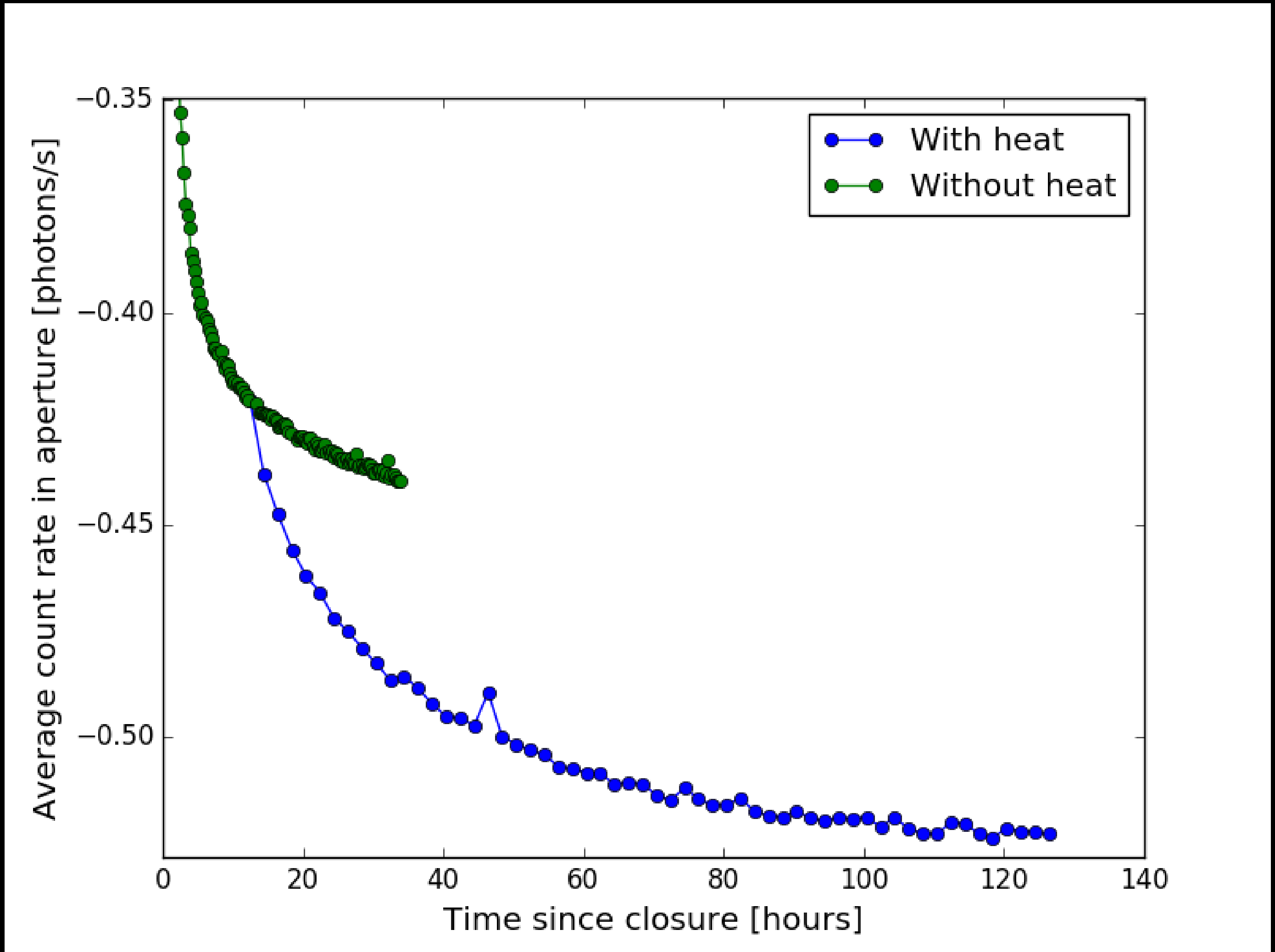
Discrete suppression: $s_i = \dfrac{b_i}{A\bar{u}_N}$

Average discrete suppression = Suppression:

$$\bar{s}_i = \frac{1}{N}\sum_i^N s_i = \frac{1}{N}\sum_i^N \frac{b_i}{A\frac{1}{N}\sum_j^N u_j} = \frac{\sum_i^N b_i}{A\sum_j^N u_j} \equiv S$$

a: opaque radius
r: telescope radius
z_0: source-starshade
z_1: starshade-telescope
N: # pixels *S* is calculated over
A: peak apodization value
b_i: blocked image pixel value
u_j: unblocked image pixel value

