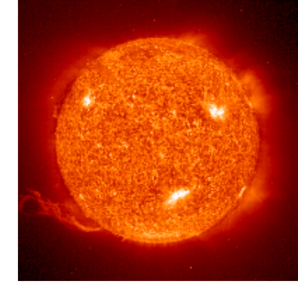


~~Detection of extrasolar planets~~

Not a good title for ELT (will be done before)!

I will "limit" myself to the
Possibility of studying terrestrial exoplanets

Key words are
studying
(spectrum, time variability, polarization . . .)
and
terrestrial

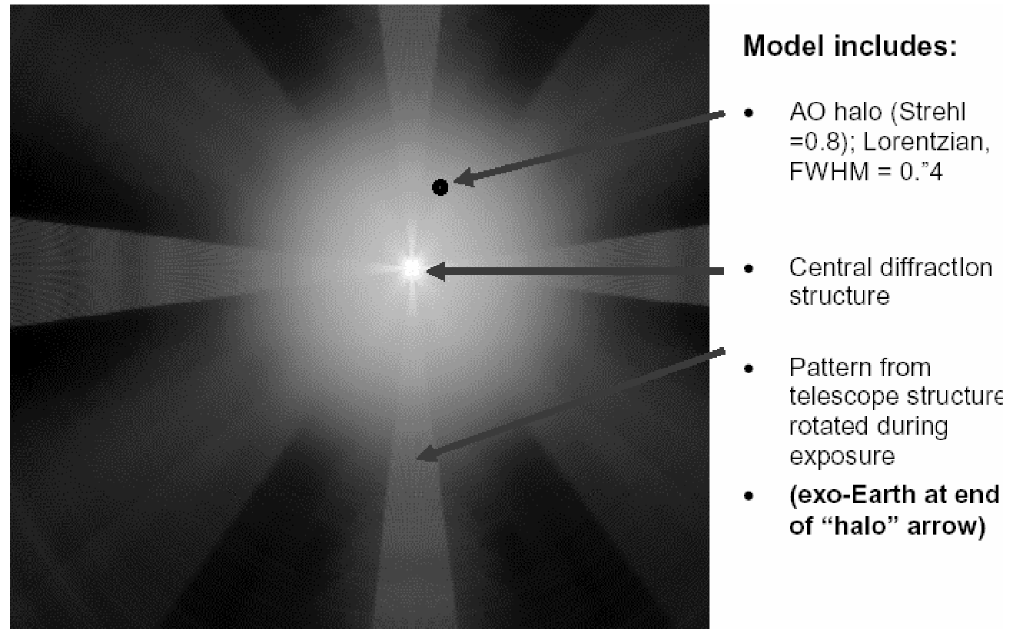
An OWL reference on the subject:

"Critical science with the largest telescopes: science drivers for a 100m ground-based optical-IR telescope"

T. G. Hawarden, D.Dravins, G.F.Gilmore, R.Gilmozzi, O.Hainaut, K. Kuijken, B.Leibundgut, M.R.Merrifield, D.Queloz & R.F.G.Wyse

Proc. of SPIE Vol. 4840

" ...The exo-Jupiter in Fig. 6 is detected [in J] at hundreds of sigma [in 10,000 s] (high resolution spectroscopy of this object could be secured in a night) and the exo-Earth is detected at around 10 sigma (for albedos of 0.7 and 0.4 respectively). While a 30-m will be hard put to detect an earth beyond ~3pc, OWL's range should be ≥25Pc. A year's observing would allow a census of the 2600-odd stars (including 360 "solar type single F, G, K stars) within this radius, yielding orbital parameters for innumerable planets."



the logics of this presentation

First we will see how far Physics allows to go in studying extrasolar earth-like planets.

Physics means: how turbulence induced wavefront *phase* errors, star photon fluxes, wind speed, etc. combine in limiting the **AO PSF contrast**. In practice:

- Assuming reasonably good conditions: **r_0(V) = 20 cm, <v> =10 m/s**
- We can calculate a PSF with the semi-analitical method of Jolissaint-Veran 2001,
- We can tune up the **actuator density** for good performances in < one arcesc field:
- We can calculate a plausible **AO PSF contrast** to see what we could do with it.
- ***We will see that the potential for extrasolar research is very good.***

Initially I will neglect
- ***Scintillation***
- ***Speckle-noise***
- ***Diffraction effects***
- ***Segmentation effects***

But later I will briefly discuss **some important implications** of the initially neglected effects

At the end I will say what I think about ***technical feasibility aspects***

Scattering of light by Residual Wavefront (phase) Error (RWE)

The RWE, i.e. the “leftovers” of the (phase) AO correction, scatters light around the star *proportionally to the Phase Power Spectral Density of the **total** RWE* (total includes the effects of “fitting”, “phase lag”, “photon noise”, “aliasing”, etc. errors).

In other words:

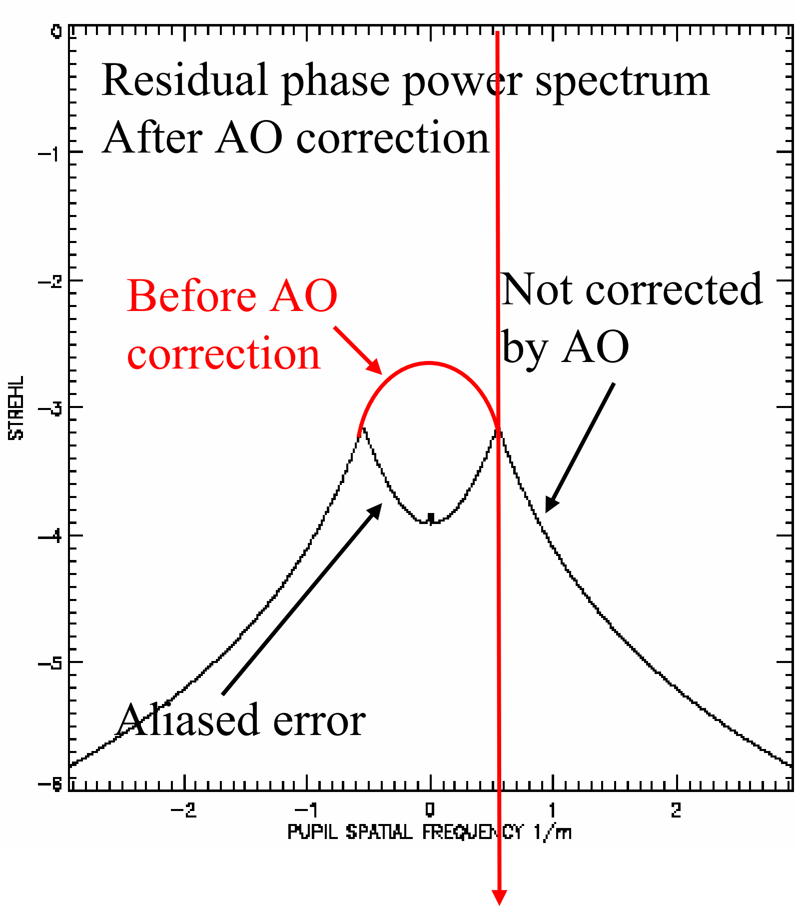
- The *RWE at spatial wavelength* W scatters light of wavelength λ at an angle **α= λ/W**
at α ~ 0.1 arcsec, in V band W ~1 m, in K band W ~4 m, 1-4 m scales are critical

- As with a given actuator separation Δ we can correct the wavefront error only at W> 2 Δ, there is always a non-corrected part of the RWE spectrum (W < 2 Δ), that produces (by aliasing) further contamination of the corrected part.

