(Noll: residual error - 10)

Exercice 3: Find the (linear) number of sub-apertures (and actuators), considering a Fried configuration, corresponding to a fitting-error-only Strehl ratio in J of 30% [D=8m, r0@500nm=12cm].

-> For next session: solve this exercice !!
(IDL batch, and also function)

(Noll: residual error - 11)

Exo_batch.pro

```
; call with: IDL> @Exo1
Diam  =8.0
r0    =0.12
Strehl=0.3
band  =1.25E-6

r0_band=r0*(band/500E-9)^(6./5)
J=(-.2944/alog(Strehl)*(Diam/r0_band)^(5./3))^(2./sqrt(3))
N=(-3+sqrt(9+8*J))/2
if N ne floor(N) then N=floor(N)+1
; see result with: IDL> print, N
```

```
function Ncalc, Diam, r0, Strehl, band
; call with: IDL> N=Exo_function(Diam, r0, Strehl, band)

r0_band=r0*(band/500E-9)^(6./5)
J=(-.2944/alog(Strehl)*(Diam/r0_band)^(5./3))^(2./sqrt(3))
N=(-3+sqrt(9+8*J))/2
if N ne floor(N) then N=floor(N)+1

return, N-1
end
```

Post-AO error budget - 9

Aliasing error

$$\sigma^2_{\text{AO syst.}} = \sigma^2_{\text{fitt.}} + \sigma^2_{\text{meas.}} + \sigma^2_{\text{alias.}} + \sigma^2_{\text{temp.}} + \ldots$$

$$\sigma^2_{\text{alias.}} \propto \left(\frac{d}{r_0}\right)^{\frac{5}{3}}$$

$$\sigma^2_{alias.} \approx 0.17 \left(\frac{d}{r_0}\right)^{\frac{5}{3}}$$

Reduce the aliasing error <=> increase the number of sensing elements (Shack-Hartmann sub-apertures, pixels of the pyramid) within the WFS

Post-AO error budget - 10

Temporal error

$$\sigma^2_{\text{AO syst.}} = \sigma^2_{\text{fitt.}} + \sigma^2_{\text{meas.}} + \sigma^2_{\text{alias.}} + \sigma^2_{\text{temp.}} + \ldots$$

$$\sigma^2_{\text{temp.}} \propto \left(\frac{\Delta t_{\text{AO}}}{\tau_0} \right)^{\frac{5}{3}}$$

$$\sigma^2_{temp.} \approx \left(\frac{\Delta t_{AO}}{\tau_0} \right)^{\frac{5}{3}}$$

Reduce the temporal error <=> make a faster system (exposure time of the WFS, computing time for the wavefront reconstruction, actuating time for the DM)

Post-AO error budget - 11

Measurement error

$$\sigma^2_{\mathrm{AO\ \ syst.}} = \sigma^2_{\mathrm{fitt.}} + \sigma^2_{\mathrm{meas.}} + \sigma^2_{\mathrm{alias.}} + \sigma^2_{\mathrm{temp.}} + \ldots$$

$$\sigma^2_{\mathrm{mes.}} = \sigma^2_{\mathrm{phot.}} + \sigma^2_{\mathrm{RON}} + \ldots$$

The measurement error has many origins:

- **photon noise**
- **read-out noise (RON)**
- **dark-current noise**
- **sky background and possibly instrumental background**
- **in case of EMCCD: (almost) no RON but additional noises (exotic dark, « excess noise factor » => Gamma-distributed noise)**

Post-AO error budget - 12

Photon noise error term

$$\sigma^2_{\text{AO syst.}} = \sigma^2_{\text{fitt.}} + \sigma^2_{\text{meas.}} + \sigma^2_{\text{alias.}} + \sigma^2_{\text{temp.}} + \ldots$$

$$\sigma^2_{\text{mes.}} = \sigma^2_{\text{phot.}} + \sigma^2_{\text{RON}} + \ldots$$

$$\sigma^2_{\text{phot.}} \propto \frac{1}{N_{\text{phot.}}}$$

$$\sigma^2_{\text{phot.}} \propto \frac{1}{N_{\text{phot.}}\, r_0^2\, \tau_0}, \quad \tau_0 \propto r_0$$

(with N_{phot}=number of photons/exposure time/subaperture)

Reduce the photon noise error term <=>

1- reduce the number of WFS elements => increase the aliasing error !!

2- increase the exposure time => increase the temporal error !!