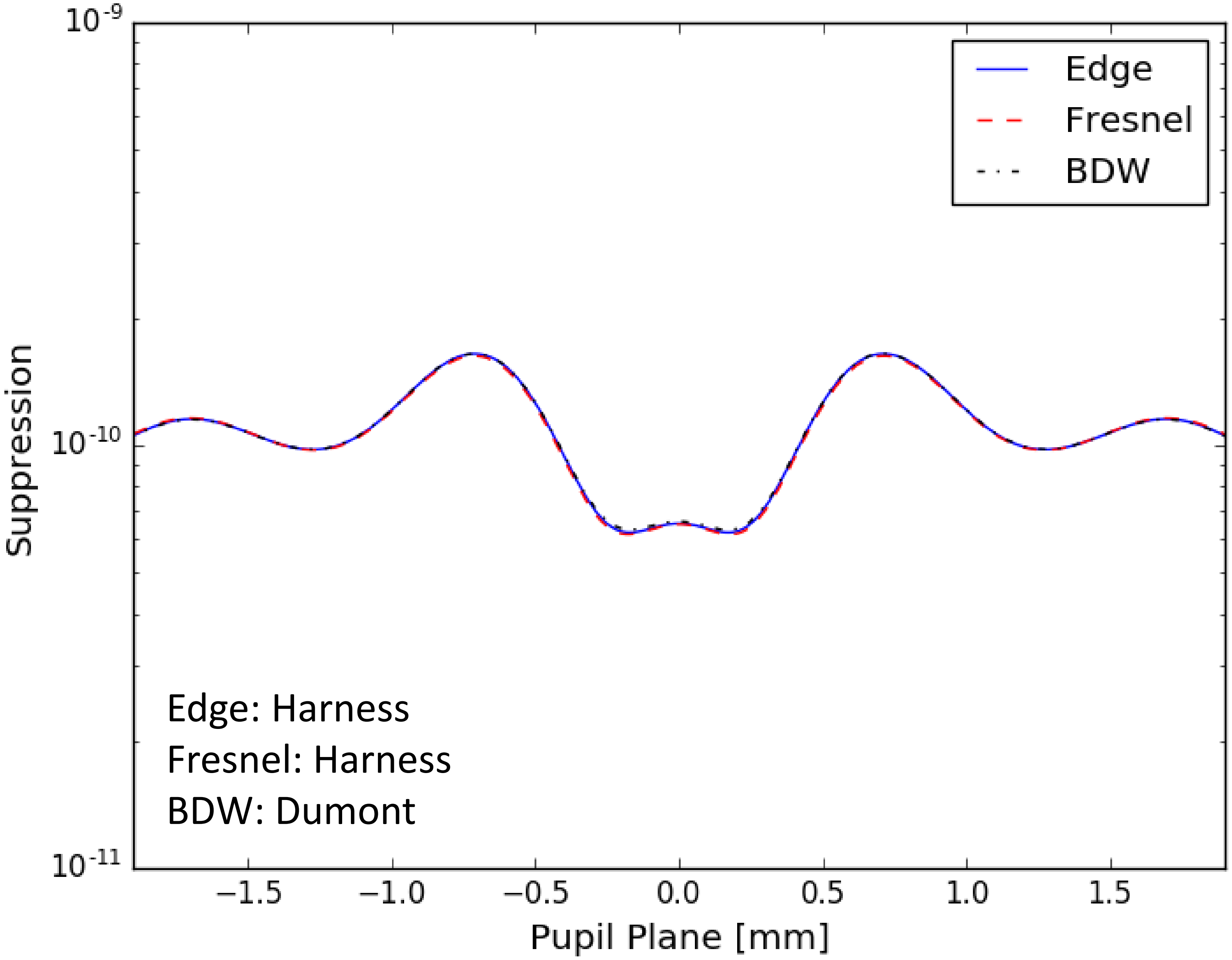
Heat sources removed

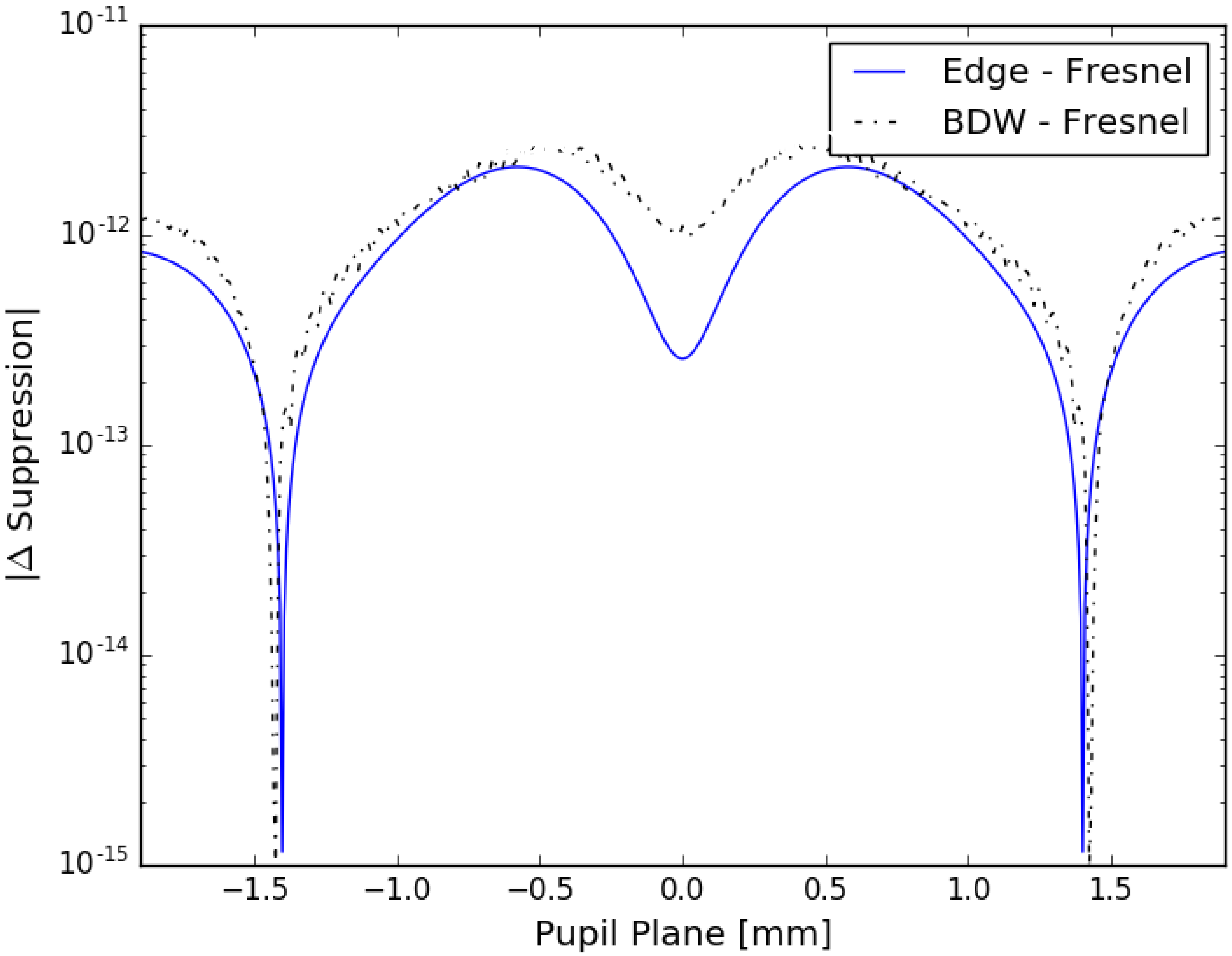


Optical Modeling

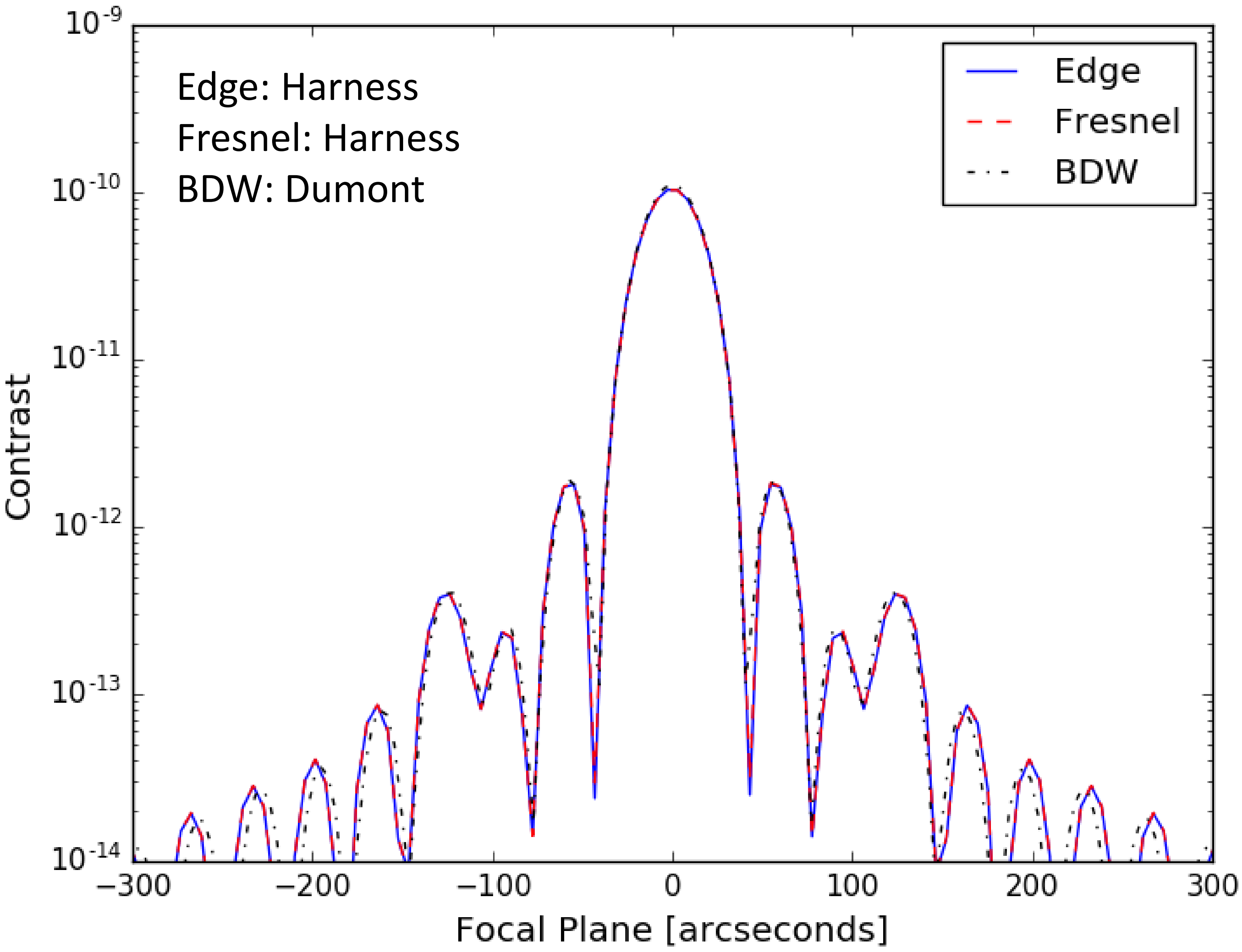
Model descriptions

- Modeling difficulty due to dynamic range (size and field strength) of starshade architecture
- Build confidence with validation of independent models
  - Show agreement between models with different assumptions
- Two families of models:
  - 2D Fresnel propagation
  - 1D line integrals of edge diffraction


Suppression
Pupil Plane [mm]
Edge
Fresnel
BDW
Edge: Harness
Fresnel: Harness
BDW: Dumont
10^-9
10^-10
10^-11
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5



Edge - Fresnel
BDW - Fresnel
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
|Δ Suppression|
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
Pupil Plane [mm]



Edge: Harness
Fresnel: Harness
BDW: Dumont
Edge
Fresnel
BDW
Contrast
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
−300
−200
−100
0
100
200
300
Focal Plane [arcseconds]

