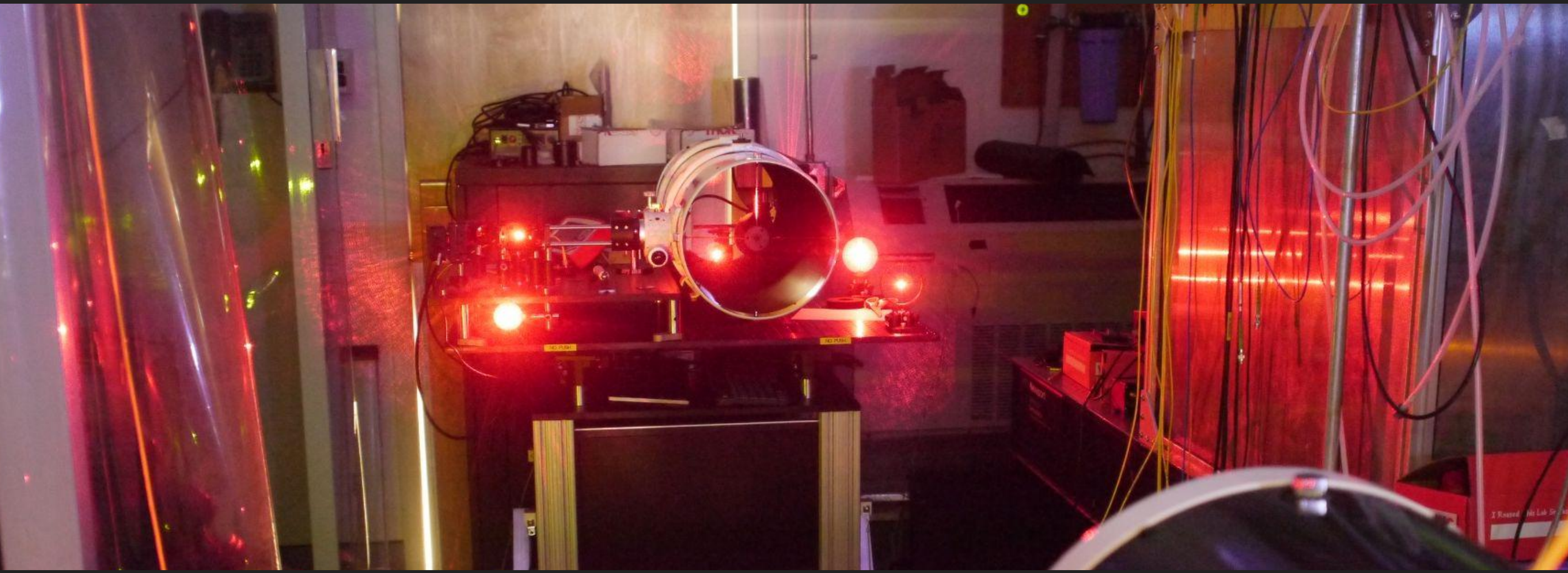
# Free Space Photon Transport

## A low-loss fiber-alternative for entanglement distribution



Brookhaven National Laboratory

Center for Distributed Quantum Processing

Stony Brook University

**Justine Haupt**
Co-PI, Free Space Link for Entangled Photon Distribution

# The NY Q-Net

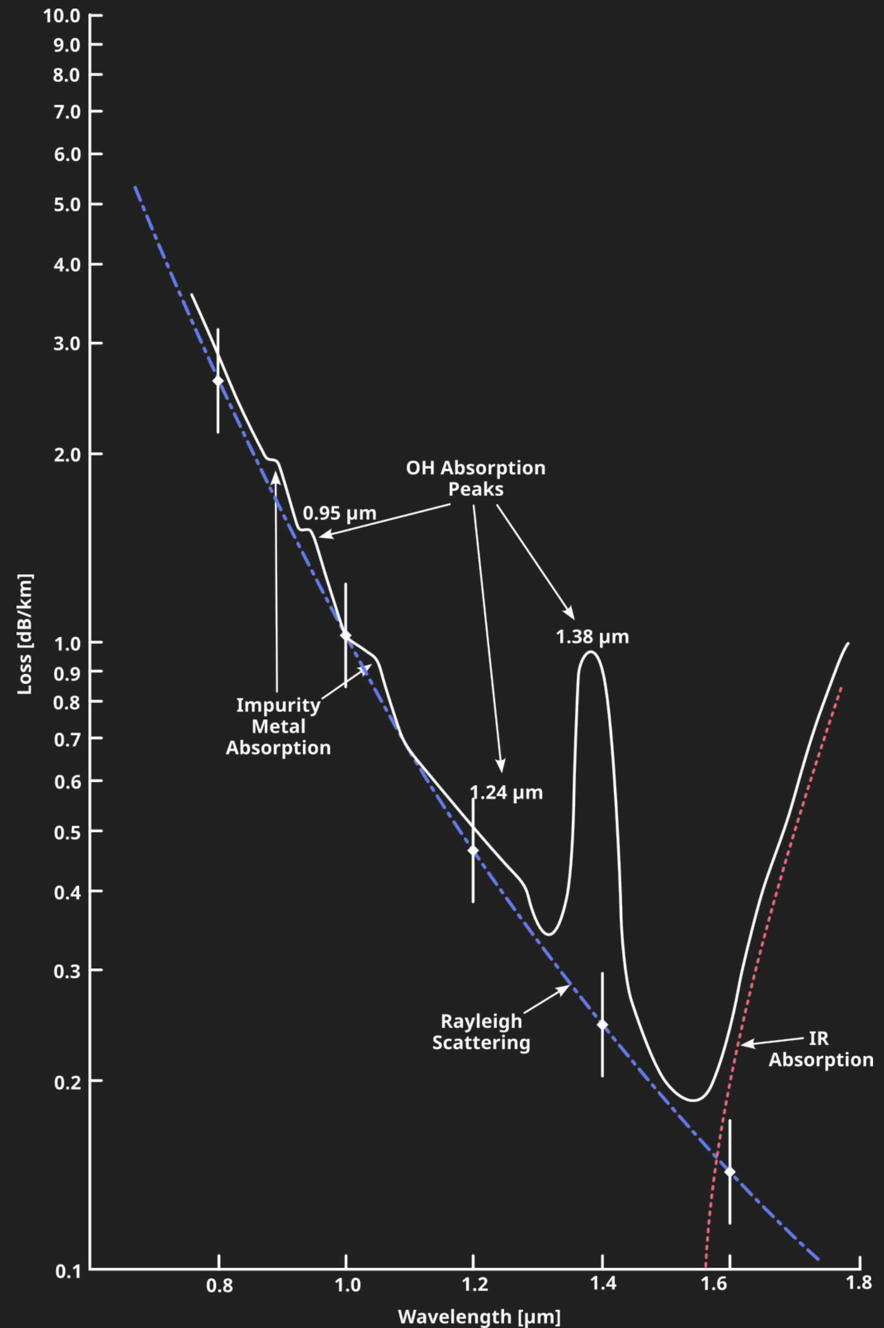

- A mostly fiber network
- Fiber path lengths > LOS

# Telecom Fiber

**Over 70km (SBU-BNL)**

- **at 1324nm ~24dB**
- **at 795nm >200dB**

- Fiber transport only viable at telecom frequencies
- Q-Memories operate at 795nm
- Up/down conversion lossy



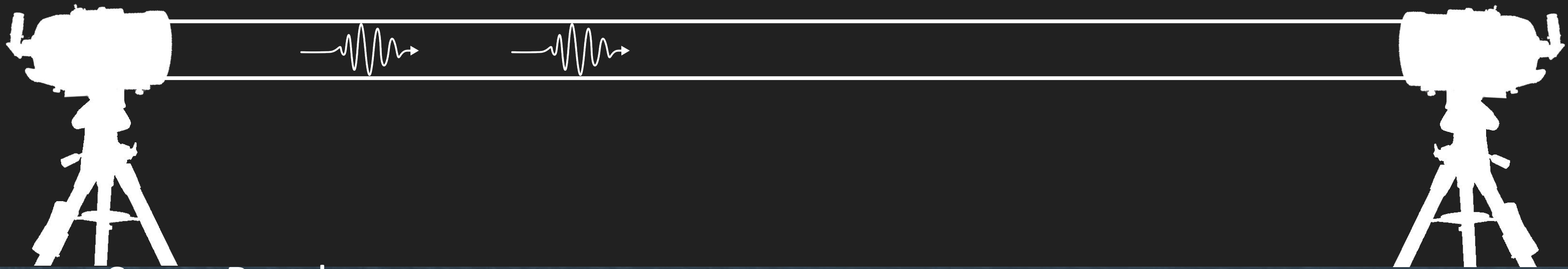

ATTENUATION IN SILICA FIBER

# The NY Q-Net

Stony Brook (SBU)
~20km
Upton (BNL)
~61km
~70km
Commack
~58km
Westbury
~47km
~70km
NYC
~50km
Garden City
Quantum Memory
Entanglement Source
Entanglement Swap
Fiber Path
Free Space Path
Stony Brook
Emitter optics
single photon source
SBU Hospital Towers
free space transmission
~20km
Upton
Receiver optics
Quantum Memory
Stony Brook University
Brookhaven National Laboratory

