

地上観測の限界と Solar-C光学磁場望遠鏡

Detection limits in solar observations;
Synergy of ground-based observations
and Solar-C

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概要

次期太陽観測衛星Solar-Cに搭載する光学磁場診断望遠鏡(SUVIT)は、1.4mの口径で宇宙から光球・彩層の高解像度撮像および高精度偏光分光観測を行い、太陽プラズマ現象の温度、速度、磁場等の物理量を計測する。一方、地上では現在口径1~1.6mクラスの太陽望遠鏡が稼働を始め、補償光学装置(AO)や画像回復処理技術の進歩にともなって、その回折限界分解能を達成することが、短時間であるにせよ、可能になってきた。これによって太陽大気には0.1秒角(約70km)の対流や彩層密度構造の存在が明らかとなり、ひのでの回折限界を超えた微小スケールでの太陽プラズマ構造が今後の太陽物理学の重要な研究対象となっている。2020年頃にはさらに口径4mの大型望遠鏡(DKIST)がハワイで稼働を開始する予定であり、そこで得られる回折限界画像の空間分解能はSUVITのそれを上回るであろう。

SUVITの使命は0.1秒角の分解能を維持しながら、広い視野に渡って 10^{-3} を超える精度の安定した偏光分光情報を取得することである。本ポスターでは、AOの波面補正能力の限界や画像回復処理における誤差伝搬をシミュレーションすることにより、地上観測で達成しうる制度限界について考察した。

1. Introduction

A goal of the next generation solar observations is

high resolution + high precision

(0.1'' + 3×10^{-4} ; target of SUVIT/Solar-C)

to understand fundamental plasma processes that generate

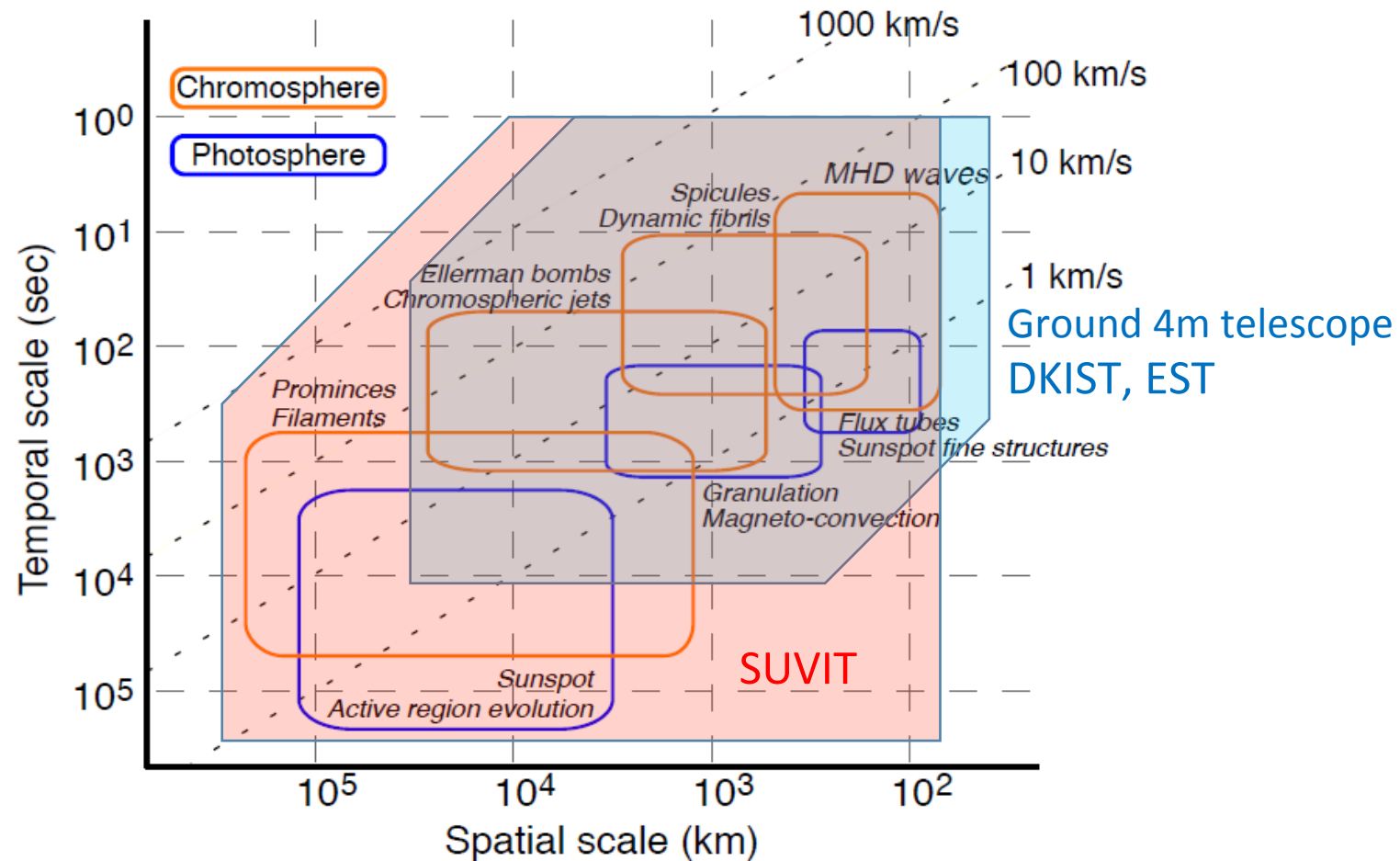
- The dynamic solar atmosphere
- Large scale eruptions
- Cyclic variation of solar magnetism

Spatial resolution in 2020 era @500nm;

ground based tel.	D = 0.5 -- 4m	0.2 ~ 0.026''
Solar-C SUVIT	D = ~ 1.4m	~0.08''

Product of spatial resolution, Δx , and photometric precision, δI , i.e., $\delta I \times \Delta x^2$ gives a measure of the 'detection limit' for elementary thermal /magnetic /kinetic energies.

Time scale vs. Spatial scale of observation targets



Large aperture ground-based telescopes meet the study of small & short-timescale targets in term of spatial resolution and time span.

Issue to be addressed in this poster

Questions:

- What is the ultimate detection limit achievable by ground and space telescopes?
- What is the uniqueness of SUVIT and what is the synergy with large ground telescopes in the study of small & short-timescale targets?

We discuss the 'Detection limit' ($\delta I \times \Delta x^2$) for space and ground observation by evaluating the photon noise and seeing noise.

2. Photon noise (Limit of space telescope)

of detected photons / resolution element [dimensionless]

$$n_{\lambda} = I_{\lambda} A T a \Delta\lambda \Delta t / hc \sim \pi/4 hc I_{\lambda} T \lambda^3 \Delta\lambda \Delta t$$

I_{λ} : solar spectrum intensity [erg/cm²/sec/str/nm]

$= I_{\lambda,c} \cdot d$, $I_{\lambda,c}$: continuum spect: line depression (~0.2 for H α)

A : aperture area of telescope $= \pi(D/2)^2$ [cm²]

D : telescope diameter [cm]

T : throughput (central obsc., optics transmission, sensor QE)

a : area of resolution element $= (\lambda/D)^2$ [str]

$\lambda, \Delta\lambda$: wavelength and wavelength resolution [cm and nm]

Δt : exposure time [sec]

Photometric accuracy

$$\delta I_{\lambda} / I_{\lambda} = \delta n_{\lambda} / n_{\lambda} = n_{\lambda}^{-1/2}$$

Photon noise

Sensitivity to intensity variation [erg/cm²/str/nm/sec]

$$\delta I_{\lambda} = I_{\lambda} n_{\lambda}^{-1/2}$$

Sensitivity to flux variation in resolution element [erg/nm/sec]

$$f_{\lambda} = 2\pi \delta I_{\lambda} (\Delta x)^2 = 2\pi I_{\lambda} n_{\lambda}^{-1/2} (\Delta x)^2$$

$$\Delta x: \text{size of resolution elem.} = 1.5 \cdot 10^{-13} \cdot \lambda / D \quad [\text{cm}]$$

