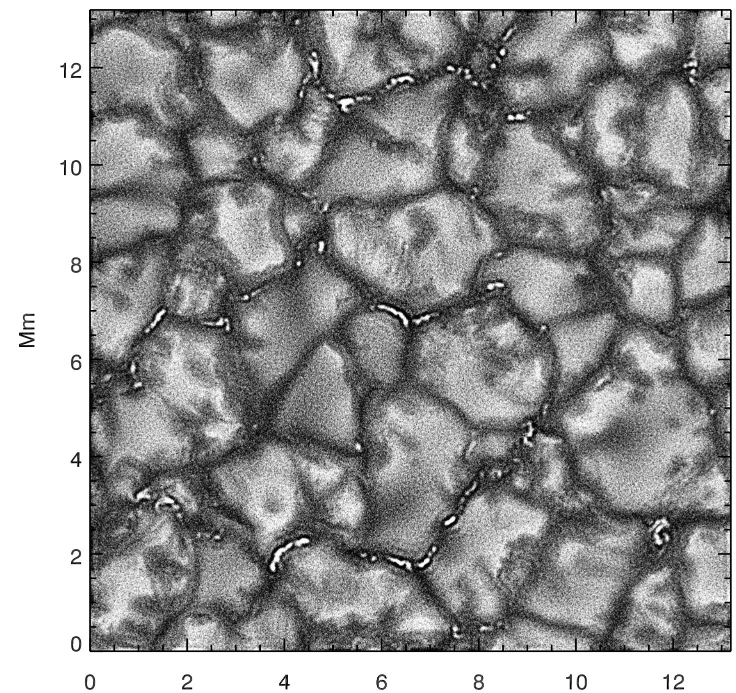
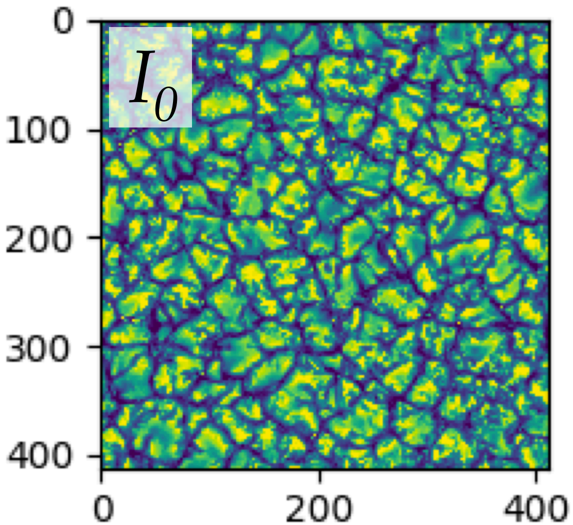
PHYS 7810: Solar Physics with DKIST

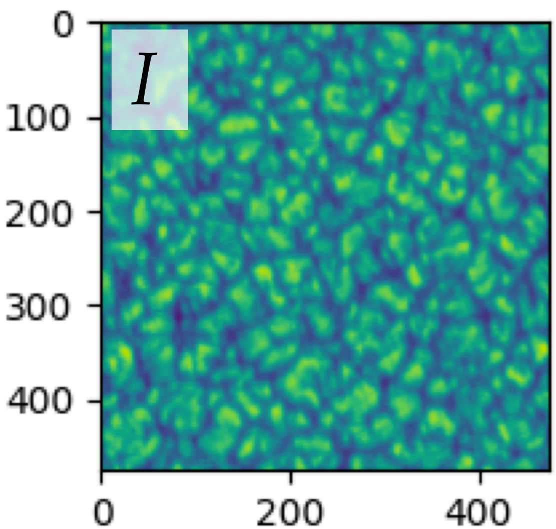
Lecture 5: Deconvolution 1

Kevin Reardon (kreardon@nso.edu)



Convolution ←→ Deconvolution





Observed Image | True Object | Optical Effects

Real Space

$$I(x,y) = I_0(x,y) \star PSF(x,y)$$

Fourier Space

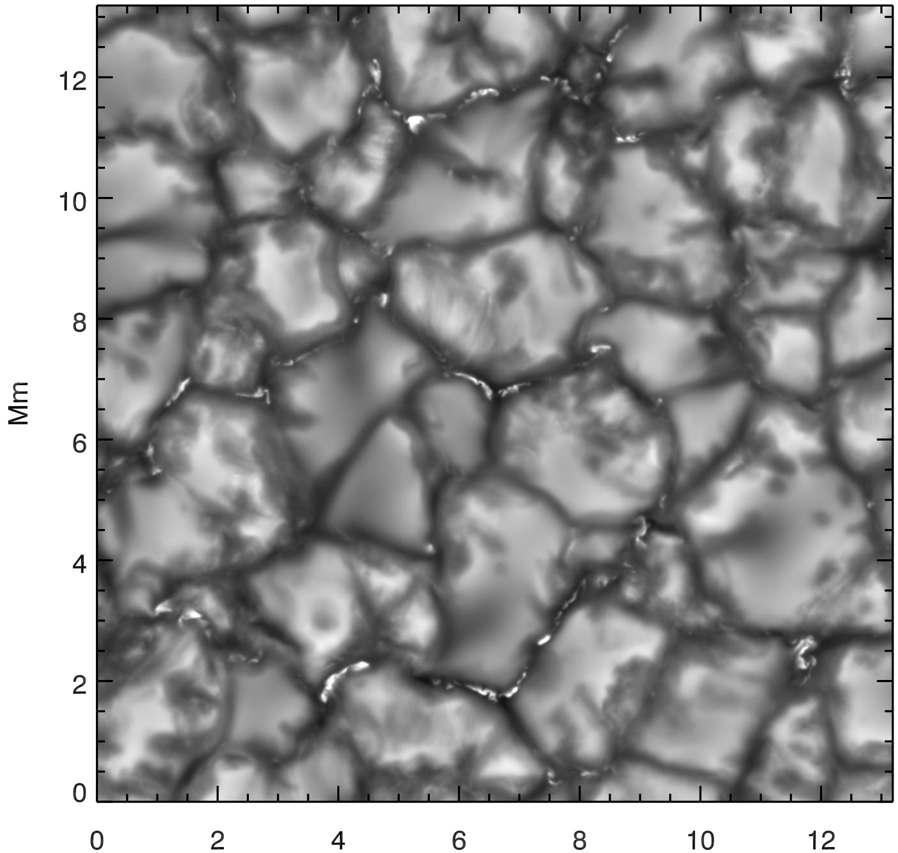
$$i(u,v) = i_0(u,v) \times MTF(u,v)$$

Reversible?

