Scintillation noise on Large and Extremely Large telescopes

James Osborn

Richard Wilson, Dora Föhring, Saavidra Perera and Vik Dhillon

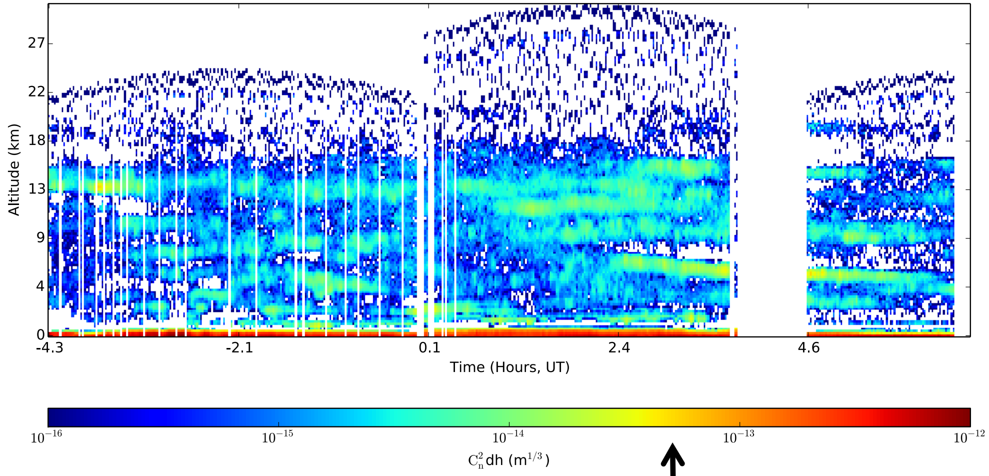
Durham University

Centre for Advanced Instrumentation

Scintillation noise on Large and Extremely Large telescopes

- Scintillation noise is variations in intensity caused by high altitude turbulence
- Atmospheric scintillation noise can be a dominant noise source for bright stars (on small and large telescopes and for all exposure times)
- Scintillation noise estimates rely on model of atmospheric turbulence
- On large and extremely large telescopes we will expect lower scintillation noise than suggested by standard equations
- We can reduce it even further using AO systems

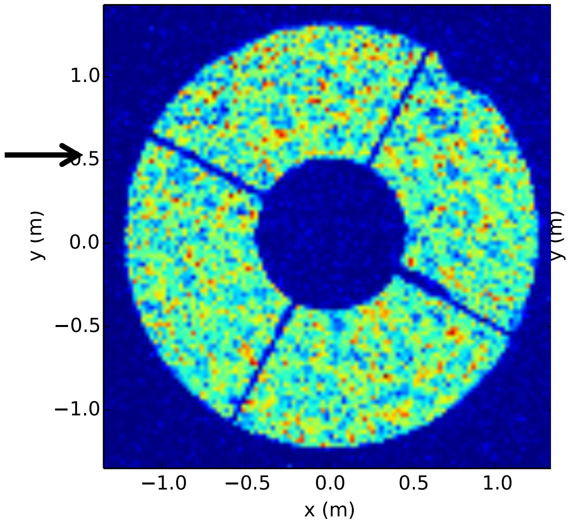
Atmospheric scintillation



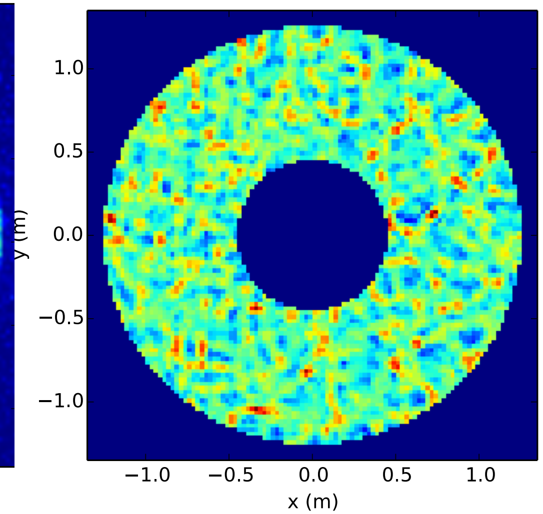
Measured turbulence profile

- Atmospheric turbulence leads to a layer of spatially and temporally varying refractive index
- Light propagating through the turbulent layer will develop spatial intensity variations
- Wind will blow spatial intensity variations across pupil leading to temporal intensity variations – scintillation

