Astronomical Scintillation, Speckles and Asteroids

Causes, effects and possible mitigation

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SOTAS Stellar Occultation Timing Association Switzerland
www.occultations.ch

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Astronomical Scintillation - review

Themes (from ESOP 43)

Causes : where does it come from?

Effects: how can it be measured and how does it affect astronomical observations?

Mitigation: modern observation techiques - can they be applied to occultation observations?

Speckle interferometry

Themes

Causes : where does it come from?

Technique: what it is and how it is used

Extension: can it be applied to occultation observations?

Causes

Causes

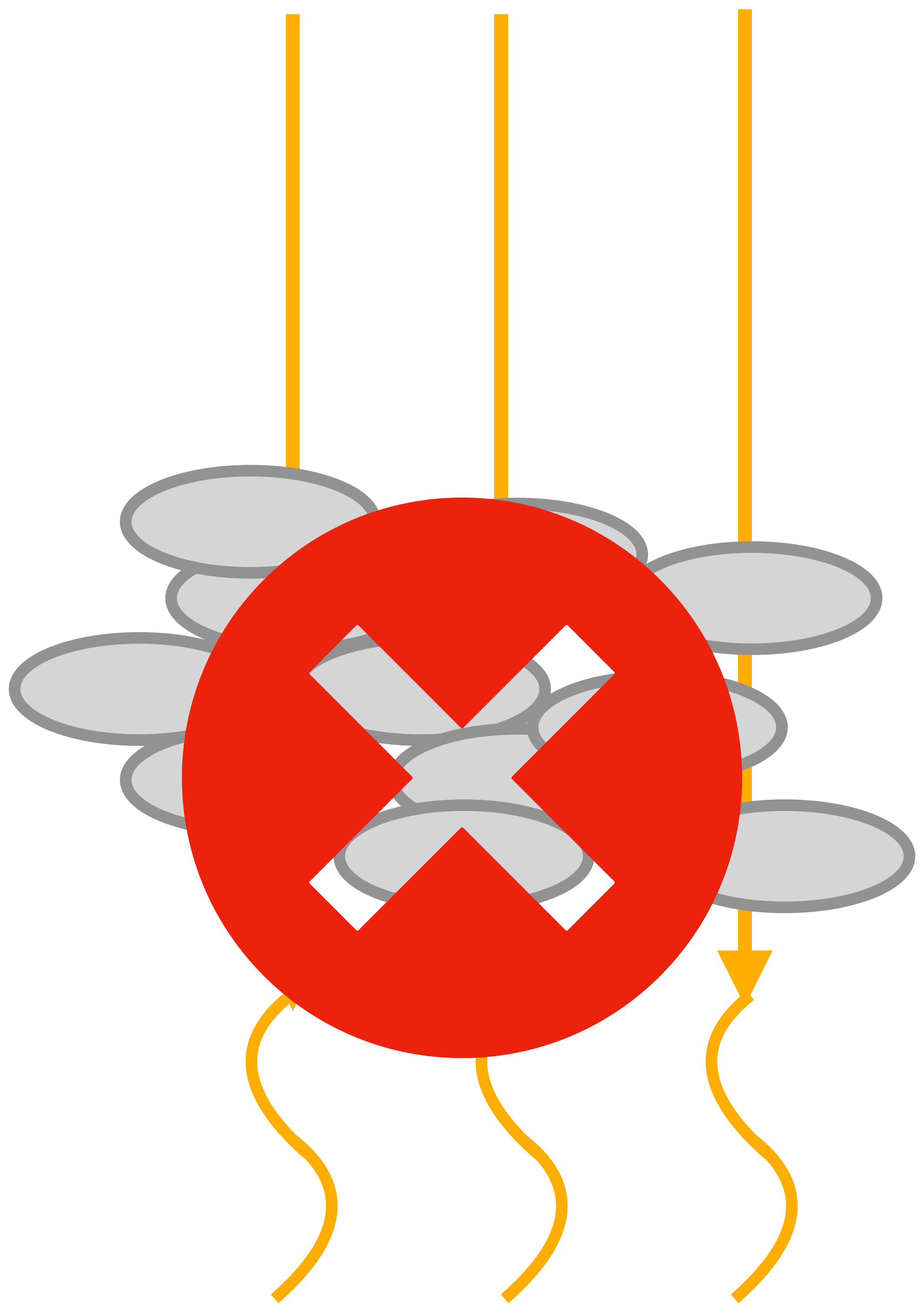
Some theory

- **Scintillation** (“twinkling”) is one of the two primary noise sources causing fluctuations in photometric measurements. The other, **shot noise**, is related to thermal noise in measurement electronics

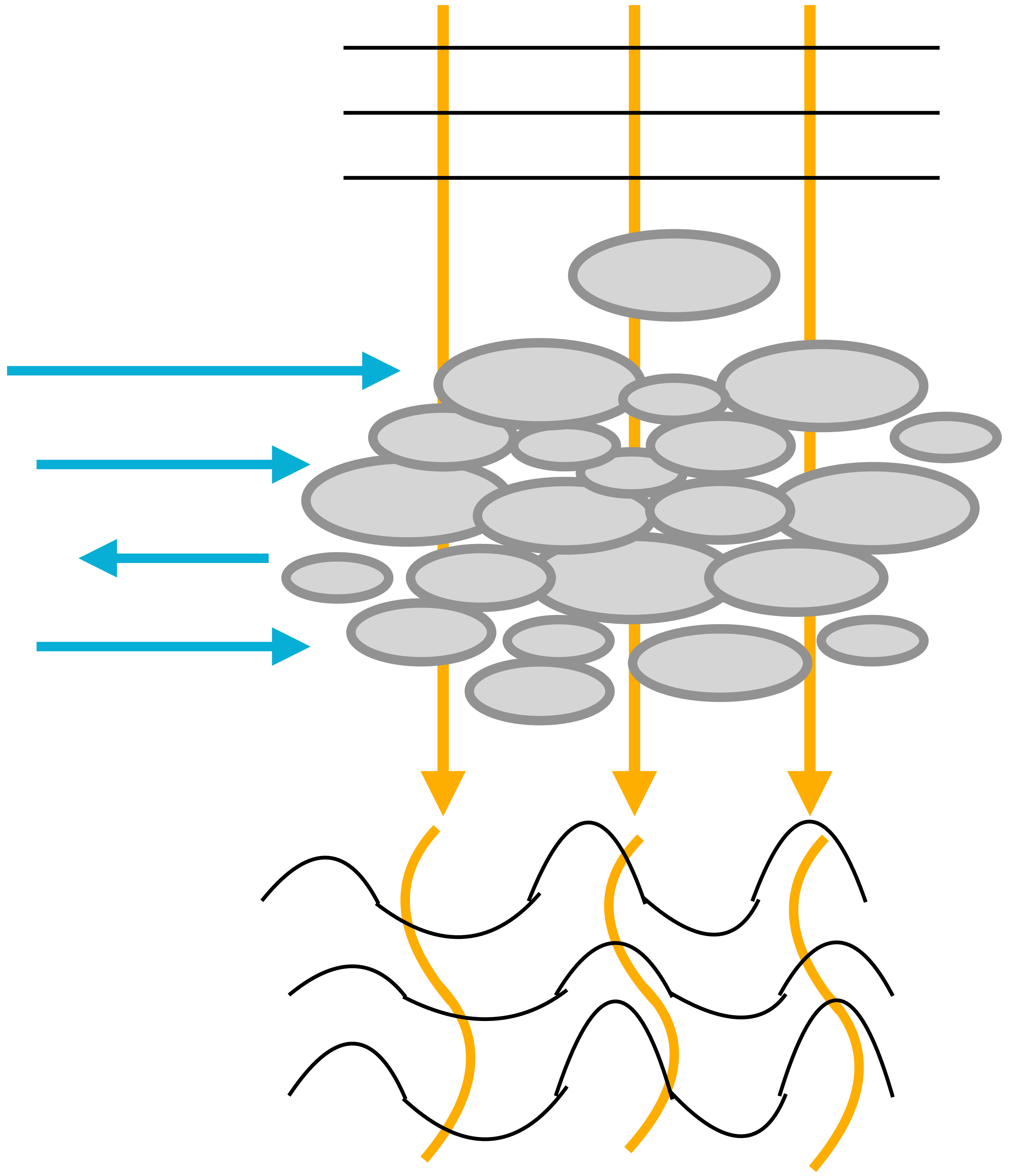
- Scintillation (at good sites) is caused mostly by high altitude winds causing turbulence in the atmosphere. This distorts the wavefronts as they pass through the atmosphere