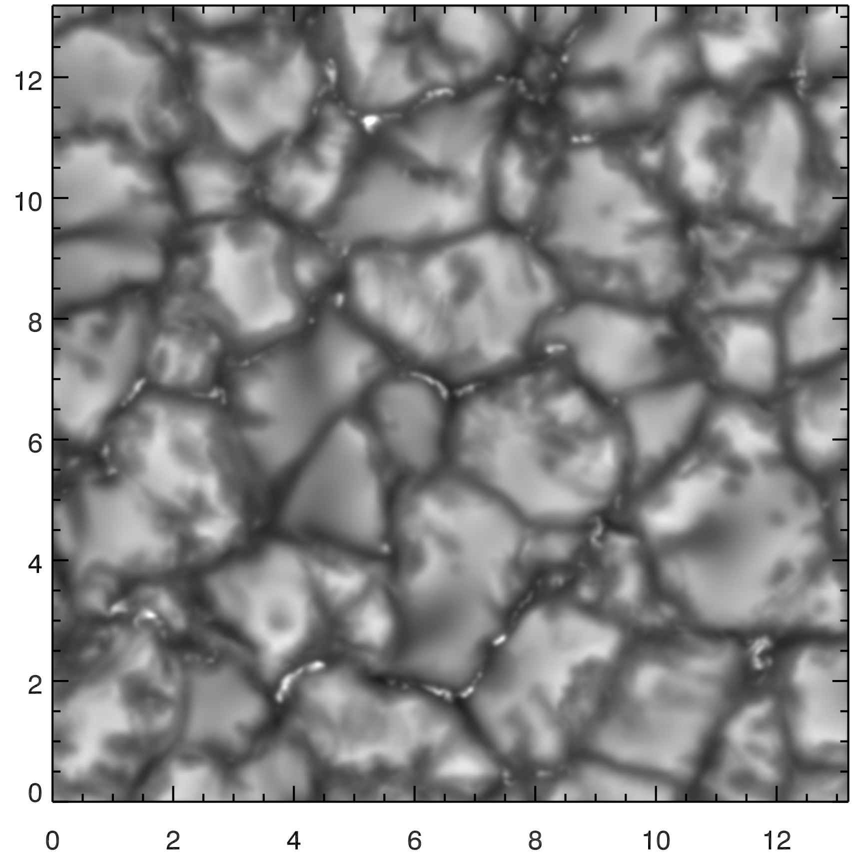
$$i_0(u,v) = i(u,v) \ / \ MTF(u,v,t)$$

Convolution Example

4-meter Diffraction Limited



1.6-meter Diffraction Limited

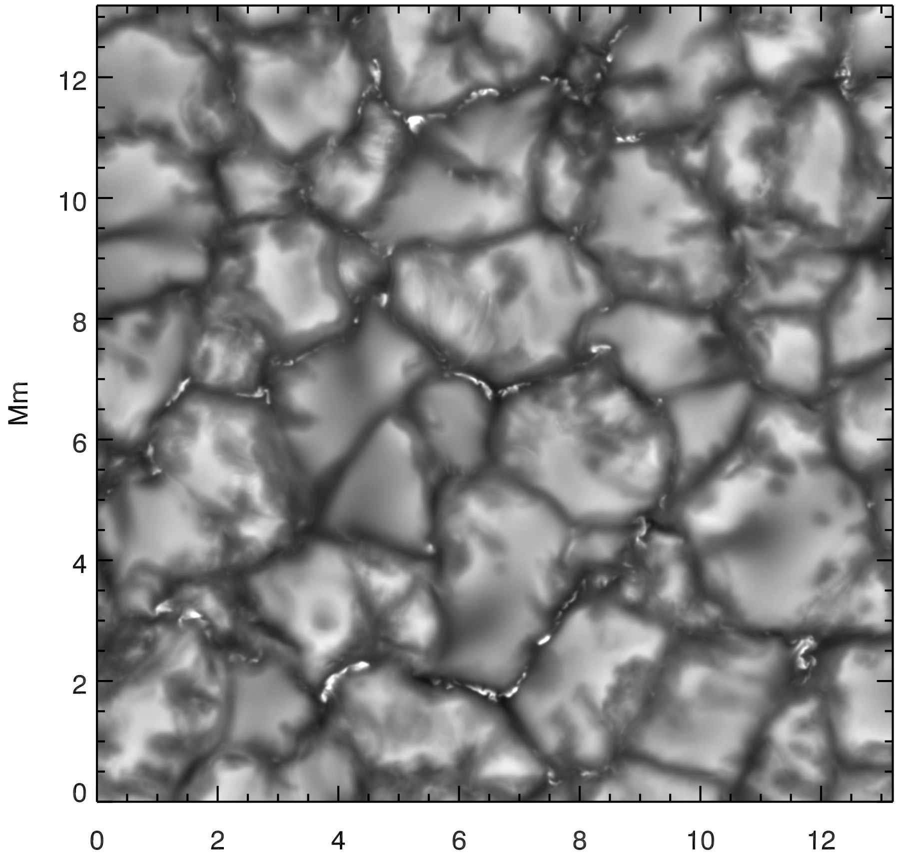


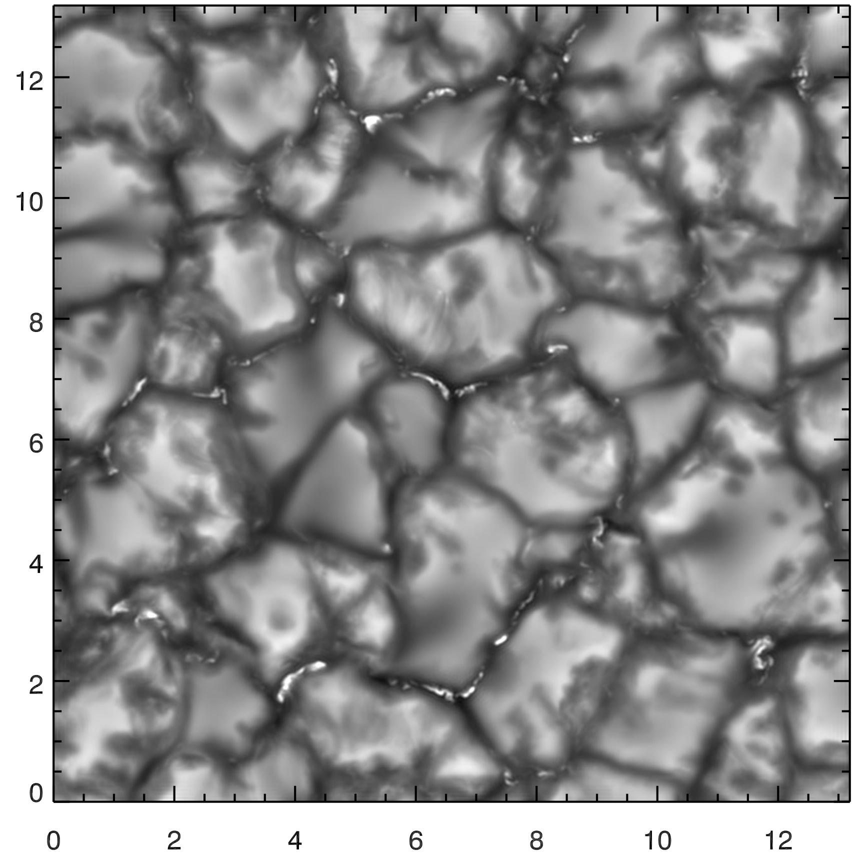
MURAM simulation, 5000 Å, 0.013"/pixel

Deconvolution Example

4-meter Diffraction Limited

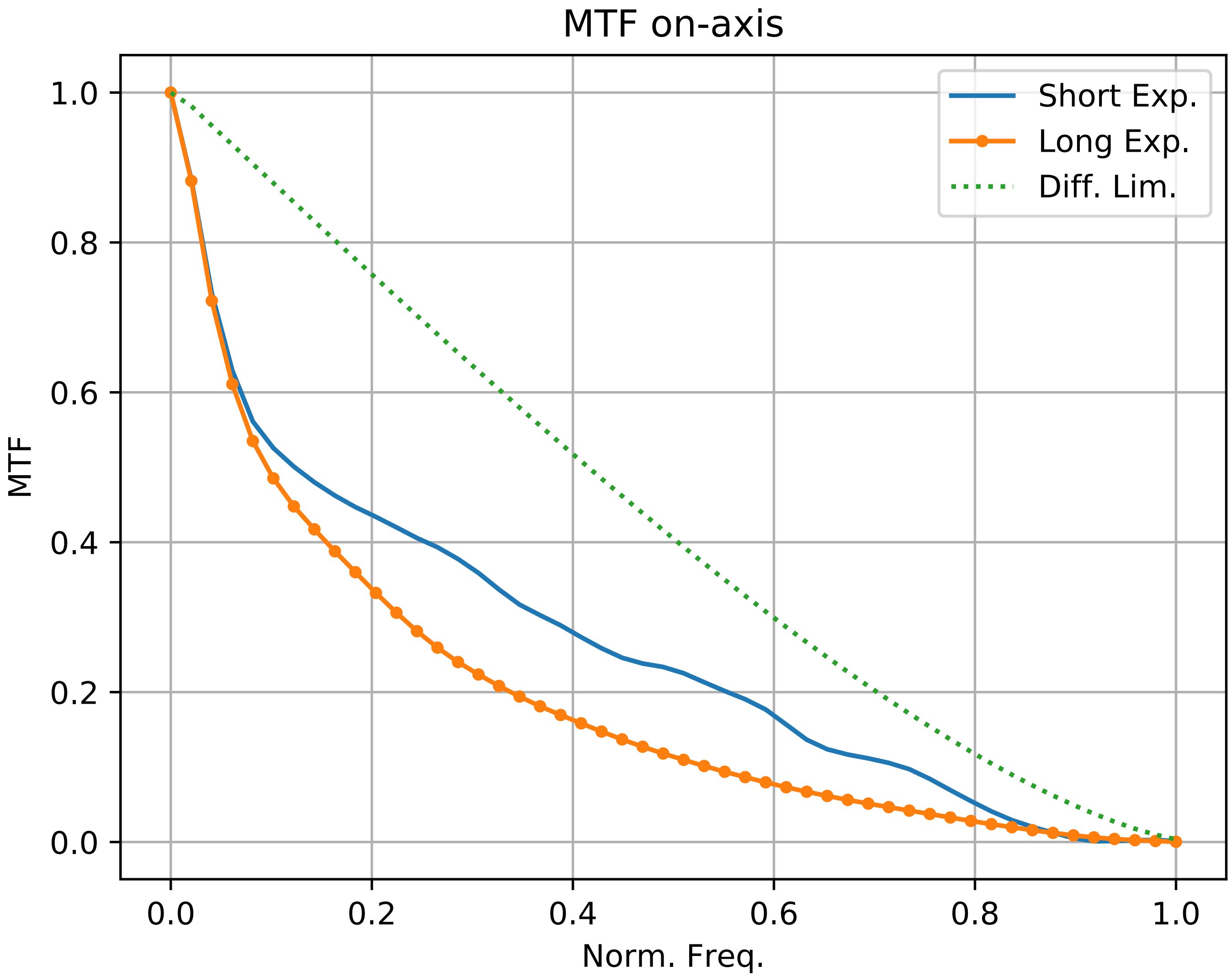
1.6-meter Diffraction Limited
Deconvolved





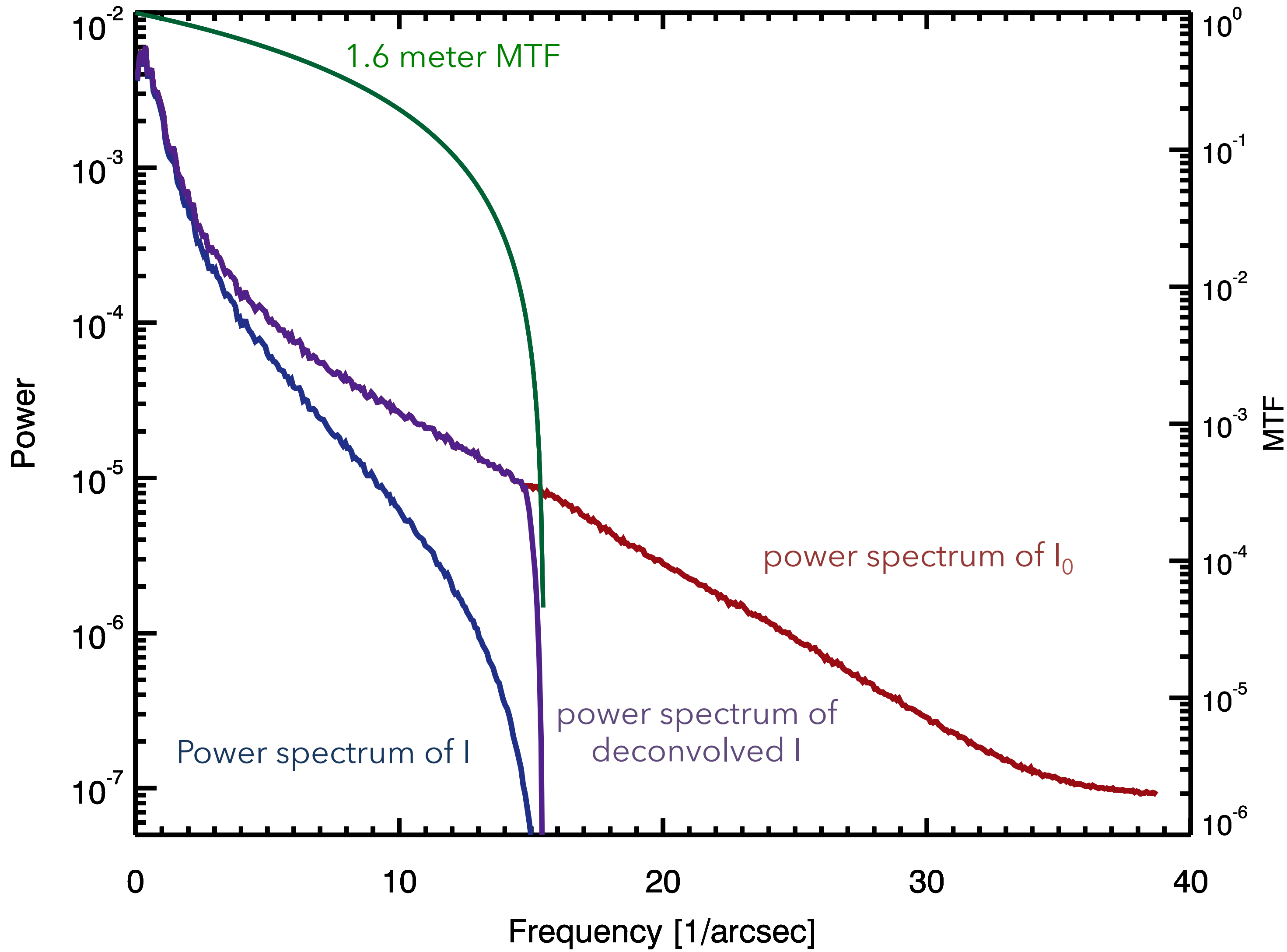
MURAM simulation, 5000 Å, 0.013″/pixel

Where does the MTF do the most damage?

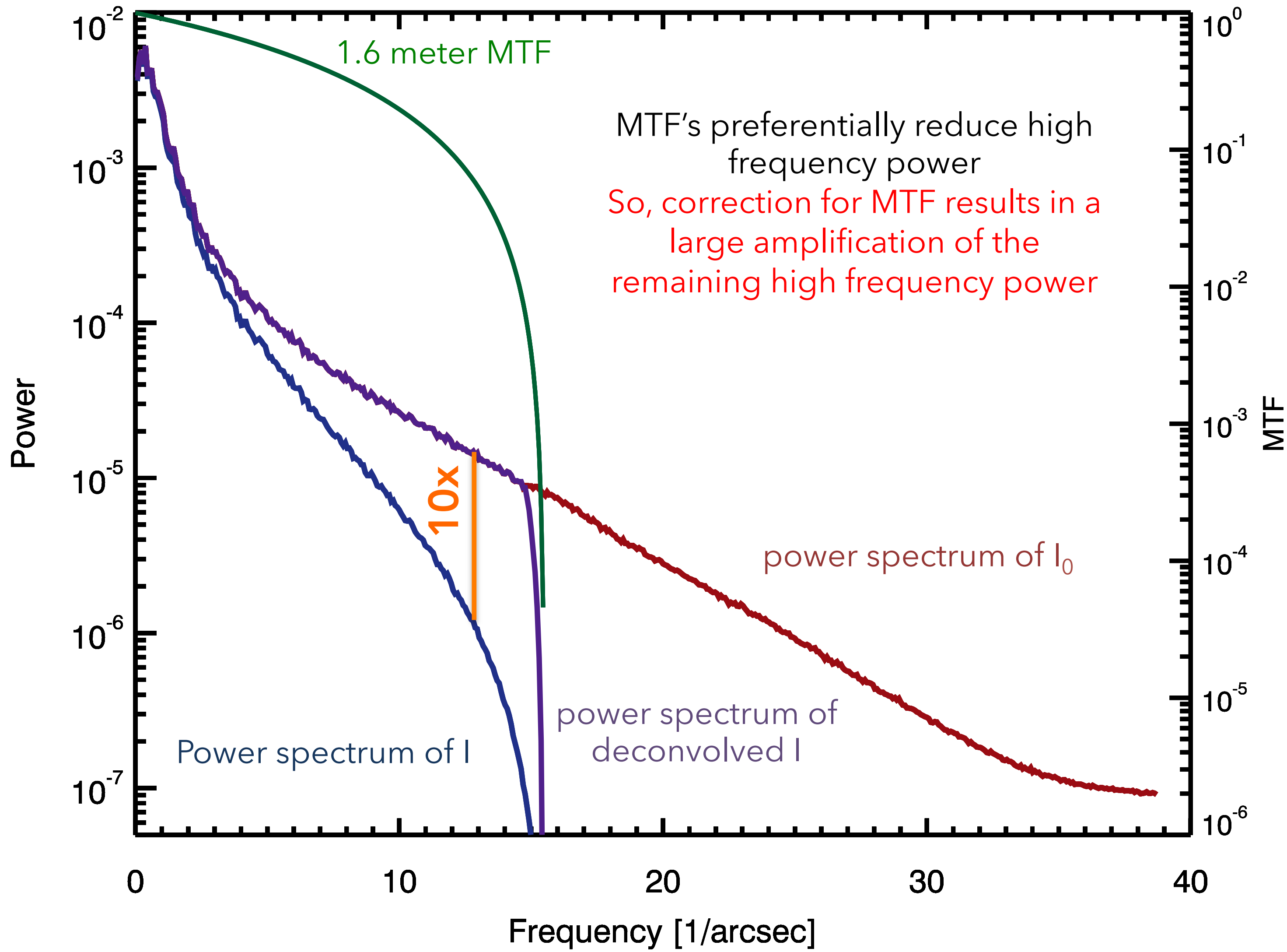


Courtesy Jose Marino

Where does the MTF do the most damage?



Where does the MTF do the most damage?



Noise!

Our Nemesis – Noise!

Noise is present in any measurement

Two key sources:

Read Noise = $d_N(x,y)$ – constant RMS

Shot Noise = $s_N(x,y) = \sqrt{I(x,y)}$

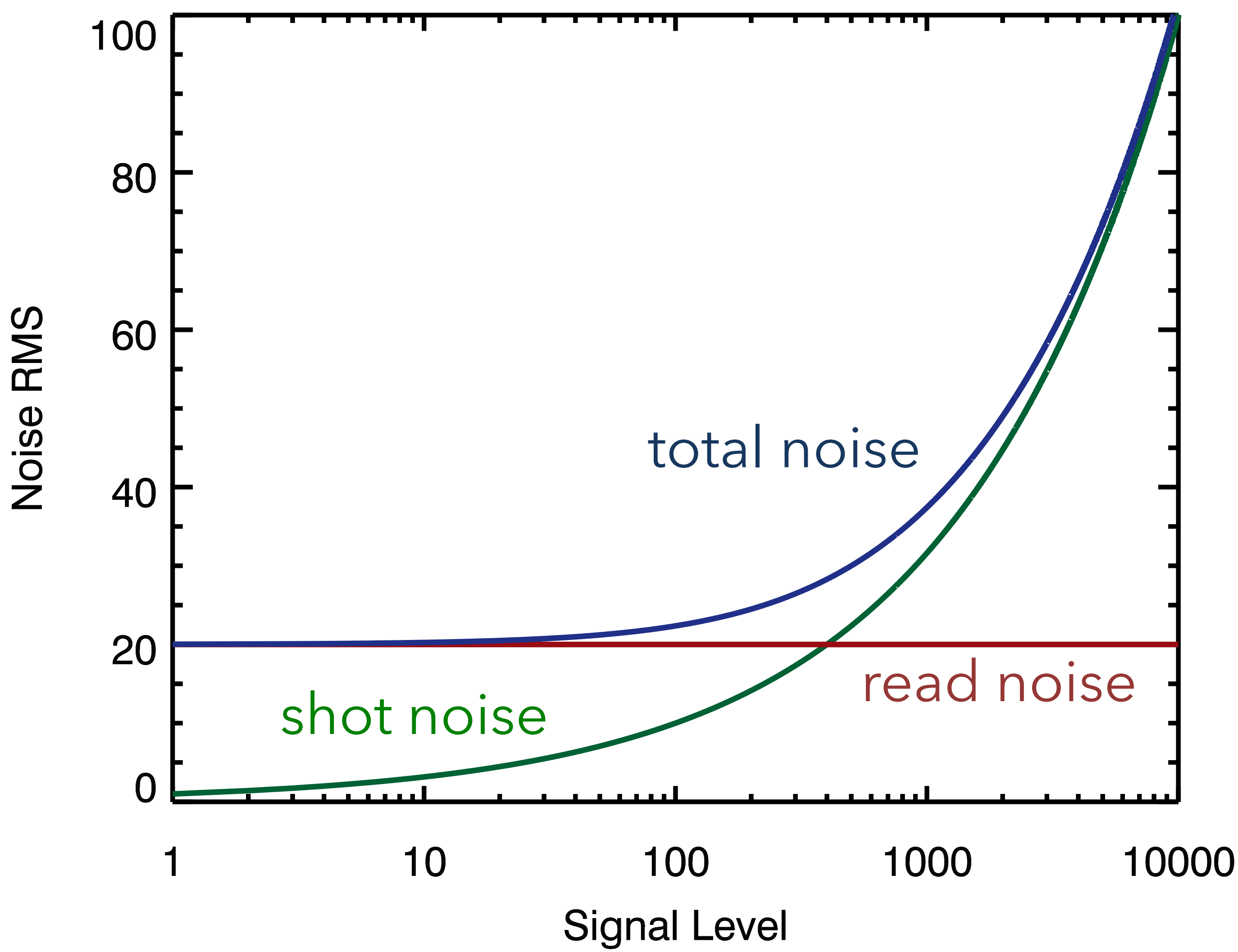
Total Noise = $(d_N^2 + s_N^2)^{½}$

What are units?