# Concept

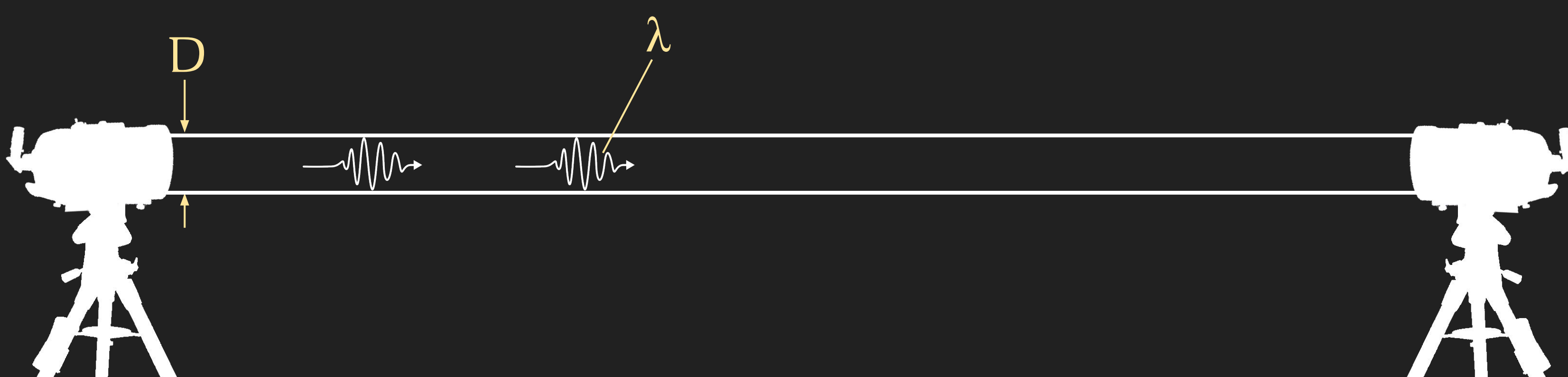
- Over-the-air (fiber-less) qubit transmission
- Point telescopes at each other
- Why telescopes? **Beam expansion**



# Diffraction Considerations

- Over-the-air (fiber-less) qubit transmission
- Point telescopes at each other
- Why telescopes? **Beam expansion**

$$\sin(HWHM) \approx \lambda/D$$

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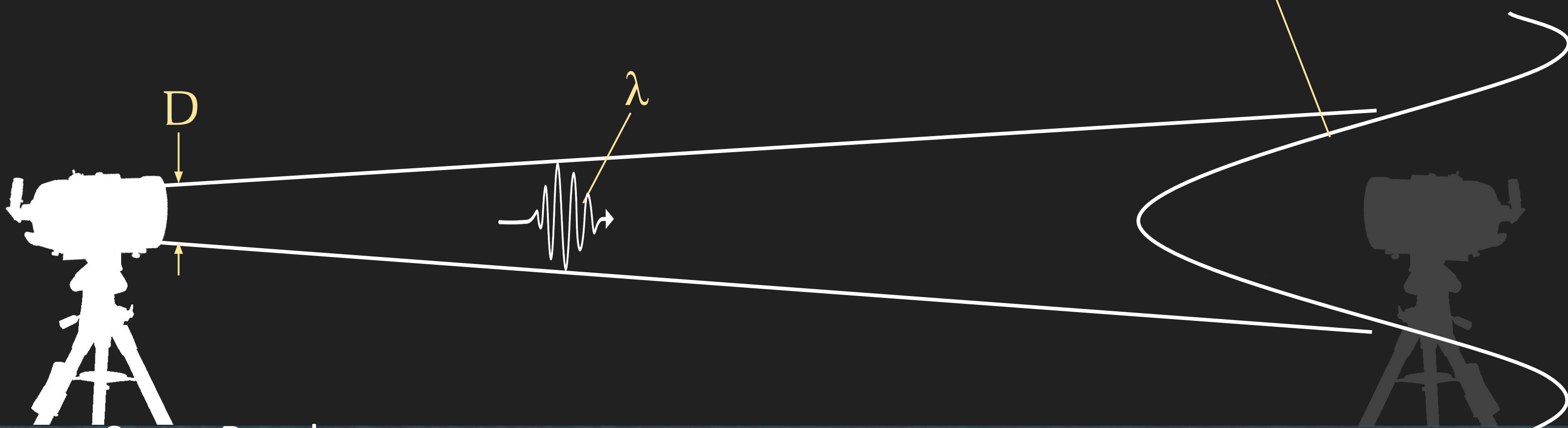
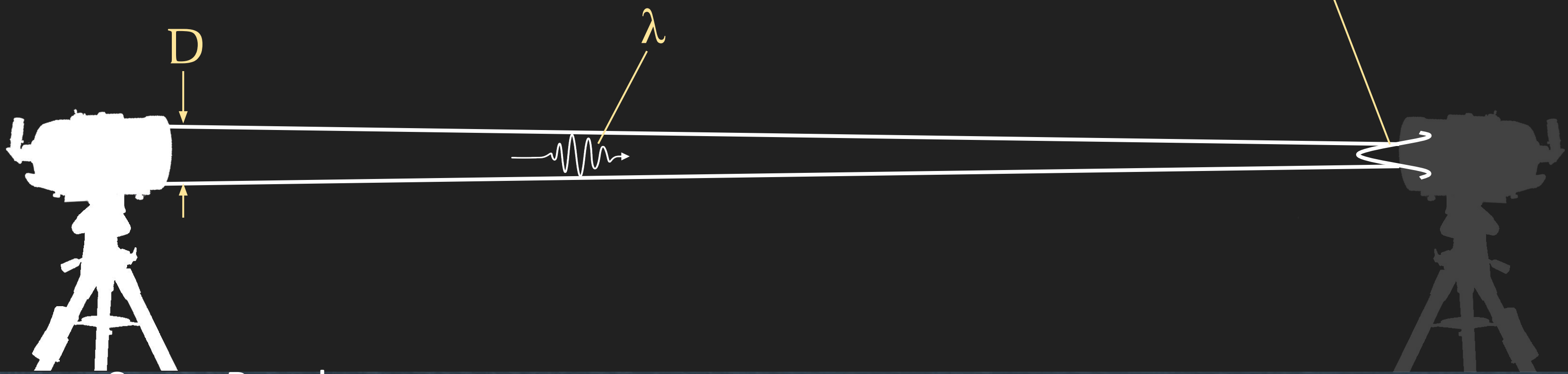