- **Scintillation** is dominated by high-altitude turbulence, with very little scintillation being caused by low-altitude turbulence. This is **different to atmospheric seeing** which blurs astronomical images. **Seeing** is dominated by the strongest layers of atmospheric turbulence, irrespective of altitude. In fact it is **the surface layer** which often dominates the seeing (Osborn et al. 2010). Therefore, it is possible for the seeing to be bad whilst the scintillation noise is low and vice versa.

- Other local sources may also have impact (buildings, water) on fluctuations



Traditional theory

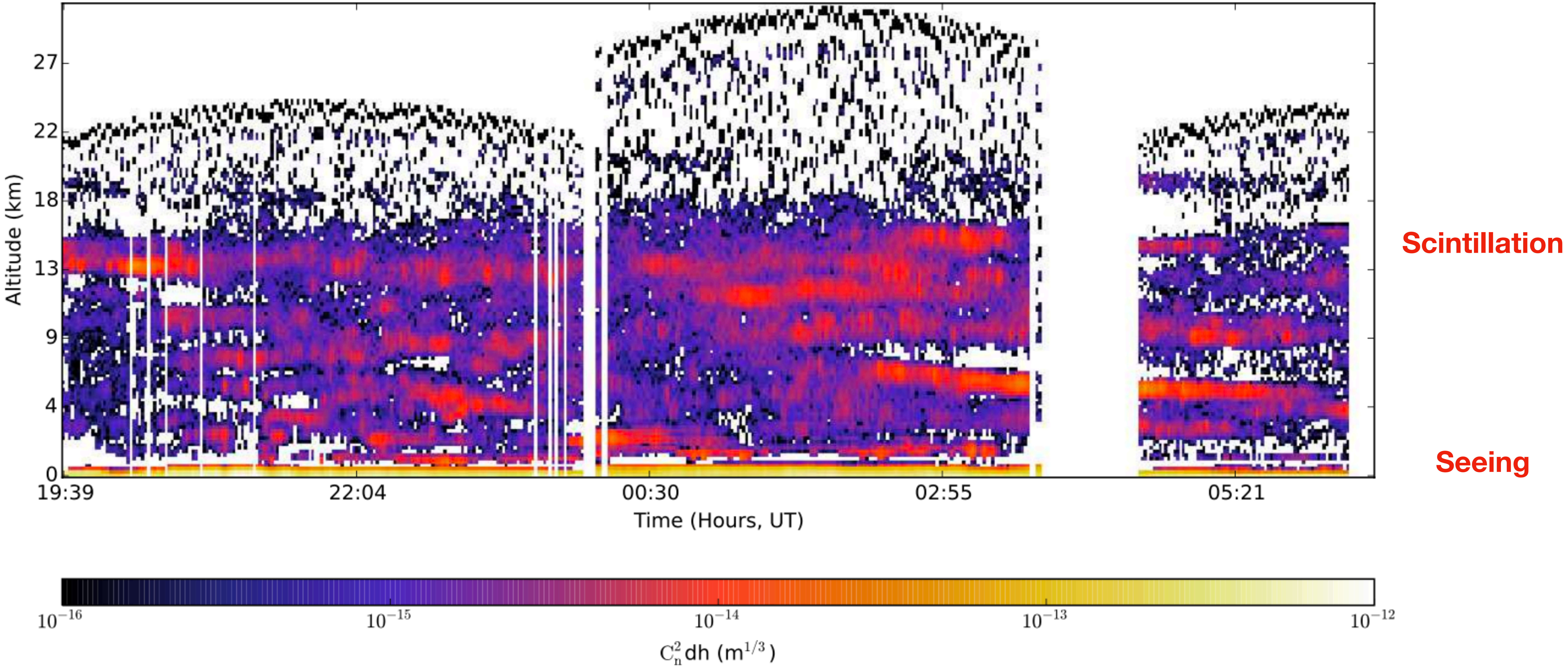


Current theory

Causes

Some more theory

- The local intensity of turbulence is characterized by the *refractive index structure constant* C_n^2. This is mostly dependent on height in the atmosphere, and also wind speed vs altitude.
- **Turbulent layers** in the Earth's atmosphere lie in the Troposphere, up to 12 km above sea level. The turbulence generally reduces with altitude, however the impact on optical wavefronts is greater the further from the layer, hence higher layers often have more impact
- The Kolmogorov spectrum predicts a falloff with scale and duration, due to the turbulent flow transitioning to laminar flow at small scales (various "bubble" sizes)
- ***Seeing*** is related to the sum of complete path variations (Fried parameter), while ***scintillation*** is dominated by high altitude variations (scintillation index). Similarly, the concept of 'lucky imaging'(and **speckle interferometry**) uses short exposures to get images during steady times. Scintillation mitigation is more interested in variations in brightness (amplitude) than steadiness of the image (phase).