Real pupil image

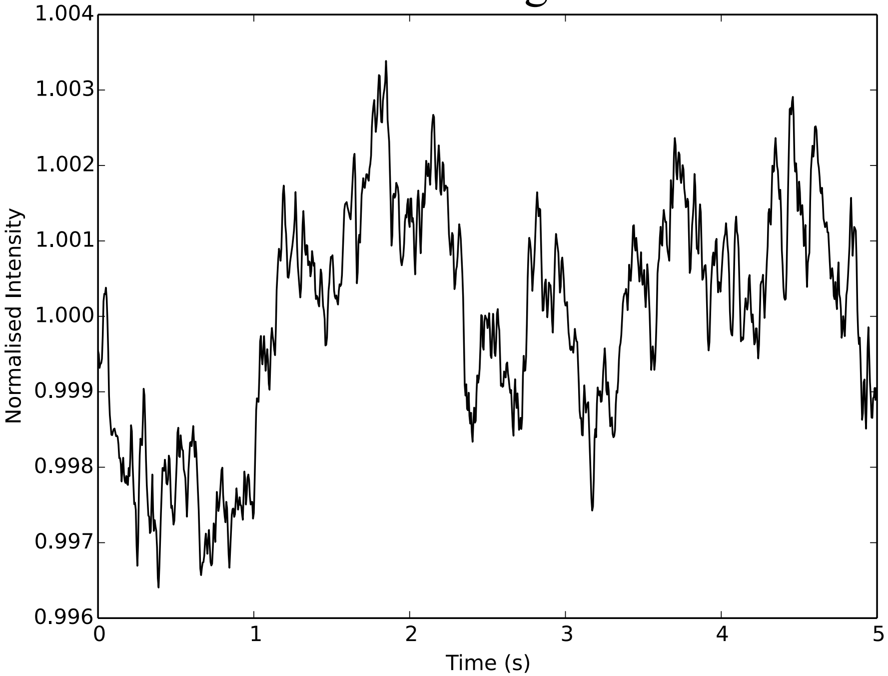


Simulated pupil image

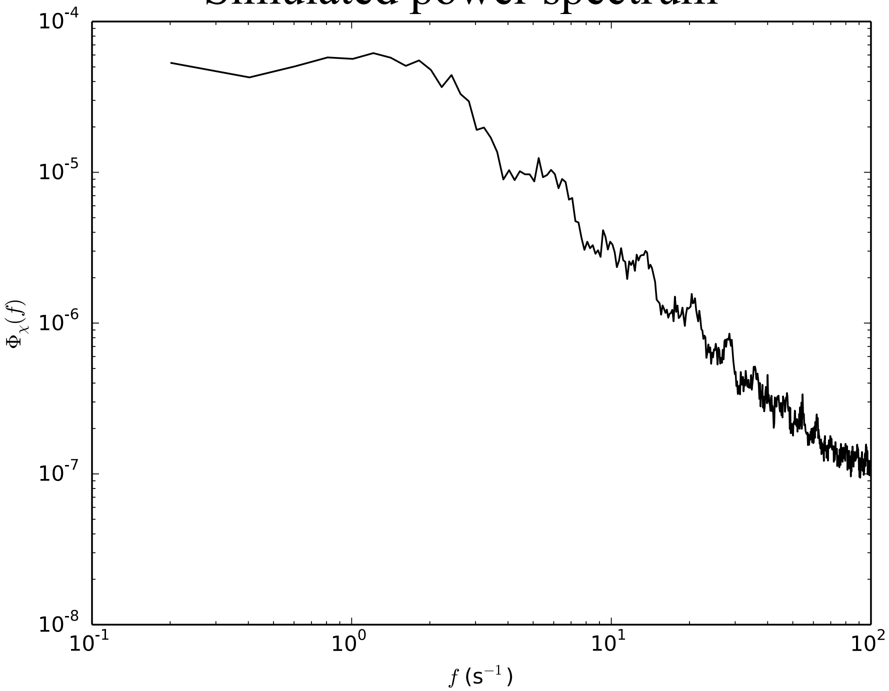


Atmospheric Scintillation

Simulated light curve



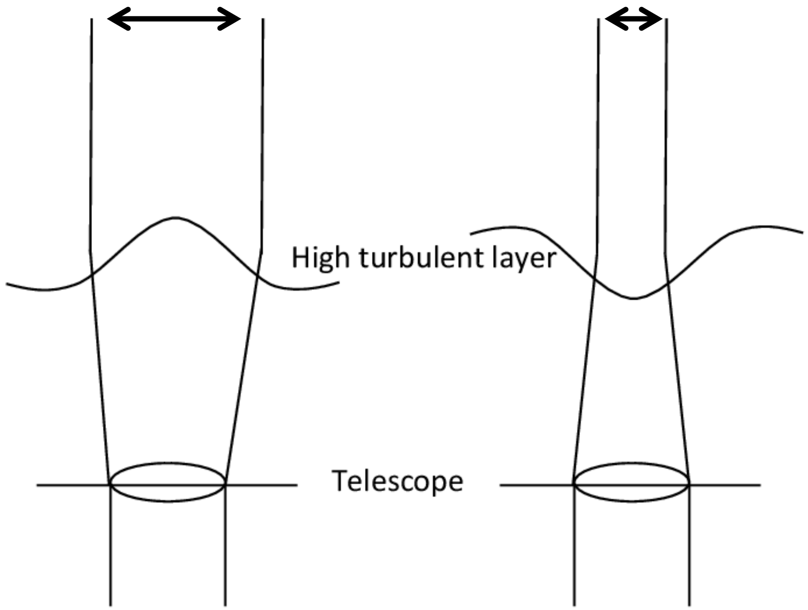
Simulated power spectrum



Low order variations as well as high order variations

Atmospheric Scintillation

- Low frequency aberrations cause intensity variations on pupil