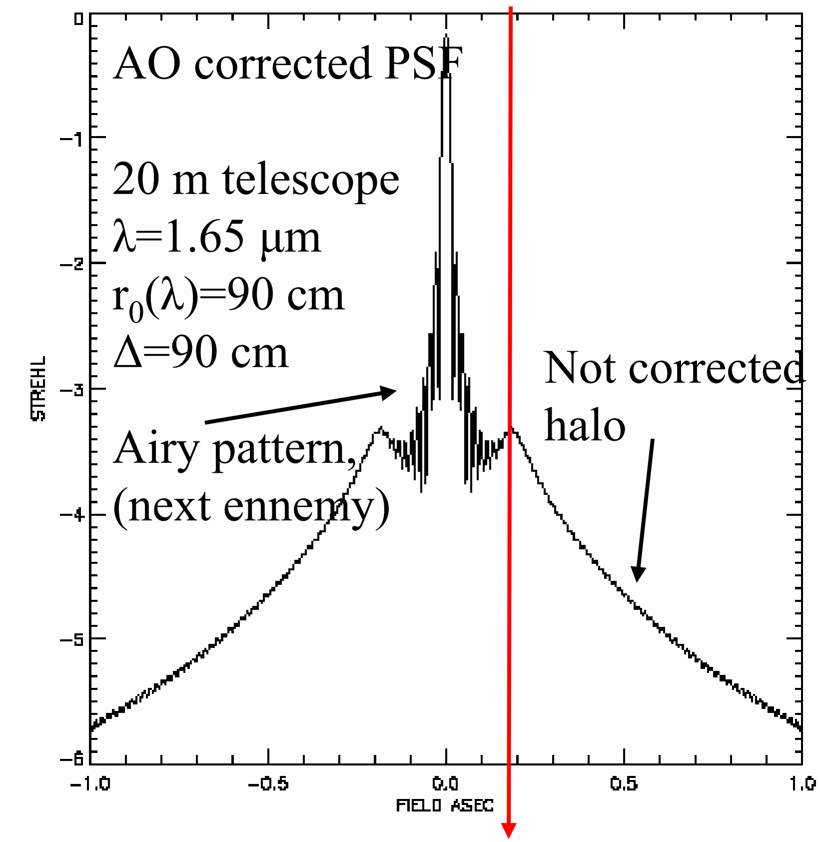
- **The correction must extend well beyond the spatial frequency of interest (W= λ/ α).**
(In other words: Δ << λ/2 α)

- The scattered light intensity I at angle α is proportional to the RWE phase variance $\boldsymbol{\sigma^2(W)}$ at the corresponding W. $\mathbf{I(\alpha) \propto \sigma^2(W) = \sigma^2(\lambda/ \alpha)}$

AO halo shape (adapted from Jolissaint and Veran 2001)



Critical spatial frequency $f_c=1/W_c=1/2\ \Delta$



Critical field angle $\alpha_c= \lambda/W_c= \lambda/2\ \Delta$

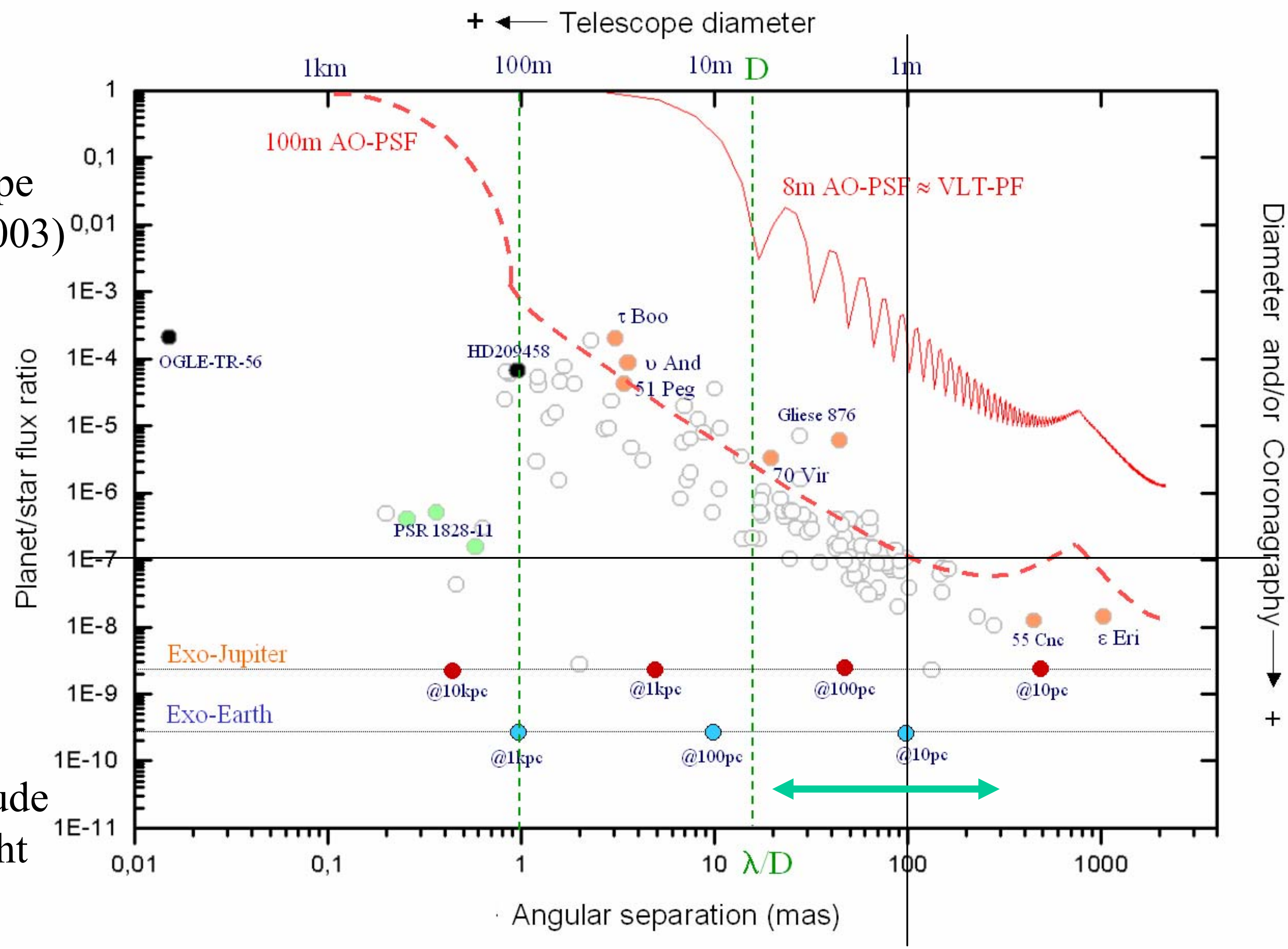
Result: V band AO PSF (theoretical contrast)

Planet/star flux ratio and angular separation for known exoplanets compared with telescope PSF (Lardiere et Al. 2003)

A) even a 100 m telescope cannot resolve some of the known planets from their stars.

B) A one arcsec field radius includes most known planets

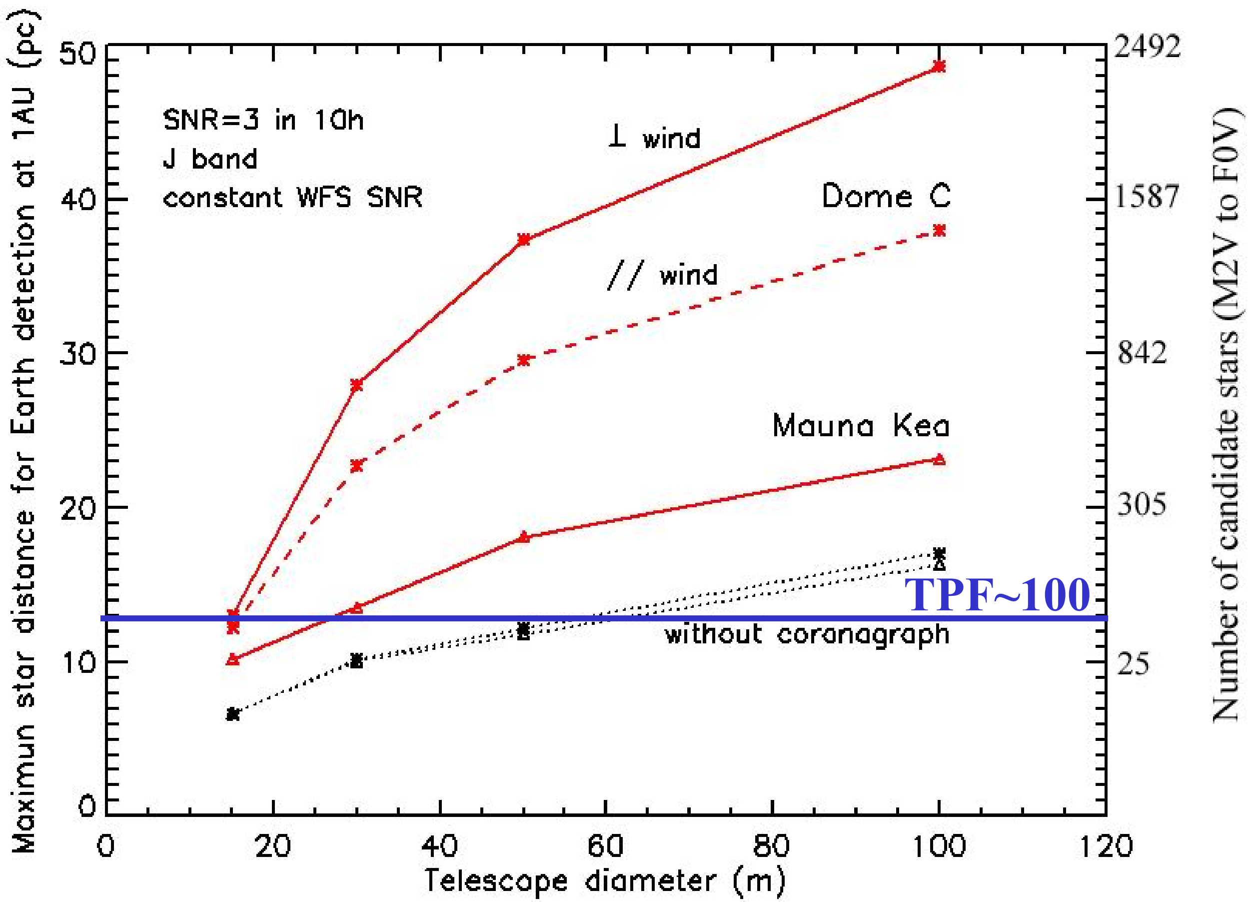
C) Exo-earths, at best distance, are about three orders of magnitude below the scattered light background