# Diffraction Considerations

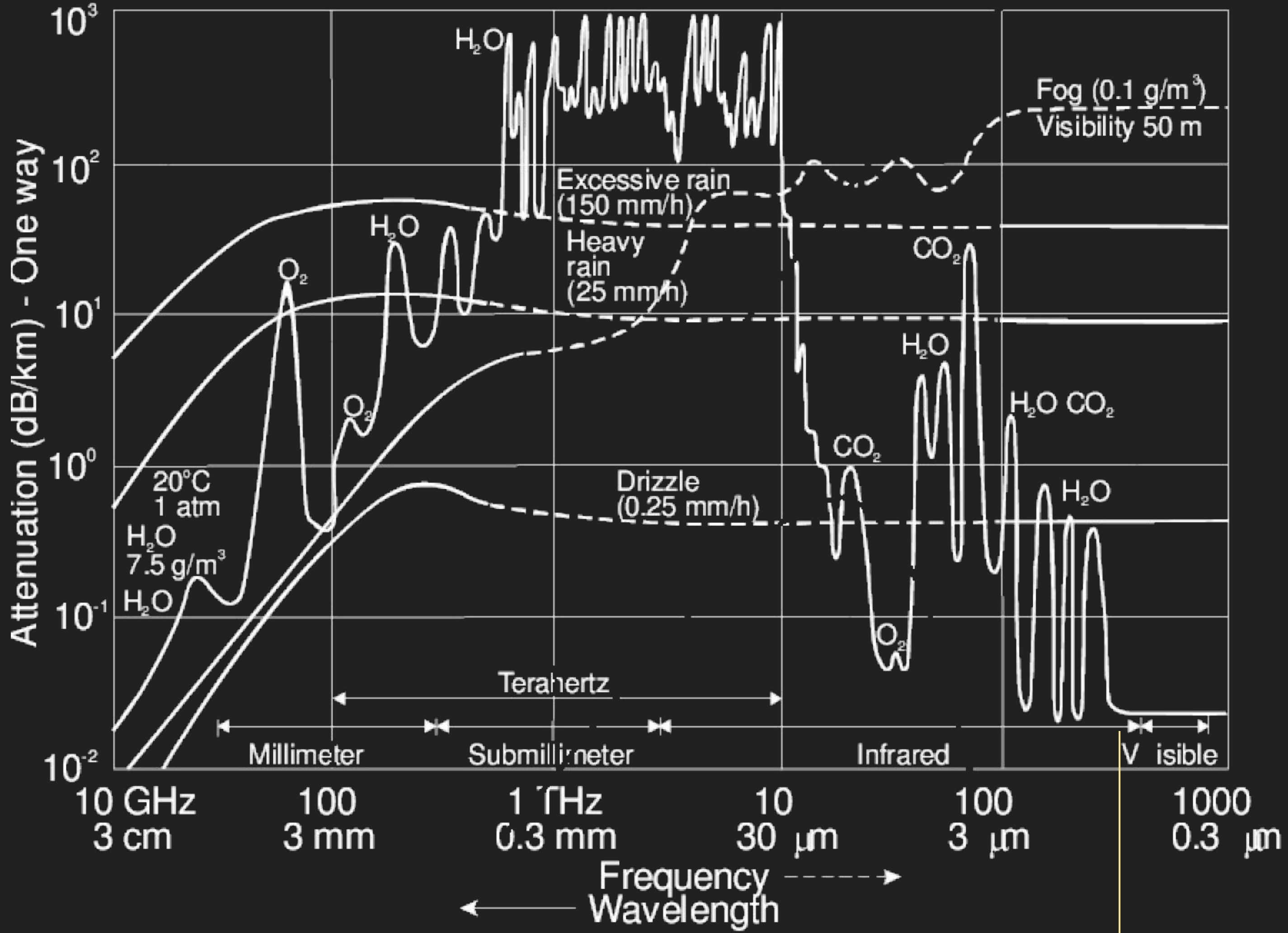
**Over 20km:**

- 0.1m -> 0.4m
- 0.2m -> 0.2m
- 0.4m -> 0.1m
- 0.6m -> 0.06m

$$\sin(HWHM) \approx \lambda/D$$




# Atmospheric Considerations



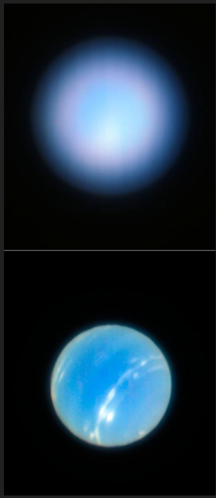

<< 0.1dB/km at 795nm

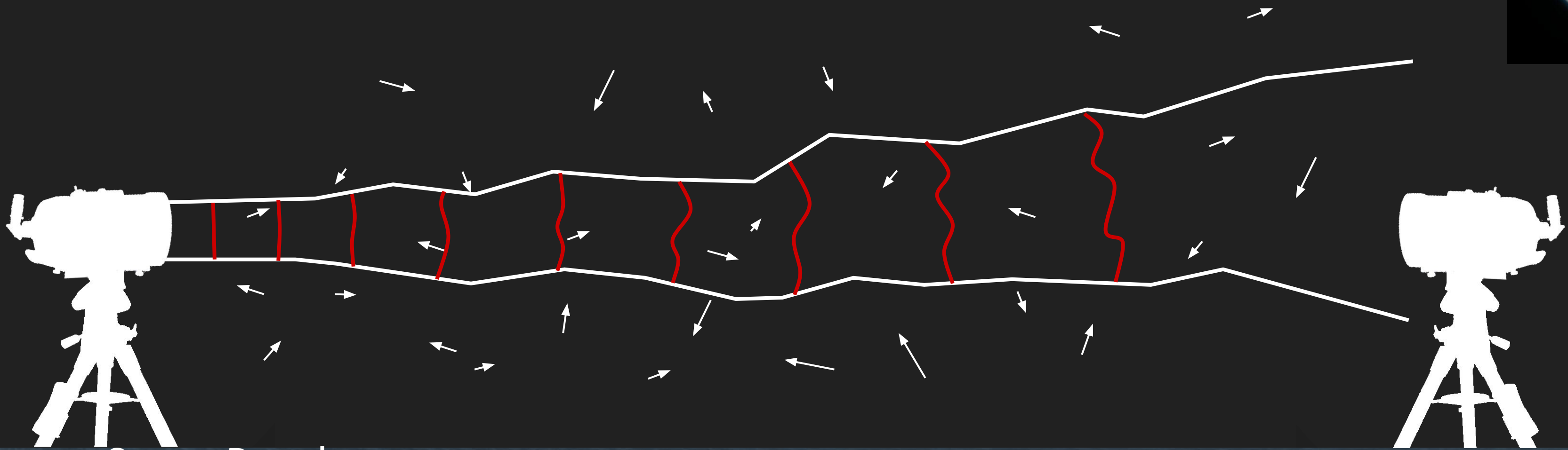
< 1dB/km at 1324nm

- Yes, weather matters

# Atmospheric Considerations

- Optical index variation due to turbulence ("seeing")
- Biggest hurdle
- Ground layer is worst

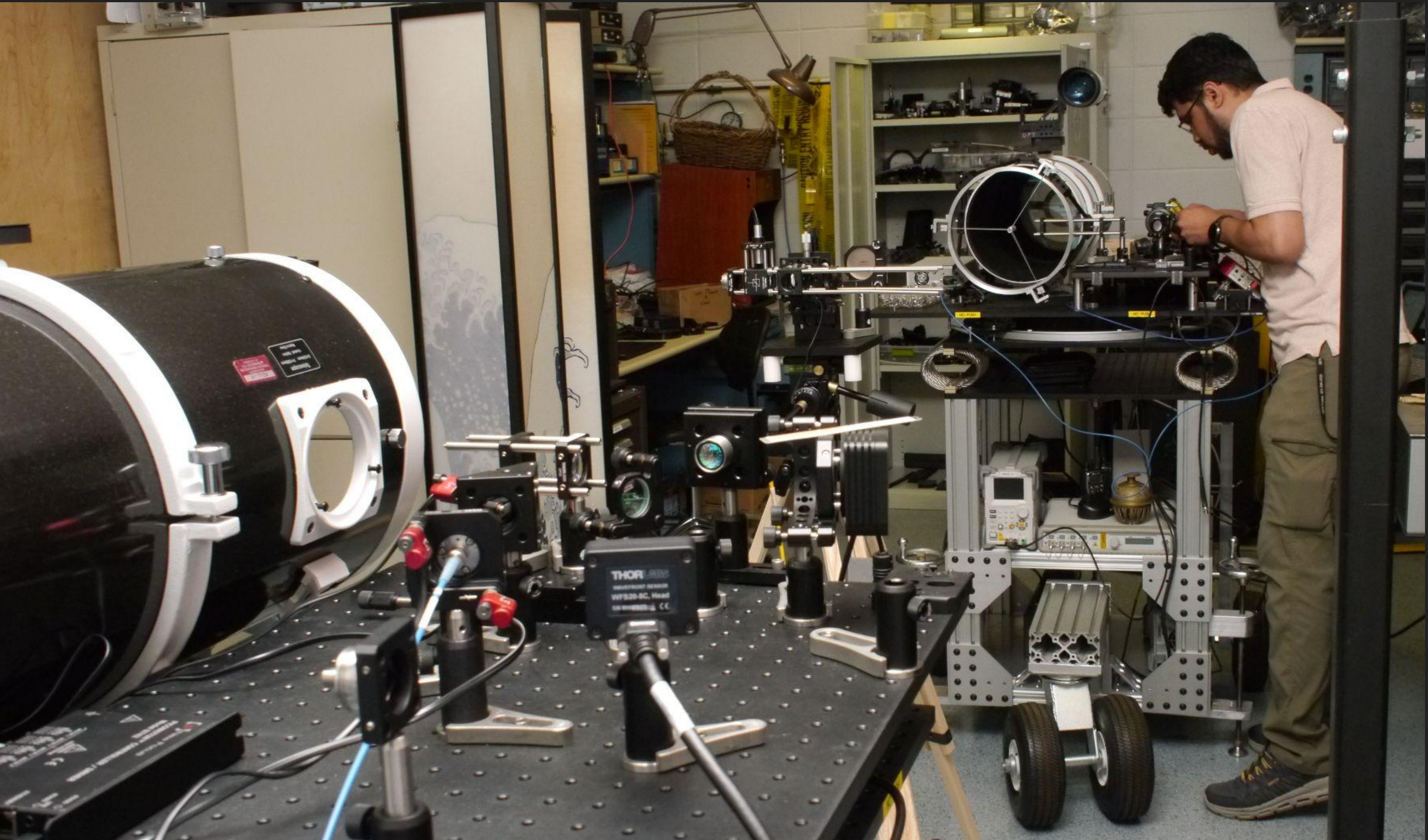




# Free Space Optics

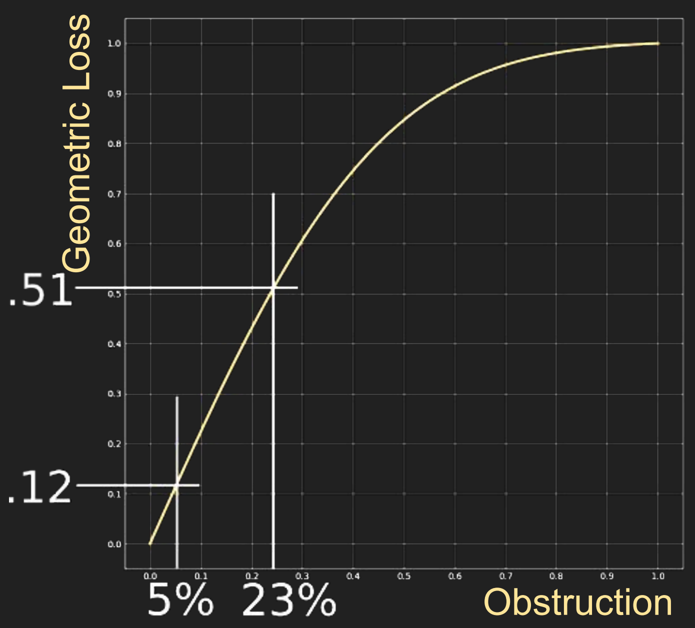
# Free Space Optics

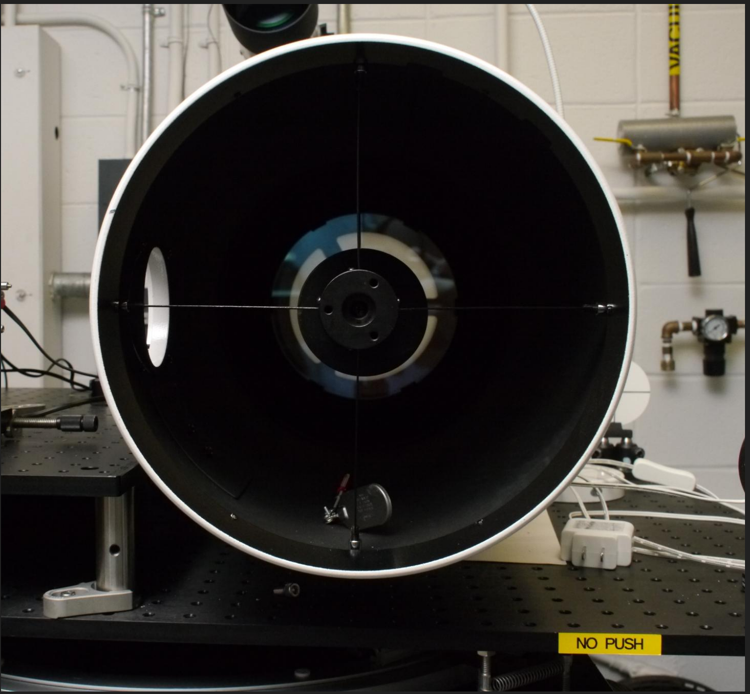
- 10” telescopes precede .6m full-scale (rooftop system)
- Platform to develop enabling tech; will be transferred directly to rooftop system