Post-AO error budget - 13

Read-out noise error term

$$\sigma^2_{\text{AO syst.}} = \sigma^2_{\text{fitt.}} + \sigma^2_{\text{meas.}} + \sigma^2_{\text{alias.}} + \sigma^2_{\text{temp.}} + \ldots$$

$$\sigma^2_{\text{mes.}} = \sigma^2_{\text{phot.}} + \sigma^2_{\text{RON}} + \ldots$$

$$\sigma^2_{\text{lect.}} \propto \frac{\sigma_e}{N^2_{\text{phot.}}}$$

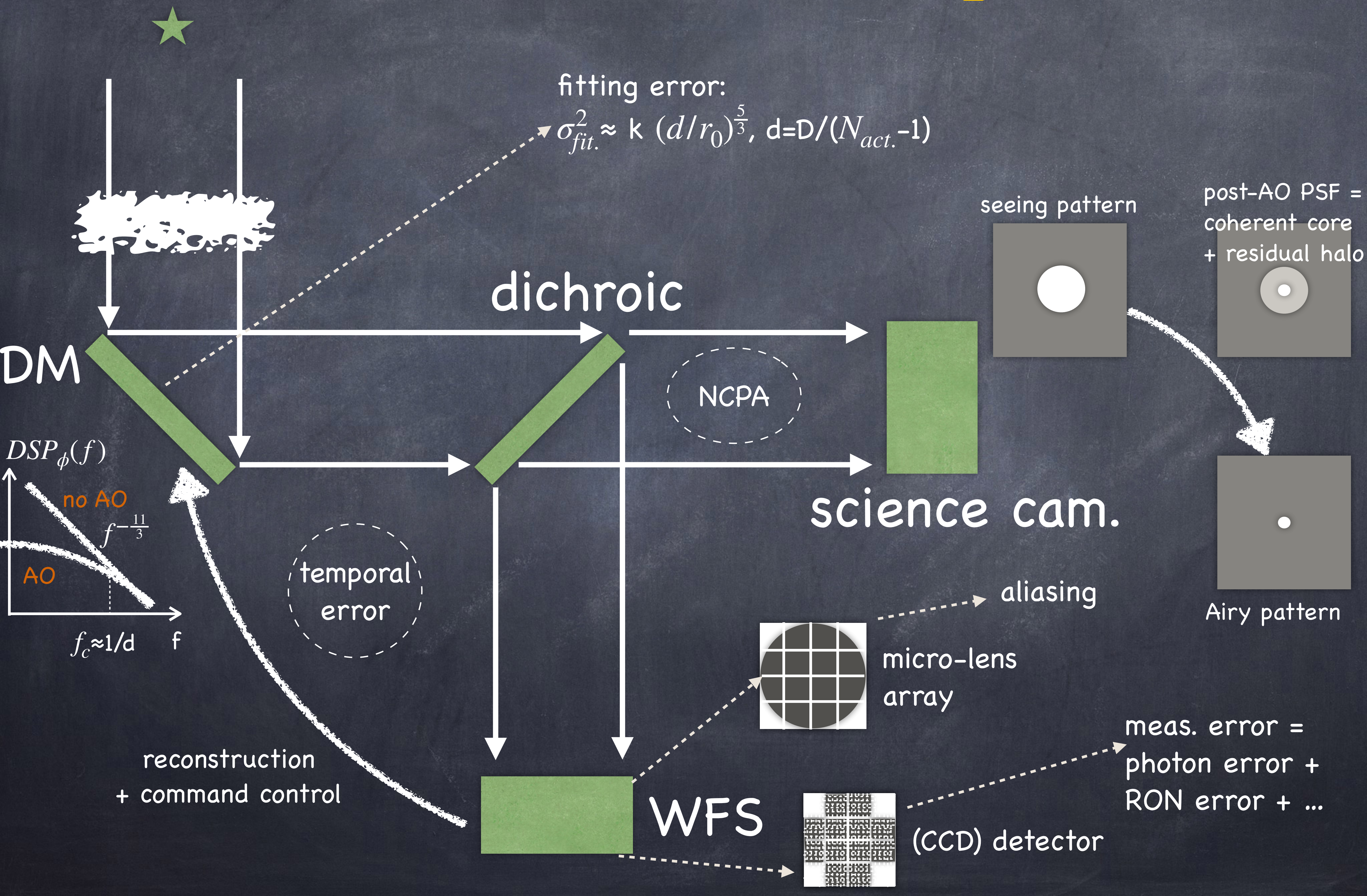
Reduce the RON error term <=>

1- reduce the number of WFS elements => increase the aliasing error !!

2- increase the exposure time => increase the temporal error !!