Radiated energy associated with the flux variation [erg]

$$\epsilon_{\lambda} = f_{\lambda} \Delta \lambda \Delta t$$

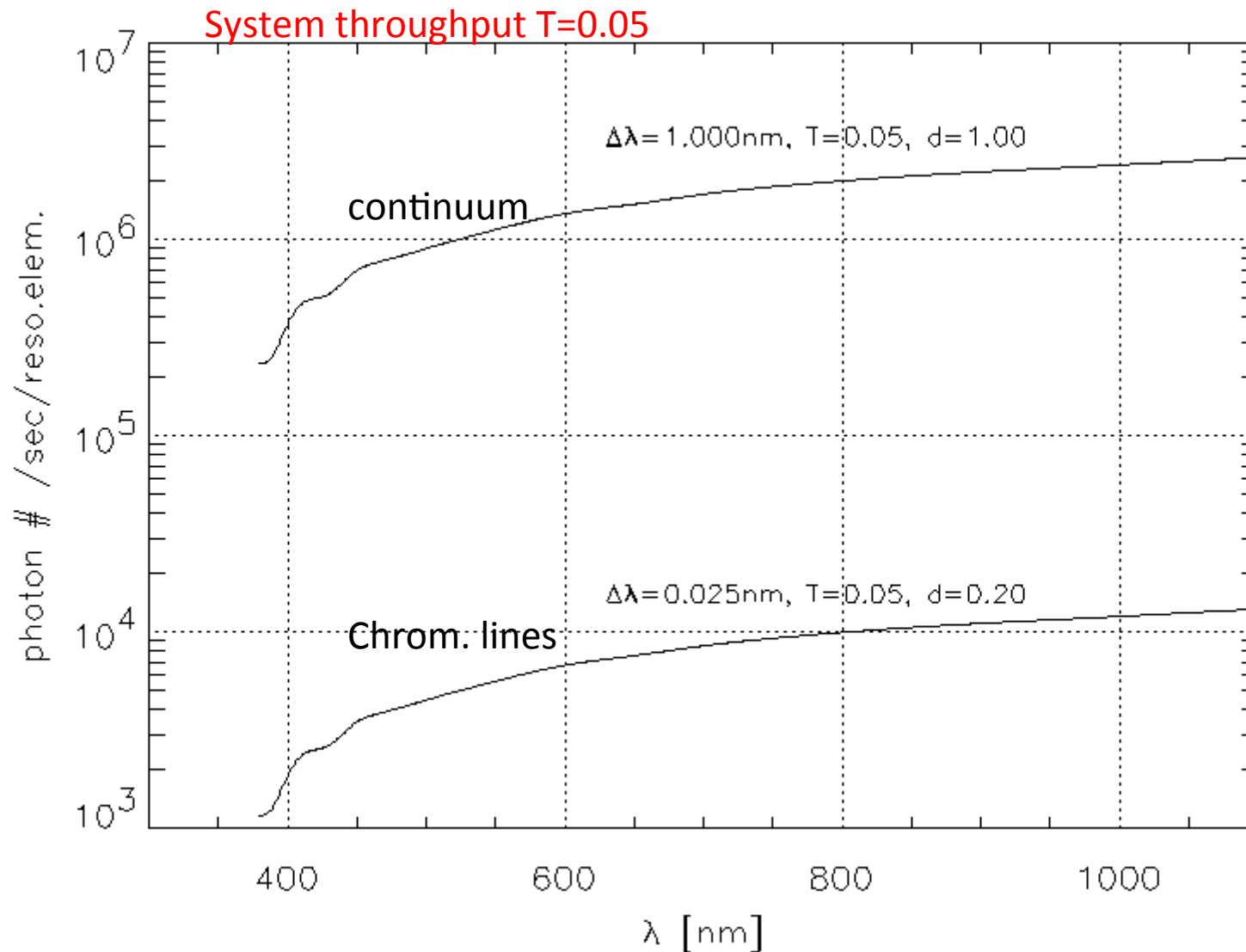
$\Delta \lambda \sim 1\text{nm}$; effective λ -range of chromospheric emissions

$\Delta t = \Delta t$; life time of events

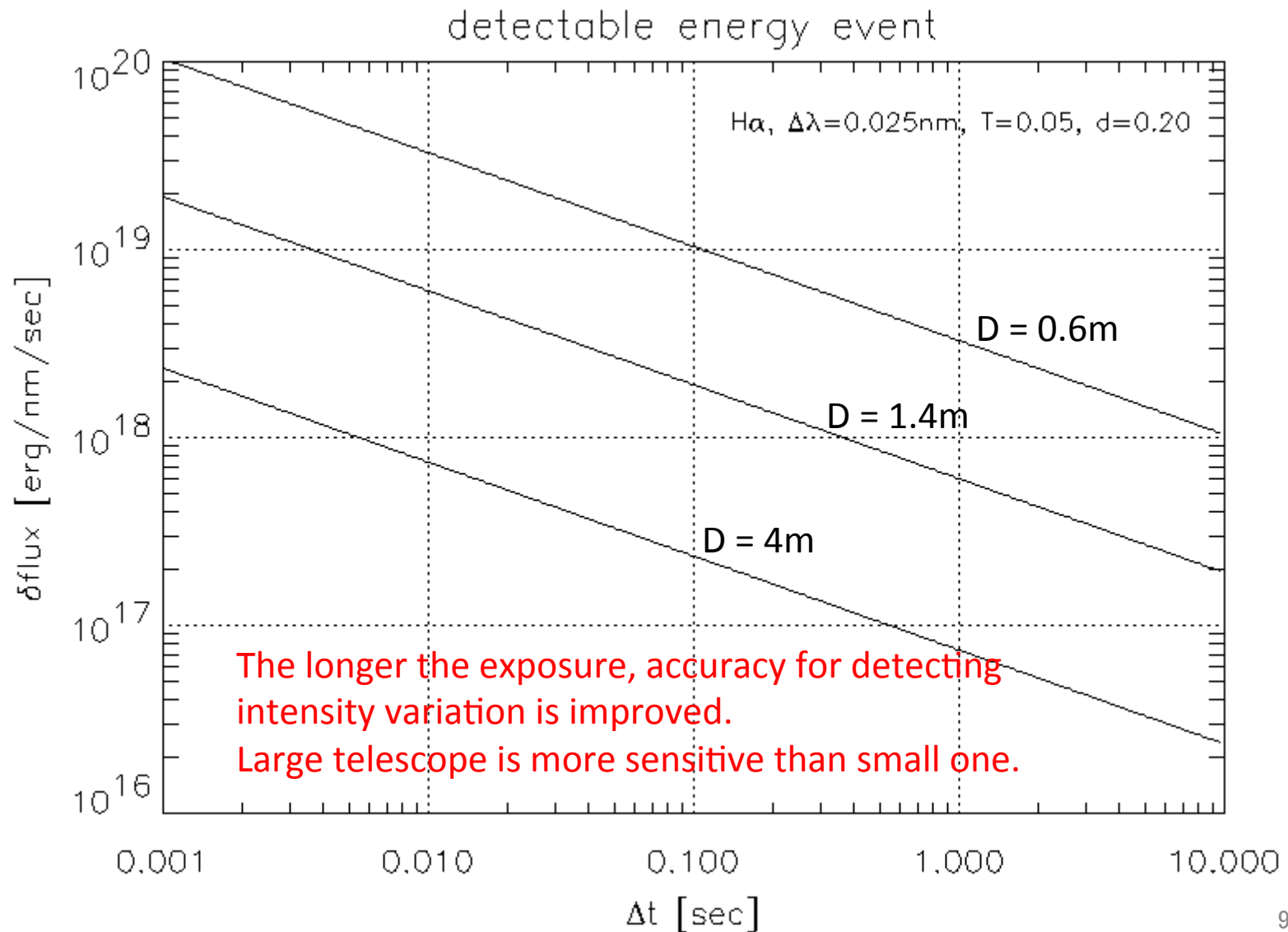
Reasonable choice for filter width in chrom. obs: $\Delta \lambda \sim 0.025\text{nm}$