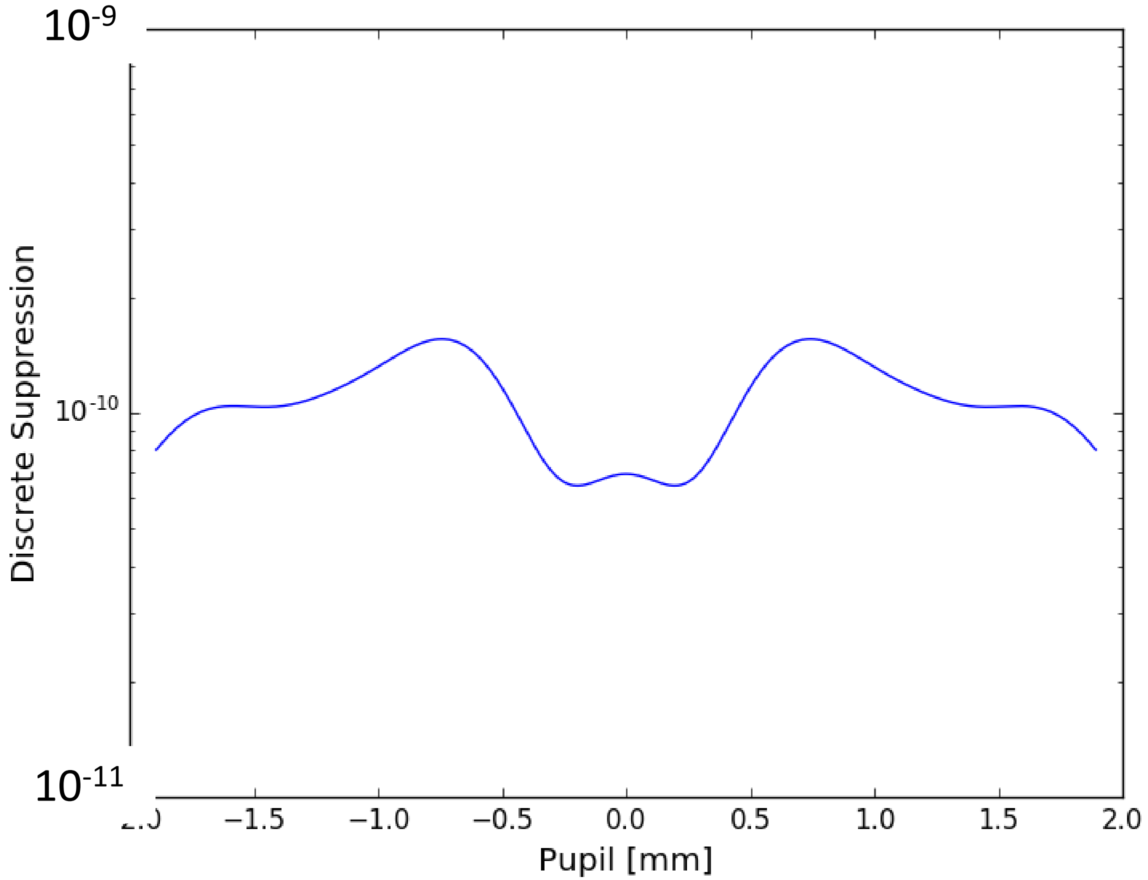
Optical models

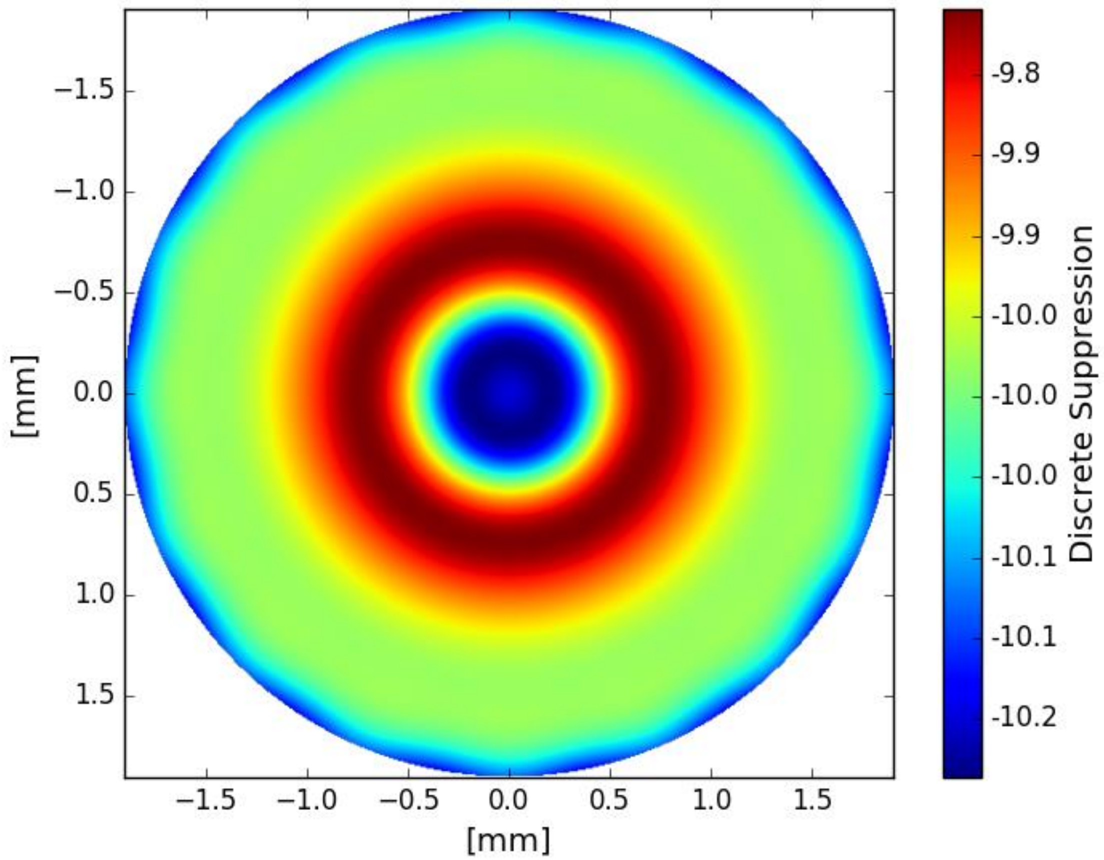
- Shared assumptions:
  - scalar diffraction
    - vector properties (e.g., polarization) are ignored