3- but also: reduce the impact of RON => use of EMCCDs…

Post-AO error budget - 14



Post-AO error budget - 15

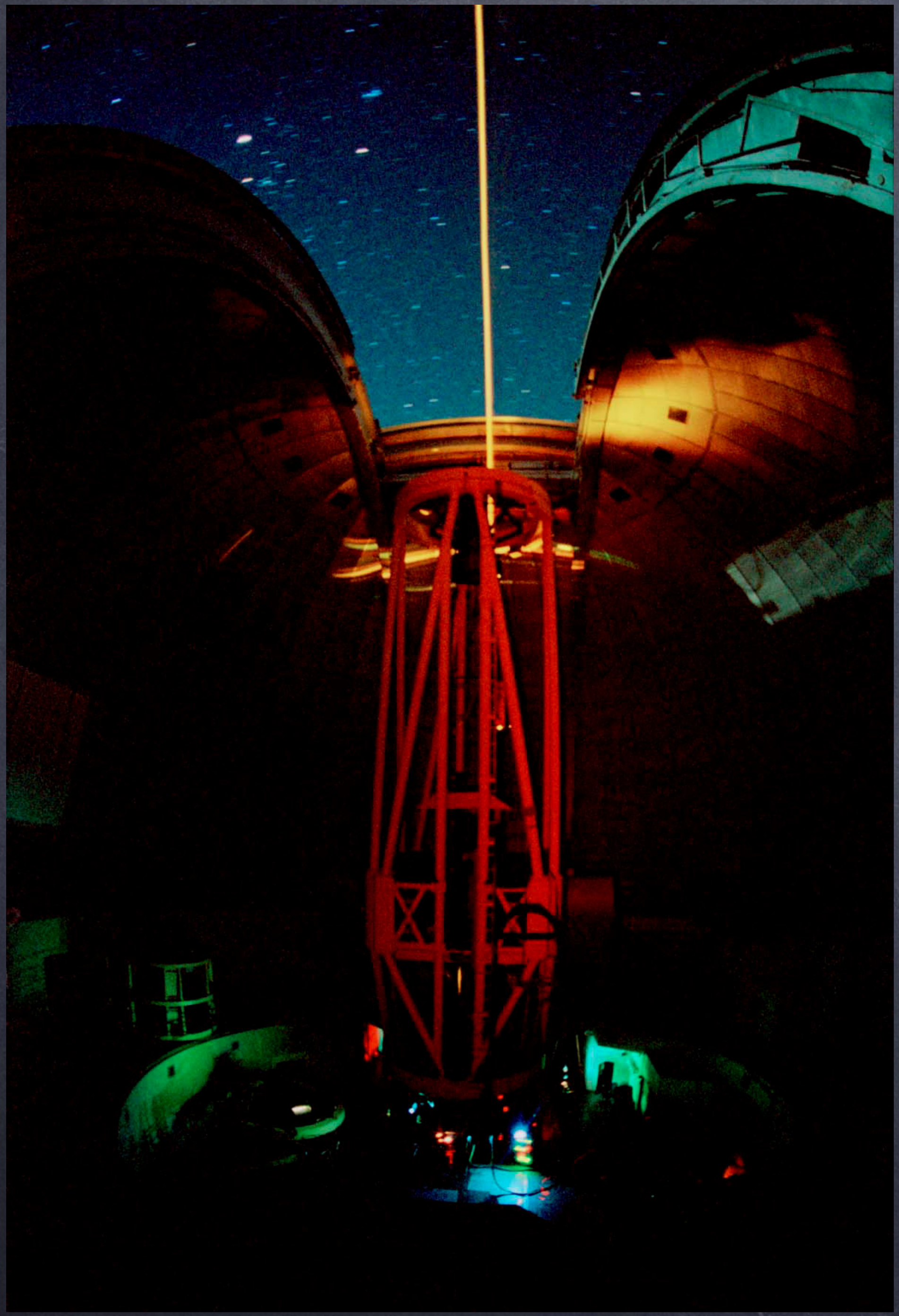
Generic case: observe as much sources as possible
Problem: most sources are (obviously!) too faint

1- find and use brighter NGS nearby…
=> anisoplanatic error !
=> use more than one brighter NGS nearby…
=> multi-reference AO system (GLAO, MCAO, MOAO)
=> yes, but: specific errors !
=> limited quality of correction

2- create a brighter source (LGS)
=> 100% sky coverage
=> yes, but here again: specific errors !
=> limited quality of correction

Laser Guide Star AO - 1

[Happer 1982, Foy & Labeyrie 1985]



(Keck Observatory)

+ https://www.youtube.com/watch?v=3BpT_tXYy_I

Laser Guide Star AO - 2

Specific LGS errors:

1- Cone effect (focus aniso.)
2- Tip-tilt indetermination
3- Perspective elongation

In addition (Na LGS case):
- Rayleigh backscattering until ~35km,
- variation of the Na layer column density (seasonally: a factor ~5! but also short time) and of the centroid height.

Science w/LGS: solar system bodies, YSO (circumstellar material), brown dwarves, Galactic novae, starbust galaxies, AGN, radio galaxies, gravitational lenses, clusters of galaxies, etc.