Detectable photons in resolution element

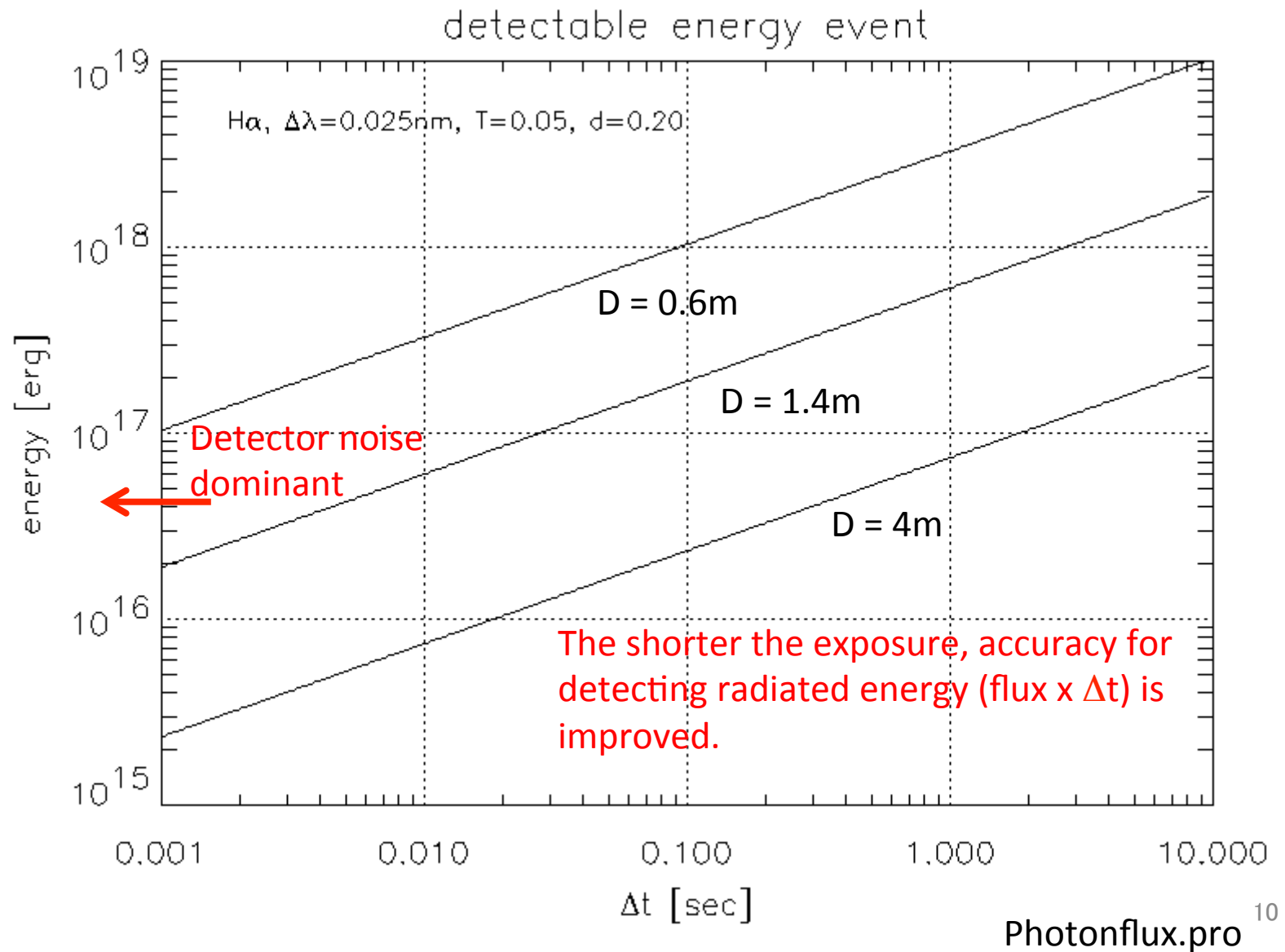
independent on telescope diameter



Detectable flux change ($\delta I_{\lambda} \times D \times 2$) with H α 1/4A filter



Detectable energy ($\delta I \Delta \lambda \times \Delta t$) with H α 1/4A filter



2. Seeing noise

Seeing is simulated by using a 'Kolmogorov phase screen'

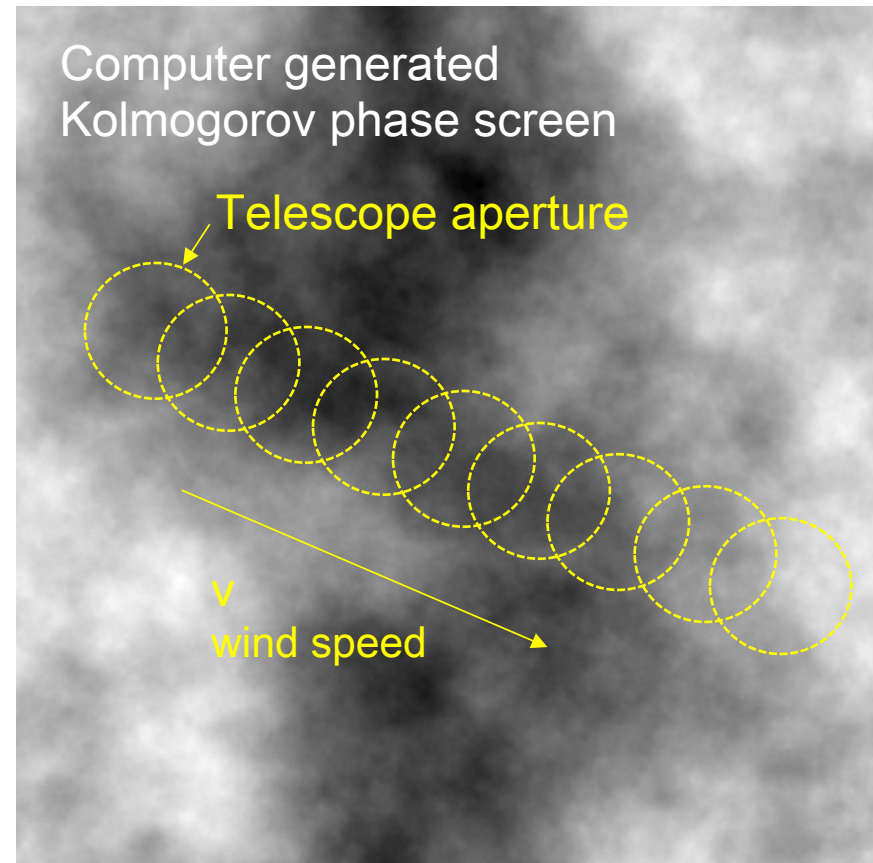
Power spectral density of wavefront error, Φ , is given by

$$\Phi(\kappa) = 0.023 r_0^{-5/3} \kappa^{-11/3} \quad [\text{rad}^2 / (\text{d}\kappa)^2, \text{ex. cm}^2]$$

where r_0 : Fried param. [cm]
 κ : spatial freq., [cm⁻¹]

Instantaneous wavefront error in the pupil of telescope (pupil function) is given by a window on the phase screen that moves across it by a wind speed, v .
(Taylor's frozen hypothesis)

Thus, property of seeing is specified by two parameters, r_0 and v .

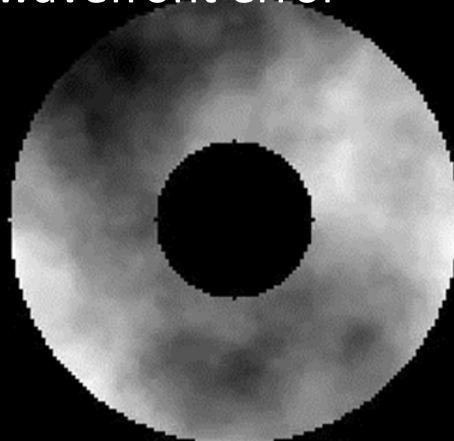


Seeing simulation ($D=60\text{cm}$, $v=10\text{m/s}$)

example

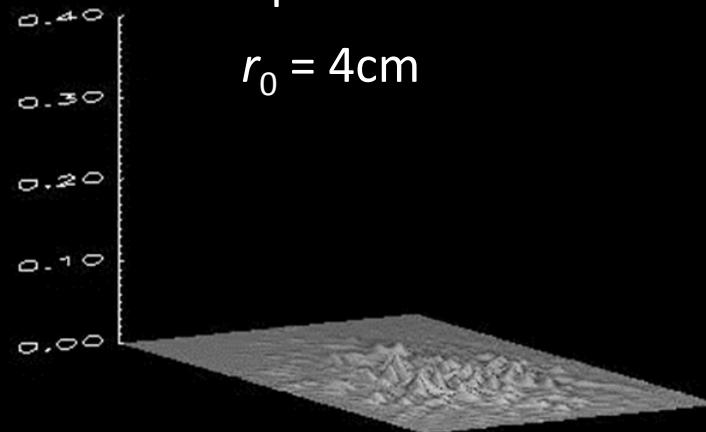
$r_0 = 4.0\text{cm}$, $D = 60\text{cm}$, $V_w = 10\text{m/s}$, $t = 0000\text{ms}$

wavefront error



0.78λ rms (tilt removed)

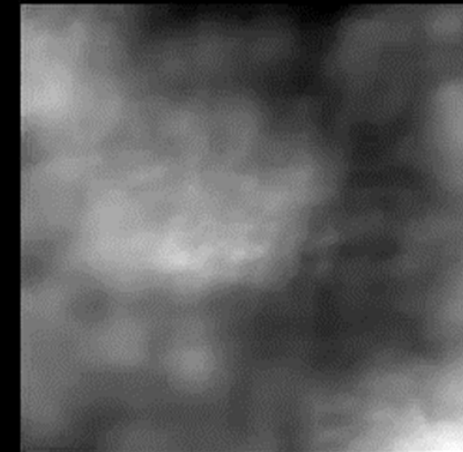
Point spread func.