  - wavelength << sizes, distances
  - Kirchoff boundary conditions
  - invoke Babinet's principle

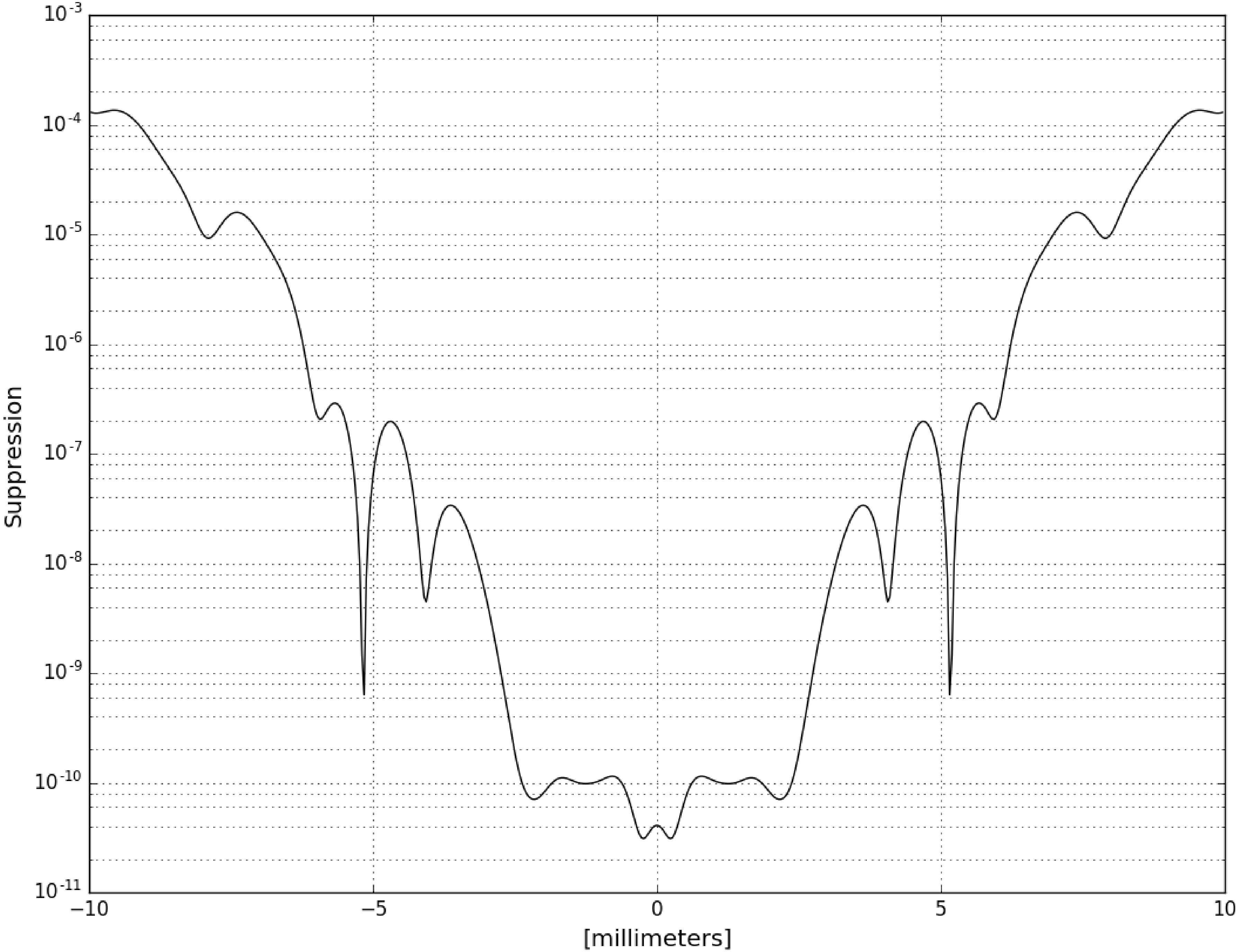
- Solve integral theorem of Helmholtz and Kirchoff with Kirchoff BCs