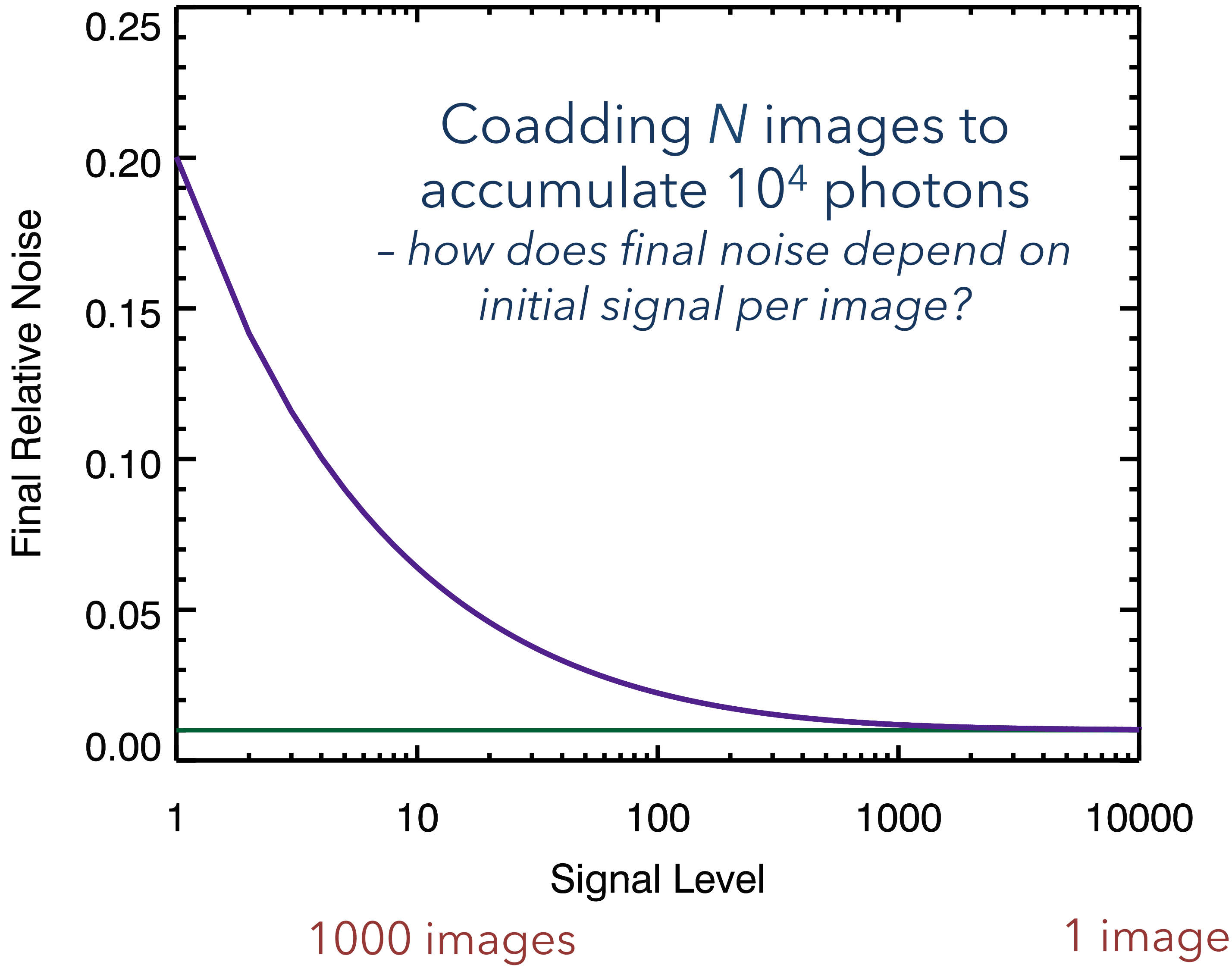
Total Noise(DN) = $(d(\gamma)_N^2 + I(\text{DN}) \times g)^{½} / g$

g = detector gain (γ/DN)

