On-sky closed loop correction of atmospheric dispersion for high-contrast coronagraphy and astrometry

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Outline of the talk

Motivation

- Exoplanets
- Atmospheric Dispersion
- Effect of Dispersion on Coronagraphy

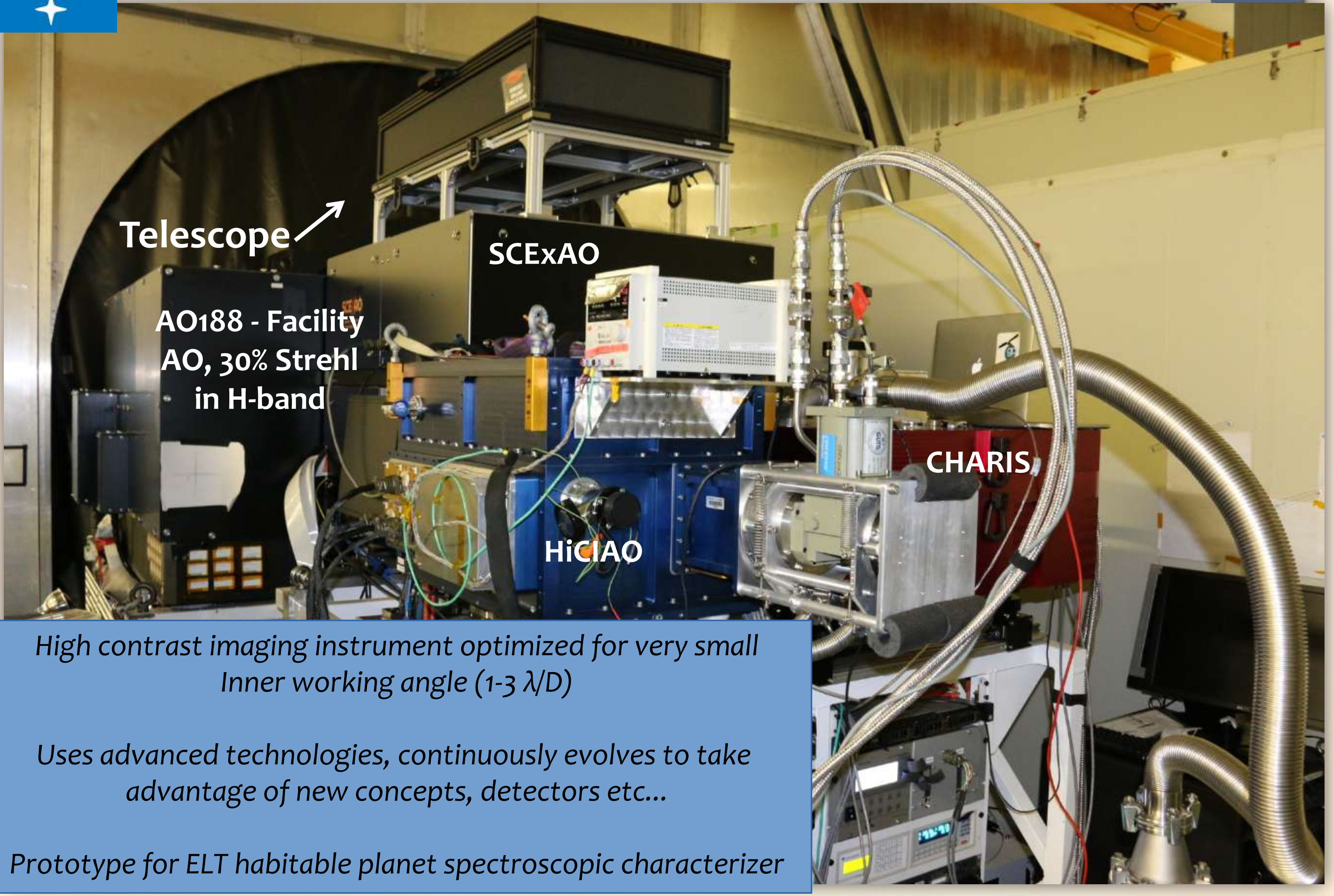
Concept

- Concept for measuring atmospheric dispersion on-sky
- Simulations

Results

- Measuring dispersion on-sky
- On-sky closed-loop results
- Coronagraph flux suppression

SCExAO (Subaru Coronagraphic Extreme Adaptive Optics)



High contrast imaging instrument optimized for very small Inner working angle (1-3 λ/D)

Uses advanced technologies, continuously evolves to take advantage of new concepts, detectors etc...