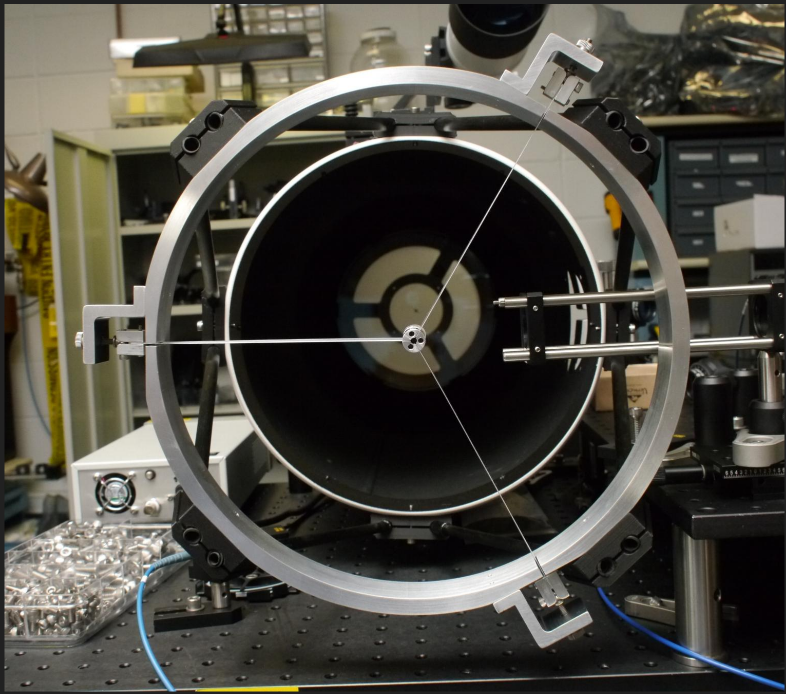
# Dealing w/ Fiber

- Telescopes are **fiber coupled**
- Compare to microwave communication links that are "wired" to local equipment
- **Fiber** is a PITA
- Core dia. = ~5μm
- Illumination falloff is Gaussian
- Not ideal for reflecting telescopes




2.3" OBSTRUCTION



.5" OBSTRUCTION

# Atmospheric Considerations

- $C_n^2$: quantifies turbulence-induced refractive index structure
- Typical range ~ $10^{-12}$ - $10^{-16}$ $m^{-2/3}$

$$C_n^2(z) = bK_H \epsilon^{\frac{1}{3}} \frac{\partial n}{\partial z^2}$$

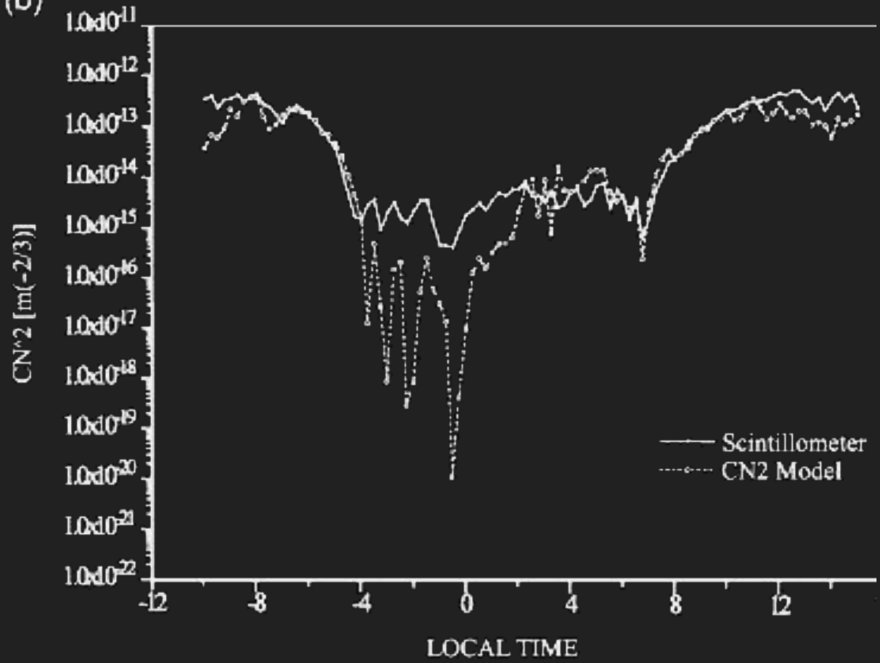
Height AGL

E dissipation rate

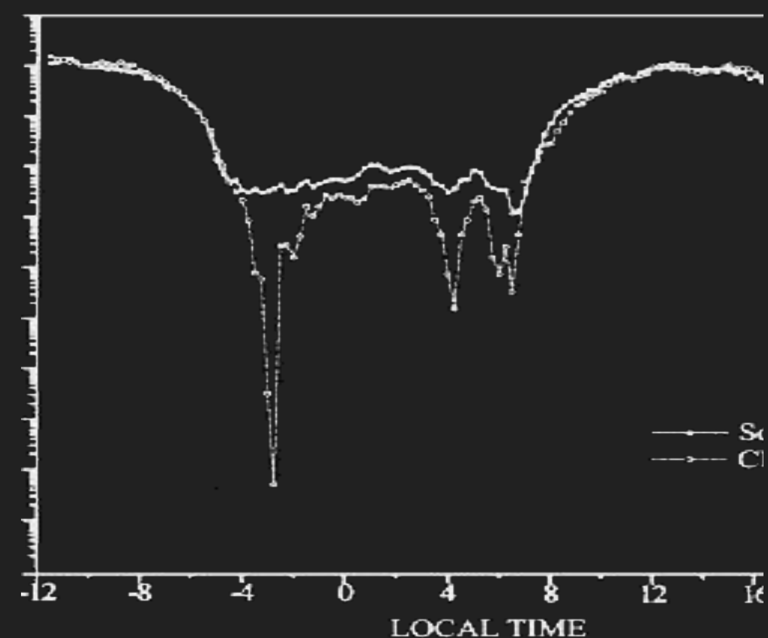
Turbulence exchange coeff. for heat

Vert. index gradient

(b)