- Phase aberrations can occur up to the 'outer scale' of the turbulence
- Beyond this size no further scintillation is generated
- Large telescopes can be larger than the outer scale
- Large telescopes have lower scintillation noise than expected



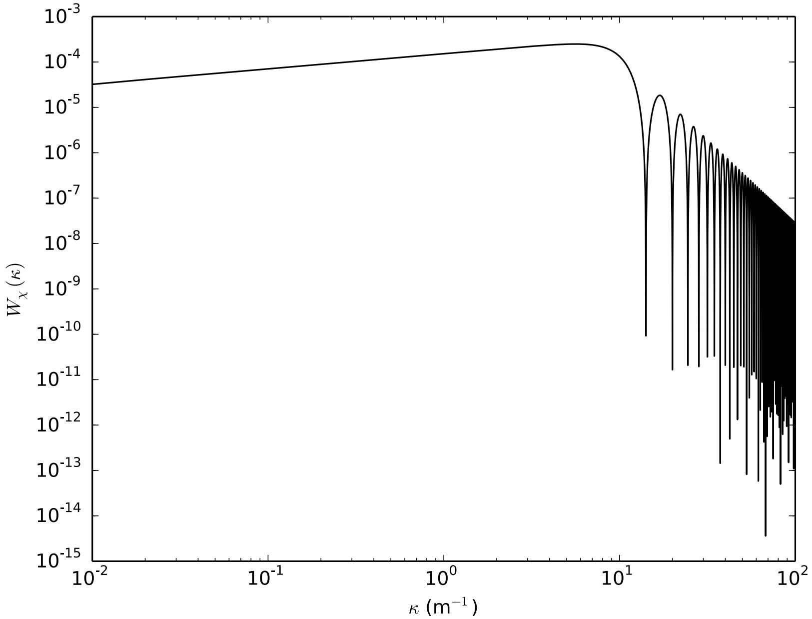
Atmospheric Scintillation

Atmospheric turbulence
phase power spectrum:

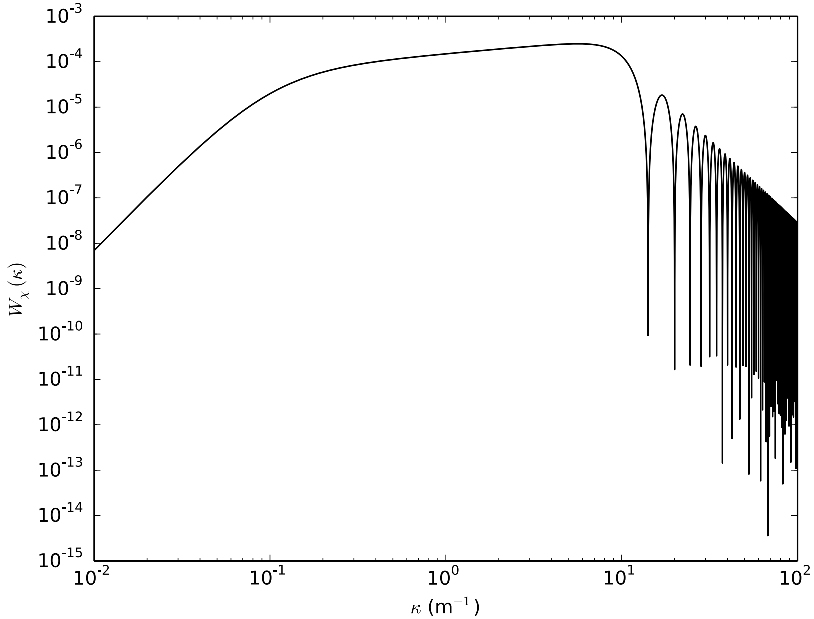
Kolmogorov: $\phi(f) = f^{-11/3}$

Von Karmen: $\phi(f) = \left(f^2 + L_0(h)^{-2}\right)^{-11/6}$

Scintillation power spectrum without outer scale



Scintillation power spectrum with outer scale



Estimating Atmospheric Scintillation Index: $\sigma^2 = \frac{\left\langle (I - \langle I \rangle)^2 \right\rangle}{\langle I \rangle^2}$

Young's equation:

$$\sigma_{\mathrm{Y}}^2 = 9 \times 10^{-6} D^{-4/3} t^{-1} (\cos\gamma)^{\alpha} \exp\left(-2h/H\right)$$

Dravins' equations: Kolmogorov (infinite outer scale) turbulence, no central obscuration at zenith

$$\sigma^2 = \begin{cases} 19.2\lambda^{-7/6} \cos(\gamma)^{-3} \int_0^\infty h^2 C_n^2(h) dh & D \ll r_F \\ 17.3 D^{-7/3} \cos(\gamma)^{-3} \int_0^\infty h^2 C_n^2(h) dh & D \gg r_F \\ 10.7 D^{-4/3} t^{-1} \cos(\gamma)^{\alpha} \int_0^\infty \frac{h^2 C_n^2(h) dh}{V(h)} & D \gg r_F,\ t \gg (\pi D/V) \end{cases}$$