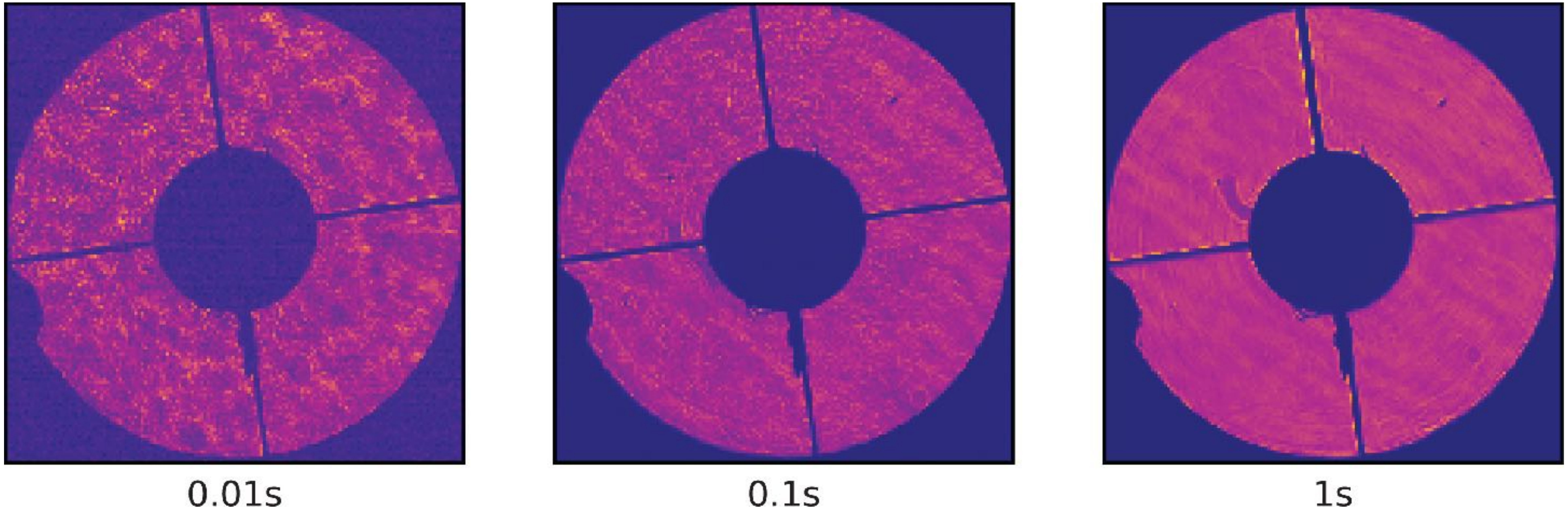


Typical tropospheric turbulence profile over several hours

Osborn, J. MNRAS, Volume 452, (2015), Pages 1707-1716

Effects

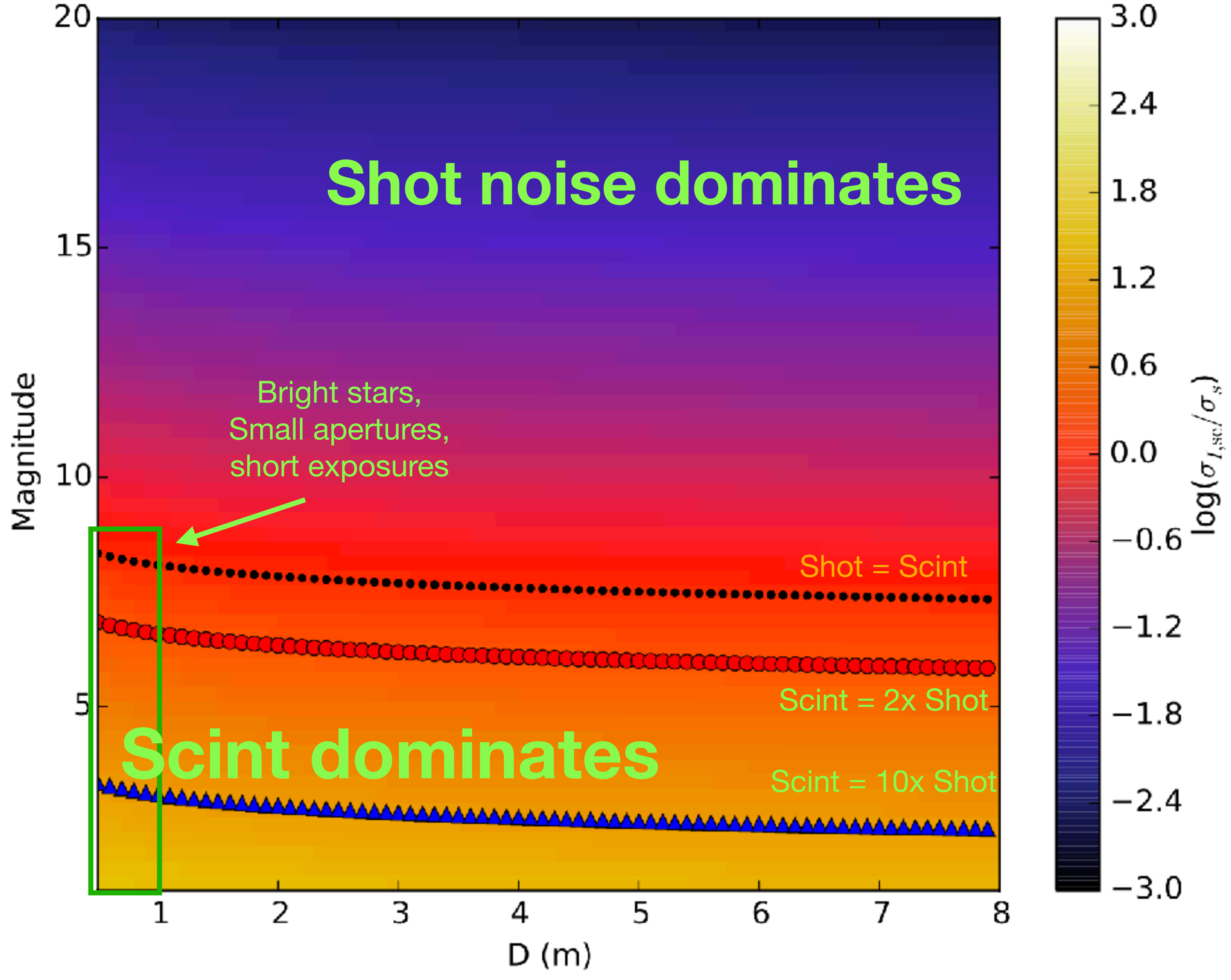
Causes Effects Mitigation



- Images on INT pupil plane: exposure time determines the correlation noise due to wind movement of turbulence

Mon Not R Astron Soc, Volume 526, Issue 1, November 2023, Pages 1235–1245,
https://doi.org/10.1093/mnras/stad2835

Theory - Short exposure scintillation noise (< 1 sec)



Short exposure (2 msec) noise sources (Osborne, 2015)

- For short exposures, noise is independent of exposure time
- For median conditions and regardless of large telescope diameter, **scintillation will be greater than shot noise** for (V -band) magnitudes less than ca.13 for long exposures and ca. 8 for short exposures.
- Impact of central obscuration of the telescope on scintillation noise: Larger secondary mirrors lead to more scintillation noise due to the smaller collecting area over which the scintillation speckles are spatially averaged.