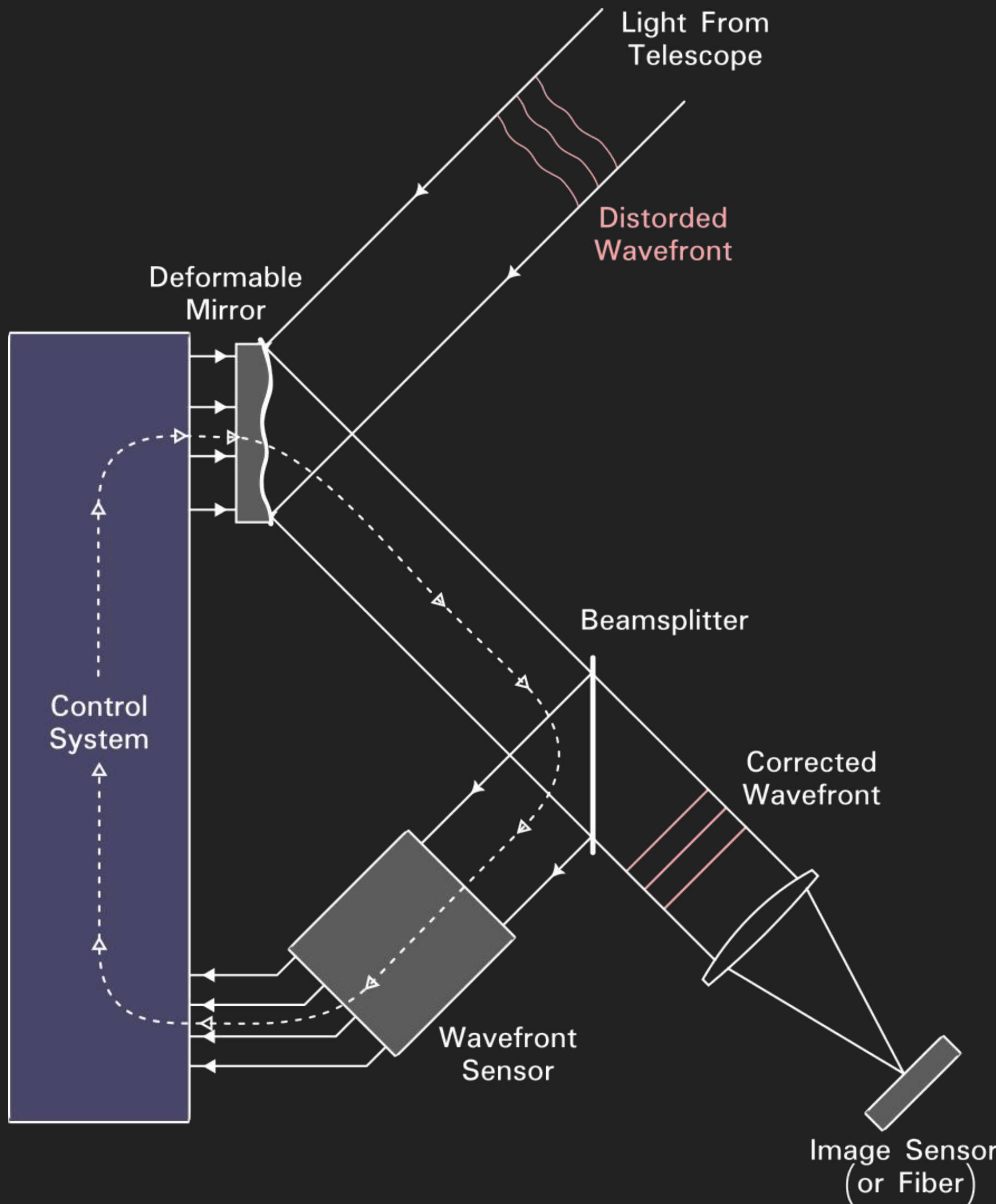



z=4m over 450m path

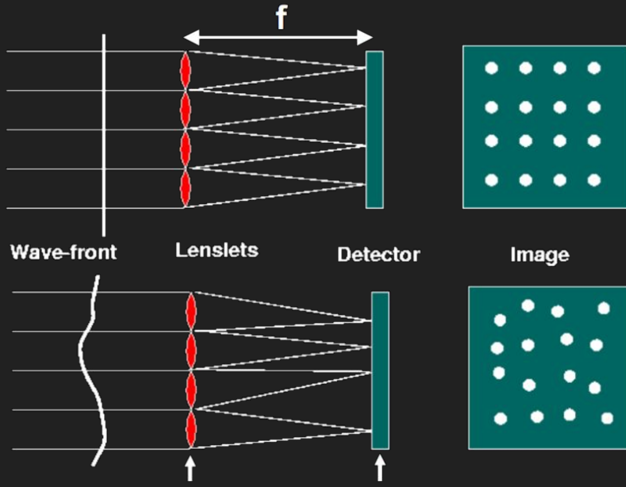



z=1m over 450m path

# Adaptive Optics




## Shack-Hartmann WFS



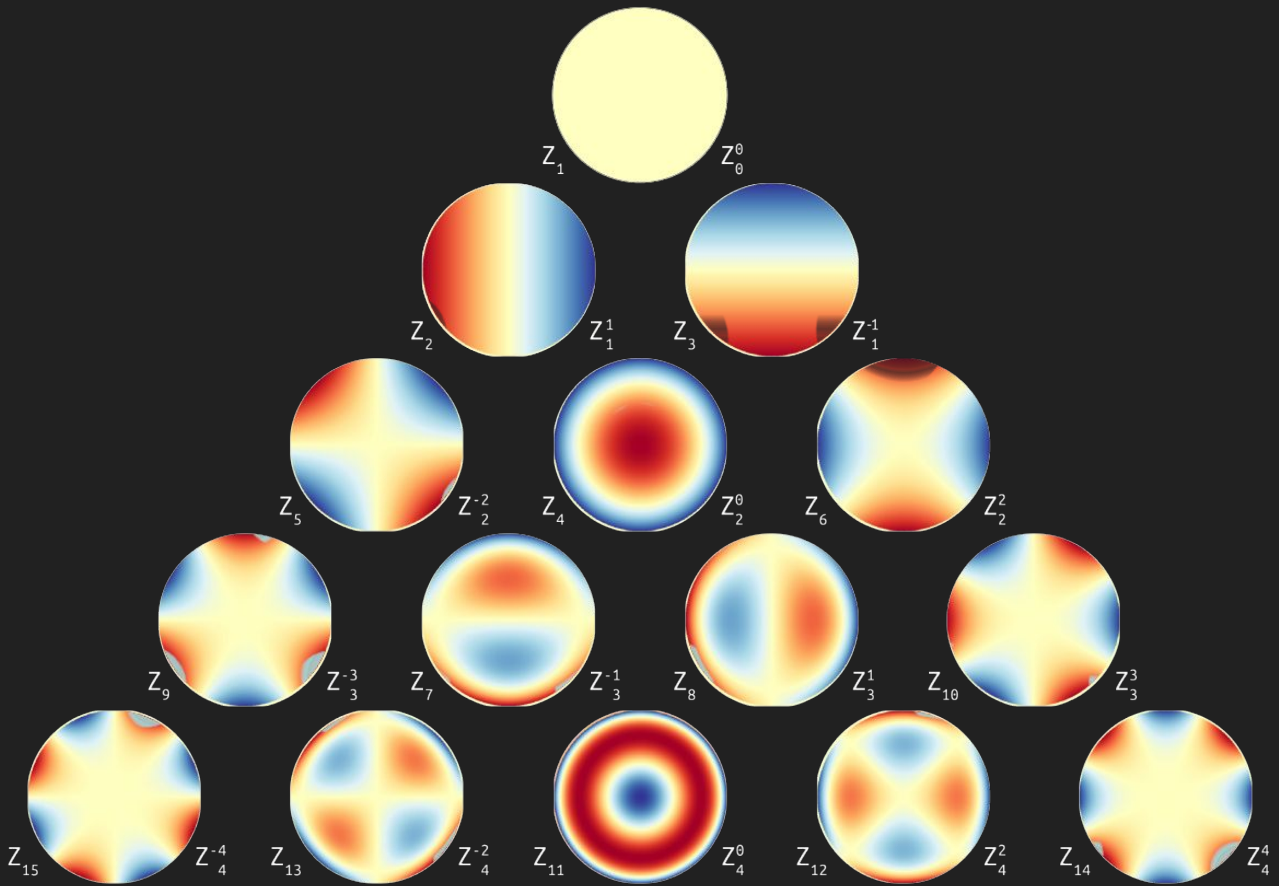

Centroid sub-samples

$$\vec{\delta} = m f_\ell \vec{\nabla} z$$

$$\begin{bmatrix} \vec{\delta}_{11} & \vec{\delta}_{12} & \vec{\delta}_{1k} \\ \vec{\delta}_{21} & \ddots & \vdots \\ \vec{\delta}_{i1} & \ldots & \vec{\delta}_{jk} \end{bmatrix}$$

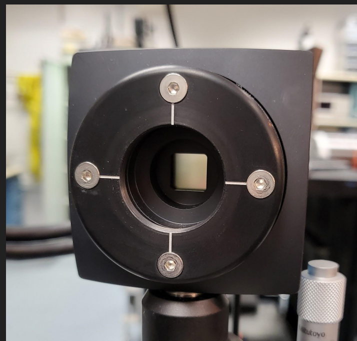
# Fitting wavefront data

$$Z_n^m(\rho,\varphi) = R_n^m(\rho)\,\cos(m\,\varphi) \qquad Z_n^{-m}(\rho,\varphi) = R_n^m(\rho)\,\sin(m\,\varphi)$$



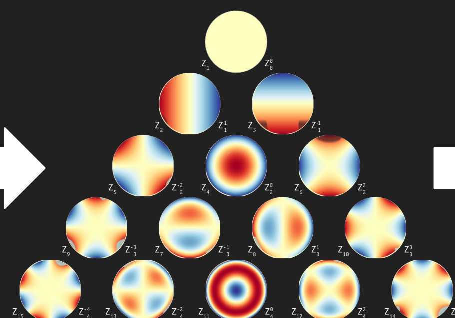

$$R_n^m(\rho) = \sum_{k=0}^{\frac{n-m}{2}} \frac{(-1)^k\,(n-k)!}{k!\,\left(\frac{n+m}{2}-k\right)!\,\left(\frac{n-m}{2}-k\right)!}\,\rho^{n-2k}$$

# Applying wavefront data



WFS

$$\begin{bmatrix} \vec{\delta}_{11} & \vec{\delta}_{12} & \vec{\delta}_{1k} \\ \vec{\delta}_{21} & \ddots & \vdots \\ \vec{\delta}_{i1} & \dots & \vec{\delta}_{jk} \end{bmatrix}$$



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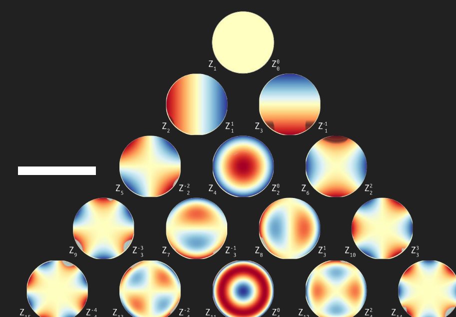
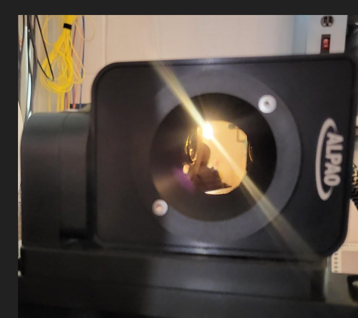


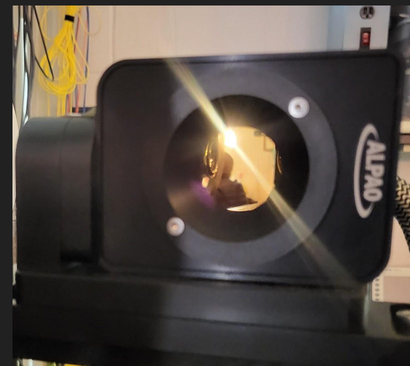


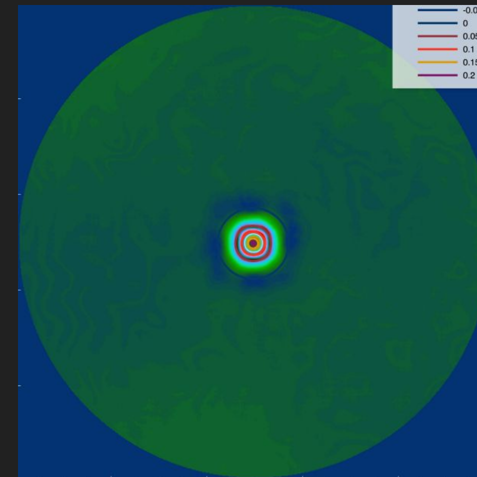
?