Prototype for ELT habitable planet spectroscopic characterizer

Collaborators

Subaru Telescope, National Astronomical Observatory of Japan
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G. Singh
J. Hagelberg
D. Defrère
D. Mawet

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N. Cvetojevic
S. Gross
T. Lagadec
A. Arriola
T. Gretzinger
P. Tuthill
M. Withford
J. Lawrence

MKIDS
B. Mazin
A. Butler
S. Meeker
J. Massie
M. Strader
J. Van Eyken

FIBER INJECTION/ PHOTONIC SPECTROSCOPY
N. Cvetojevic
C. Schwab
B. Norris
S. Gross
C. Betters
J. Lawrence

POST CORONAGRPAHIC SPECTROSCOPY
H. Kawahara
T. Kotani

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D. Hall
S. Jacobson
D. Atkinson
M. Chun
I. Baker

CHARIS
J. Kasdin
T. Groff
J. Chilcote
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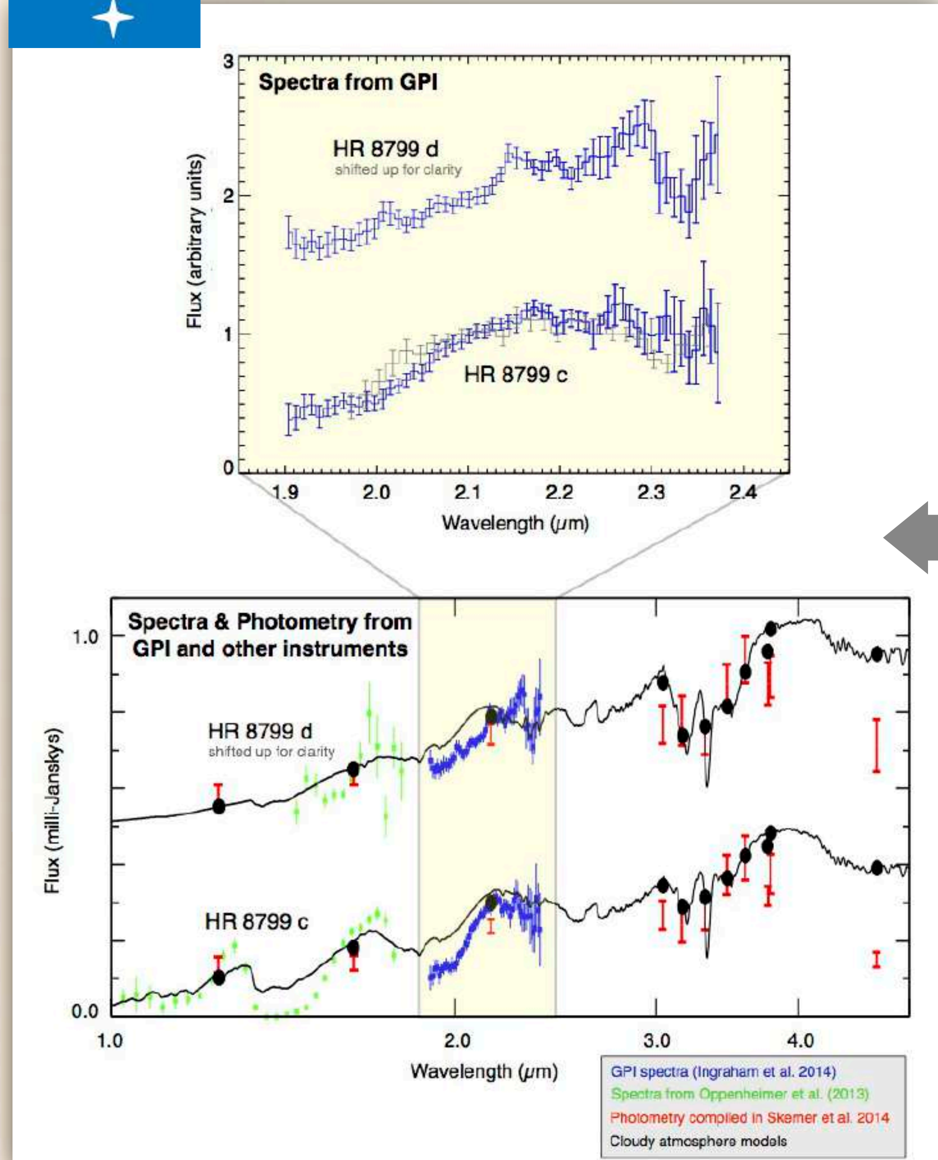
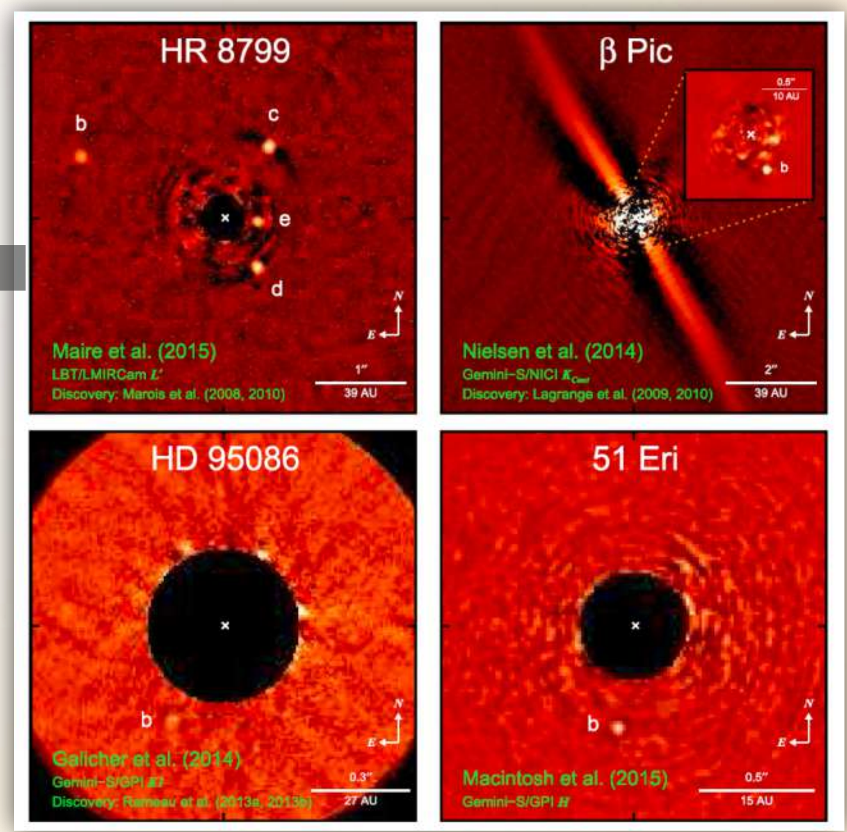
Exoplanets Detected So Far