Small aperture, D< ≈5cm

Larger aperture, D> ≈30cm

Larger aperture and finite exposure time, t> ≈0.5s

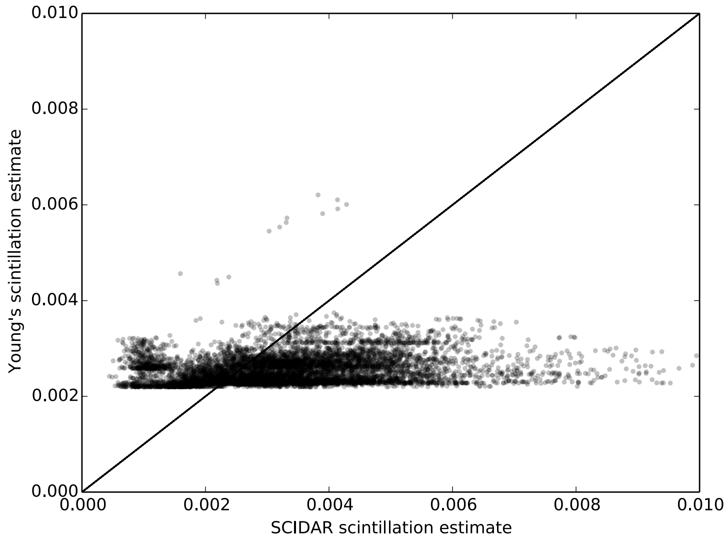
In full, with central obscuration with d/D = ε, outer scale L_0, zenith angle γ.

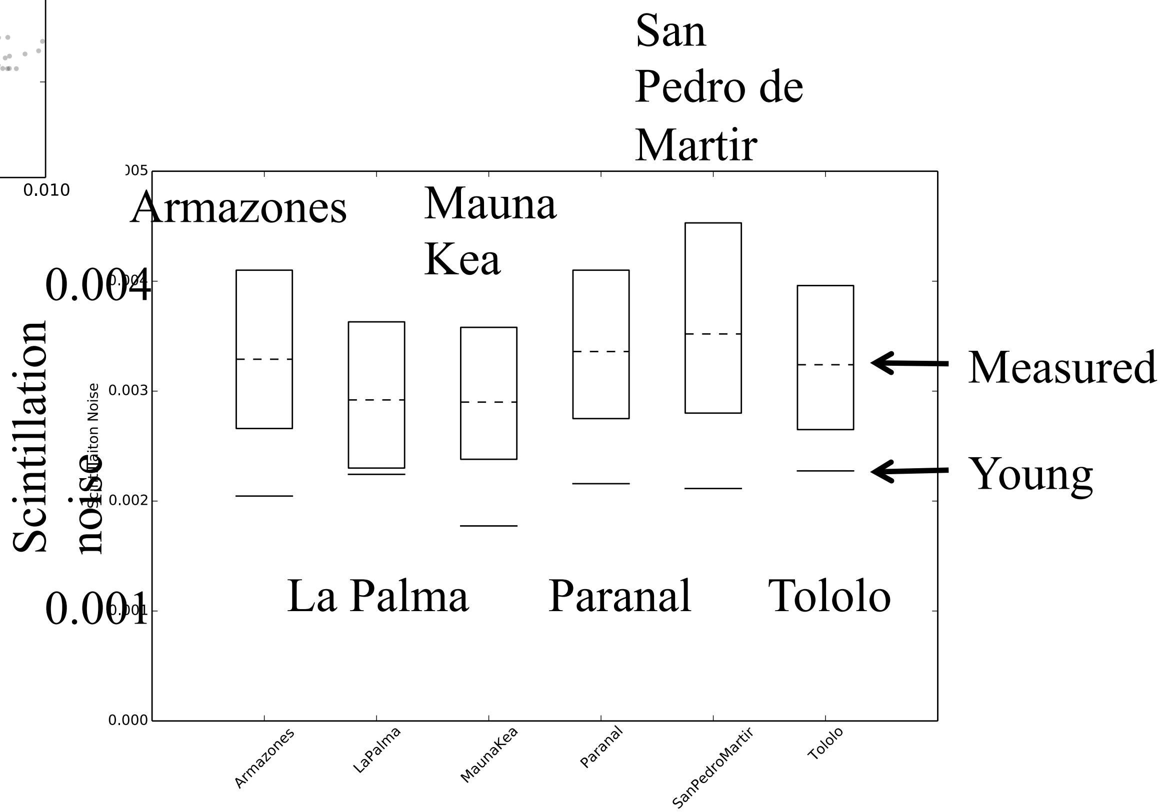
$$\sigma^2 = 12.24 D^{-4/3} t^{-1} \cos(\gamma)^{\alpha} \int \frac{C_n^2(h) h^2}{V_\perp(h)} \int (q^2 + (D/L_0(h)^2))^{-11/6} q^2 (\mathrm{J}_1(\pi q) - \epsilon \mathrm{J}_1(\pi \epsilon q))^2 / (1 - \epsilon^2)^2 \mathrm{d}q \mathrm{d}h$$