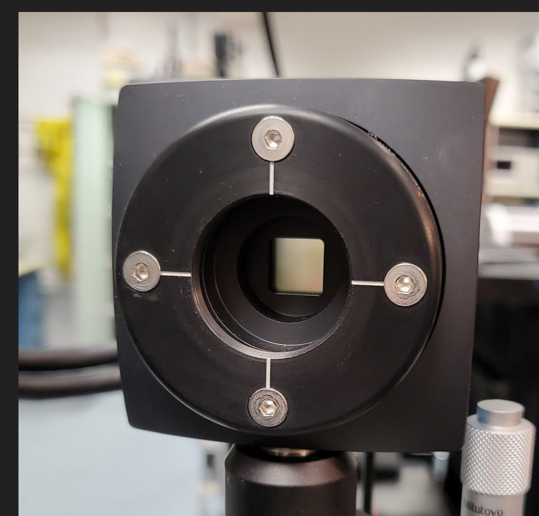
# Map DM Response

$$\begin{bmatrix} z_{11} & z_{12} & z_{1k} \\ z_{21} & \ddots & \vdots \\ z_{i1} & \dots & z_{jk} \end{bmatrix}$$

Poke Matrix



$$\begin{bmatrix} \vec{\delta}_{11} & \vec{\delta}_{12} & \vec{\delta}_{1k} \\ \vec{\delta}_{21} & \ddots & \vdots \\ \vec{\delta}_{i1} & \dots & \vec{\delta}_{jk} \end{bmatrix}$$

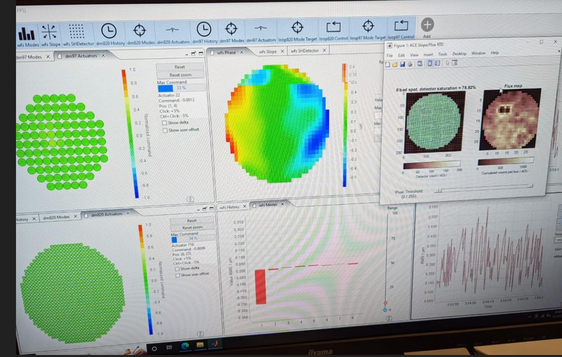
Interaction/Influence/
Transfer function

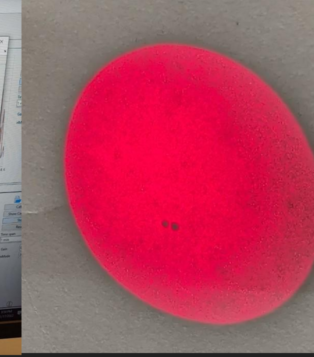
**CONTROL MATRIX**

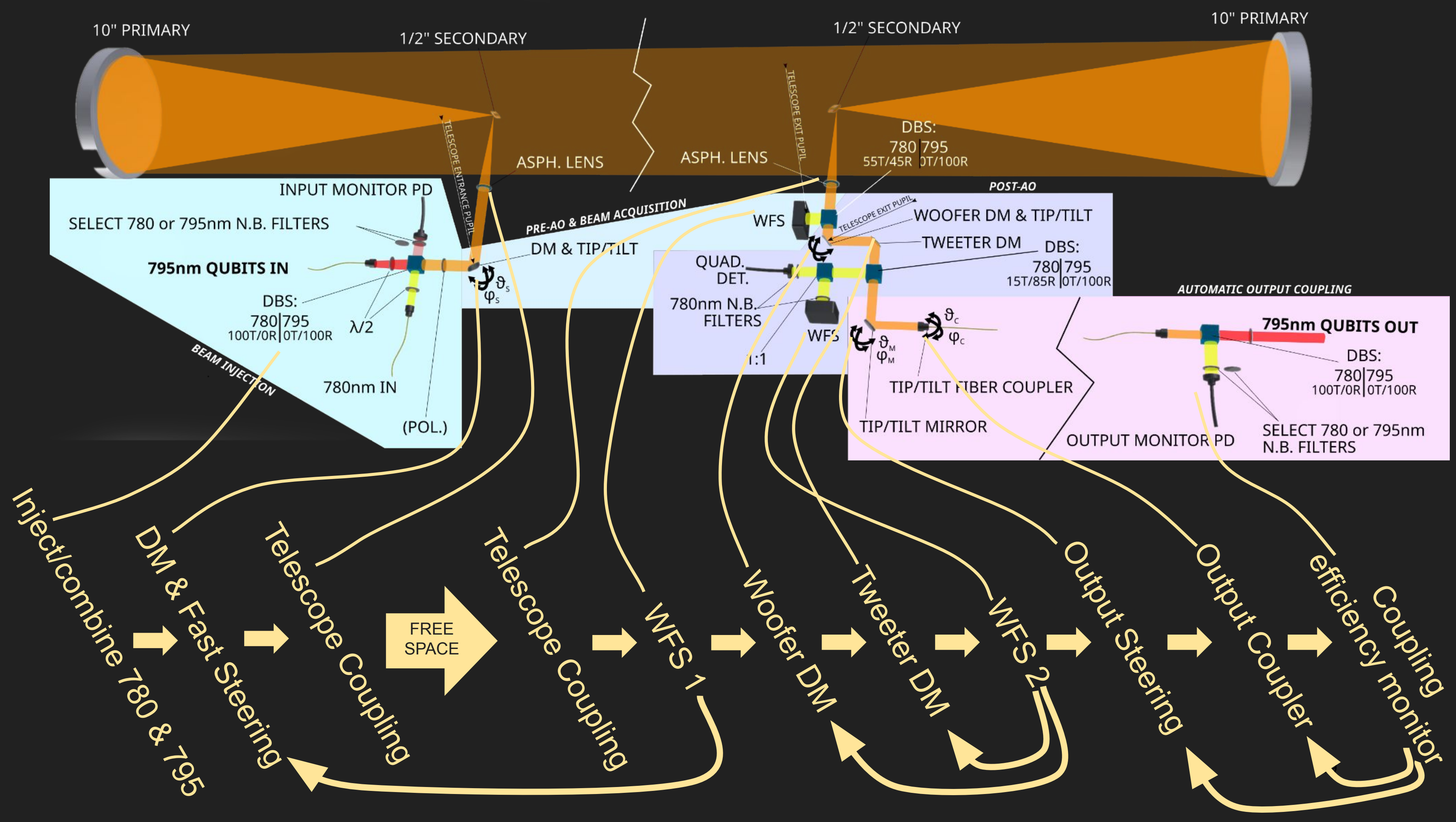
# Applied adaptive optics

**795nm:** Singe-Photon Source

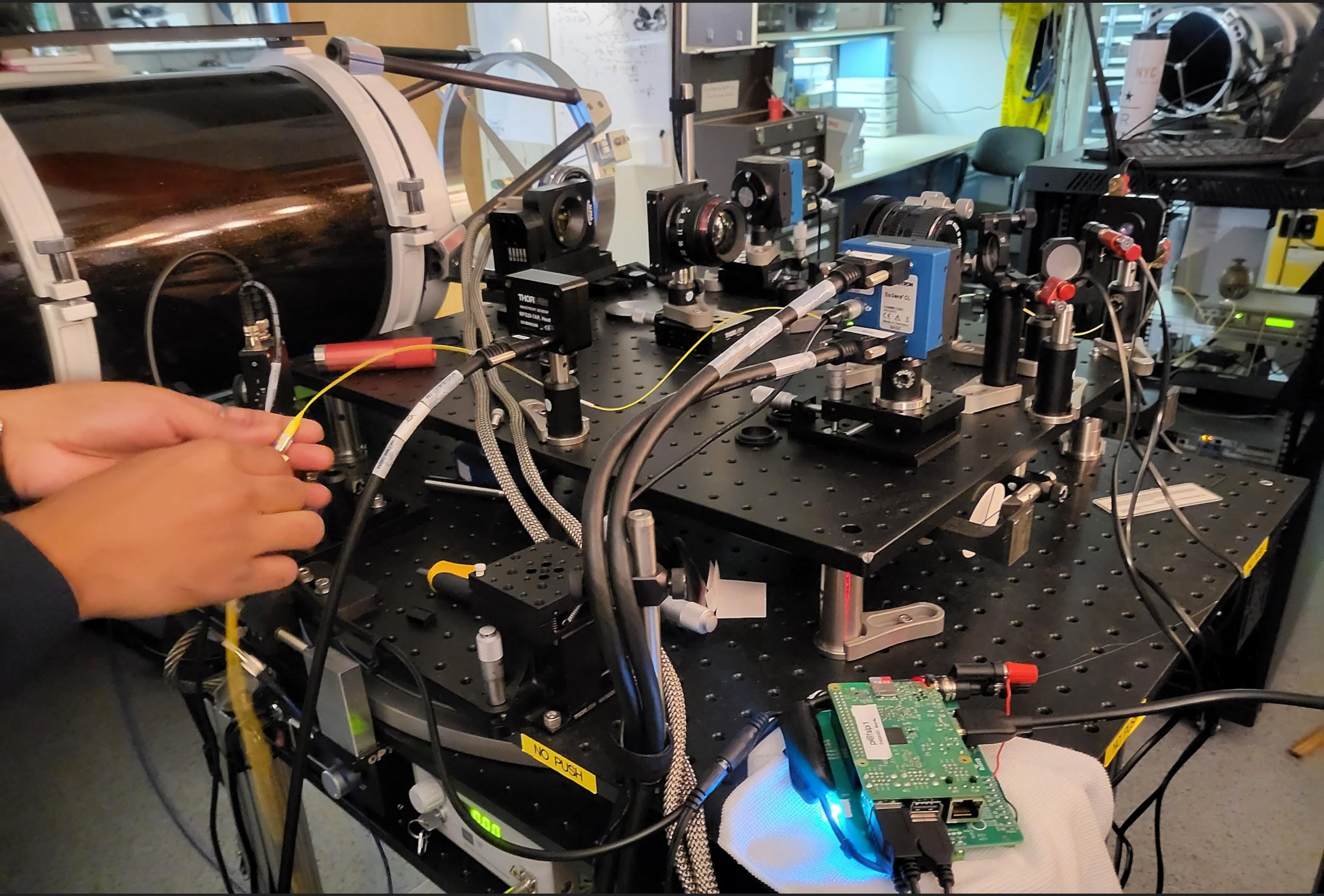
**780nm:** Utility/proxy for initial acquisition, wavefront sensing, active alignment