Stellar sample size (choose your telescope and location)

With a **~ 30 m** telescope (at "Mauna Kea")
one **can explore** at short wavelength the entire
TPF (goal) sample
of **~ 100 stars**
in **1000 hours**

With a **100 m** telescope in "Antarctica" one can obtain **R > 1000 spectra** of the
TPF sample
at short wavelength
(R to K)
in **1000 hours**

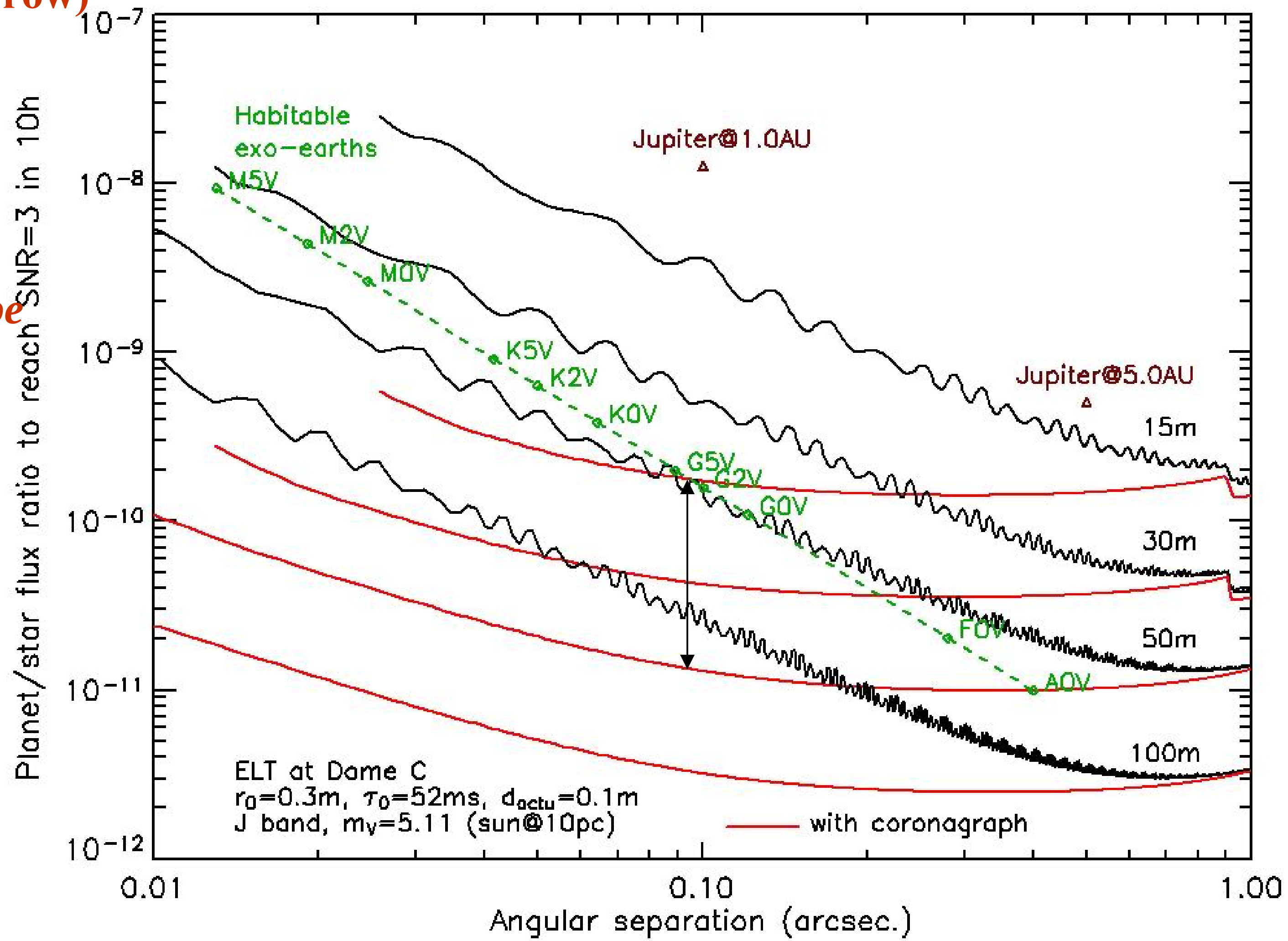


What you can do with different telescope sizes (L) @ "Dome C" (Lardiere et Al. 2003)

Example (see black arrow)

The Sun-Earth system
At 10 PC
Would be detected
In J filter ($R_J = 4$)
By a 50 m (sq) telescope with 2.5x10^5 actuators
In ten hours
At S/N ~ 30.
(in 6 min at S/N 3)

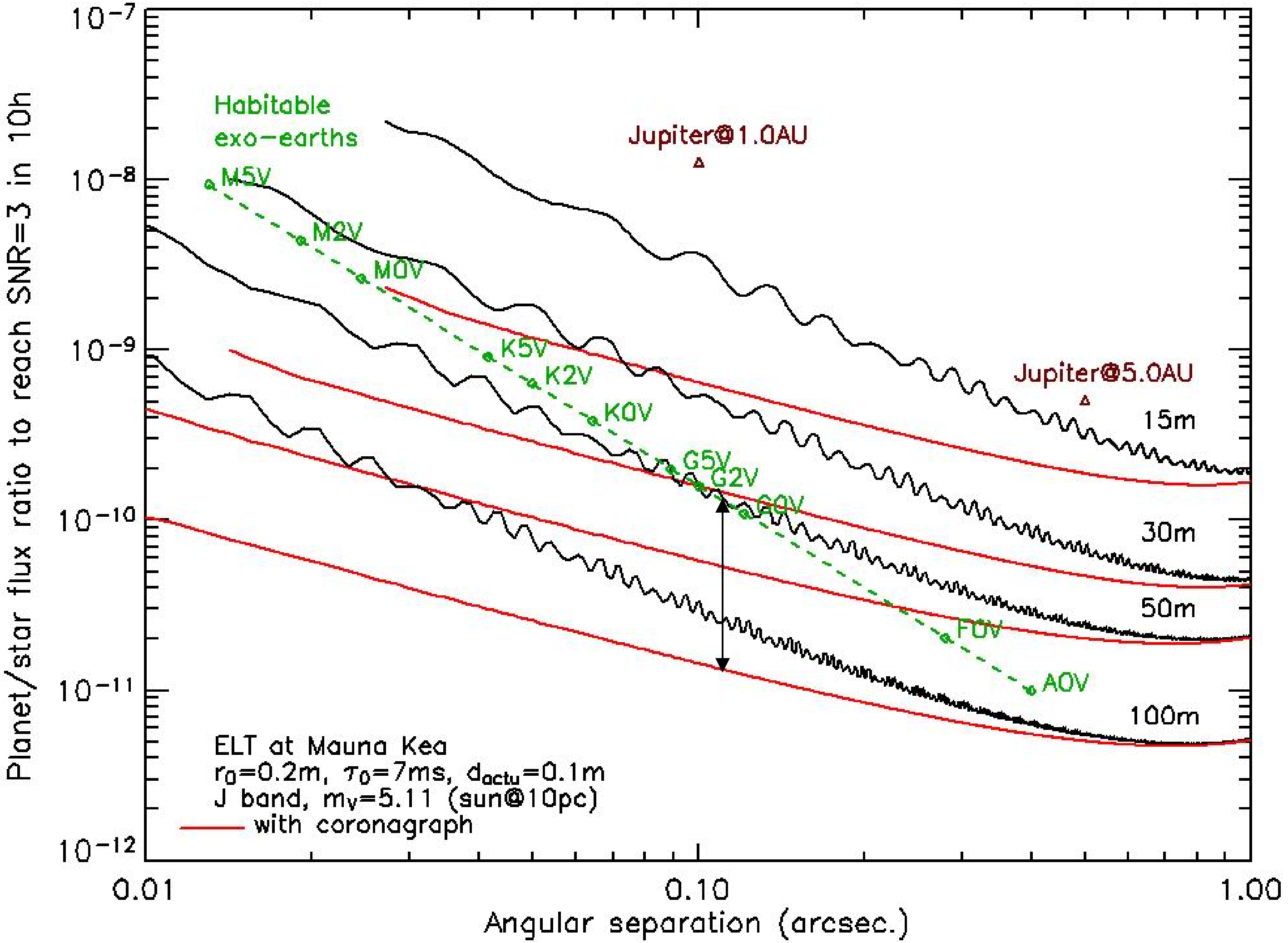
Spectroscopy with
S/N ~ 5 (per sp. el)
At R=144
[$R = R_J * (30/5)^2$]
Would also require
About ten hours