α = -3 to -4 depending on wind direction

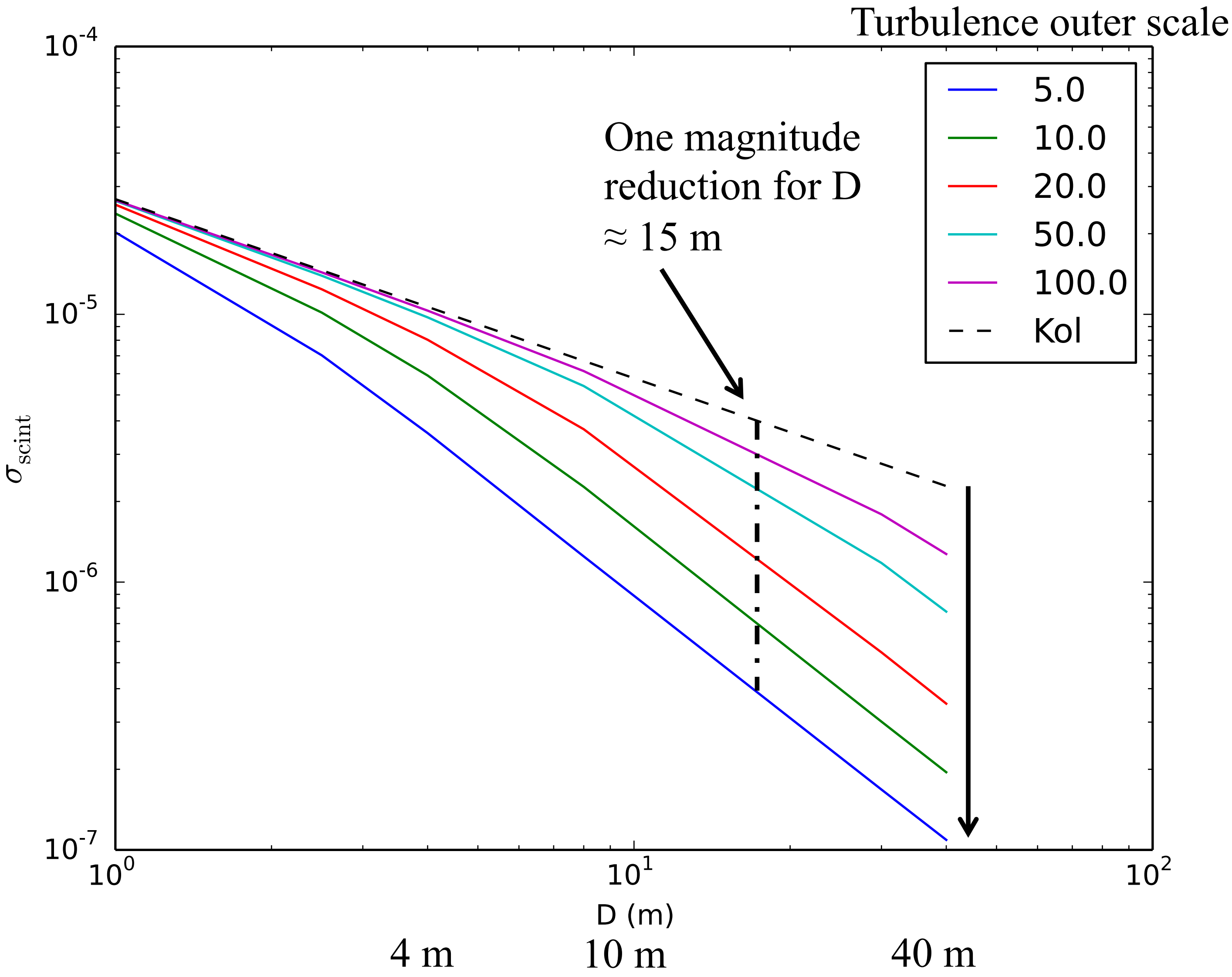
q = *Df*, where *f* is the spatial frequency