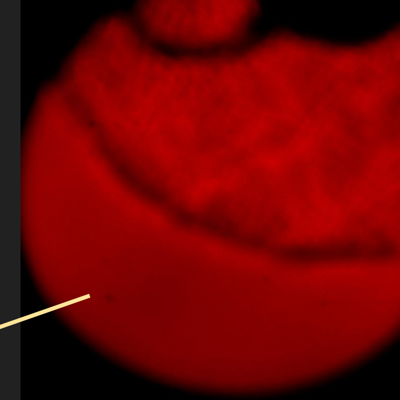


# Applied adaptive optics

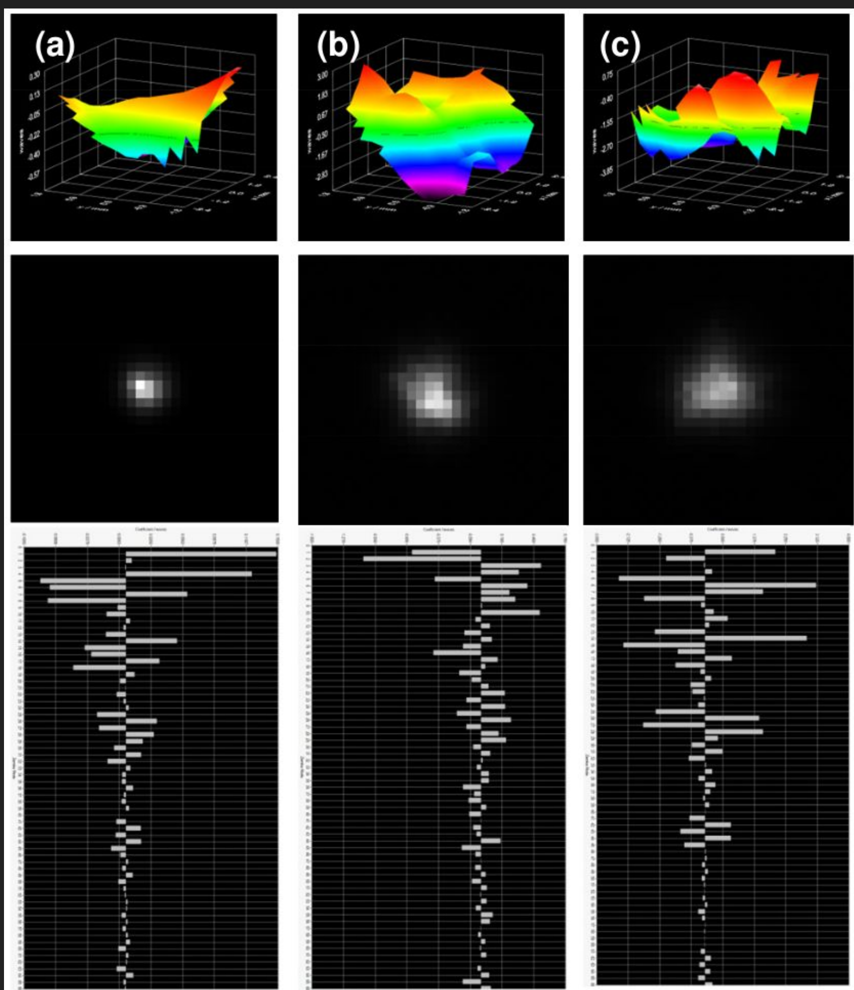


# AO Testing

- Developing the adaptive optics requires atmosphere emulation
- Basic/dumb method: A rotating plate with hairspray on it



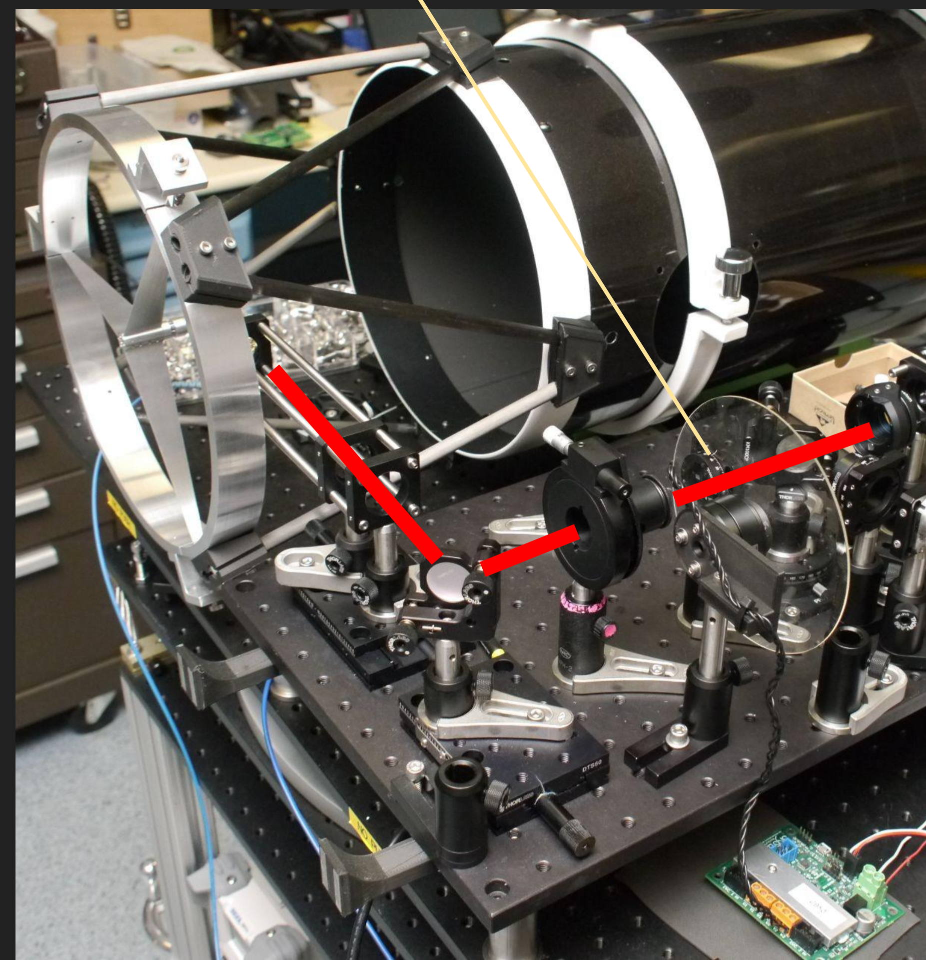
Rotating Phase Screen




Wavefront

Image

Zernike Coeffs.

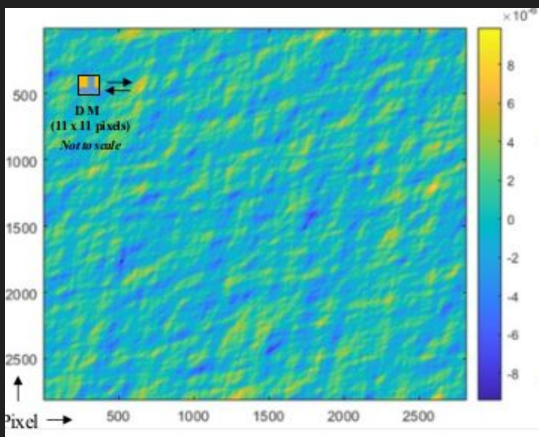


# Emulating 20km of atmosphere in the lab

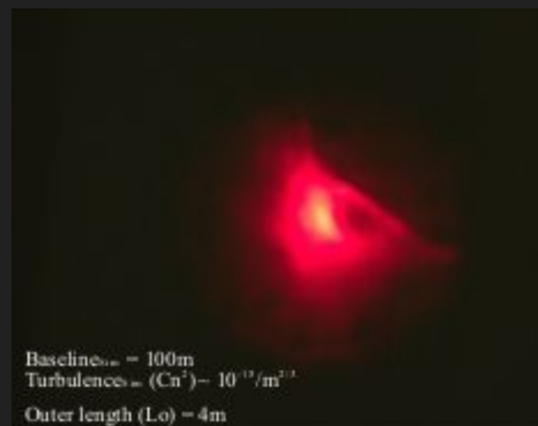
## Simulating the atmospheric effects of the 21km baseline

*Promising results flattening the emulated wavefront and coupling back to fiber*

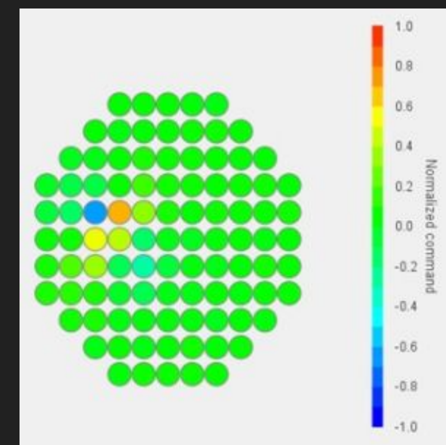
Simulation of atmospheric wavefront (virt. phase screen fed to emulator DM)