What you can get with different telescope sizes (L) @ Mauna Kea (Lardiere et Al. 2003)

Same Solar case,
Same arrow (factor 10)
Same performances

Now one needs:
A 100 m (sq) telescope with
~ 10^6 actuators

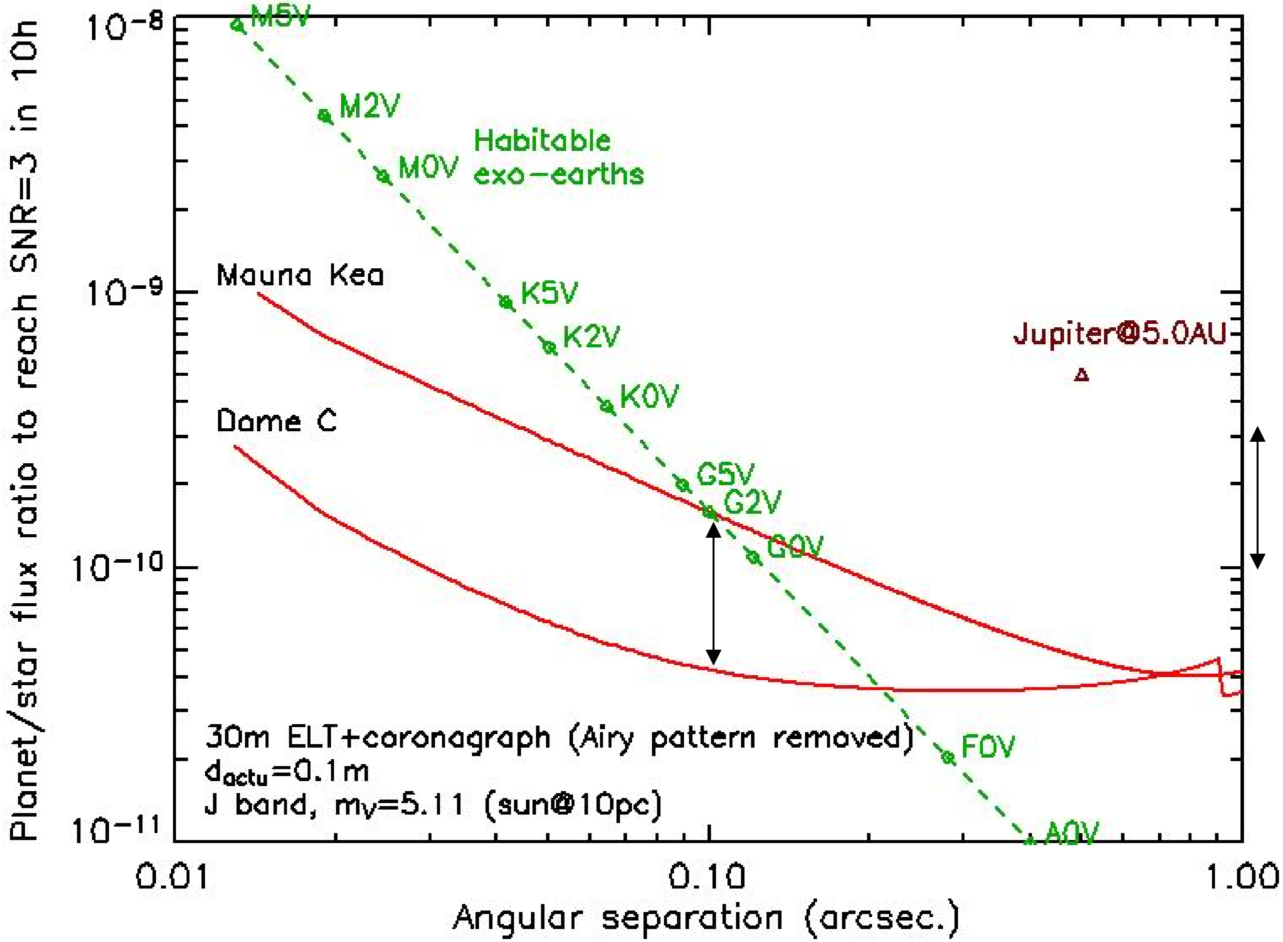


Which planets the competition could see from the two sites with a 30 m telescope? (Lardiere et Al. 2003)

Not bad!

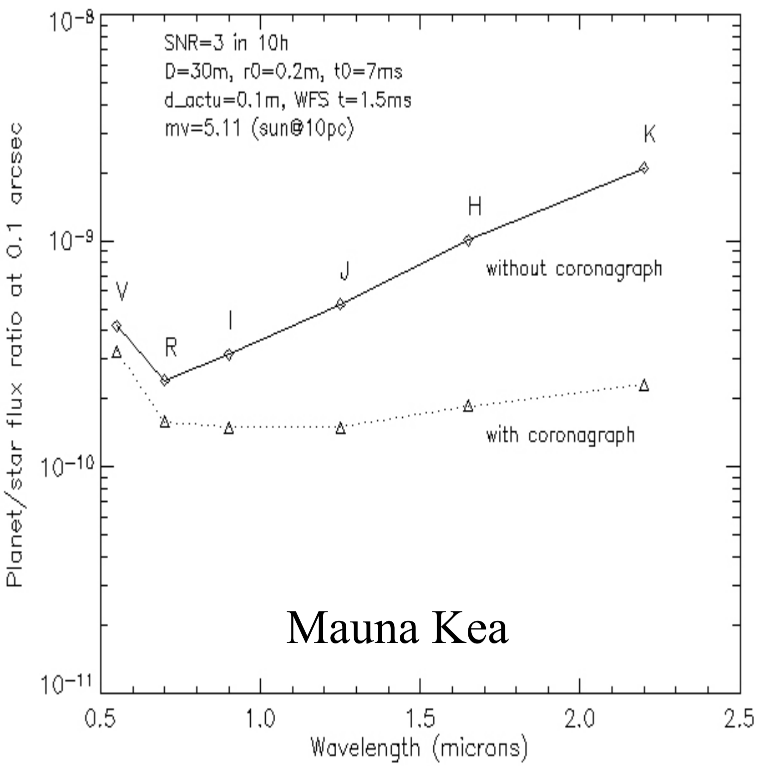
10 hours for an Earth at 10 Pc (at 3 σ) from MK,