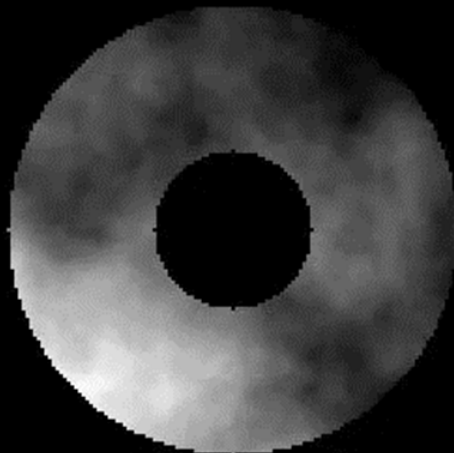
$r_0 = 4\text{cm}$

original: Hinode G-band

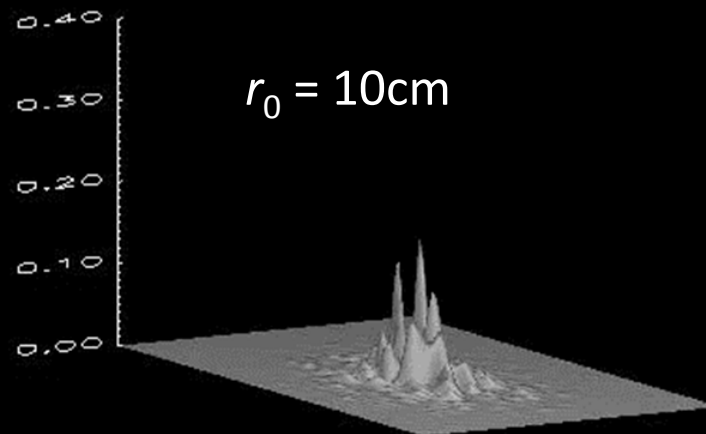
Degraded image



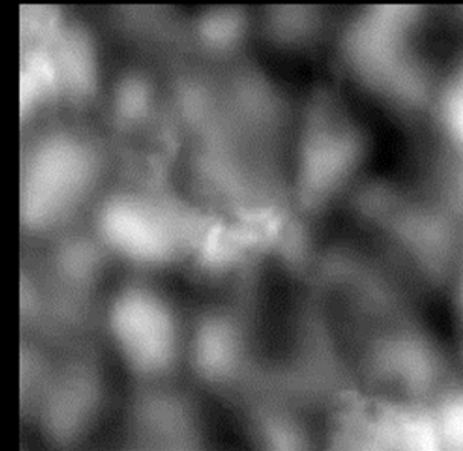
$r_0 = 10.0\text{cm}$, $D = 60\text{cm}$, $V_w = 10\text{m/s}$, $t = 0000\text{ms}$



0.28λ rms (tilt removed)

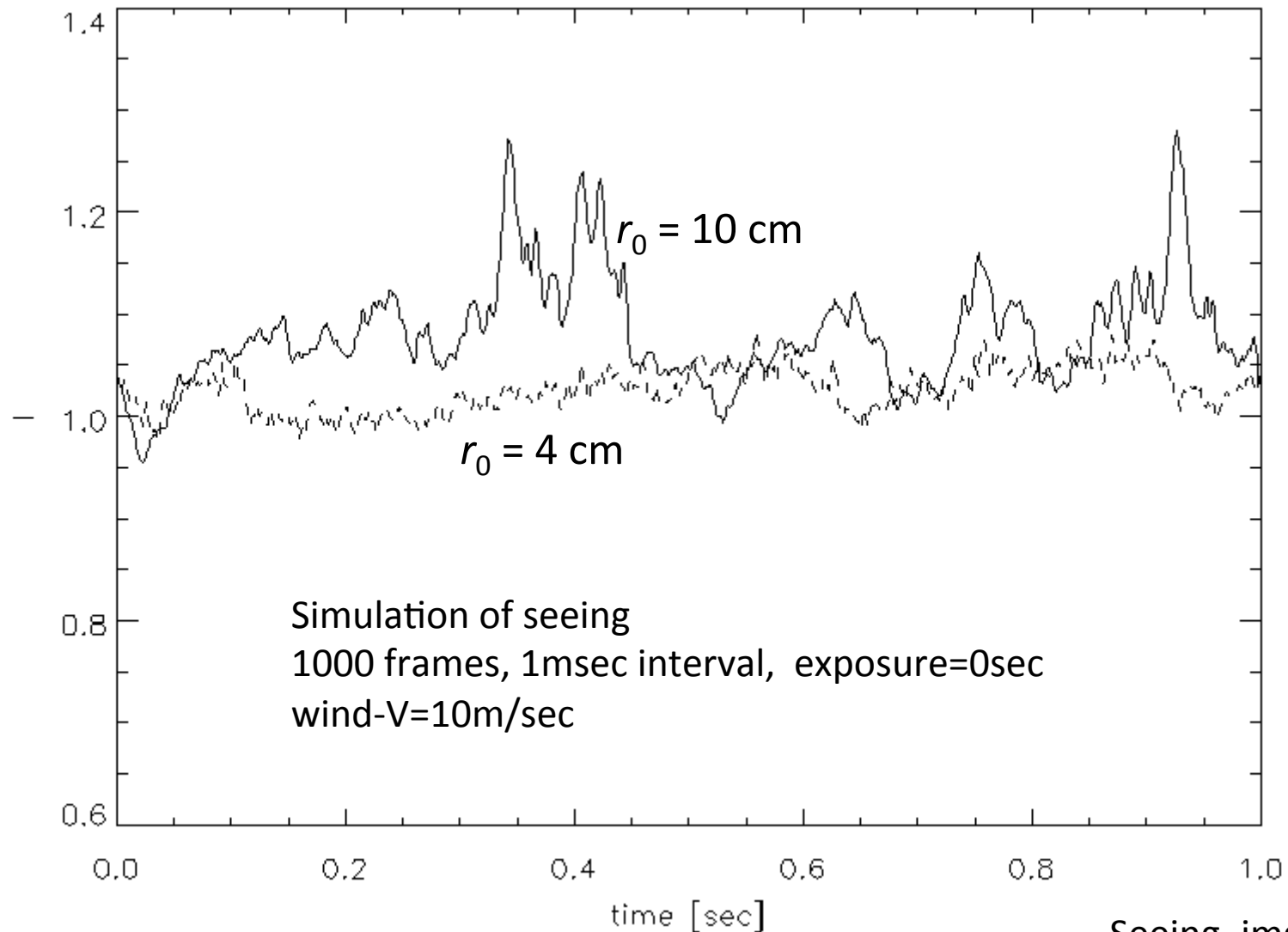


$r_0 = 10\text{cm}$

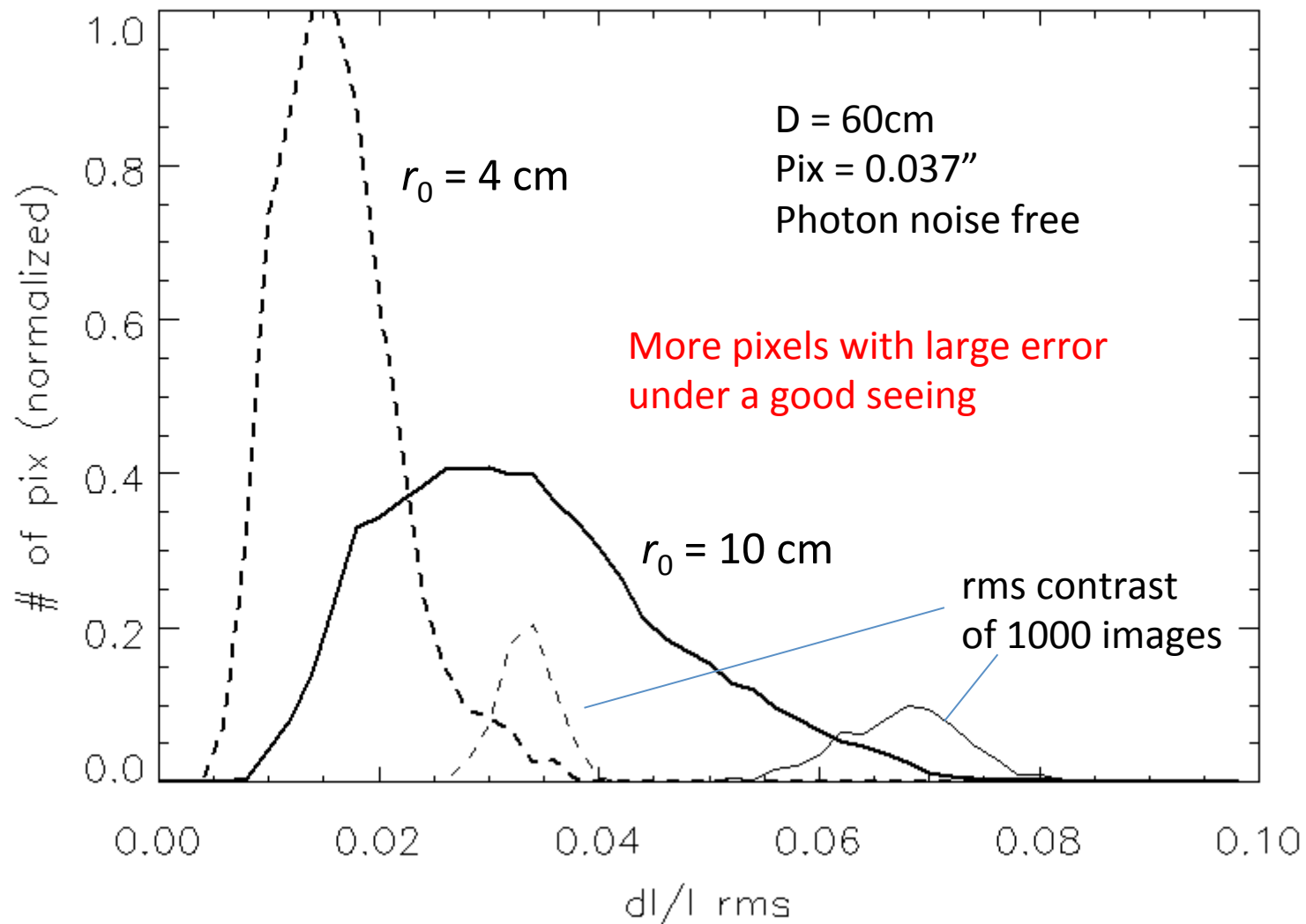


Seeing noise

Intensity profile of central bright point (sun is stationary)