Young’s approximation



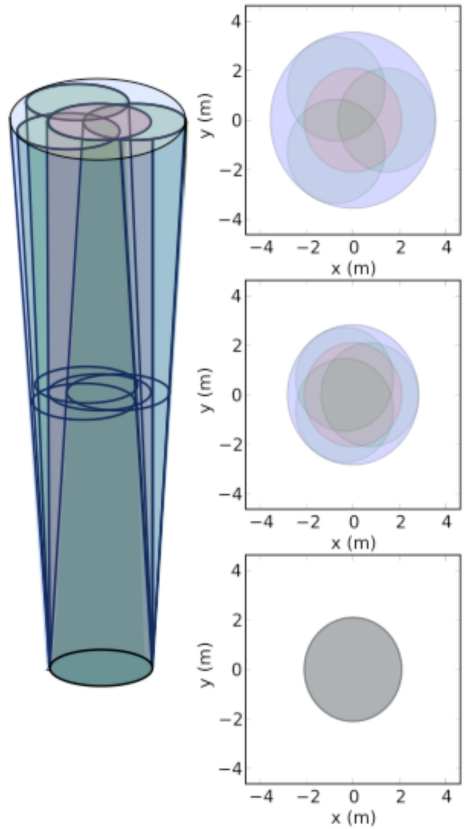


Scintillation noise on Large Telescopes



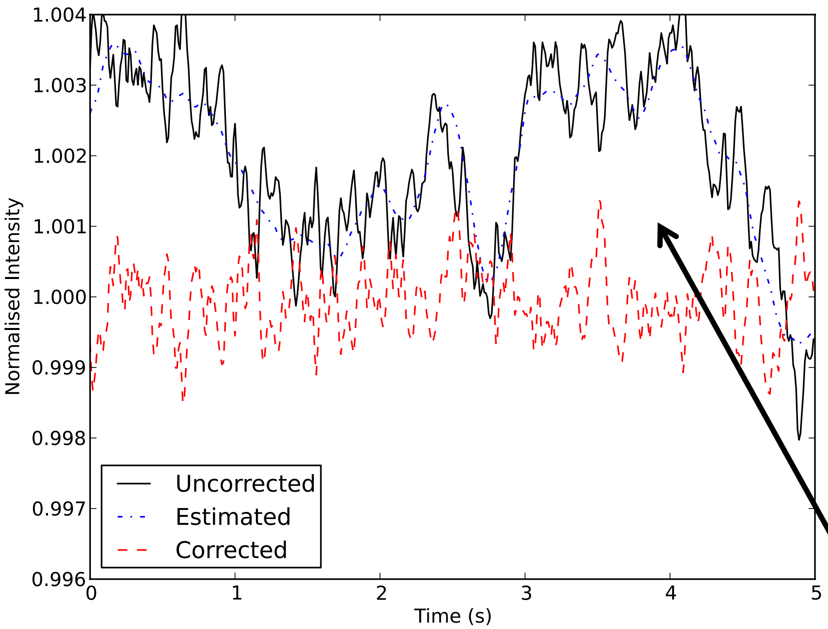
Correcting Scintillation on Large telescopes

- Adaptive Optics systems use multiple wavefront sensors to probe the turbulent atmosphere
- Optical tomography to estimate volume of turbulent phase in the atmosphere
- Theoretically propagate phase to ground using Fresnel propagation
- Estimate scintillation signal at correct wavelength and integrate over exposure time
- Normalise light curve