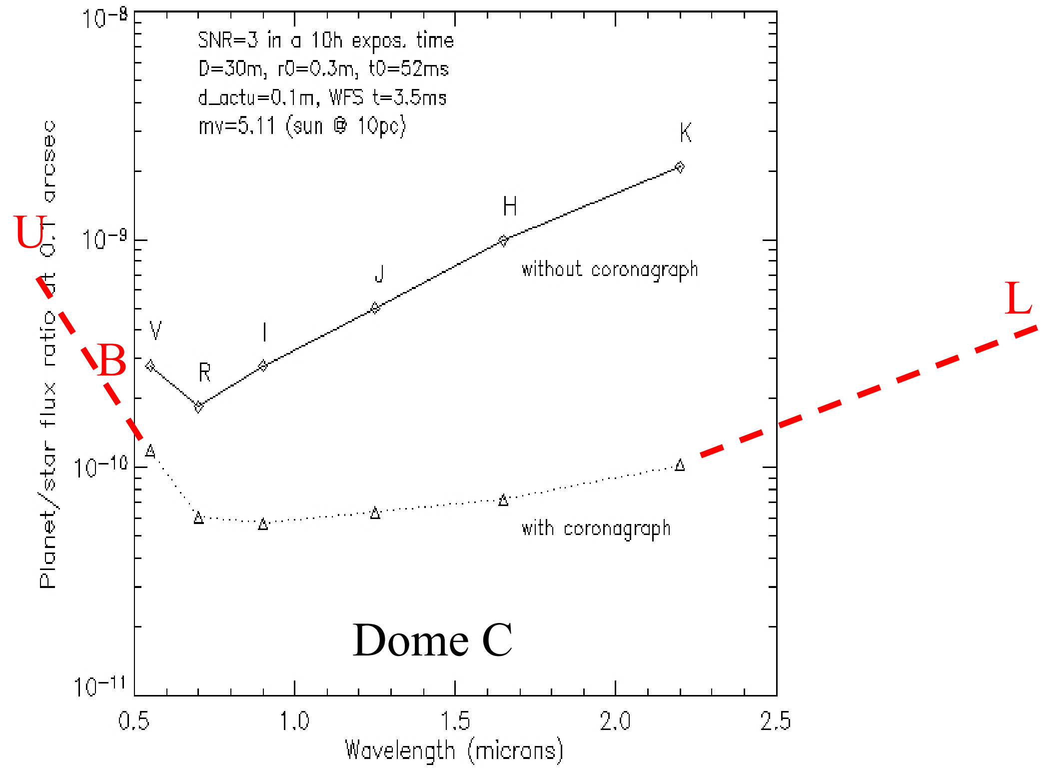
1 hour from Dome C



What happens at other wavelengths?
(Lardiere et Al. 2003)

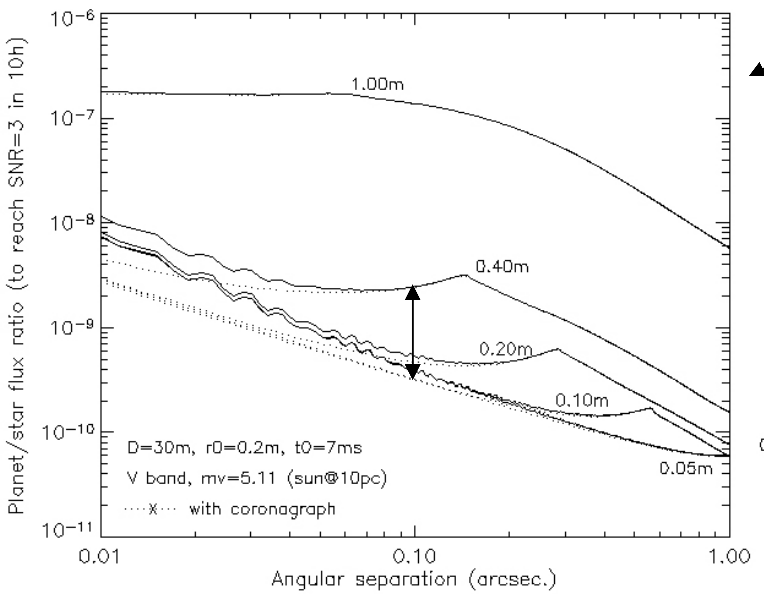
Going to longer wavelengths the increasing r_0/Δ compensates the decreasing λ/D.
An option for L band at Dome C, where the thermal background is reduced by 10^{-3}!
V is not at all bad, R, I, J are optimum. B and U should be explored, could be used for diagnostics of many non-terrestrial planets (or maybe even terrestrial ones. . .)



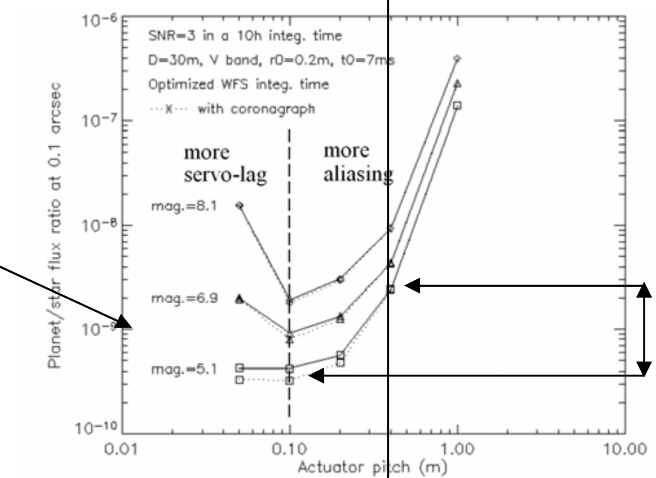


Some more technicalities
(Lardiere et Al. 2003)

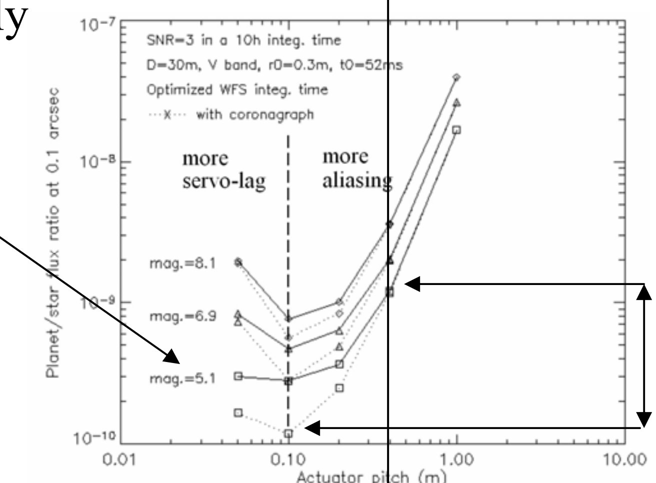
Effect of different actuator separation Δ



Selecting the best Δ
For Mauna kea
(10 cm)



And for Dome C
(Again, indipendently
10 cm)



Going from Δ=10 cm to Δ=40cm
(adequate for S ~ 0.8 in J) changes the exo-earths detection treshold by one order of magnitude.
(*detection time by two orders of magnitude*)

A few words on the neglected AO effects

The effects on contrast of intensity fluctuation on the pupil (scintillation) are similar but much smaller than those of phase "corrugation".
Scintillation can be controlled in a Multiconjugate AO System, but at the cost of adding complexity (and some extra residual phase error).
In the following I assume that scintillation is removed by correcting phase errors in a MCAO scheme, IF NECESSARY (work is in progress).

If there are slowly varying terms in the residual wf error, part of the the scattered light will concentrate in speckles, making the detection of planets much more difficult.
There are ways of avoiding the formation of specles that allow achieving a Signal to Noise ratio limited by "Poisson" photon noise, although this may require a COMPLEX "planet finder" instrument. ***(see Angel 2002)***

More work is certainly needed on both above subjects, but Poisson fluctuations of the rate of arrival of the photons scattered by residual wavefront phase error remain the main AO limitation to the study of exoplanets

The ennemies of Extreme Contrast

Many factors work against the study of terrestrial exoplanets from the ground:

1. **Atmospheric turbulence** (only partially corrected by Adaptive Optics)
2. **Diffraction effects**
   - By pupil outher edge (largely curable by pupil shape choice + coronagraphy)
   - By pupil inner edge (smaller effect, but more difficult to cure.
   - By secondary support structure (spikes only in a few directions)
   - By primary (and other) mirror segmentation (a variety of small, but nasty, effects)
3. Vibrations of optical components
4. Non uniform reflectivity (amplitude variations)
5. Scattering by defects, edges, dust . . .