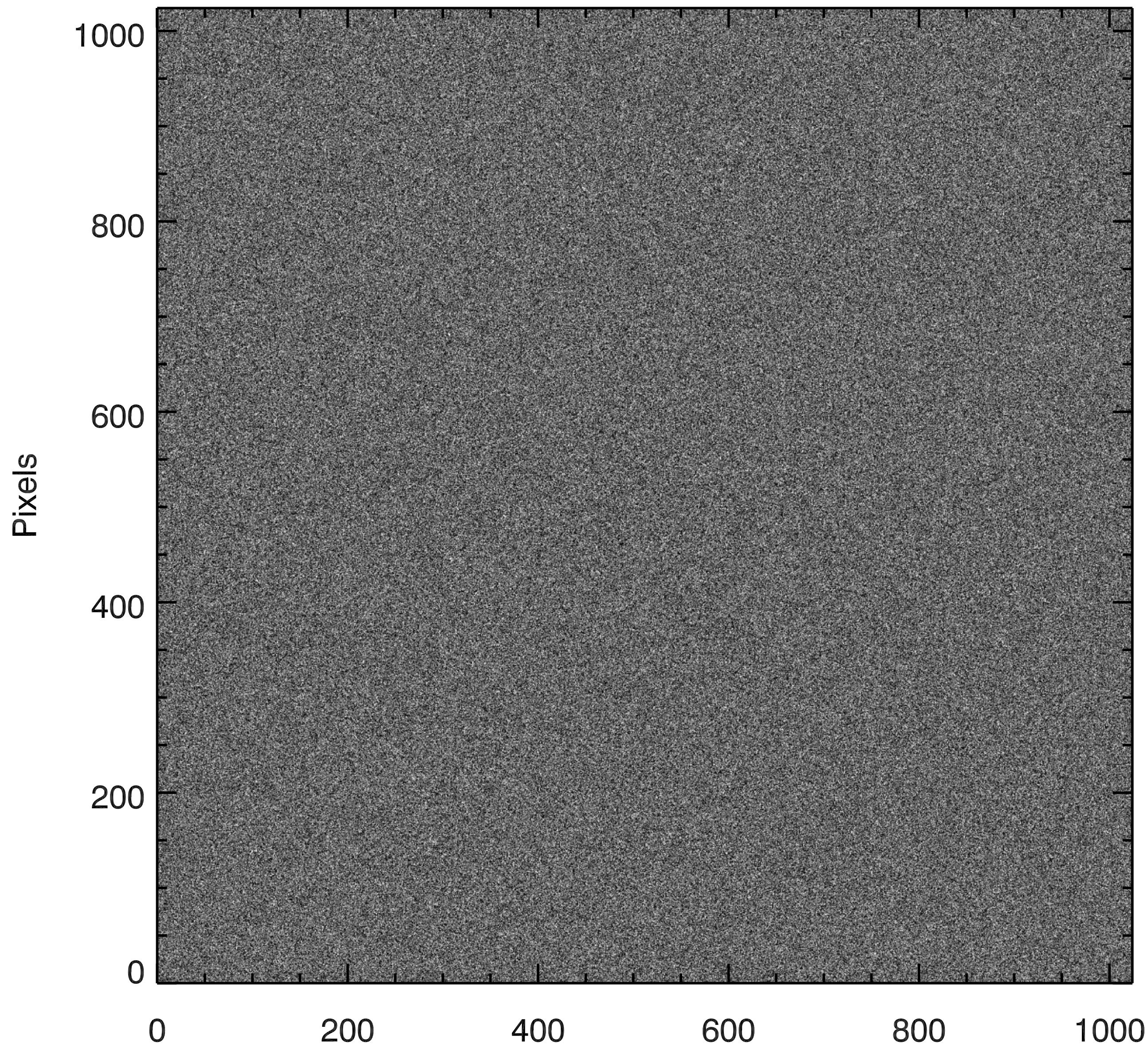
Noise Regimes



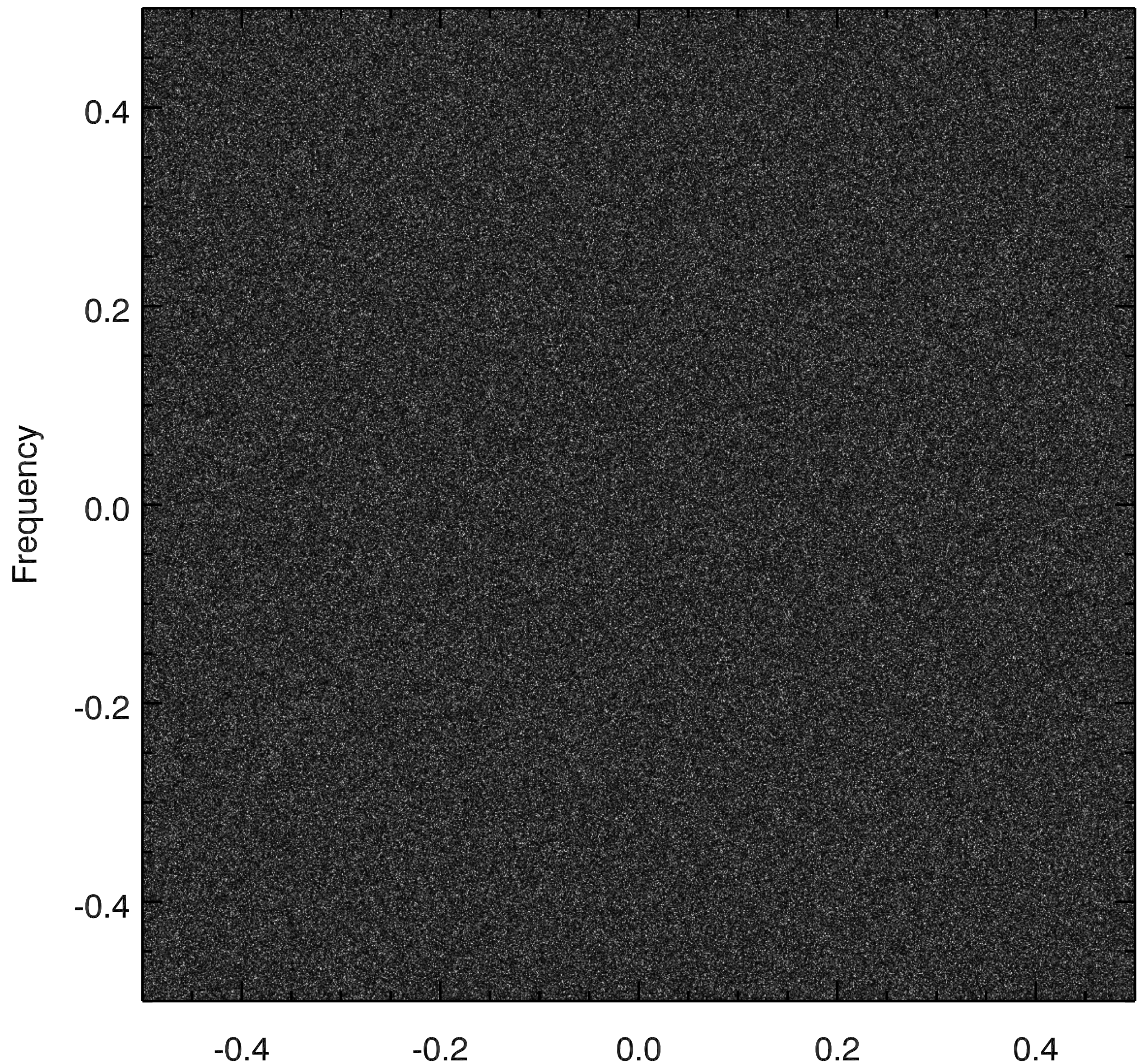
Noise Reduction with coadding



Real Space Noise



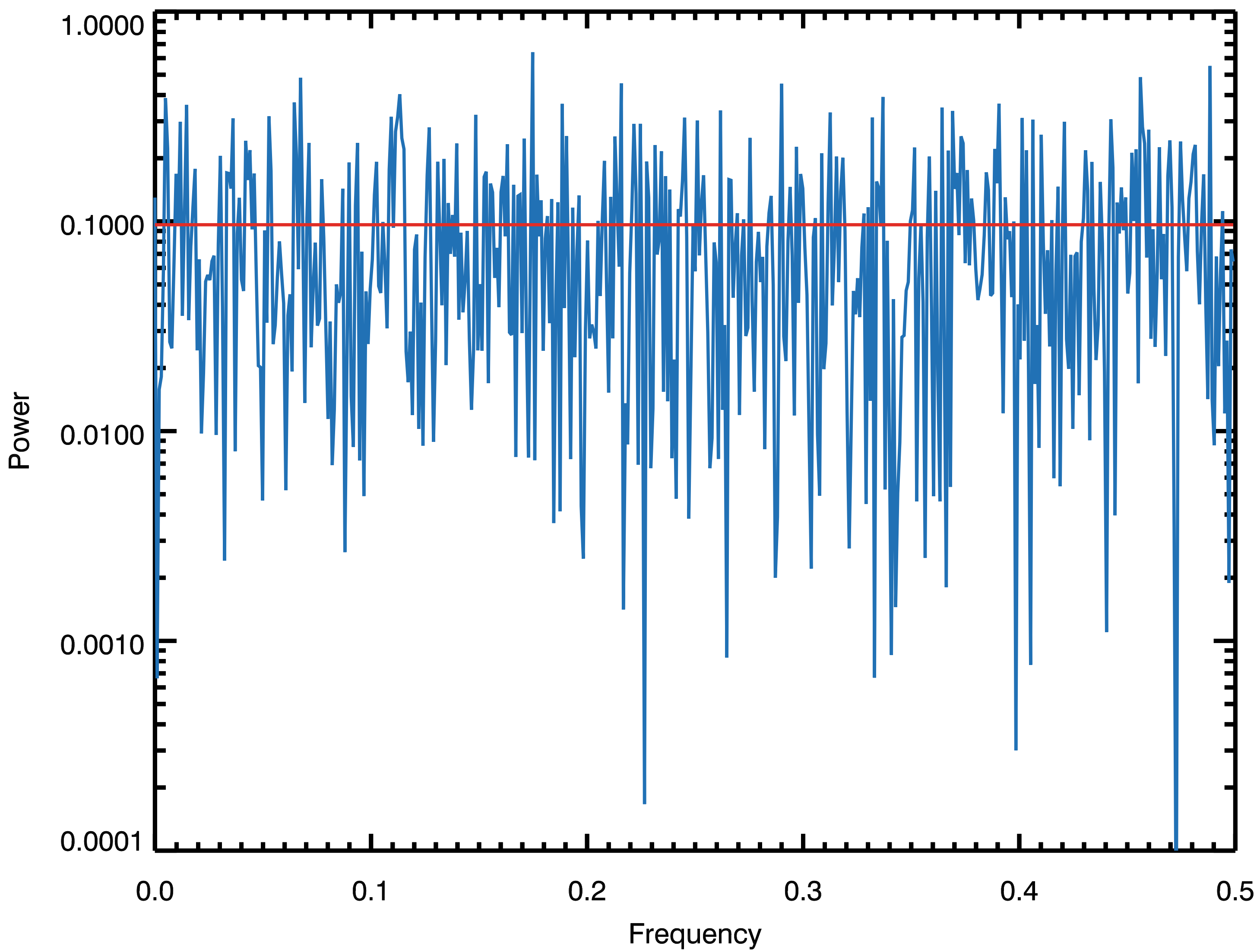
Fourier Space Noise



Our Nemesis – Noise!

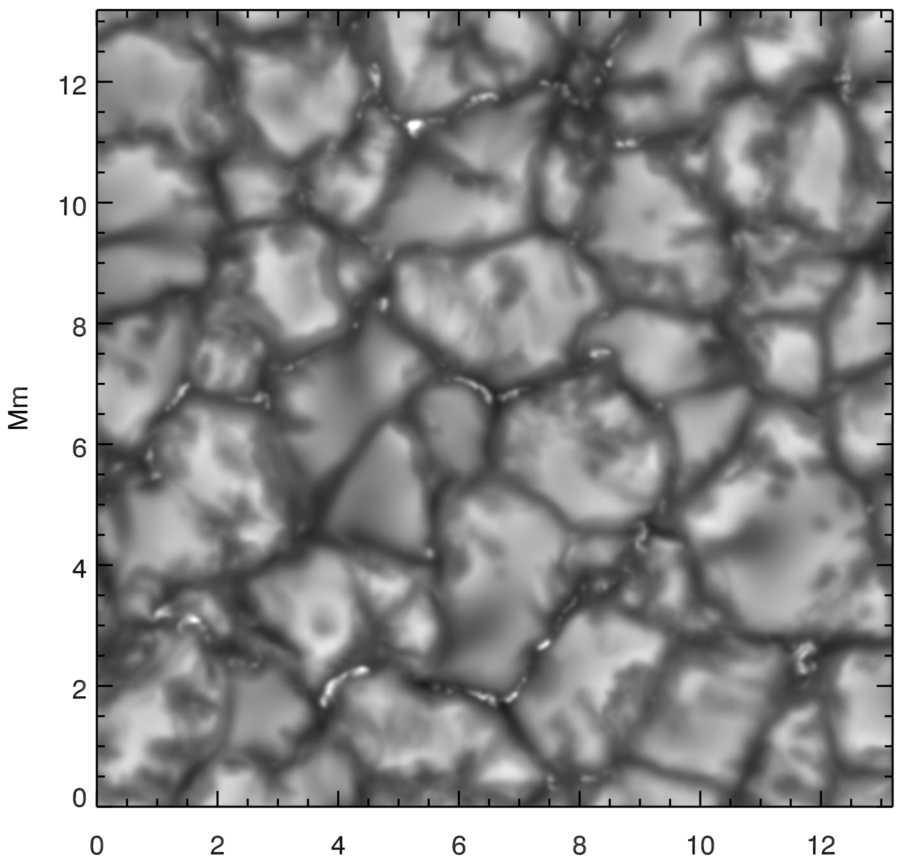
- Noise is present in any measurement
- Noise carries through to Fourier space
- Often becomes comparable to signal at high frequencies.

Power Spectrum of Noise

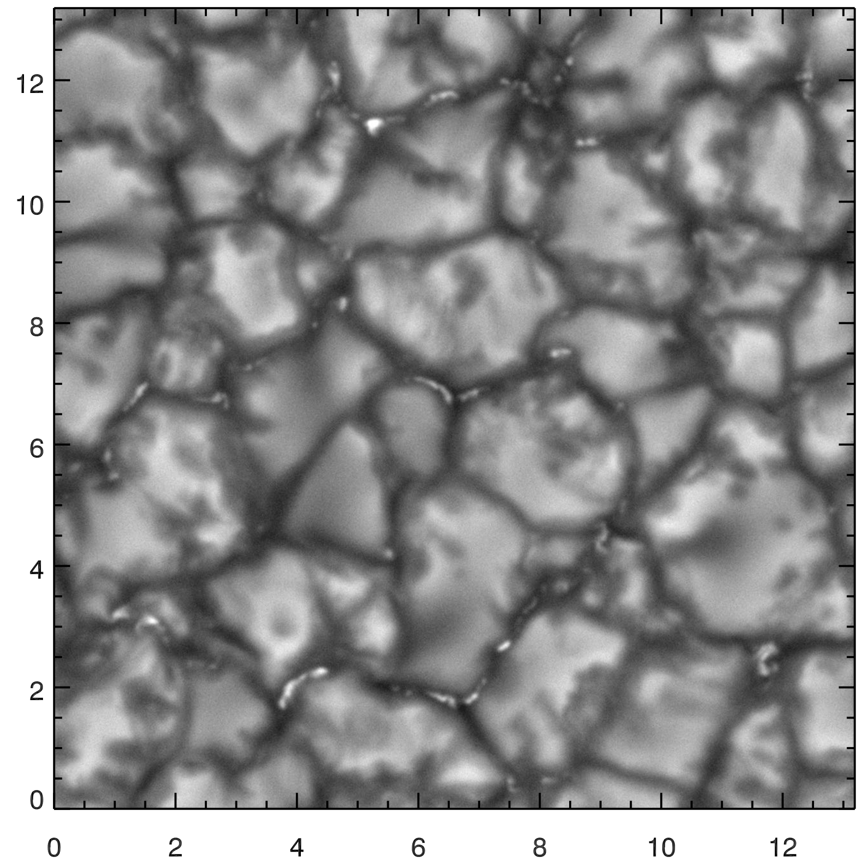


Deconvolution with noise

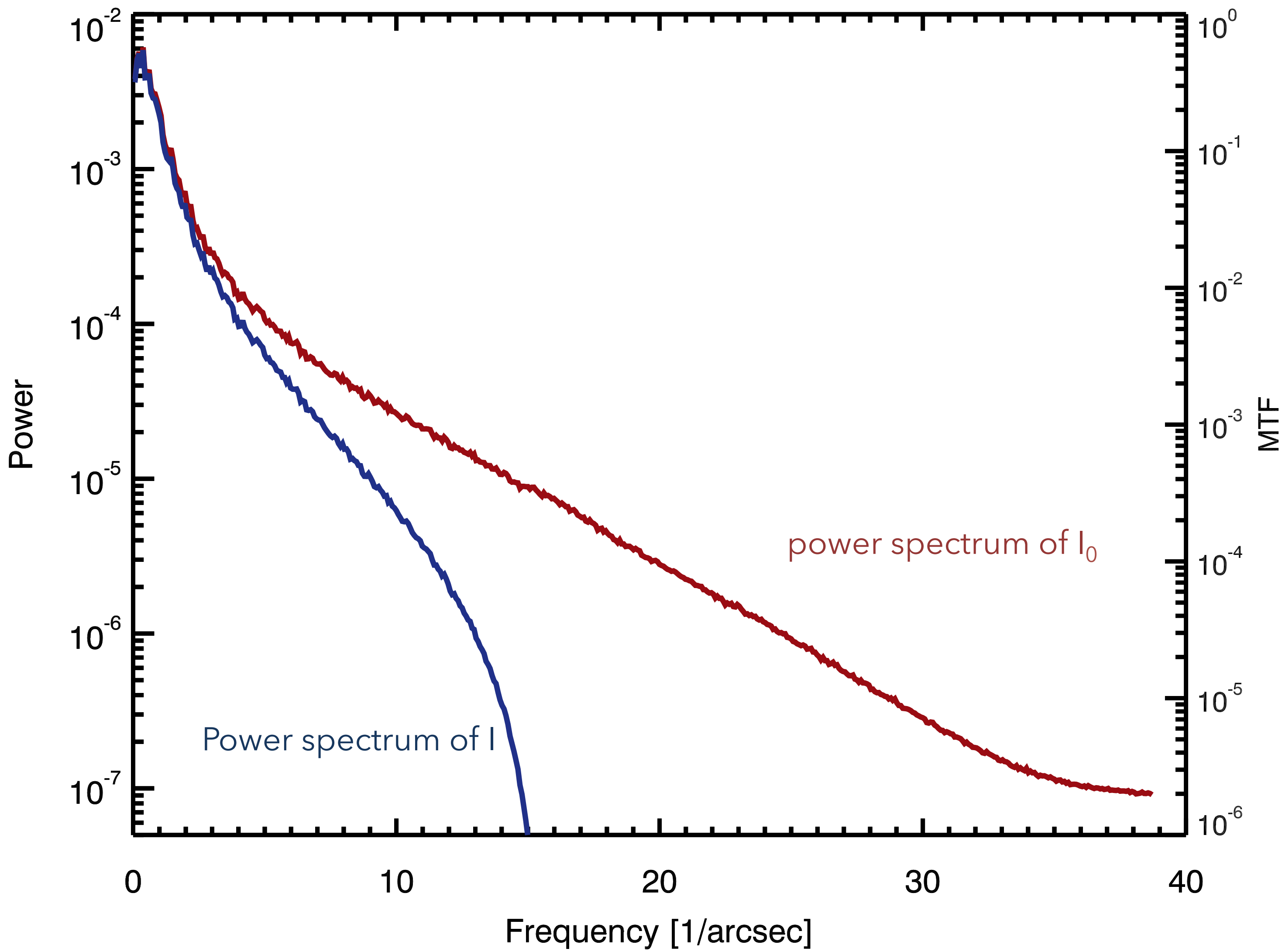
4-meter Diffraction Limited



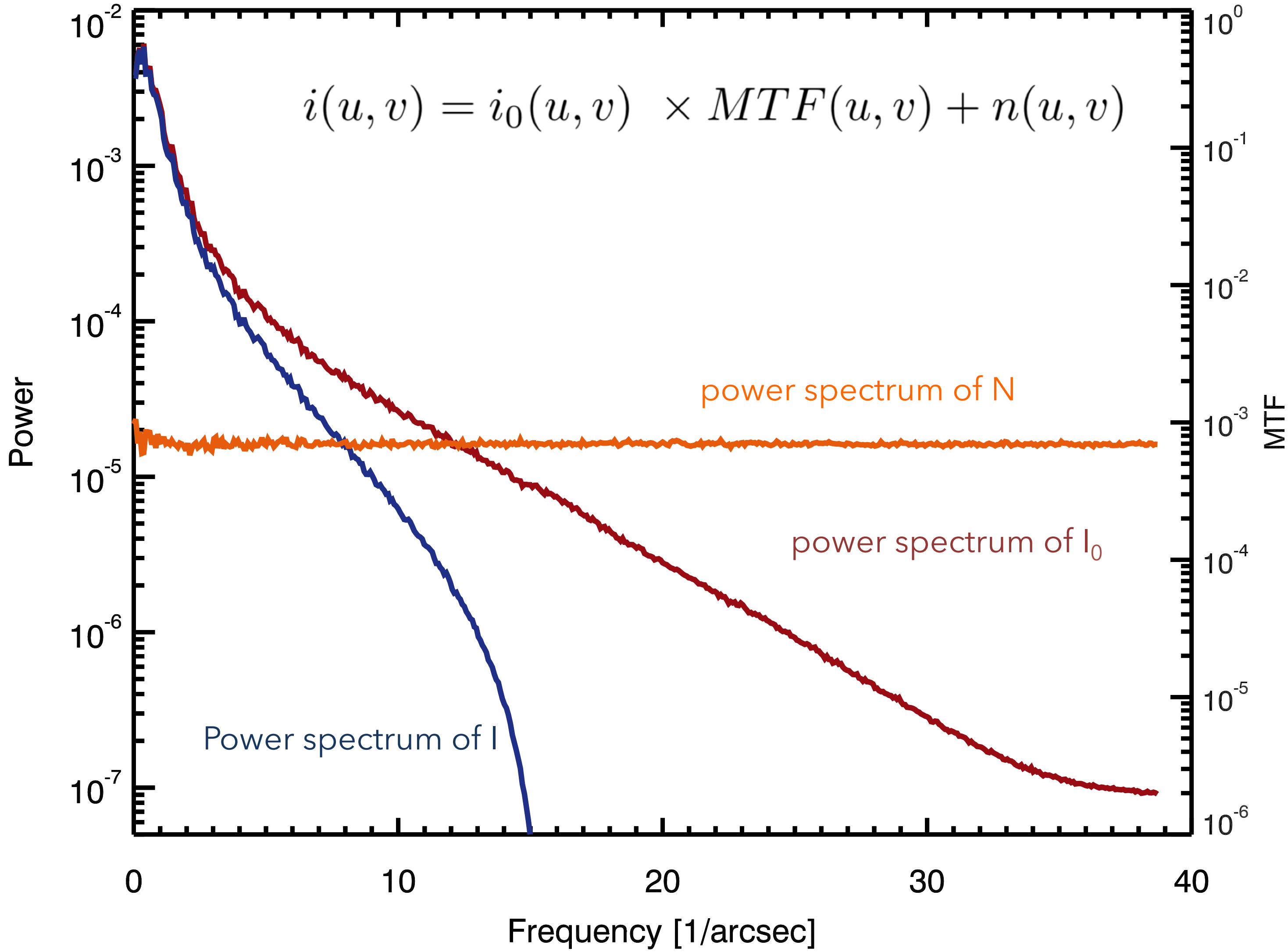
1.6-meter Diffraction Limited
+ 2% noise