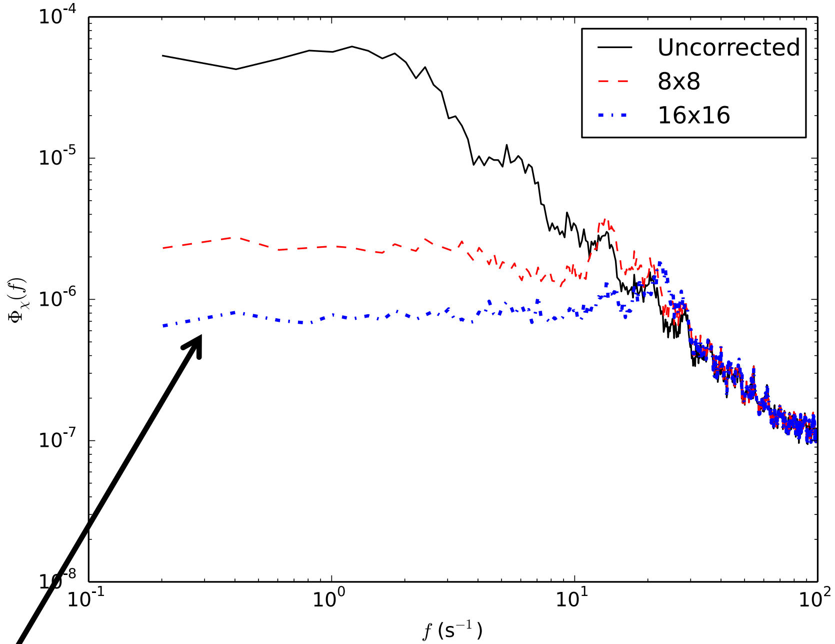


Correcting Scintillation on Large telescopes

Example simulated light curve



Power spectrum of light curve

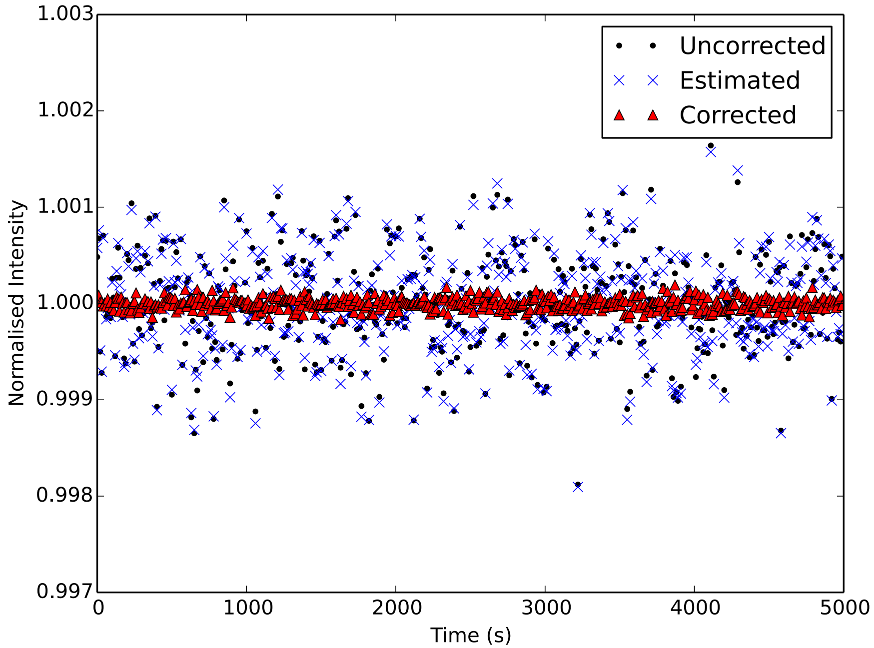


D = 8m

Low frequency scintillation noise reduced

Long exposure (10s) light curve

- Simulated multiple long exposures
- 16x16 AO, D=8m, t_exp=10s
- Scintillation noise reduced by an order of magnitude
- 0.04% to 0.003%



High-Precision Photometry on Large Telescopes

- Scintillation noise will be lower on larger telescopes than expected ($D \geq \approx 4$ m)
- Scintillation on large telescopes can be reduced further using the AO telemetry and tomographic scintillation correction
- Ultra-high precision photometry
  - Adaptive Optics image correction
  - Scintillation correction
  - Multi-wavelength imaging / transit spectroscopy