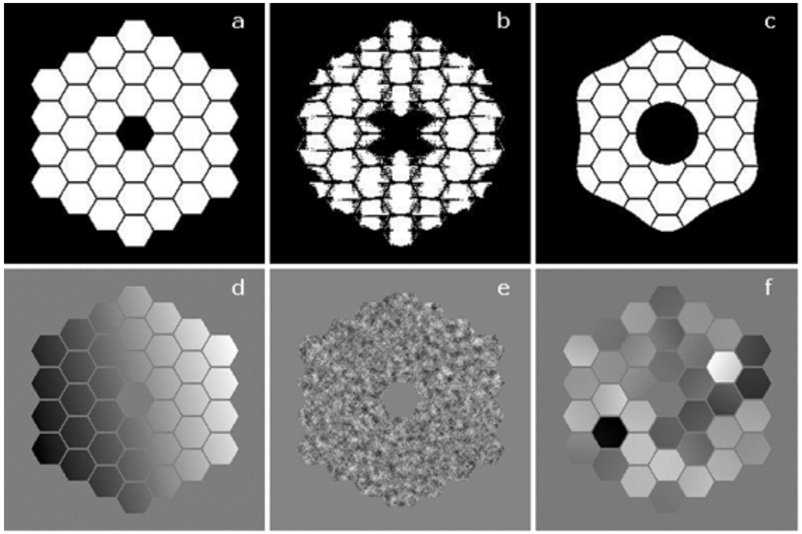
Only N 1 is specific of groundbased telescopes (and is the worst ennemy).

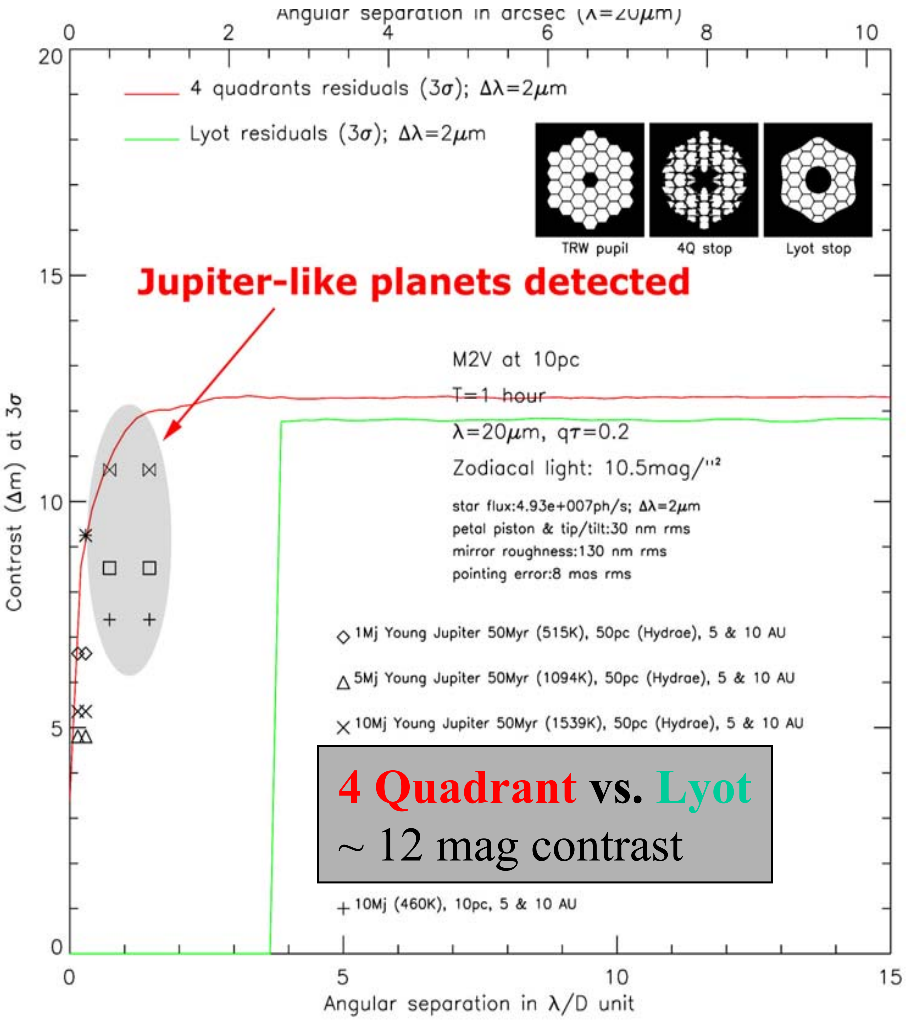
All the other effects are ***in principle*** tractable by

- appropriate telescope design choices
- coronagraphyc techniques
- severe tolerancing

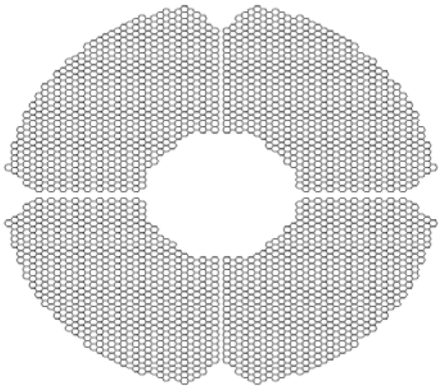
diffraction effects

Various coronagraphyc techniques can reduce the light diffracted out of the peak,
But
• Complex pupil shape is a problem
• Chromatism is another problem
• High contrast translates in high light loss
Therefore, to make the problem manageable,
• make the pupil as “clean” as possible
• don’t ask for extreme contrast increase





JWST, TRW version, MIRI (Obs. Paris)

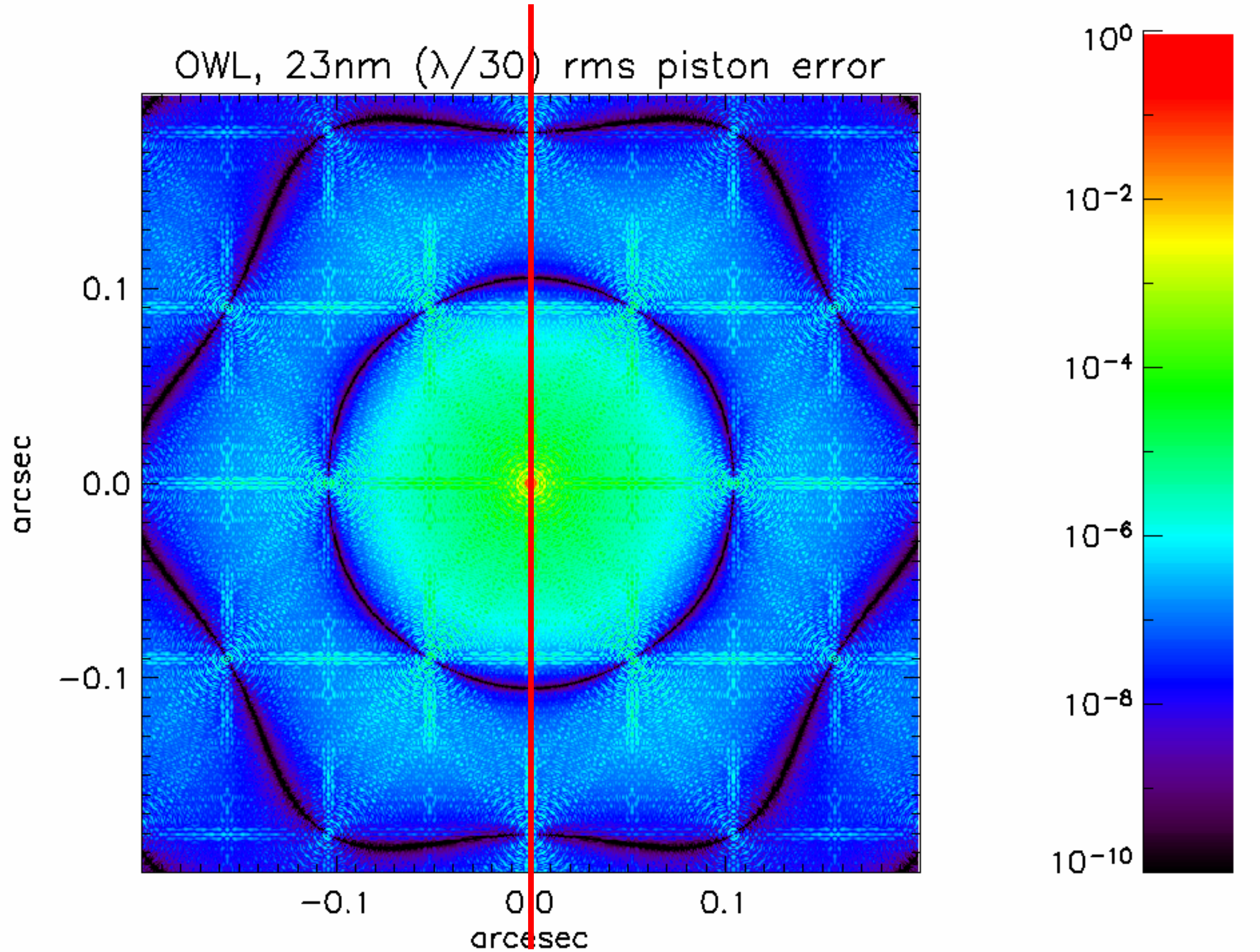


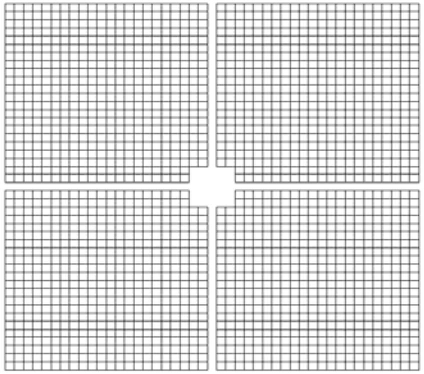
OWL-like pupil, R band

100m diameter,
10mm gap,

1.6m side-to-side hexagonal segments
33% obscuration

PSF at 700 nm
computed by A Riccardi
Following the analytical
approach of
Yaitskova_et_Al_2002,