$$\frac{A_r A_s}{4\pi} \iint_S \frac{e^{ik(r+s)}}{rs} \left[\left(\frac{1}{r} - ik \right) cos\,(n, r) - \left(\frac{1}{s} - ik \right) cos\,(n, s) \right] dS$$

Nominal performance





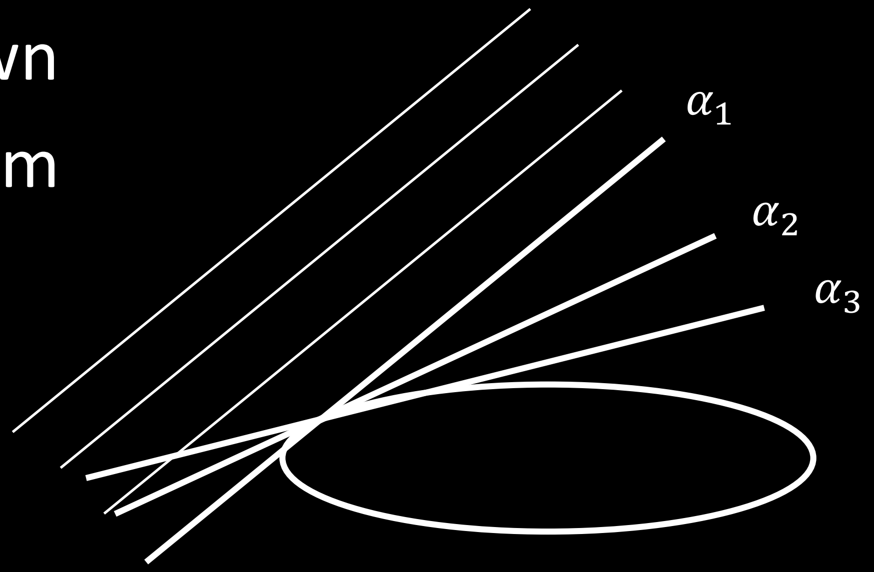


Suppression
[millimeters]
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
−10
−5
0
5
10

Modeling Wavefront Errors

- Edge algorithm assumes interior field is known
- Decompose phase error into angular spectrum of plane waves

$$A\left(\alpha\right) = \int f\left(x\right) e^{-i2\pi\alpha x}\, dx$$



$$\begin{aligned} U\left(p\right) &\propto \int U_0\left(x\right) e^{\frac{ik}{2z}\left(x-p\right)^2} e^{\frac{ik}{2z_0}x^2} \left[e^{i\phi(x)}\right] dx \\ &\propto e^{\frac{ik}{2z}p^2} \int U_0\left(x\right) e^{\frac{ik}{2az}x^2} e^{-\frac{ik}{z}px} \left[\int A\left(\alpha\right) e^{i2\pi\alpha x}\, d\alpha\right] dx \\ &\propto e^{\frac{ik}{2z}p^2} \left[A * \mathcal{F}\left(U_0 e^{\frac{ik}{2az}x^2}\right)\right]_{\left(\frac{p}{\lambda z}\right)} \end{aligned}$$

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