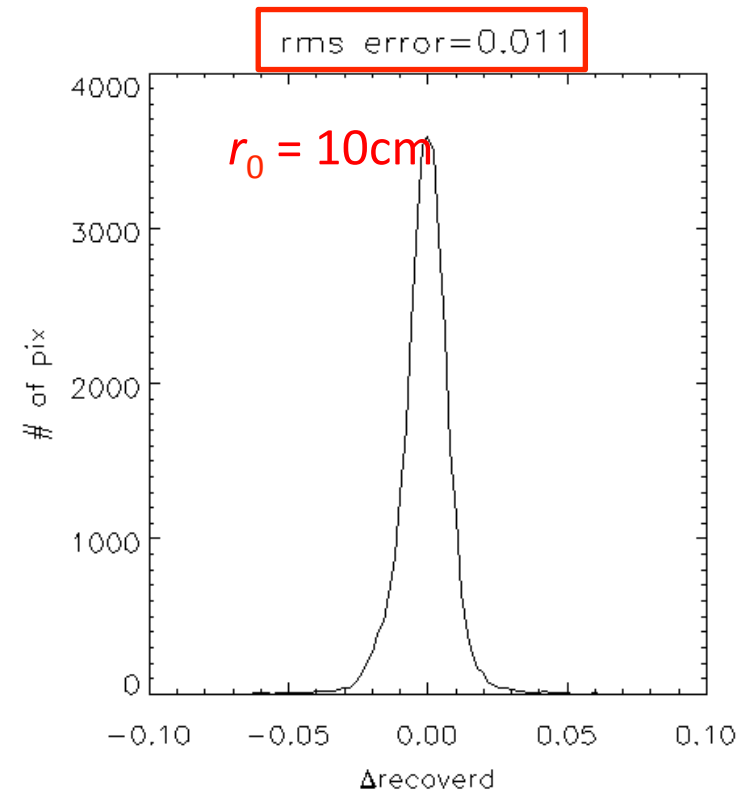
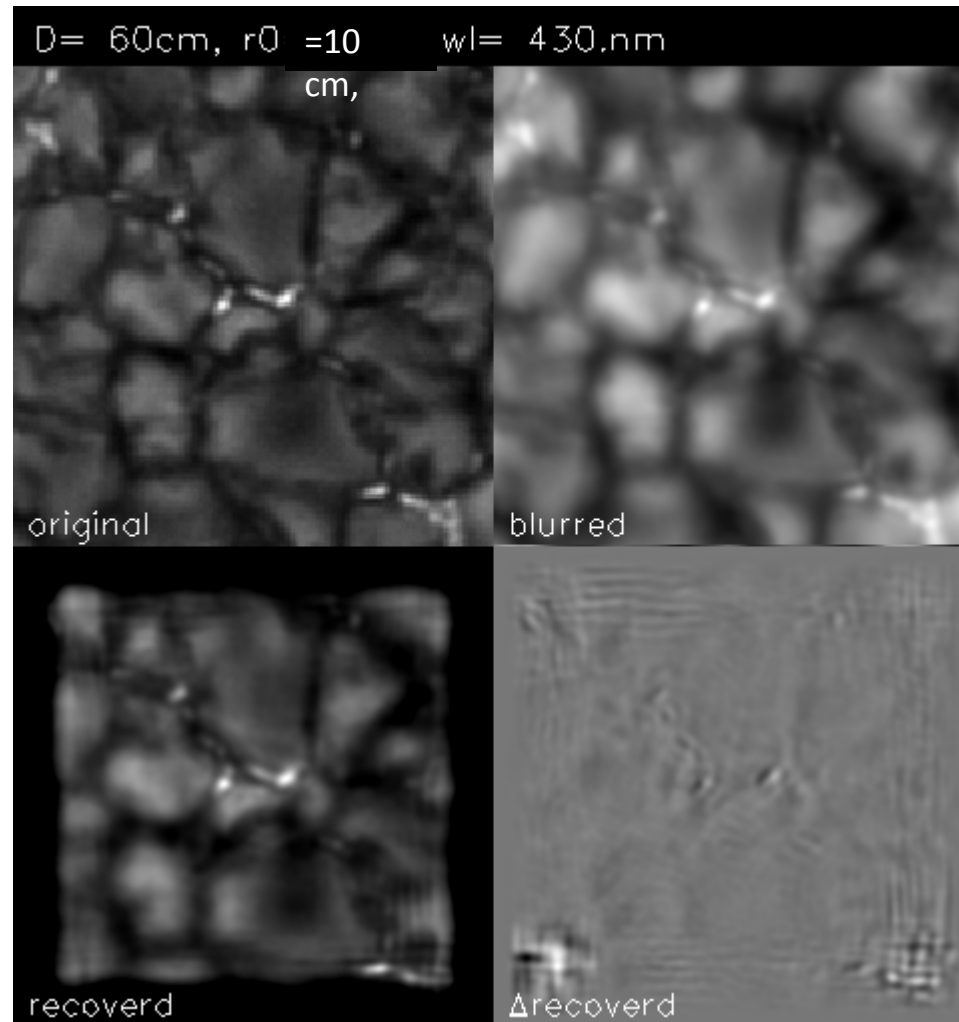


Seeing noise; histogram of rms error



3. Improvement by image reconstruction

We examine reduction of seeing noise by speckle masking image reconstruction.

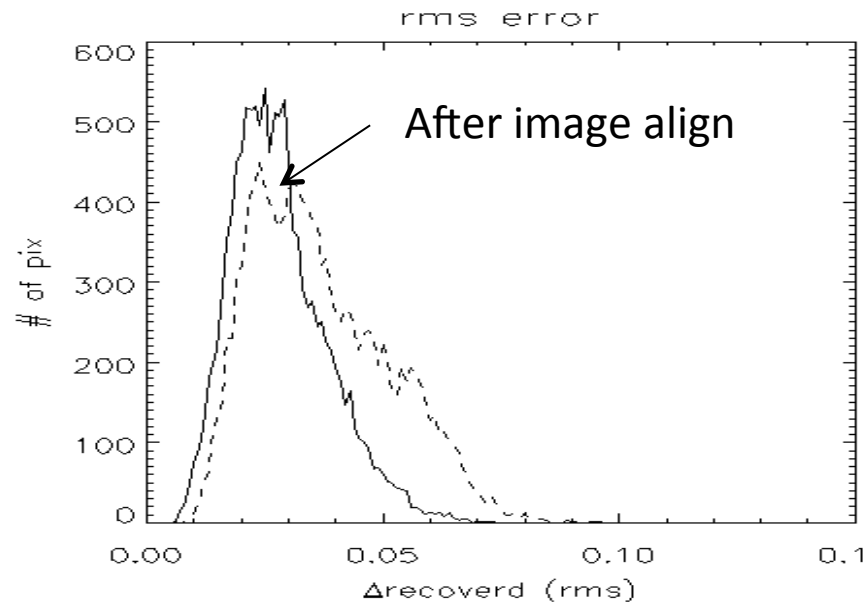


Difference of two reconstructed images using different sets of 100 frames out of 1000 frame,
Set-1 – frame# = [0,10,20,,,990]
Set-2 – frame# = [5,15,25,,,995]