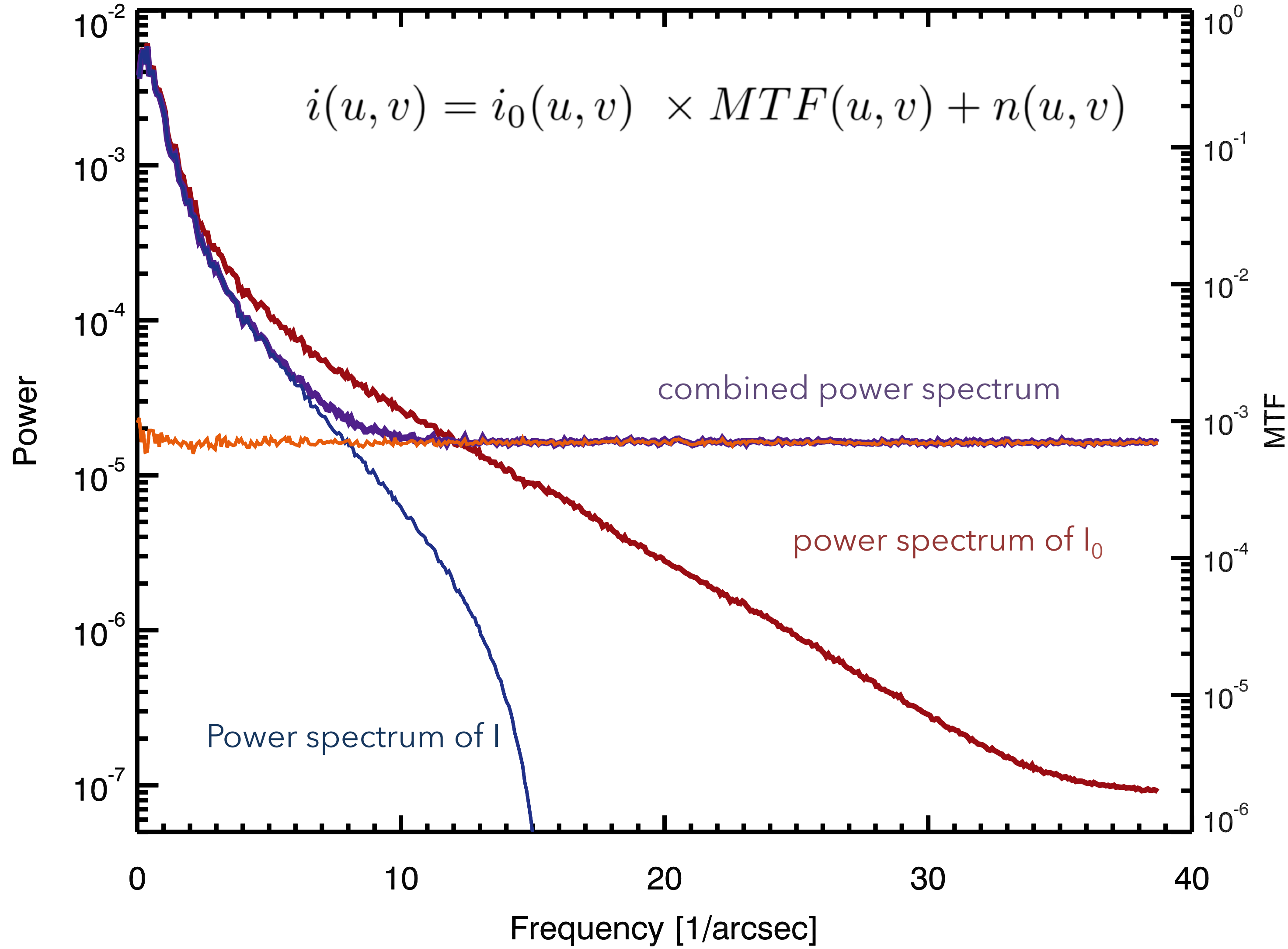


Deconvolution with noise



Deconvolution with noise

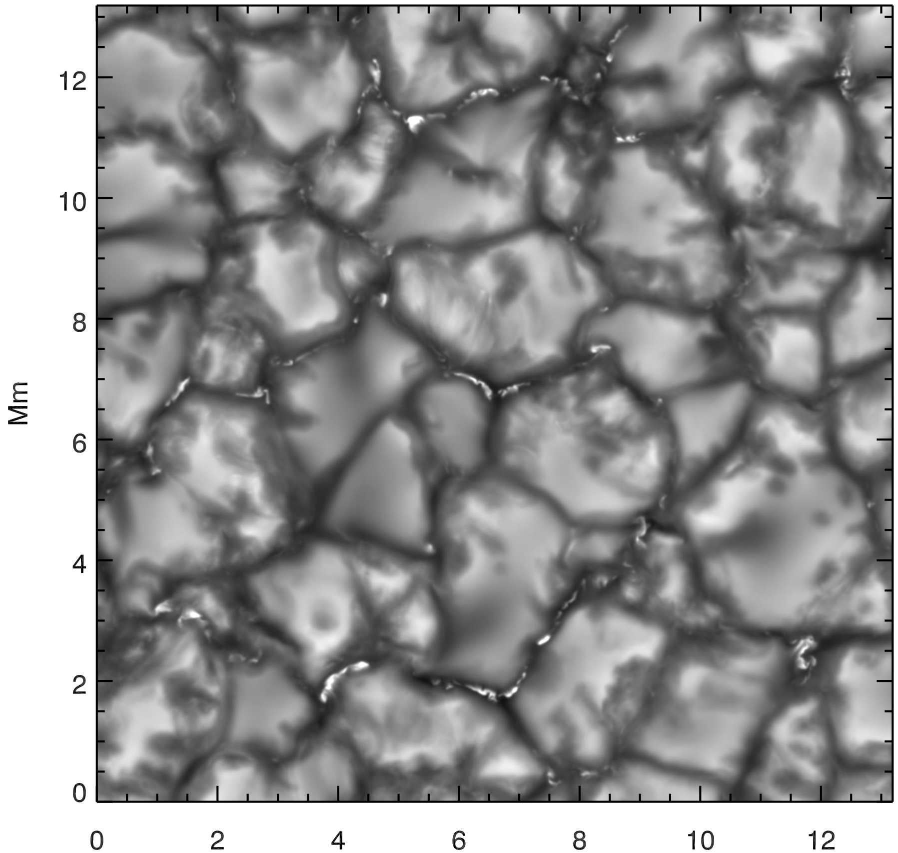




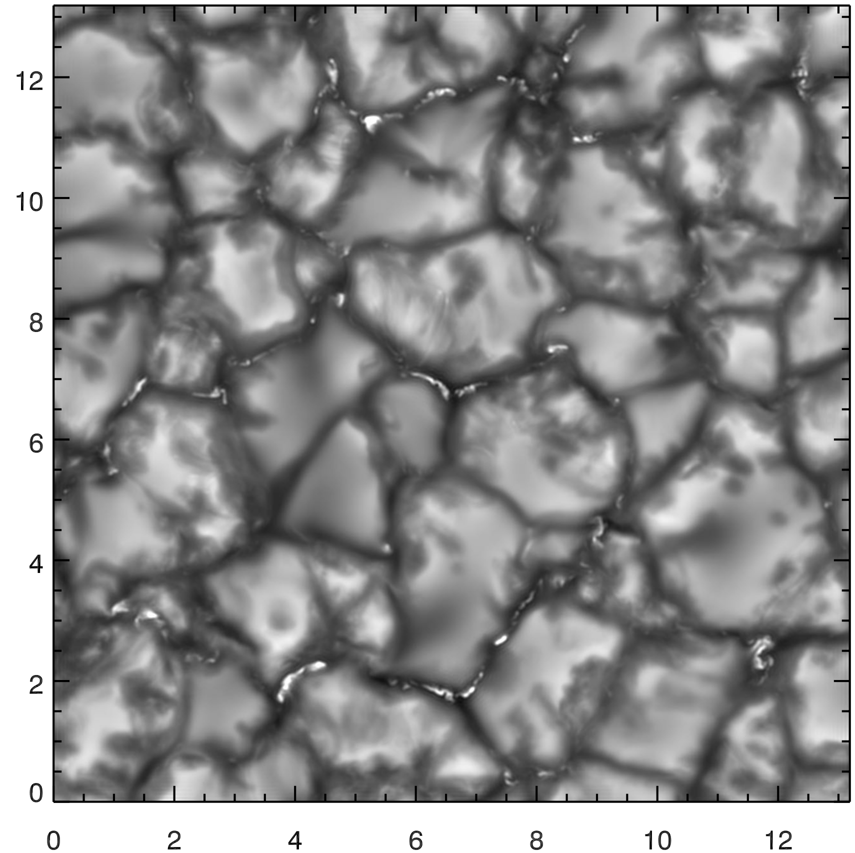
$i(u,v) = i_0(u,v) \times MTF(u,v) + n(u,v)$
combined power spectrum
power spectrum of I_0
Power spectrum of I
Power
MTF
Frequency [1/arcsec]
0
10
20
30
40
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}