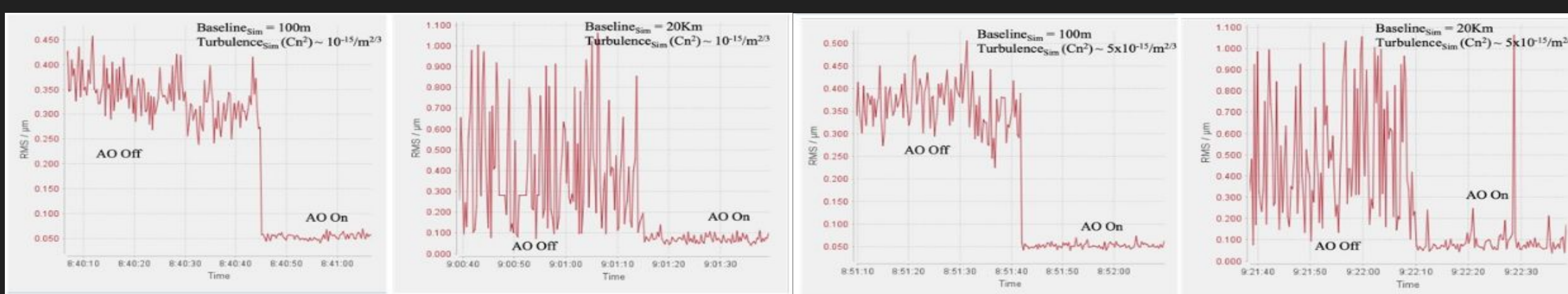

Proxy beam after perturbation by simulated atmosphere




Correction commands sent to corrector DM

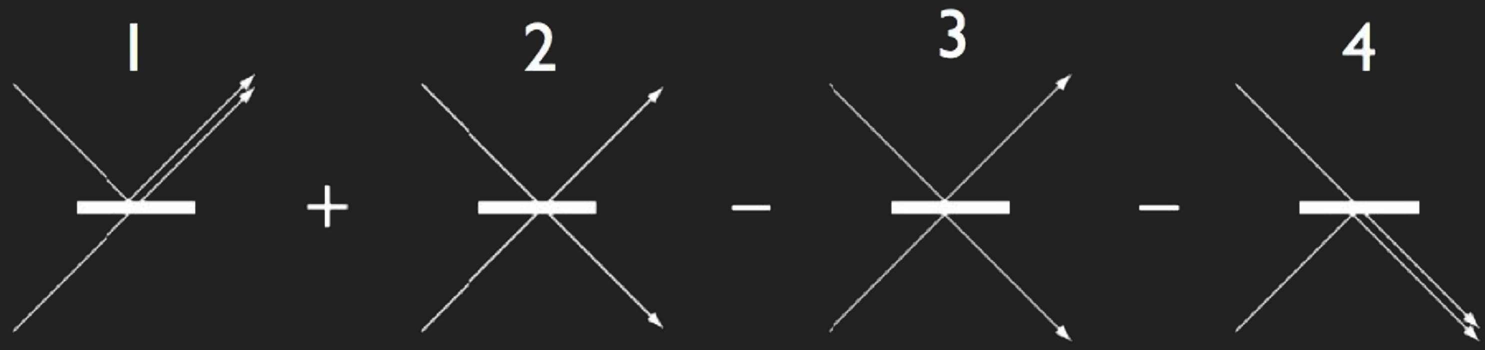


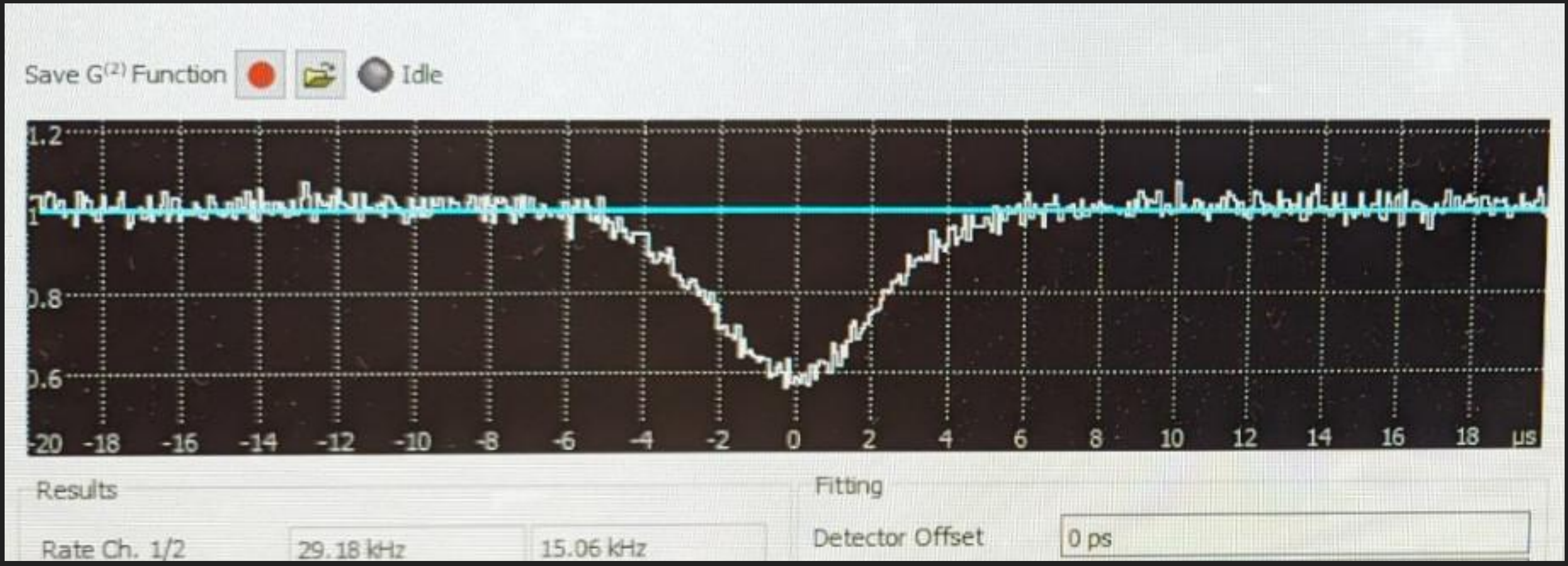

Relative SM fiber coupling efficiency (each plot shows *without* and then *with* AO correction)



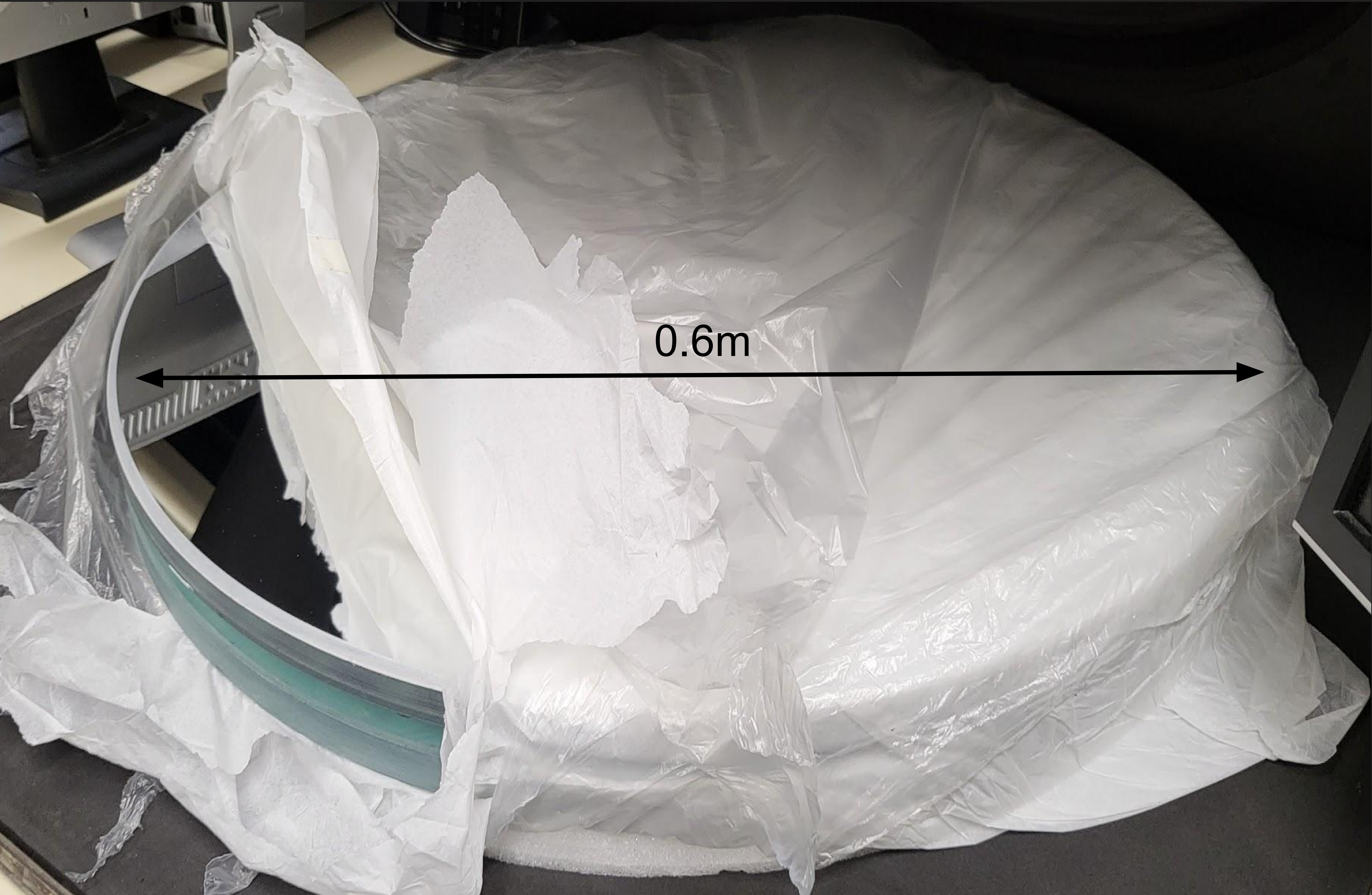
# Single-Photon Ready

- Hong-Ou-Mandel effect demonstrated
- FSL over 2m with no atmosphere emulation/compensation



# Next Steps: Full-size mirrors



# Next Steps: To the roof

# Next Steps: To the roof



# Next Steps: To the roof