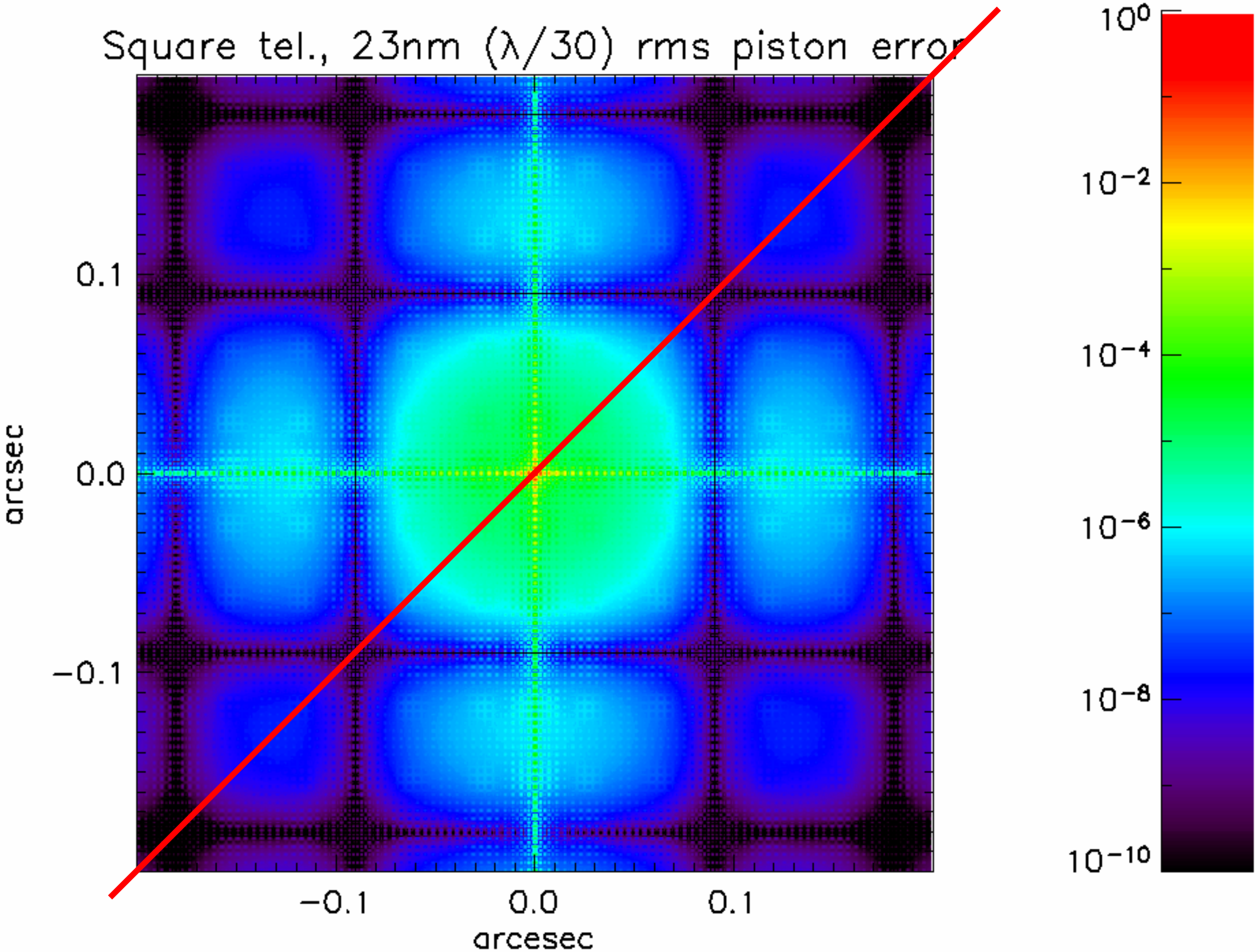
71 m square pupil, R band

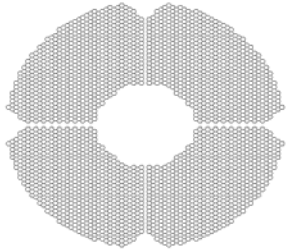
100m diagonal ~ same area as OWL

1.6m side square segments

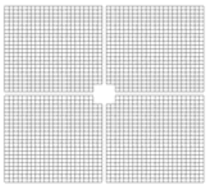
10mm gap, 10% obscuration

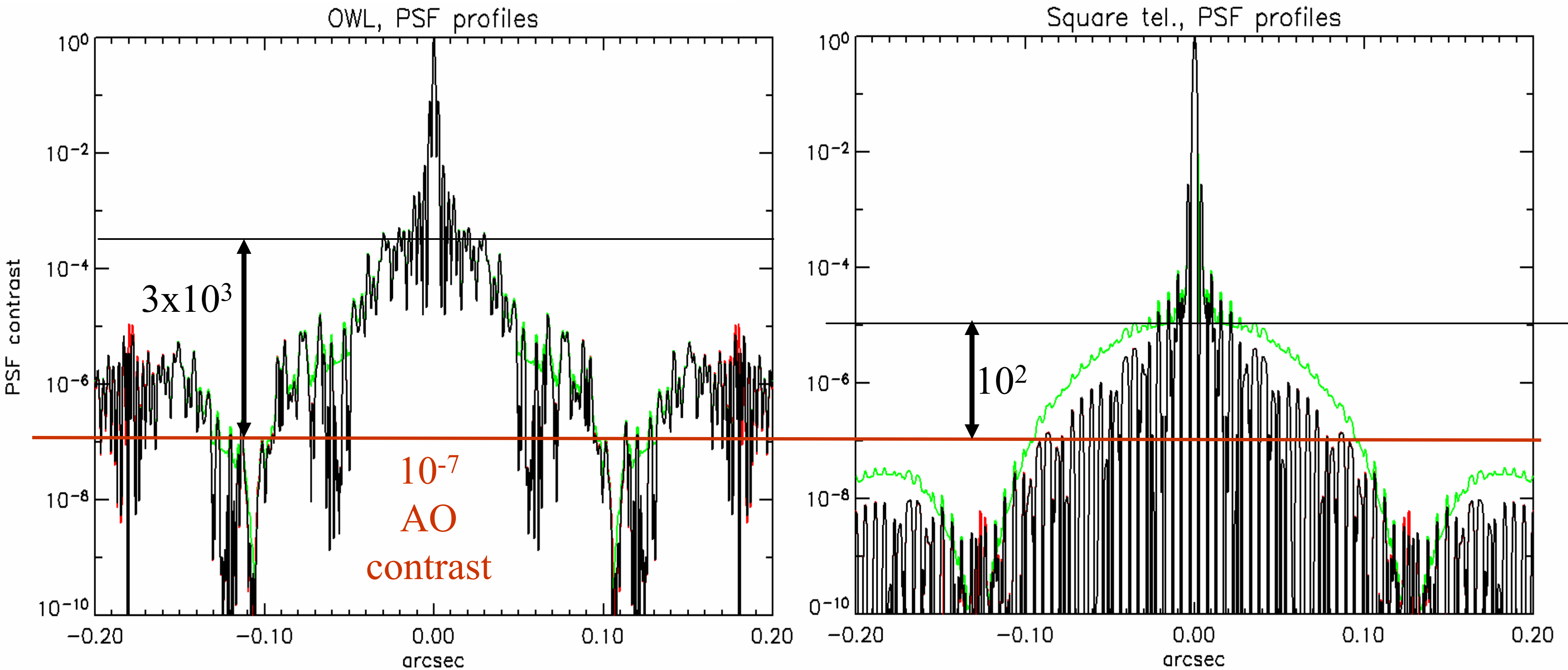
PSF at 700 nm
computed by A Riccardi
Following the analytical approach of
Yaitskova_et_Al_2002,





Comparison of the 700 nm profiles





Black, no gaps Red, 10mm gaps **Green, 23nm rms wf piston**

Coronagraphy can remove most of the structure, *BUT NOT PISTON*

Is Piston Error the *show stopper*?