Deconvolution Example

4-meter Diffraction Limited

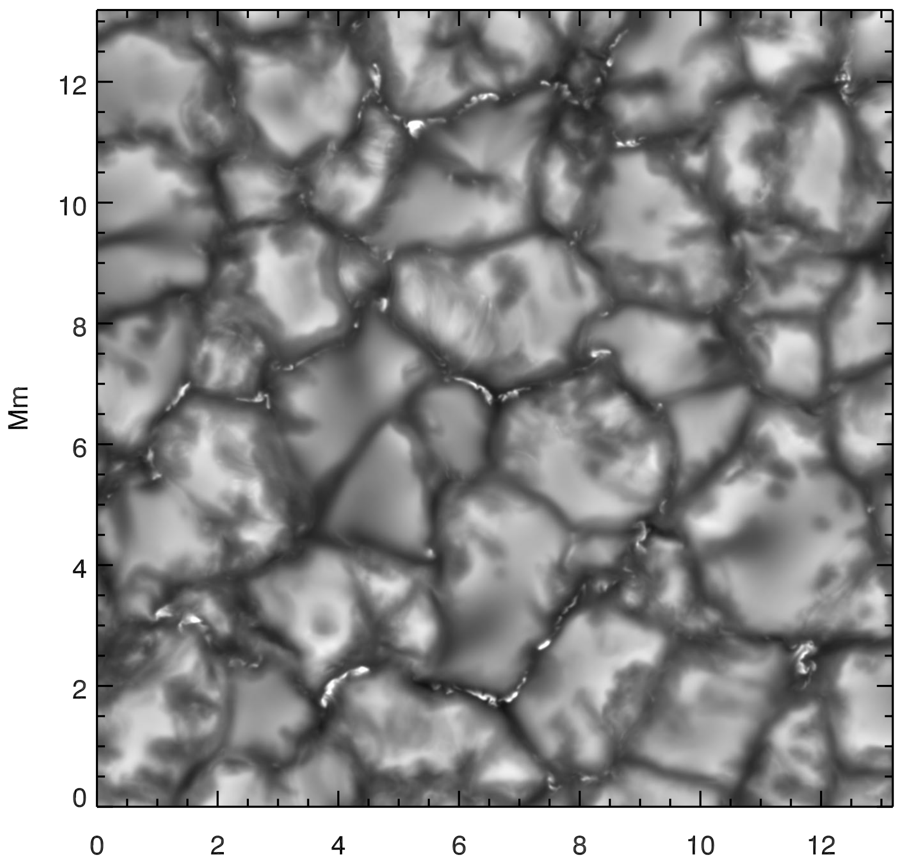


1.6-meter Diffraction Limited
Deconvolved, No noise

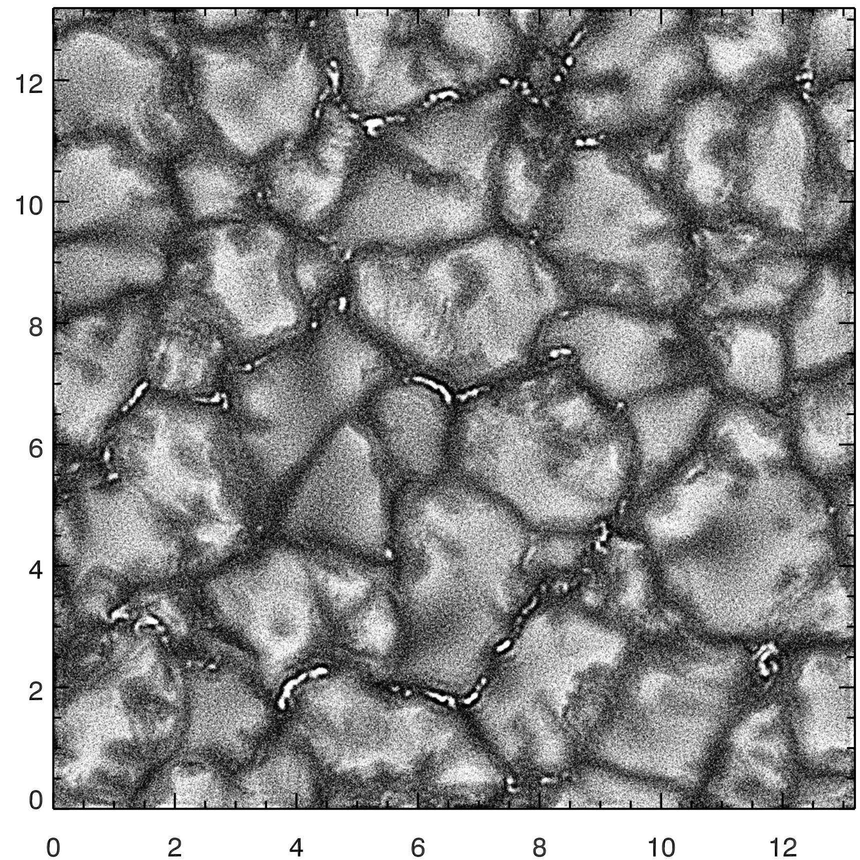


Deconvolution Example/Exercise

4-meter Diffraction Limited

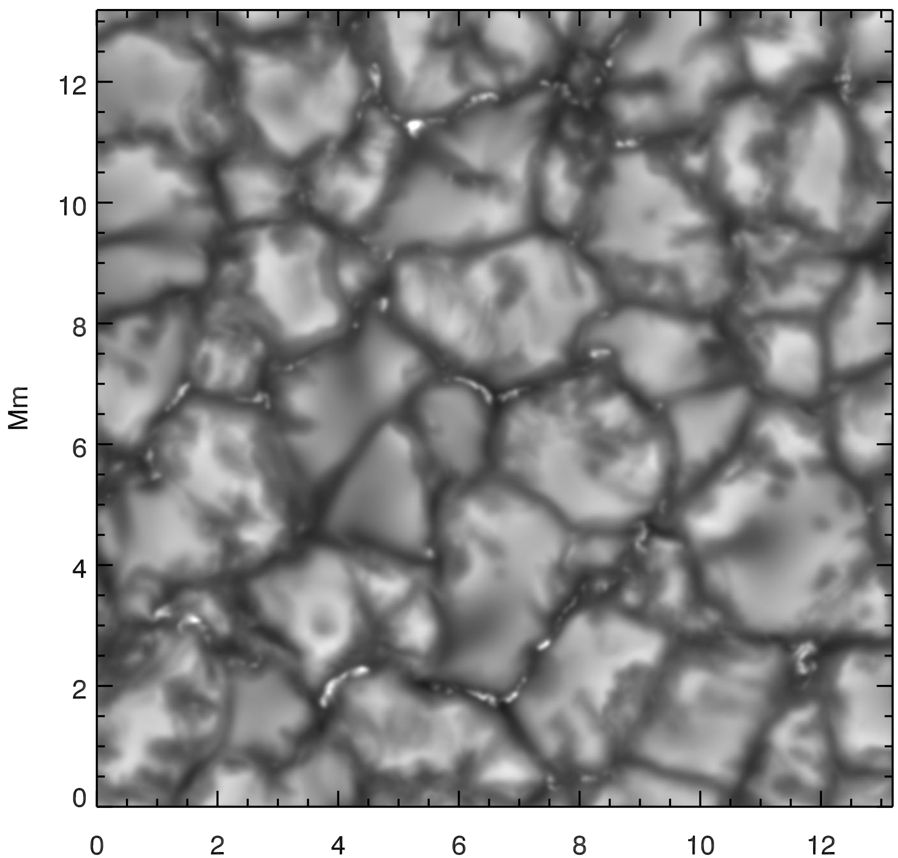


1.6-meter Diffraction Limited
Deconvolved, 2% noise

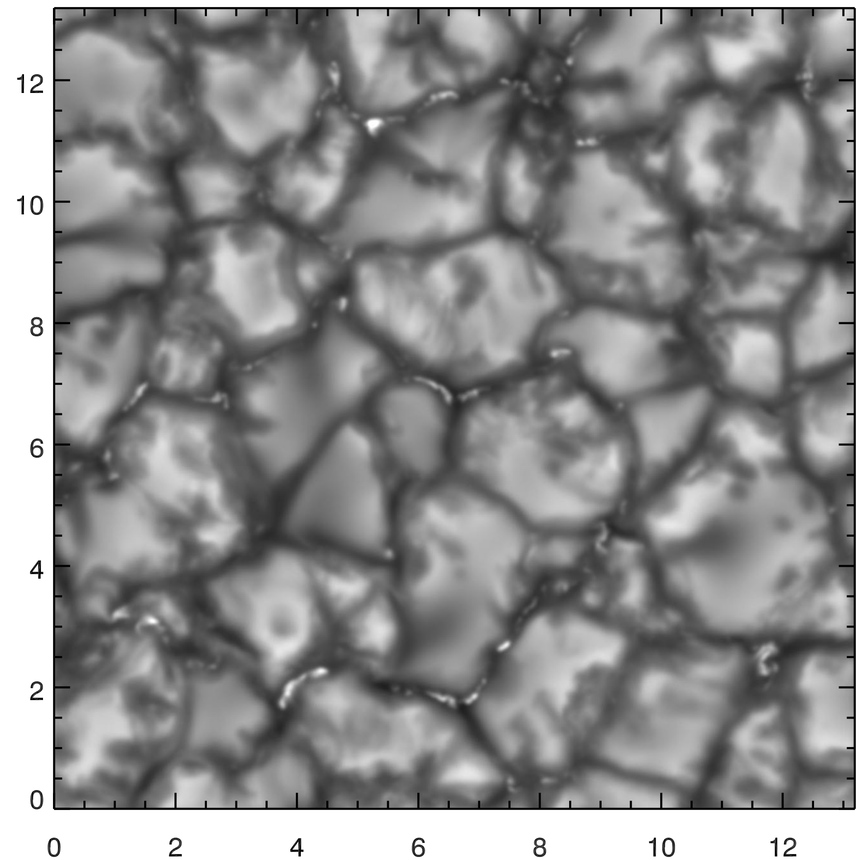


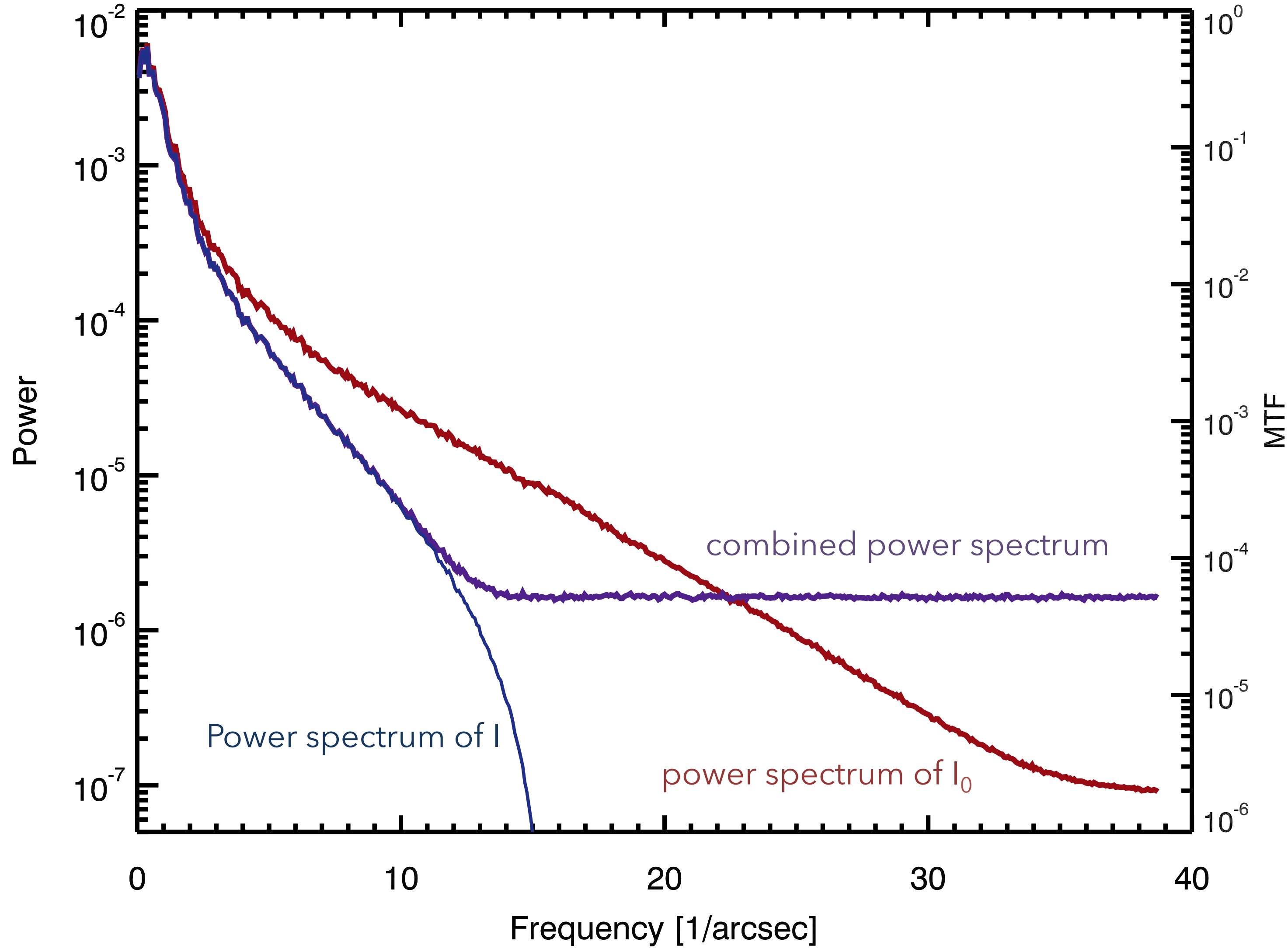
Deconvolution Example/Exercise

4-meter Diffraction Limited



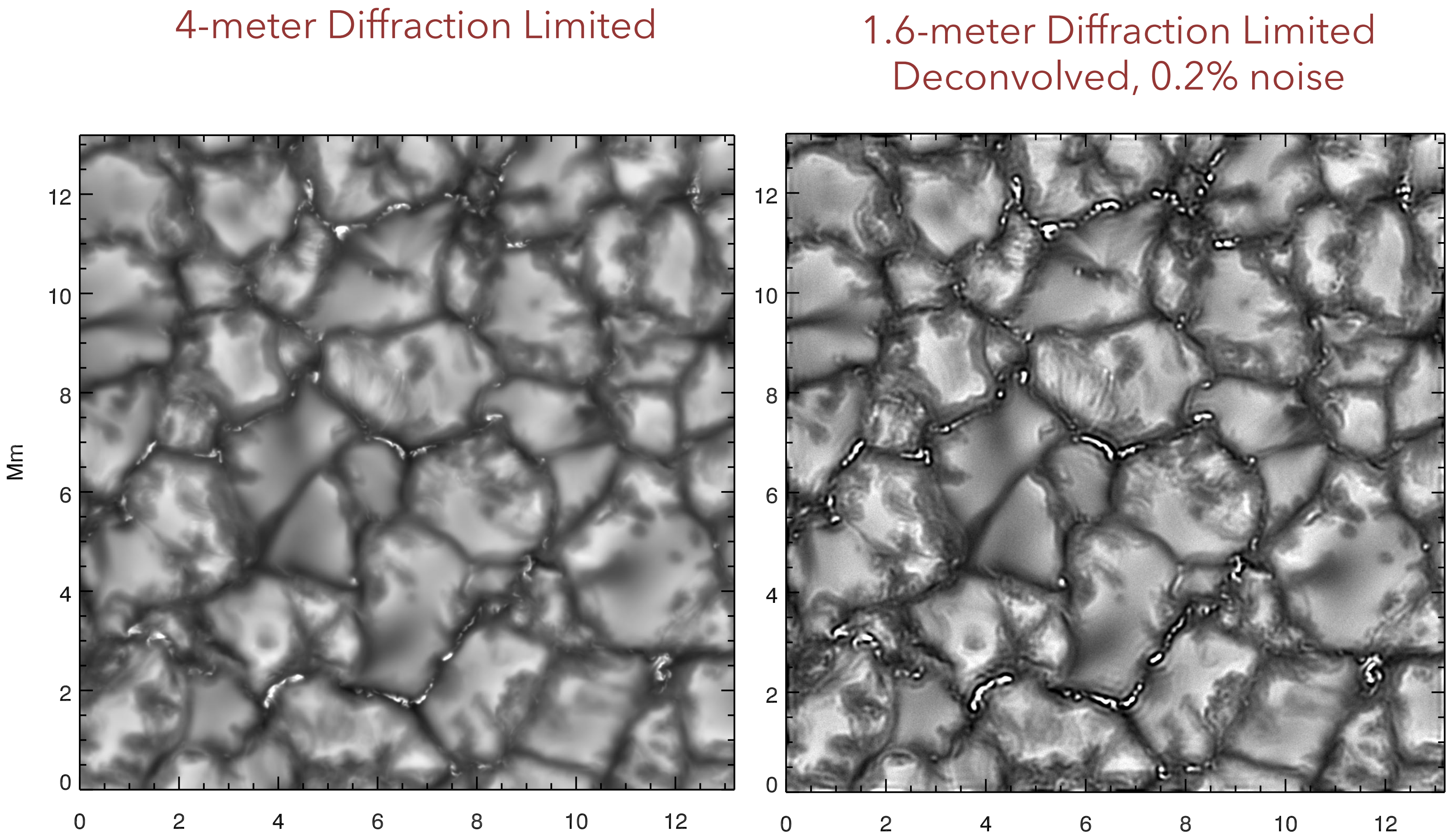
1.6-meter Diffraction Limited
+ 0.2% noise