Atmospheric Conditions (Wind, elevation, height)
Turbulence
Distortion (Seeing)
(Scintillation)
Speckle interferometry
Lucky imaging
Short exposure time
Long exposure time
Small Aperture (Single speckle)
Large Aperture (Blurred speckles)
(Noise reduces with exposure time)

Mitigation

Mitigation

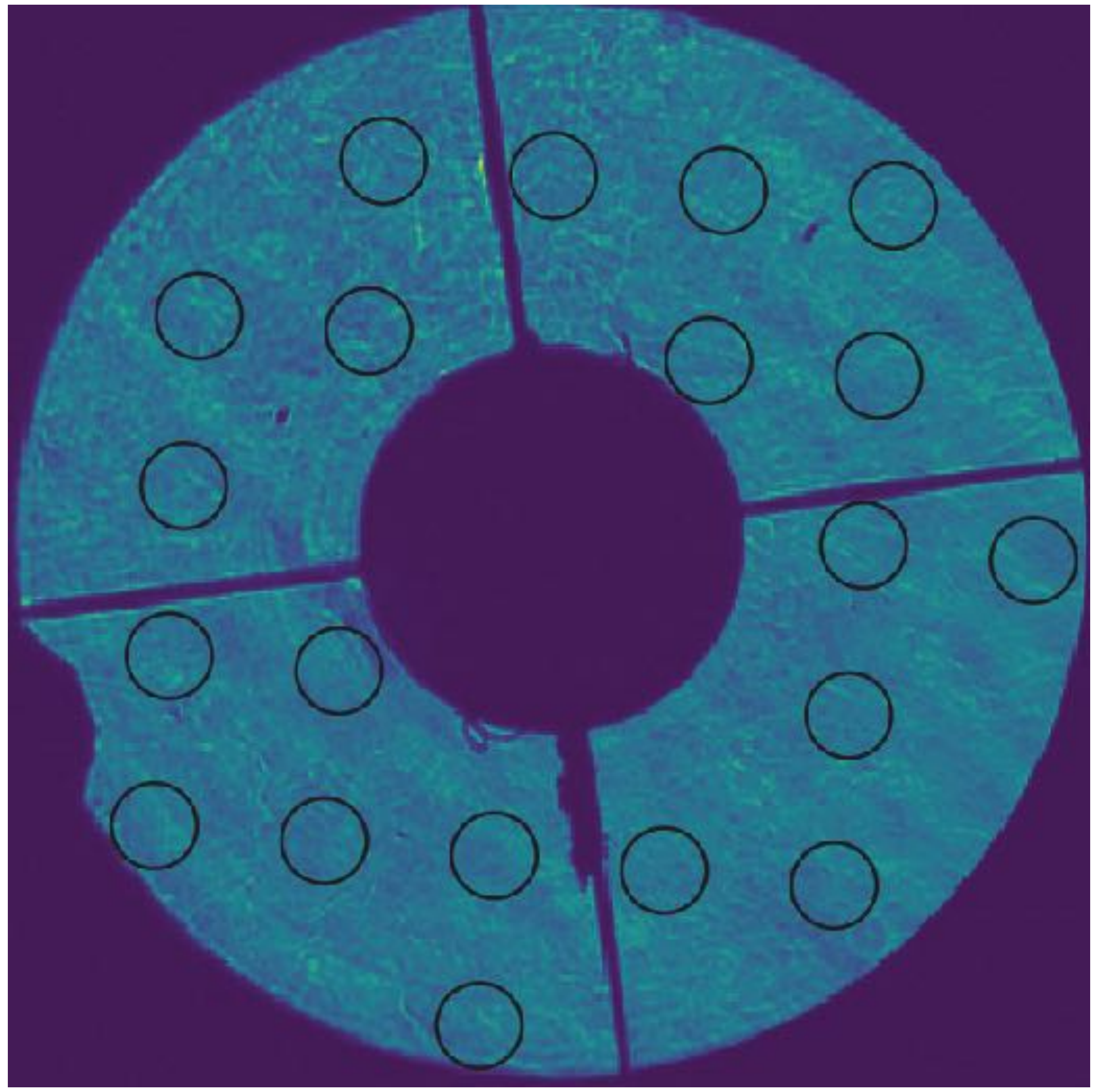
Recent advances in observing techniques

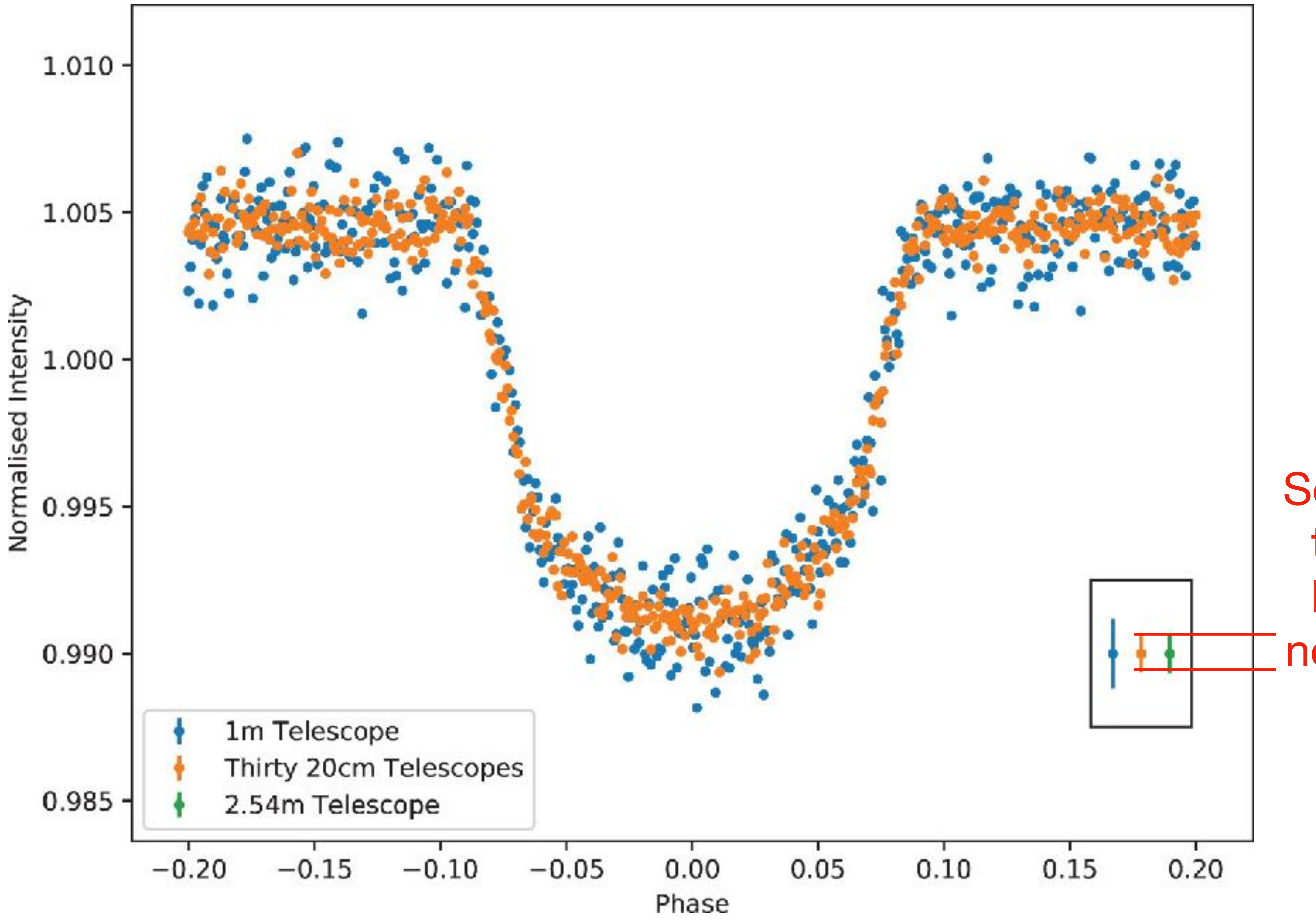
- Dravins made some first measurements in the 1990s, with goal of opening new ‘temporal windows’ in Astronomy
- Aim today is to reduce noise in accurate ground-based photometry
- Osborne and others developed the idea of a ‘sparse array’ photometer, using multiple telescopes