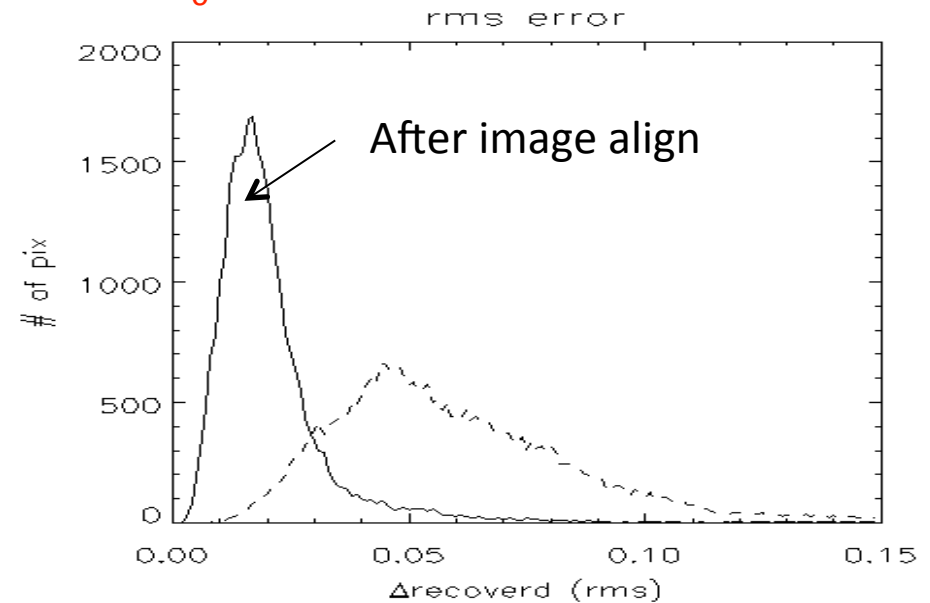
Seeing noise after image reconstruction

Use 50 frames in every 0.1sec, rms error among 10 reconstructed images

$r_0 = 4$ cm



$r_0 = 10$ cm

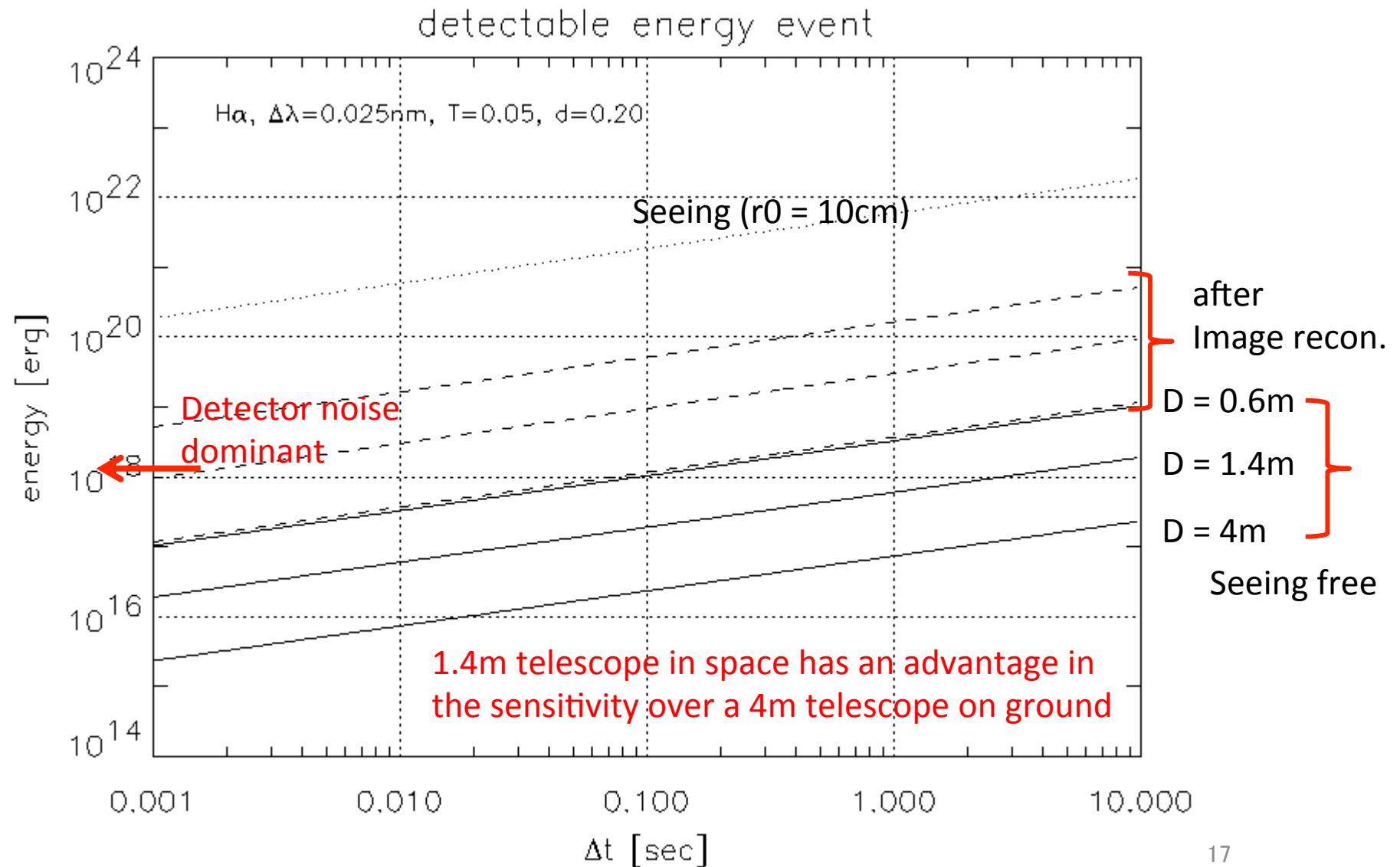


Noise after image reconstruction

$\delta I/I = 0.01 \sim 0.05$ under a good seeing

Speckle masking does improve the spatial resolution close to the diffraction limit, but it does not help much for the high precision photometry aiming for $\delta I/I \sim 0.0001 - 0.001$.

Detectable energy with H α 1/4A filter



4. Effect of adaptive optics

AO is not a perfect system. Its residual wavefront error is given,,

Narrow bandwidth $\sigma_{BW}^2 = (f_g / f_s)^{5/3}$ [rad²]

Pure time delay $\sigma_{TD}^2 = 28.4 (\tau_s f_g)^{5/3}$

WF fitting error $\sigma_F^2 = 0.28 (d/r_0)^{5/3}$

$f_g = 0.427 v / r_0$ Greenwood freq. (v: wind speed)

f_s : system cutoff freq. (~70Hz)

τ_s : time delay [sec]

r_0 : Fried's param. [cm]

d : size of DM element on pupil [cm]

Anisoplanatism $\sigma_A^2 = (\theta / \theta_0)^{5/3}$, θ : angle from guide target

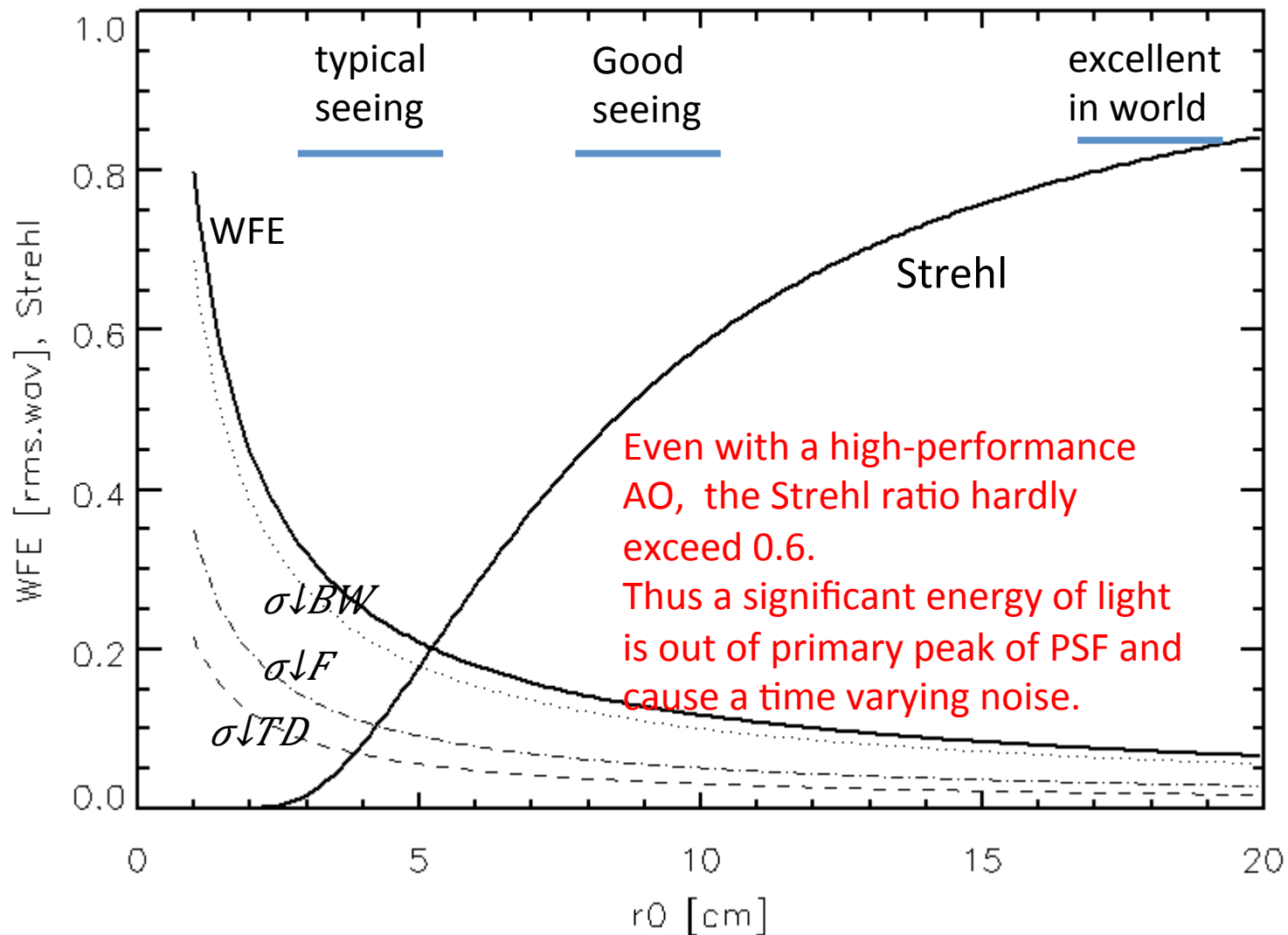
$\theta_0 = 0.314 r_0 / h (\lambda / \lambda_0)^{6/5} \cos^{18/5}(\zeta)$ isoplanatic angle

$\lambda_0 = 500$ nm, $h \sim 1500$ km (typ.)