Piston errors send light mostly within an angle $\alpha \sim \lambda/d$ (d=segment size)
To reduce the piston problem we could:

- **use much larger segments**, to obtain $\alpha \sim$ 20-30 mas (d >5 m at V) (doesnt work at longer wavelength)
- **use much smaller segments**, to obtain $\alpha >$ 1000 mas (d< 0.2 m at V) (this works well in principle, but the number of segments diverges and their control becomes a new big problem)
- ***reduce piston rms error by ~ an order of magnitude*** (from ~20 nm to ~ **2 nm wf**) Scaling from Esposito et Al. 2003 one finds that 2 nm rms WF differential piston error can be measured by a Pyramid WFS on a star of mag ~ 8 with sufficient bandwidth (tens of Hz) to control segment vibrations and atmospheric terms.

Differential segment piston can (MUST) be controlled adaptively!

so ... what type of AO is needed *to study exo-earths*?

Appropriate wf corrector(s):

- **A very high order corrector ($\Delta \sim 10$ cm, > 2 kHz bandwidth, any conjugation)**
  The high order corrector MUST be segmented to control segment piston
  this has profound (positive?) implications on many AO parameters
- **Possibly a medium order corrector at a high conjugate to control scintillation**

And, in addition:

- **A Piston sensitive wavefront sensor (Pyramid WFS, for instance)**
- **Large, fast WFS detectors**
- **A lot of computing power (maybe)**

Opinions on segmented correctors

If a typical segment is ~ 2 m^2 we only need ~ 200 DoF per segment.

The problem is NOT in the corrector size or complexity, but in accuracy of correction, gap size, edge effects, speed, reliability, cost . . .

Let different approaches compete, then choose the winner!

Options (in my personal order of preference):

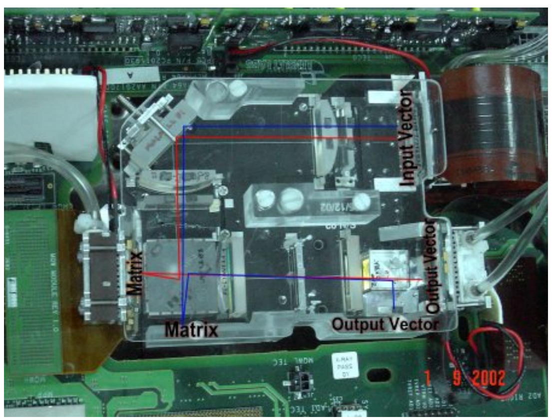
1. use **adaptive primary mirror segments** (Riccardi et Al. 2003)
2. use **"adaptive secondary technology" with higher actuator density** somewhere else in the telescope (with segmentation scaled from primary segmentation)
3. use **segmented, buttable, Piezo or MEM correctors on *piezo tripods*** (piston-tip-tilt) at a re-imaged pupil (with segmentation scaled from primary segmentation)

Opinions on WFS, detectors, computers

Piston sensitive WaveFrontSensors:

• there are many good ideas and approaches for split pupils
• there are quantitative laboratory measurement in one case (Esposito et Al. 2003, on Pyramid sensor)
• there are enough photons

Not anymore a problem



Computing power

• *segmented correctors can use hierarchical algorithms*
• computational needs ca also be reduced in other ways
• if necessary, optical computing is becoming reality!
(an optical DSP doing 8 Tera Multiply+Add Operations/s soon on the market by a company from Israel)

Fast, large detectors

A 512x512 LLLCCD (E2V ccd 87, 11 Mpix/s) is on the market only needs multiple (24) readout amplifiers (known technology)

It will not remain a problem for a long time!

Opinions on telescope and site

A: Telescope

- We better avoid using a large but not optimized telescope for detection because a smaller, well optimized and well located, telescope can outperform the larger one.
- A telescope optimized for extrasolar planets can do everything else optimally (the corrected field can be increased with the addition of extra post-focus conjugates)

B: Site

- We need to understand whether Antarctica really is what somebody says: something intermediate between ground and space (Storey et Al. 2002)
- If it is, that is the place to go to!
  (even with a small 30 m telescope)

Conclusion

Let's start discussing
what we want to learn
about extrasolar planets,
earths in particular
they seem to be
well within reach
of
ELT

Correspondence of file names with references

To make consultation easier I will place the following files (cited in the slides) at the address:

www.arcetri.astro.it/~salinari/ELT

Angel_2002.pdf: R. Angel, *"Imaging exoplanets from the ground"*, ASP Conference Series, *Scientific Frontiers in Research on Extrasolar Planets*, eds. S. Seager and D. Deming, Washington D.C. 2002.

Jolissaint_Veran_2001.pdf: L. Jolissaint and J.Veran, *"Fast computation and morfologic interpretation of the Adaptive Optics Point Spread Function",* Venice 2001 Conf. *Beyond Conventional Adaptive Optics,*

Esposito_et_Al_2003: S. Esposito, E. Pinna, A. Tozzi, P. Stefanini, N. Devaney, "Co-phasing of segmented mirrors using pyramid sensors" SPIE Proceedings, S Diego.

Hawarden_et_Al_2002.pdf: T. G. Hawarden, D.Dravins, G.F.Gilmore, R.Gilmozzi, O.Hainaut, K. Kuijken, B.Leibundgut, M.R.Merrifield, D.Queloz & R.F.G.Wyse, "*Critical science with the largest telescopes: science drivers for a100m ground-based optical-IR telescope*", Proc. of SPIE Vol. 4840

Lardiere_et_Al_2003.pdf: O. Lardiere, P. Salinari, L. Jolissaint, M. Carbillet, A. Riccardi, S. Esposito,; *"Adaptive optics and site requirements for search of earth-like planets with ELTs "* (Proc. of II Backaskog conference on ELTs)

Riaud_et_Al_2001.ps: P. Riaud, A. Boccaletti, D. Rouan, F. Lemarquis, A. Labeyrie, *"The four-quadrant phase-mask coronagraph. II, Simulations",* PASP 113:1145-1154, 2001 September.

Riccardi_et_Al_2003.pdf: A. Riccardi, C. Del Vecchio, P. Salinari, G. Brusa, O. Lardiere, D. Gallieni, R. Biasi, P. Mantegazza, "Primary adaptive mirrors for ELTs: a report on preliminary studies" (Proc. of II Backaskog conference on ELTs)

Storey_et_Al_2002.pdf: J. Storey, M. Burton, M. Ashley, *"Antartica as stepping stone to space", http://www.phys.unsw.edu.au/~mgb/Antbib/stepping-stone.pdf*

Verinaud_Esposito_2002: C. Verinaud and S. Esposito, ``*Adaptive optics correction of a stellar interferometer with single pyramid wavefront sensor,''* Opt. Letters , 2002.

Yaitskova_et_Al_2002.pdf: N. Yaitskova, K. Dohlenb, P. Dierickx, *"Diffraction in OWL: effects of segmentation and segment edge misfigure",* Proc. of SPIE Vol. 4840

Useful scaling rules and relations (Lardiere et Al. 2003)

Symbols and definitions

Fried's coherence length	r_0
Coherence time	τ_0
Turbulence weighted wind speed	v_0
Telescope diameter	D
Actuator separation	Δ
Field angle	α
Contrast due to RWE	$C(\alpha)$

$$C(\theta) = \frac{\sum_n \sum_n PSF(\theta)}{\iint_\infty PSF}$$

(sums on planet pixels)

Contrast with coronagraph	$Co(\alpha)$
Strehl ratio	S
Integration time	T
Photon flux usable by wfs	Q_{ph}

Scaling rules:

$\alpha = \lambda/W$

$C(\alpha) \propto D^{-2}$ (at given α, $S \sim 1$)

$C(\alpha) \propto (\Delta/r_0)^2$ (if not limited by Q_{ph})

$Q_{ph} \propto (r_0)^3/v_0$