Applications

- Low noise photometry of Exoplanet transits
- Observations of Cataclysmic variable stars
- Occultations as well? (Especially shallow, bright star events)

Causes Effects **Mitigation**



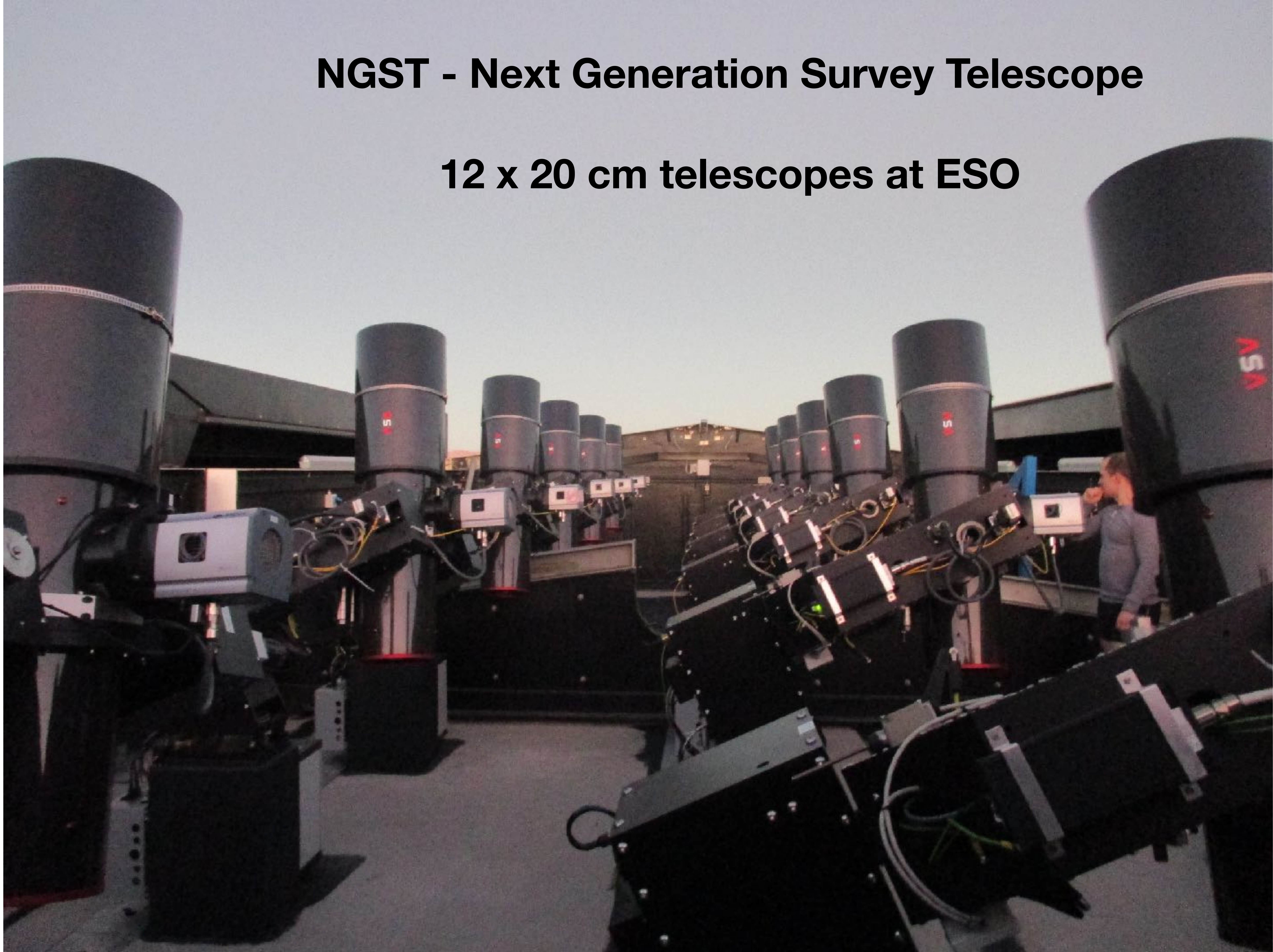


It is possible to simulate the use of several apertures for exoplanet transit measurements (Hartley, et al, 2023, data from Isaac Newton 2.5m Telescope)

Mon Not R Astron Soc, Volume 526, Issue 1, November 2023, Pages 1235–1245, https://doi.org/10.1093/mnras/stad2835

NGST - Next Generation Survey Telescope

12 x 20 cm telescopes at ESO



System described in:

Wheatley P. J. et al., 2018, MNRAS, 475, 4476

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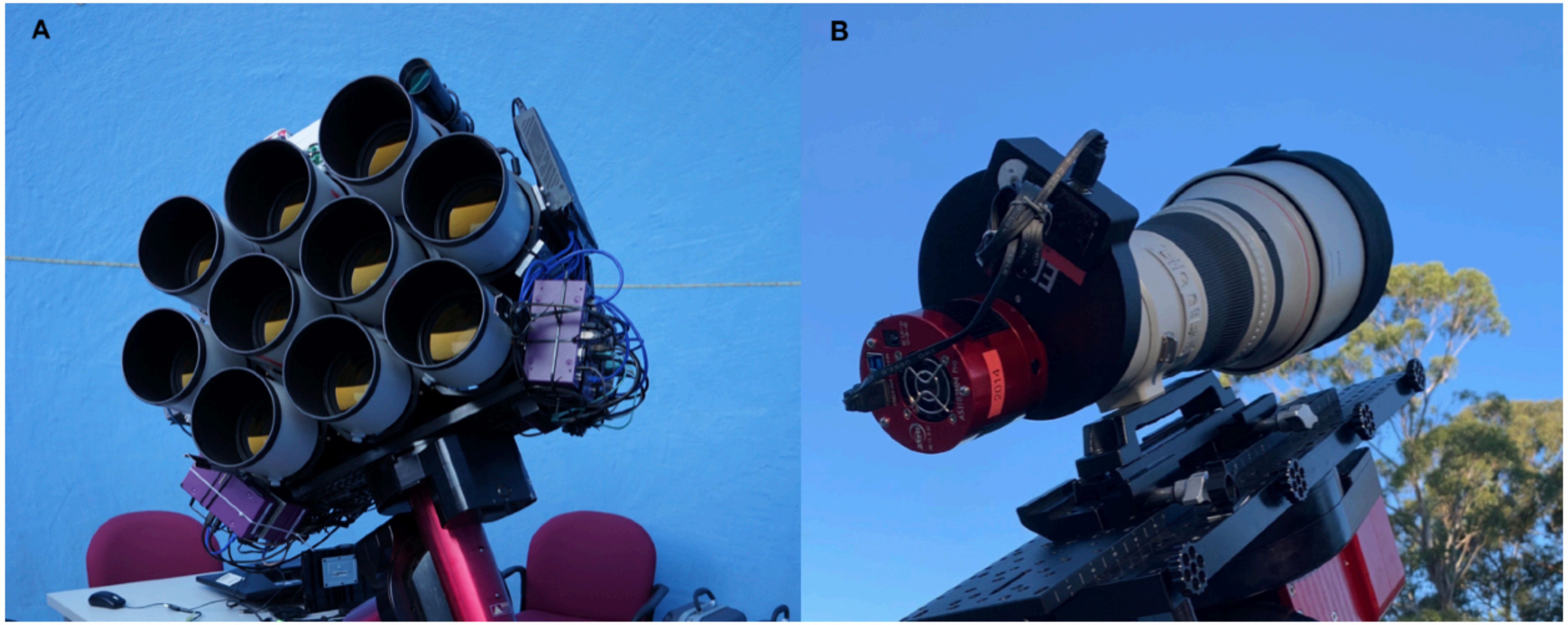
Multiple aperture refractor systems
‘*Dragonfly*’ (Canada). & ‘*Huntsman*’ (Australia)



Hartley, K.E.; Farley, O. et al. (2023)

Abraham, R.G.; van Dokkum, P.G. et al. (2022)

Mitigation

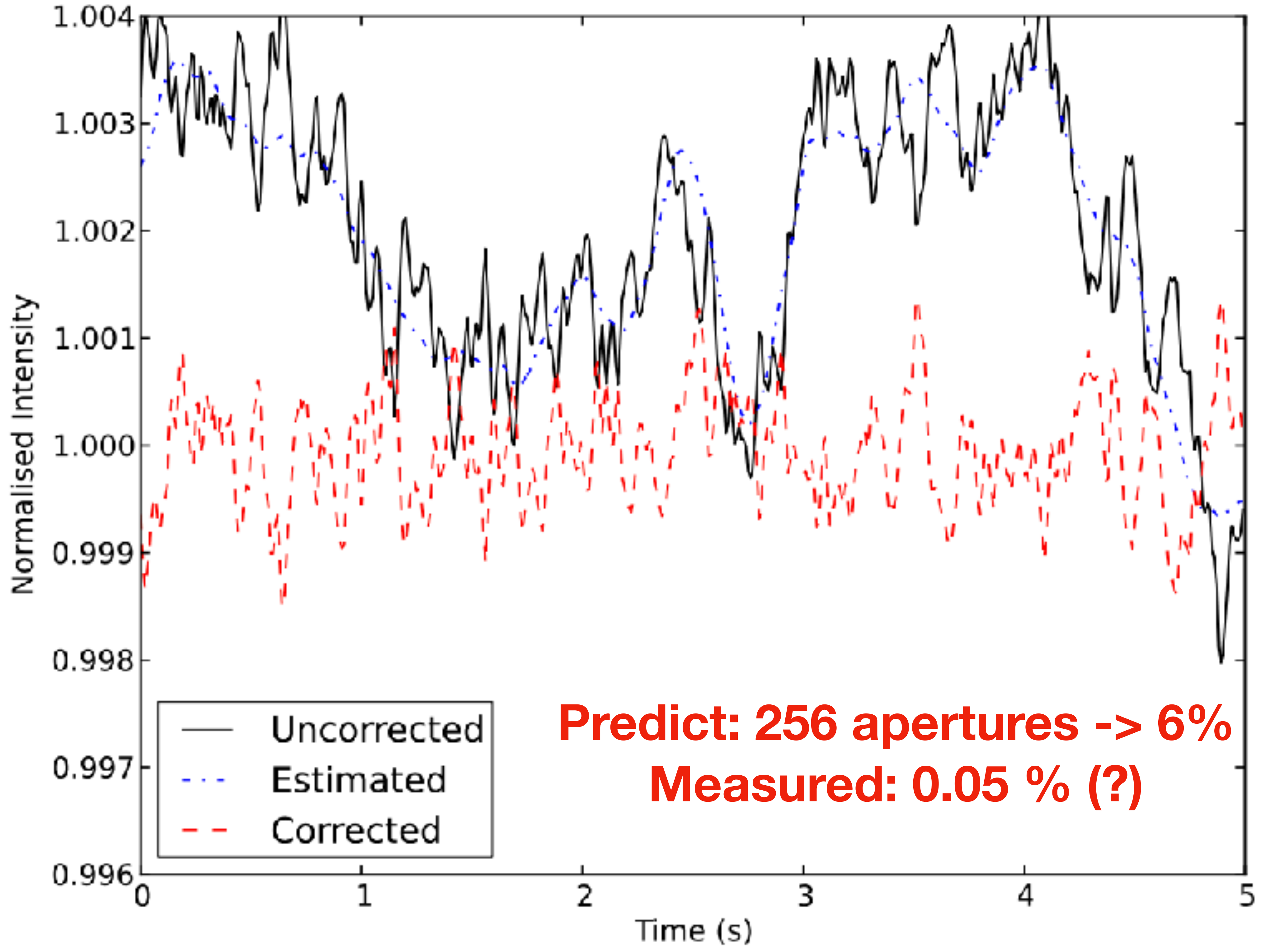
What can we do for occultations?

- Use of multiple apertures will probably <u>not</u> improve signal for fainter stars
- Potentially can reduce noise for **bright object occultations**, using several smaller apertures /sensors - *especially where scintillation dominates over shot noise*
- Scintillation levels will vary with weather conditions and locations, so measurements several different locations are recommended; urban locations in particular may show different performance
- Is frame synchronisation possible?