AO residual wavefront error

Hida DST; Good performance AO

$v_{\text{wind}} = 10 \text{ m/sec}$, $d = 5.5 \text{ cm}$, $f_s = 74.0 \text{ Hz}$

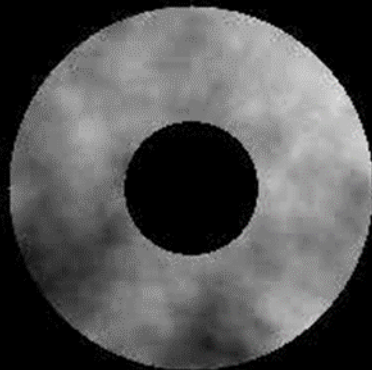


AO simulation (by Dr. N. Miura)

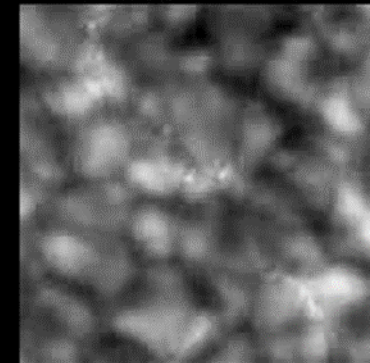
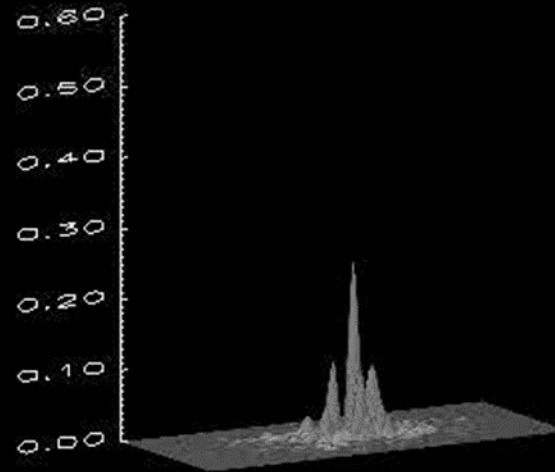
Recovery of wavefront error is simulated using an AO model.

$r_0 = 9.6\text{cm}$, $D = 60\text{cm}$, $V_w = 10 \text{ \& } 20\text{m/s}$, $t = 0000\text{ms}$

AO-off

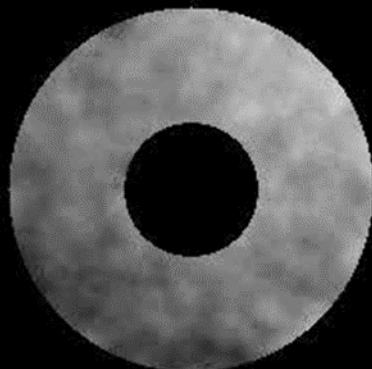


0.316λ rms

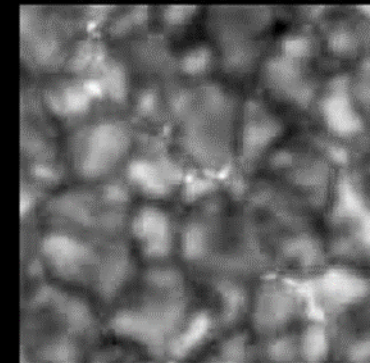
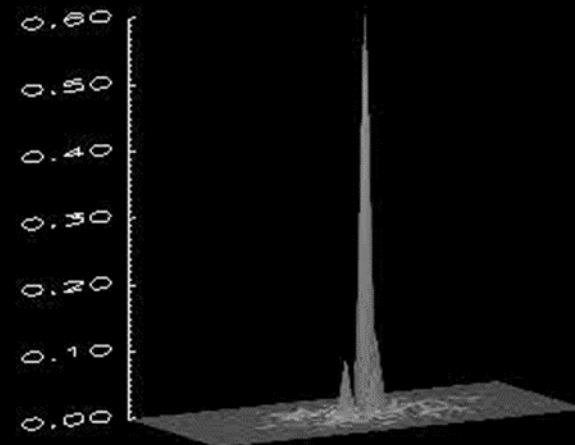