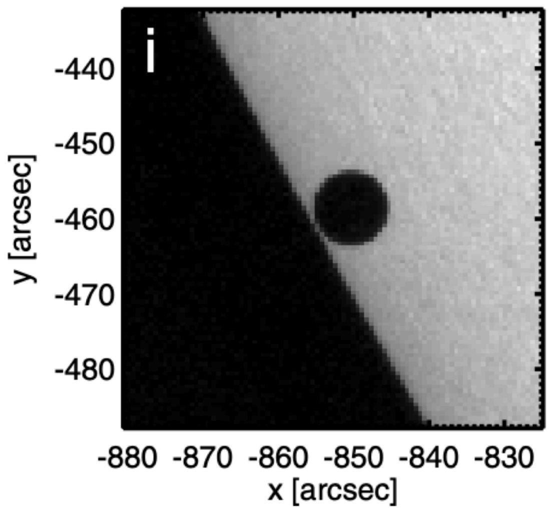


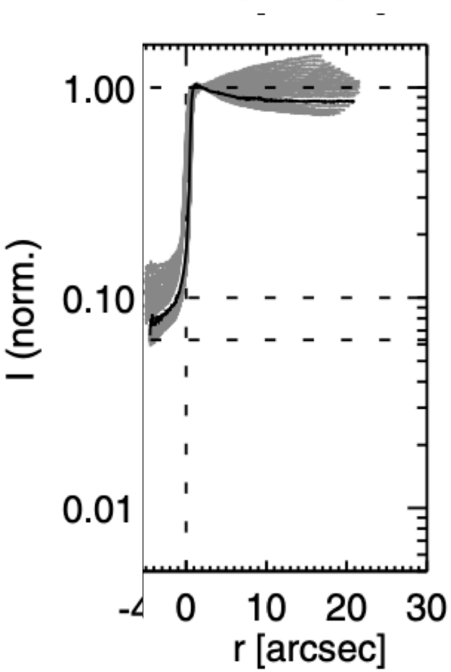
Power
MTF
Frequency [1/arcsec]
combined power spectrum
Power spectrum of I
power spectrum of I_0
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
10
20
30
40

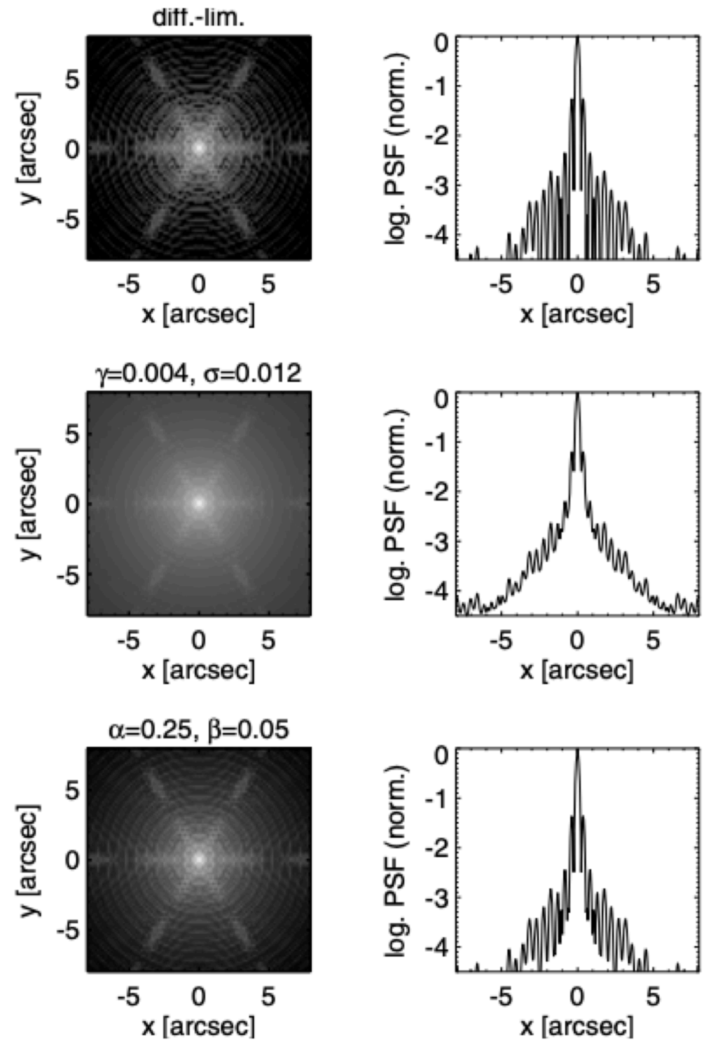
Deconvolution Example/Exercise



It is possible…







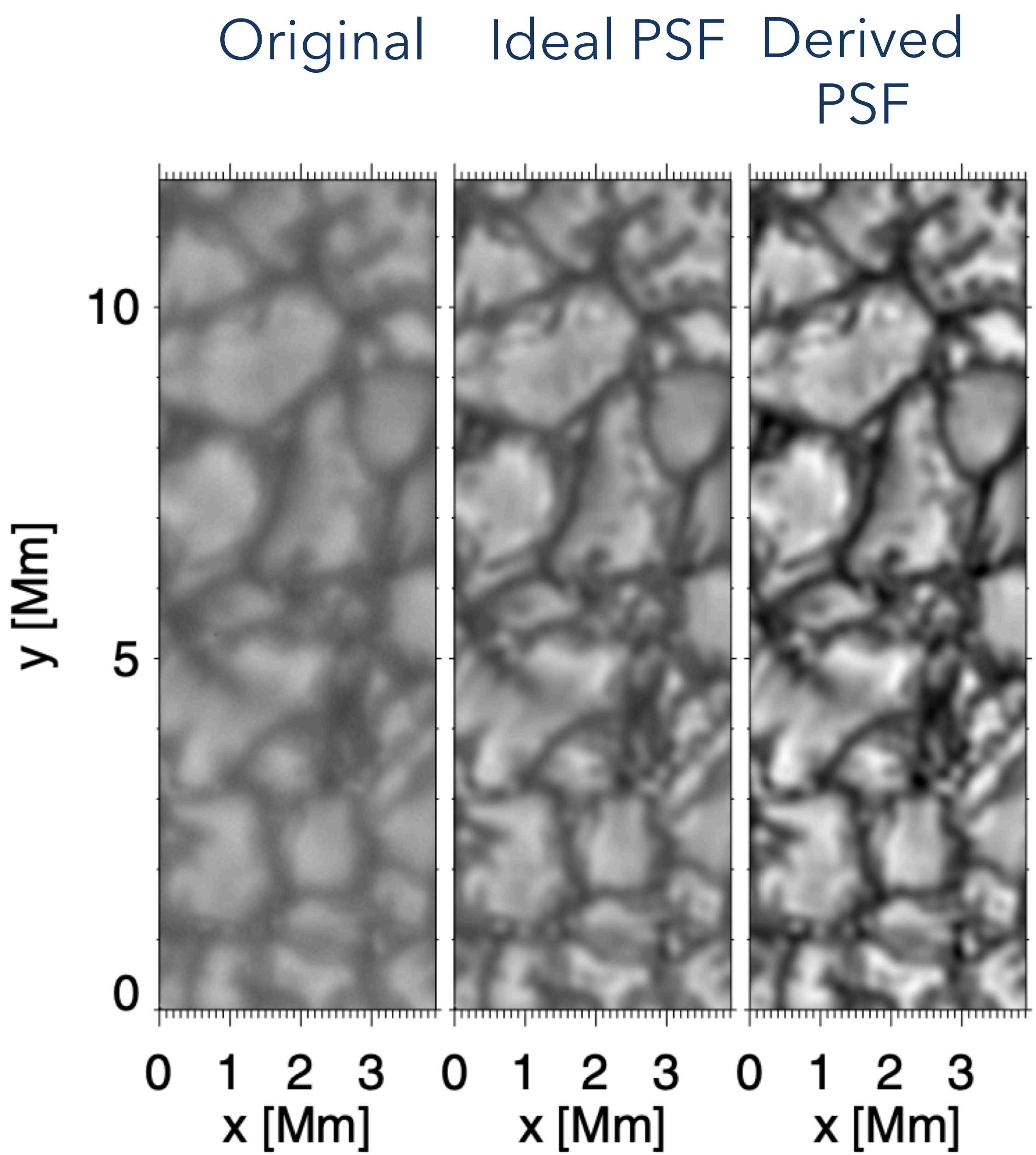
Telescope

Scattered Light

Combination

Wedemeyer-Böhm et al. 2009

It is possible…!

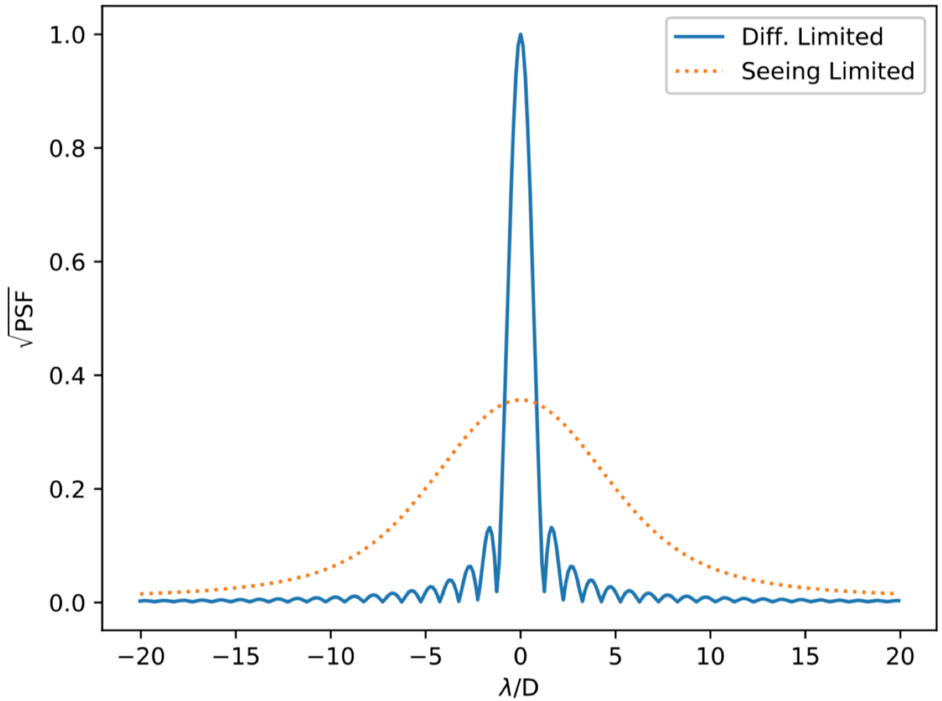


Wedemeyer-Böhm et al. 2009

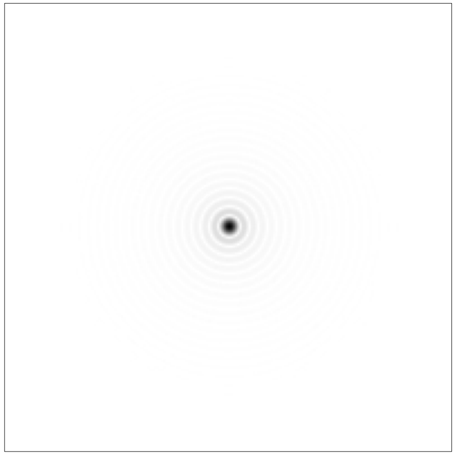
Ground-based PSF is more problematic

- PSF varies on timescales of milliseconds
- Averaging over time (>1 second) results in a more stable "long-term" (or seeing-limited) PSF
- But the long-term PSF greatly attenuates high frequencies
- Only reliable estimate for PSF comes from AO lock point