Mitigation

Example of simulation

- Simulated signal of single aperture vs. multiple aperture
- **Reduction in scintillation would be proportional to √(N)** where N is the number of apertures.
- For 2 apertures, 1/√(N) is 70%
- For 7 (Hexagonal + center), noise is 1/2.6 or 38%



Example light curve for an **8 m telescope, 16x 16 sub-apertures, 0.02 s simulated exposure time,** 5s total simulation time and a turbulent laver of strength 1.05x 10-13 m1/3 at 10 km. The solid line shows the measured light curve, the dot-dashed line shows the estimated light curve from the reconstructed wavefront and the dashed line indicates the corrected light curve. **The scintillation noise has been reduced from 0.2 to 0.05 per cent.**

Speckle Interferometry

Speckle Inteferometry

Where does it come from?

- Atmospheric distortion causes the image of a star to be broken into ‘speckles’
- Very short exposures (less than 0.1 sec) can ‘freeze’ these - similar approach to ‘Lucky Imaging’
- The **speckles contain detailed information about the star at the diffraction limit**, which can be extracted by Fourier processing and adding together data from many exposures (up to thousands)
- The technique was developed in the 1970s by Labeyrie and other professionals (e.g. Kitt Peak). It is now also commonly used by amateurs with apertures down to 20 cm diameter.

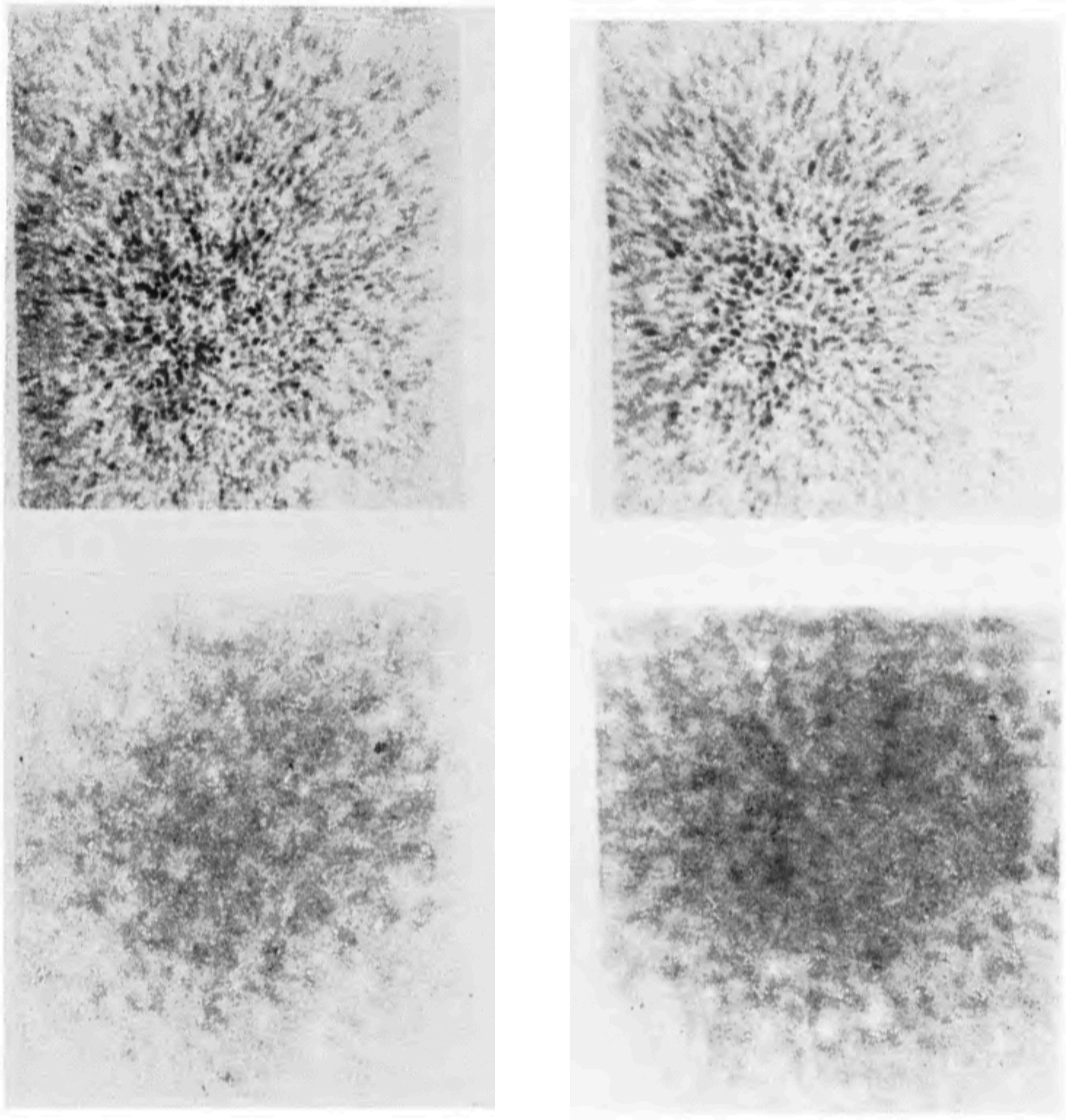
Technique

What it is and how it is used

- Use of speckle interferometry can image large stars directly, when they are above the diffraction limit of a large telescope

- The most important application is to resolve very close binary stars - accurate separation and P.A. measurement is possible.

- A large part of the WDS catalog is now improved with speckle observations by both professionals and amateurs