Time delay = 1msec
97 elem. Deformable mirror
 ϕ 60cm telescope

AO-on

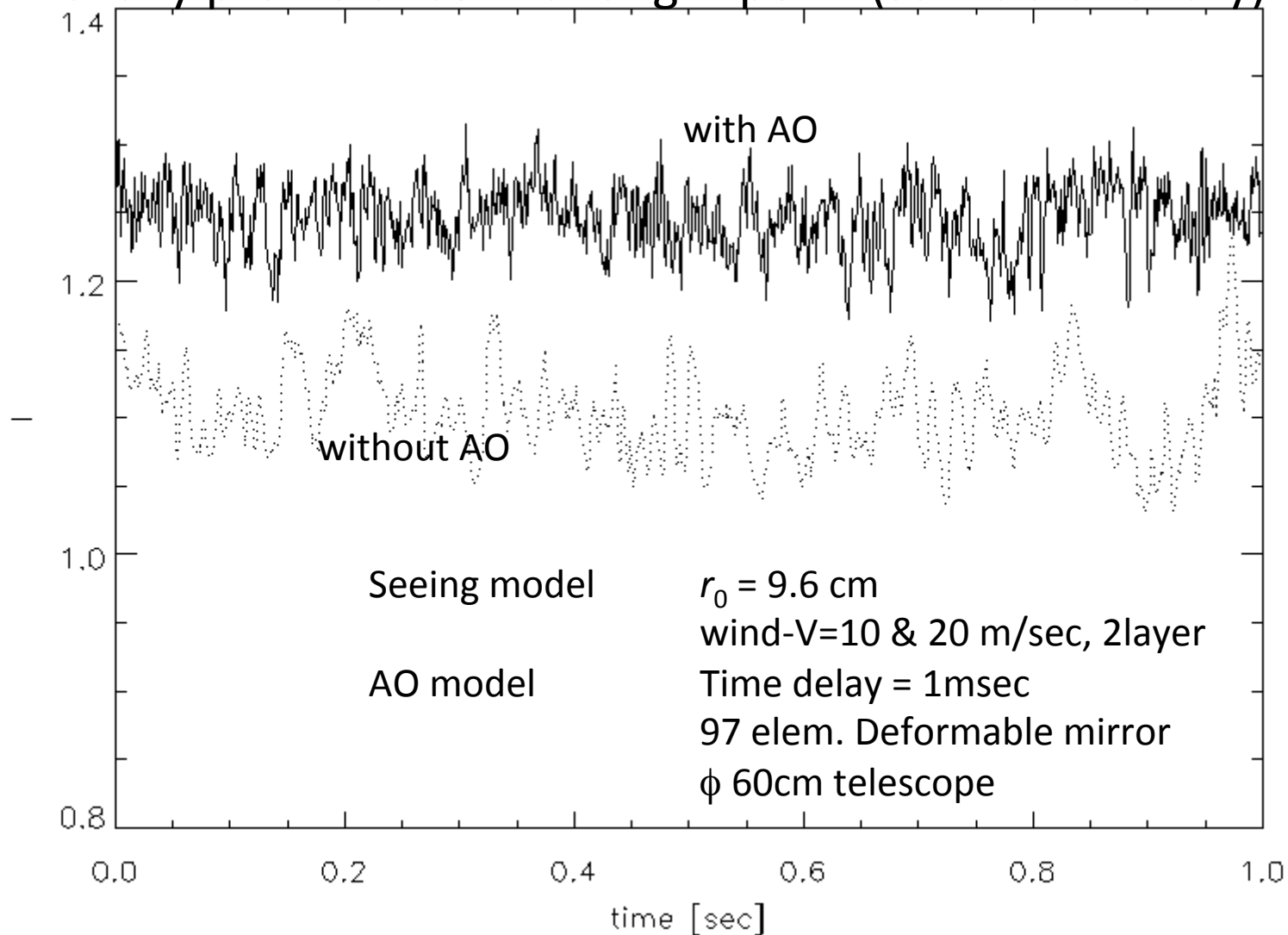


0.284λ rms

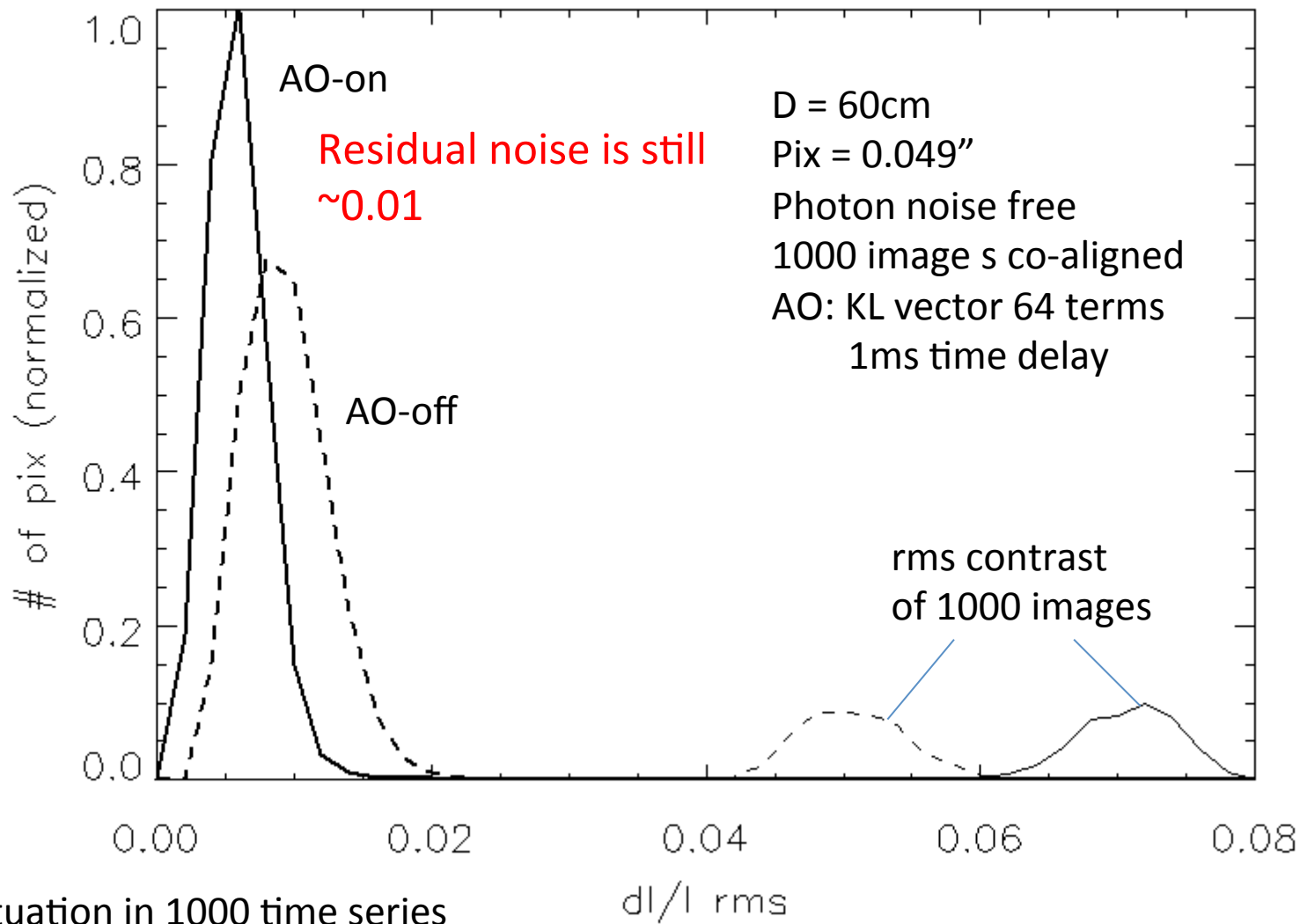


Seeing noise with/without AO correction.

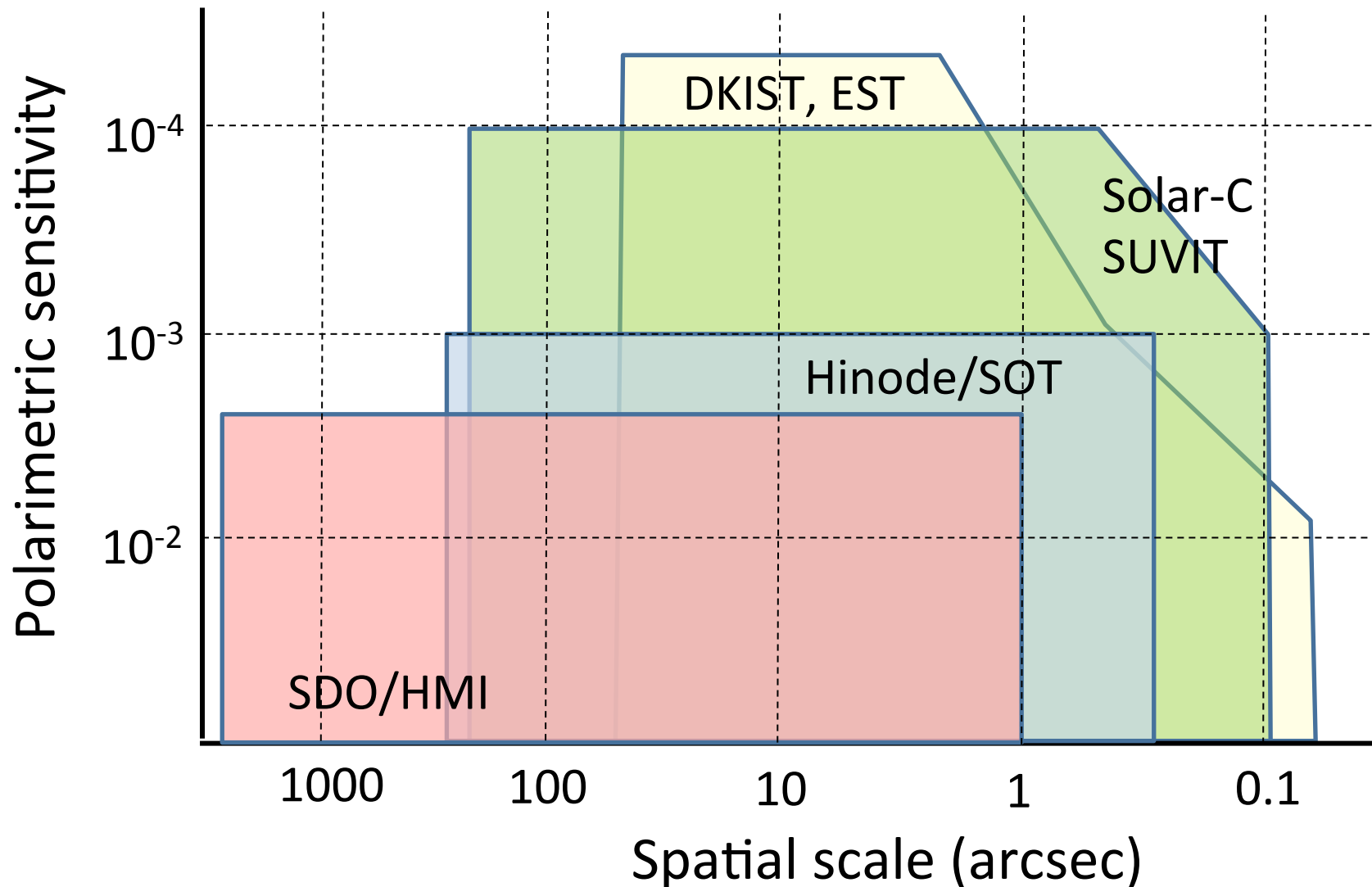
Intensity profile of central bright point (sun is stationary)



Seeing noise after AO correction.



Prospected photometric accuracy vs. spatial scale (not fully justified)



Summary

- We performed a simulation of noise under seeing to evaluate the detection limit [(photometric accuracy) x (area of resolution element)²] of ground based and space observations.
- Image reconstruction (spackle masking) and adaptive optics do improve the spatial resolution close to the diffraction limit, but residual noise (0.01~0.05) after the correction is still far larger than $dI/I \sim 0.0001 - 0.001$.
- 1.4m telescope in space has an advantage in the polarimetric sensitivity over the DKISP, while DKISP will obtain highest spatial resolution for a few hours of period.
- Simulation was performed only for $\phi 60\text{cm}$ telescope. Need further realistic simulations.

Acknowledge: Dr. N. Miura for performing the AO simulation.