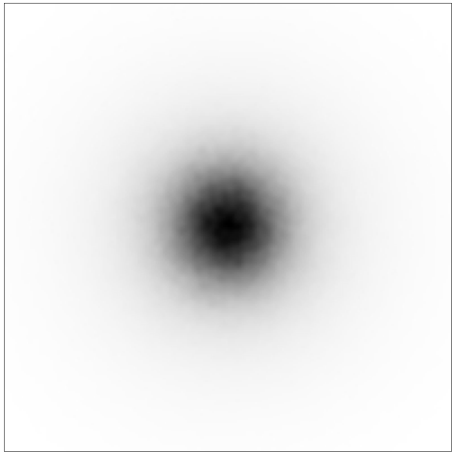
Long-term PSF



Diffraction Limited PSF



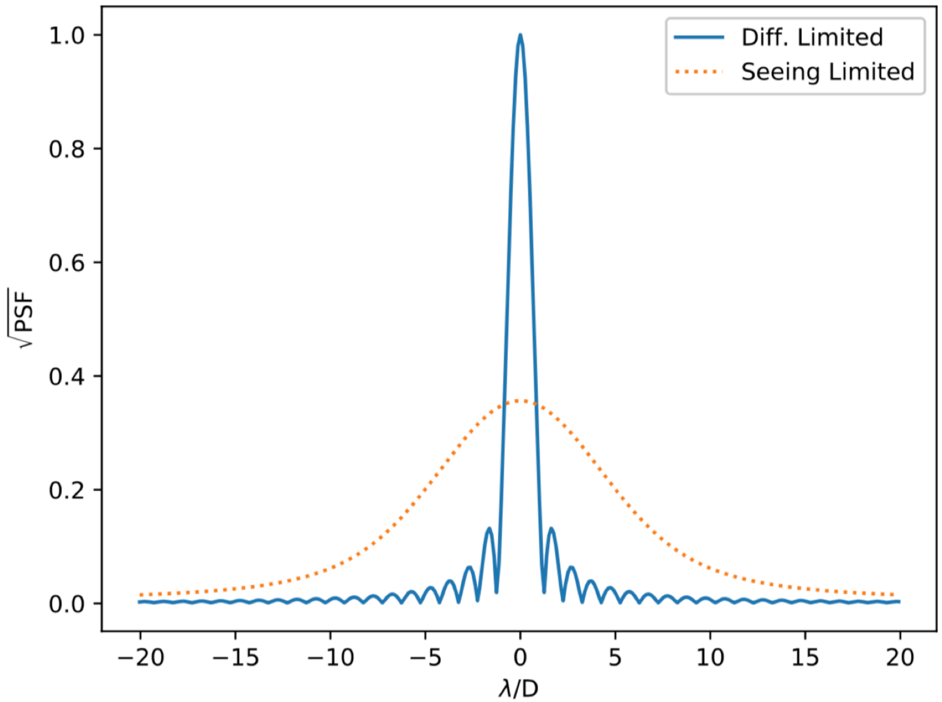
Seeing Limited PSF

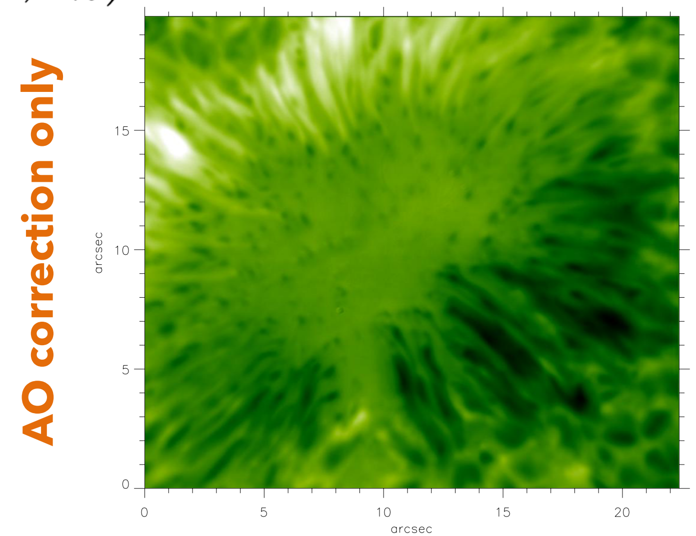


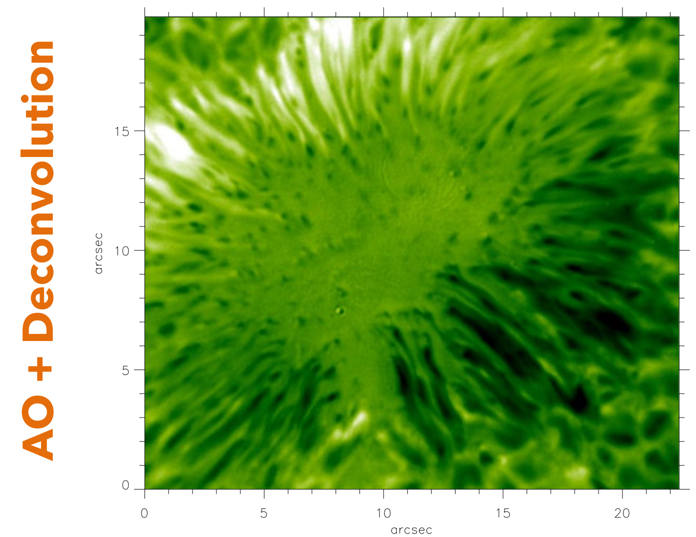
Average over many realizations of the MTF

$$< i_n(u,v) > = i_0(u,v) \times < MTF_n(u,v,t_n) >$$

$$< i_n(u,v) > = i_0(u,v) \times < MTF_n(u,v,t_n) >$$







Marino et al. 2006

“Instantaneous” PSF

- Depends largely on the atmospheric distortions
- a priori, it is unknown

$$i(u,v) = i_0(u,v) \times MTF(u,v)$$

?

How to determine PSF

This assumes a constant MTF

$$i(u,v) = i_0(u,v) \times MTF(u,v)$$

But the MTF is time varying

$$i(u,v) = i_0(u,v) \times MTF(u,v,t)$$

So each image *n* taken at time t_n has its own distinct MTF

$$i_n(u,v) = i_0(u,v) \times MTF_n(u,v,t_n)$$

This allows us to use multiple realizations to try to separate the time-varying contributions of the MTF from the constant object i_0.

Warning! The original object is constant only if the solar scene doesn't evolve during our observations.
try calculating: pixel size [arcsec] x 720 km/arcsec ÷ 7-10 km/sec (sound speed)

How to determine PSF

What do we do with multiple realizations?

$$i_n(u,v) = i_0(u,v) \times MTF_n(u,v,t_n)$$

Recall from last week that the PSF comes from the products of an aperture mask (A) and a distribution of phases across that mask

$$E_s = \oint A(x', y') e^{i\phi(x'y')} e^{-ik(xx'+yy')/R} dx' dy'$$

aperture (constant)

Phases (time varying)

PSF
$$P_{ij} = A_{ij} \exp\{i\phi_{ij}\}$$

Fit phases as a sum of functions

Phases
$$\phi_{ij} = \theta_{ij} + \sum_{m \in \mathcal{M}} \alpha_{ijm} \psi_{im}$$

Basis functions

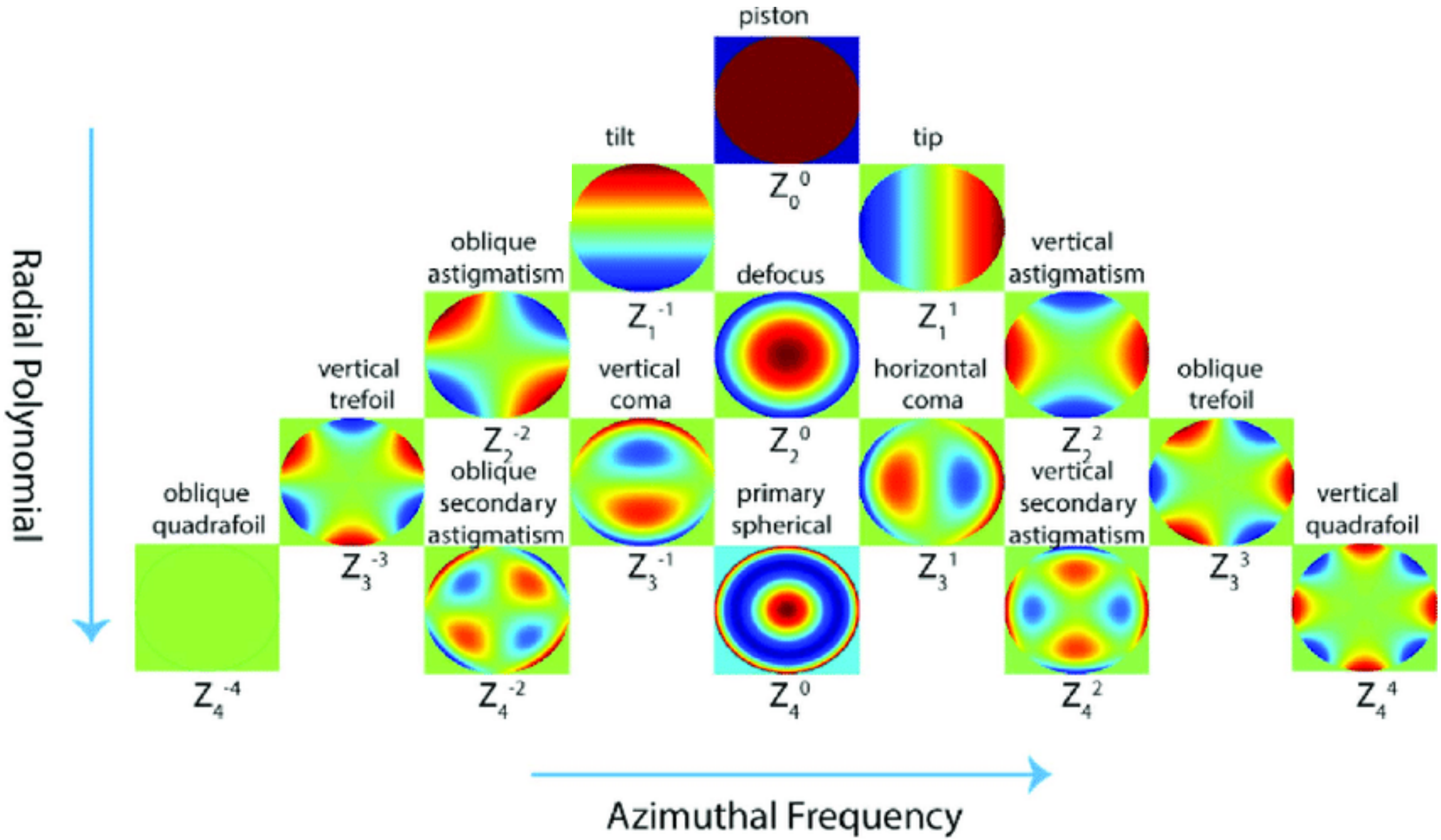
so we just need to find the vector of coefficients

Coefficients
$$\boldsymbol{\alpha} = [\, \boldsymbol{\alpha}_1 \; \boldsymbol{\alpha}_2 \; \ldots \; \boldsymbol{\alpha}_I \,]^{\mathrm{T}}$$

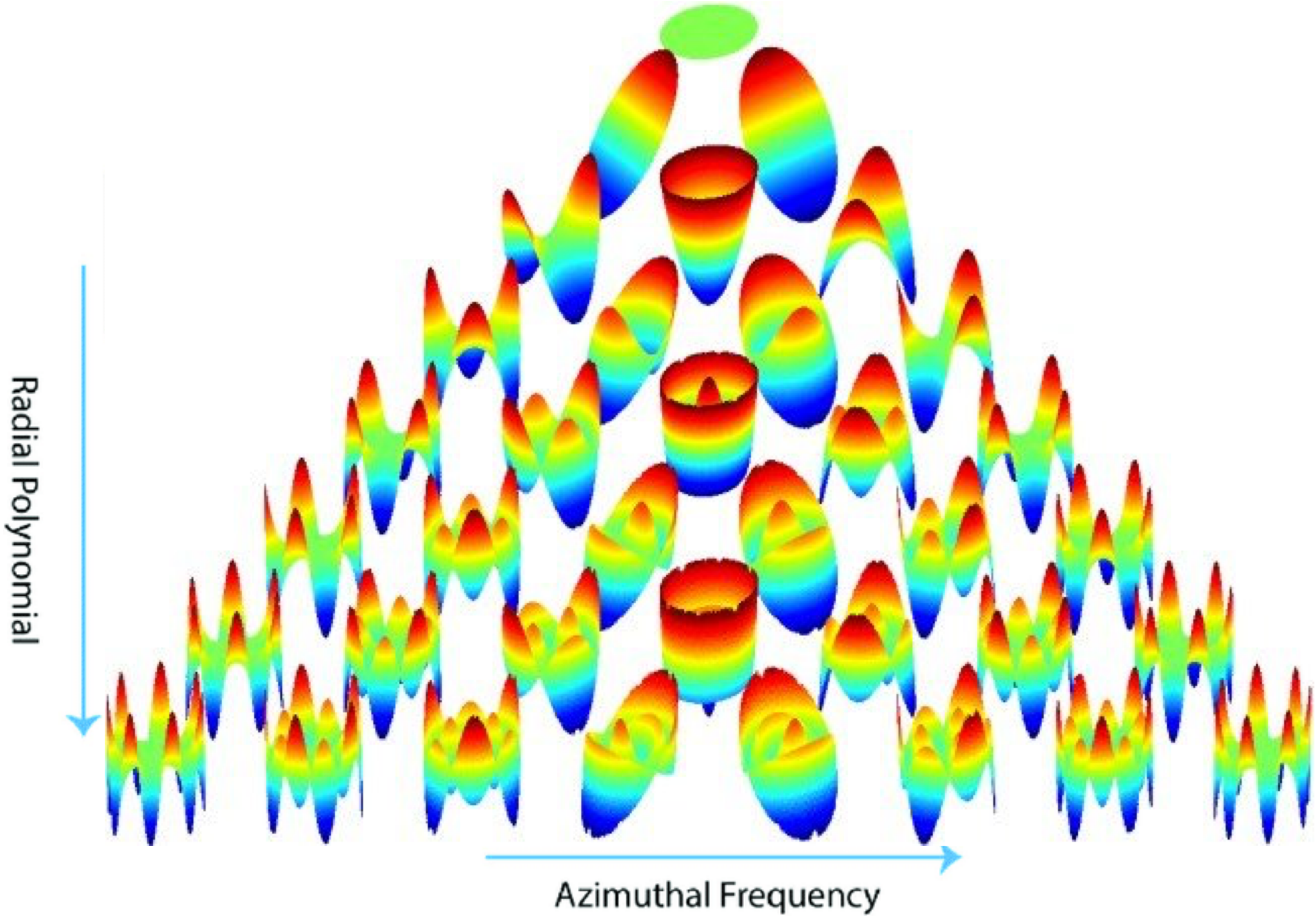
van Noort *et al.* 2005

What basis function to use?

Zernike 2-D circular polynomials



What basis function to use?



How to determine PSF

$$\phi_{ij} = \theta_{ij} + \sum_{m \in \mathcal{M}} \alpha_{ijm} \psi_{im}$$

so we just need to find the vector of polynomial coefficients

$$\boldsymbol{\alpha} = [\, \boldsymbol{\alpha}_1 \ \boldsymbol{\alpha}_2 \ \ldots \ \boldsymbol{\alpha}_I \,]^{\mathrm{T}}$$

Use the following metric, which is independent of original object

$$L_i(\alpha_i) = \sum_{u,v} \left[\sum_{n}^{N} i_n^2 - \frac{|i_n^* M\hat{T}F_n)|^2}{(|M\hat{T}F_n|^2 + \gamma)} \right]$$

Sum metrics of individual modes to get a global metric

$$L = \sum_i w_i L_i$$

w_i – weights applied to different modes

van Noort *et al*. 2005