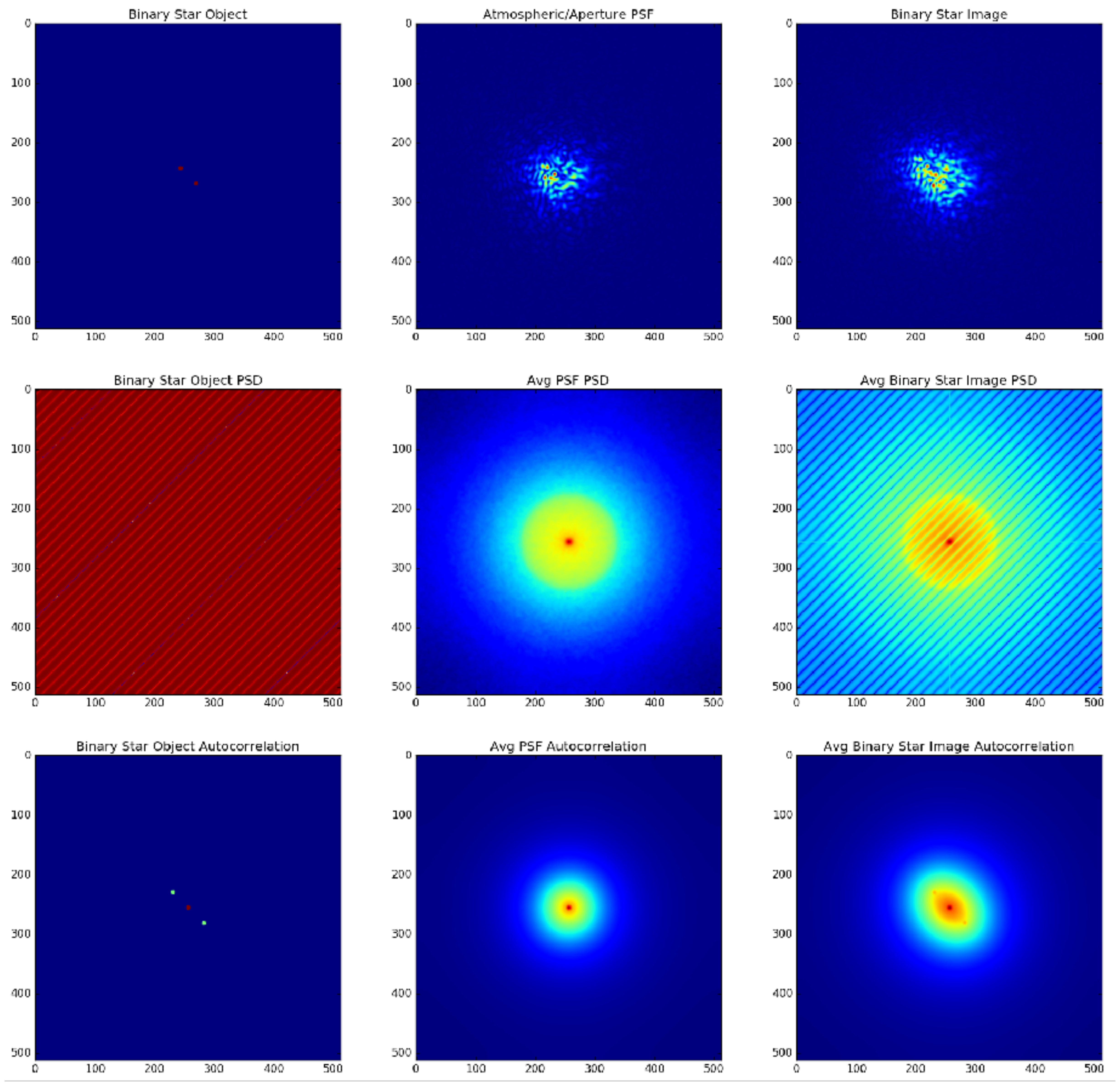


Early results from 1970s, taken with Palomar 200 -inch telescope (Gezari, et.al.)

Fourier 2D Power spectra (optically generated from film)

(Small diameters indicate larger features)

Early results from 1970s, taken with Palomar 200 -inch telescope (Gezari, et.al.)



Simulated results (Smidth,2016)

Results taken with a 1.2 m telescope + QHY cameras, (2-10msec exp.)

pair	RA & Dec	mags	PA	rho	date	delta PA	delta rho
STF 10 AB	00148 +6250	8.04 8.55	175.70	17.550	2022.164	-0.2	+0.01
STF 79	01001 +4443	6.04 6.77	194.60	7.890	2022.339	+0.8	+0.015
STT 21 /3/	01030 +4723	6.76 8.07	175.15	1.364	2022.164	+0.1	+0.02
STT 34 AB /4/	01499 +8053	7.58 8.12	294.43	0.526	2022.167	-11	+0.18
STF 180 AB	01535 +1918	4.52 4.58	0.48	7.334	2022.164	-0.4	-0.009
BU 525 /2/	02589 +2137	7.47 7.45	275.2	0.544	2022.164	-2.0	~0
STF 333 AB /5/	02592 +2120	5.17 5.57	210.07	1.348	2022.164	-0.2	+0.04
STT 65 /2/	03503 +2535	5.73 6.52	204.1	0.558	2022.167	+1.0	-0.03
STF 479 AB	04009 +2312	6.92 7.76	126.62	7.522	2022.167	~0	~+0.34?

Typical Speckle Results - close double stars

- Anton, Ohlert (2022)

Extension

What can we do for occultations?

- Speckle observing has not been attempted for asteroids (as far as I know). Ceres, Vesta, or a bright close NEO may be able to resolved(?)
- For amateurs, it could also be applied before and after occultations under the following conditions:
  - **Long focal length** (high plate scale)
  - Very short exposure times (typ < 50 msec), so **only bright stars and asteroids**
  - Many observations need to be averaged, so a **slow-moving object** is preferred
  - **It may be possible to detemine if a miss has happened**, and which side of the path the observer is located. Precision to 0.1 arcsec is possible, depending on brightness
  - Bright Appulses and short shallow events **also** could now be observable as well!
- Speckle observation quality will vary with weather conditions and location. This is more important because the lower turbulence levels have more impact.

Summary

Summary

What can we do for occultations?

- **Causes of scintillation** are well-known and understood, however there are large variations from site to site and weather conditions

- **Effects and measurement** is also well-documented, mostly for professional sites. As yet, few amateurs are able to monitor their local conditions

- **Mitigation** may be possible with multiple small apertures. However for short exposure regime (e.g. video) the results are unclear. More observations, specifically from private observatories (non-professional locations) could clarify theory

- **For occultations**, theory suggests that bright stars and longer exposures benefit from mitigation. This will not help with fainter stars but could help resolve shallow events involving brighter targets in poor seeing conditions.

Bibliography

Academic publications on the topic of Scintillation and Multiple apertures

- Dravins, D., Lindegren, L., Mezey, E., Young A. T. (1997) *Atmospheric Intensity Scintillation of Stars* PASP 109, p173
- O'Brien,S., Bayliss, D. et al. (2022) *Scintillation-limited photometry with the 20-cm NGTS telescopes at Paranal Observatory* MNRAS, **509**, (2022), 6111-6118
- Hartley, K.E.; Farley, O. et al. (2023) *Optical sparse telescope arrays and scintillation noise* MNRAS **526** p.1235
- Abraham, R.G.; van Dokkum, P.G. et al. (2022) *Distributed Aperture Telescopes and the Dragonfly Telephoto Array* in Proc. SPIE 12182, *Ground-based and Airborne Telescopes IX*
- Osborn et al. (2010) MNRAS **406** p.1405
- Osborn, J. ; Föhring, D. et al. (2015) *Atmospheric scintillation in astronomical photometry* MNRAS **452** p.1707

Bibliography

Academic publications on the topic of Speckle Interferometry

- Labeyrie, A. (1970) Astron. & Astrophys, Vol. 6, p85 - 87
- Gezari, Labeyrie & Stachnik (1972), Astrophys. J. , Vol 173
- McAlister (1976), PASP, Vol. 88, p 317-322
- Caloi (2008) J. Double Star Observ. (JDSO) V 4 Nr 3
- Harshaw, Rowe & Genet (2017) JDSO V. 13 Nr. 1.
- Smidth, N.C. (2016) MSc Thesis, Cal Tech (San Luis Obispo)
- Anton, R. & Ohlert, J.M. (2022) JDSO V. 19, Nr. 2

Thank You

Web sources

JDSO.org Journal of Double Star Observation

Washington Double Star Catalog
http://www.astro.gsu.edu/wds/wdstext.html#files

Note that the Dragonfly project is using Citizen Science for searches of transits in its data:
Planet Hunters NGTS https://ngts.planethunters.org via Zooniverse