Directly imaged exoplanets so far: 44

- Young hot Jupiter's
- Far from the host-star



Direct Imaging of Exoplanets

High angular resolution:

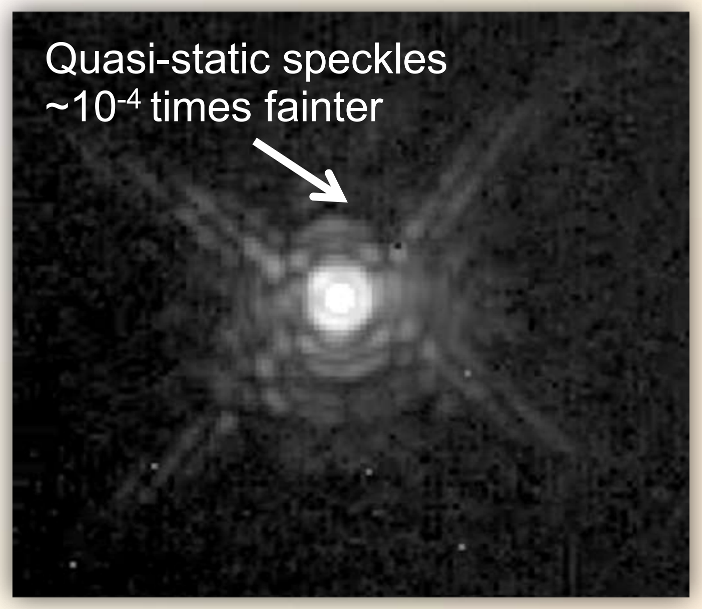
1. Typical angular size for a planetary system 1".
2. 8-10 m class telescopes have 45 mas resolution in H-band
3. ***Easy for ground based telescopes.***

High-Contrast (The ratio of the planet light to the star light):

1. 10^{-6} for young Jupiter size planet .
2. 10^{-10} (Earth in reflected light) Earth-like exoplanet around solar type stars.
3. **Easy for space based telescopes.**

Ground Based High-contrast Imaging:

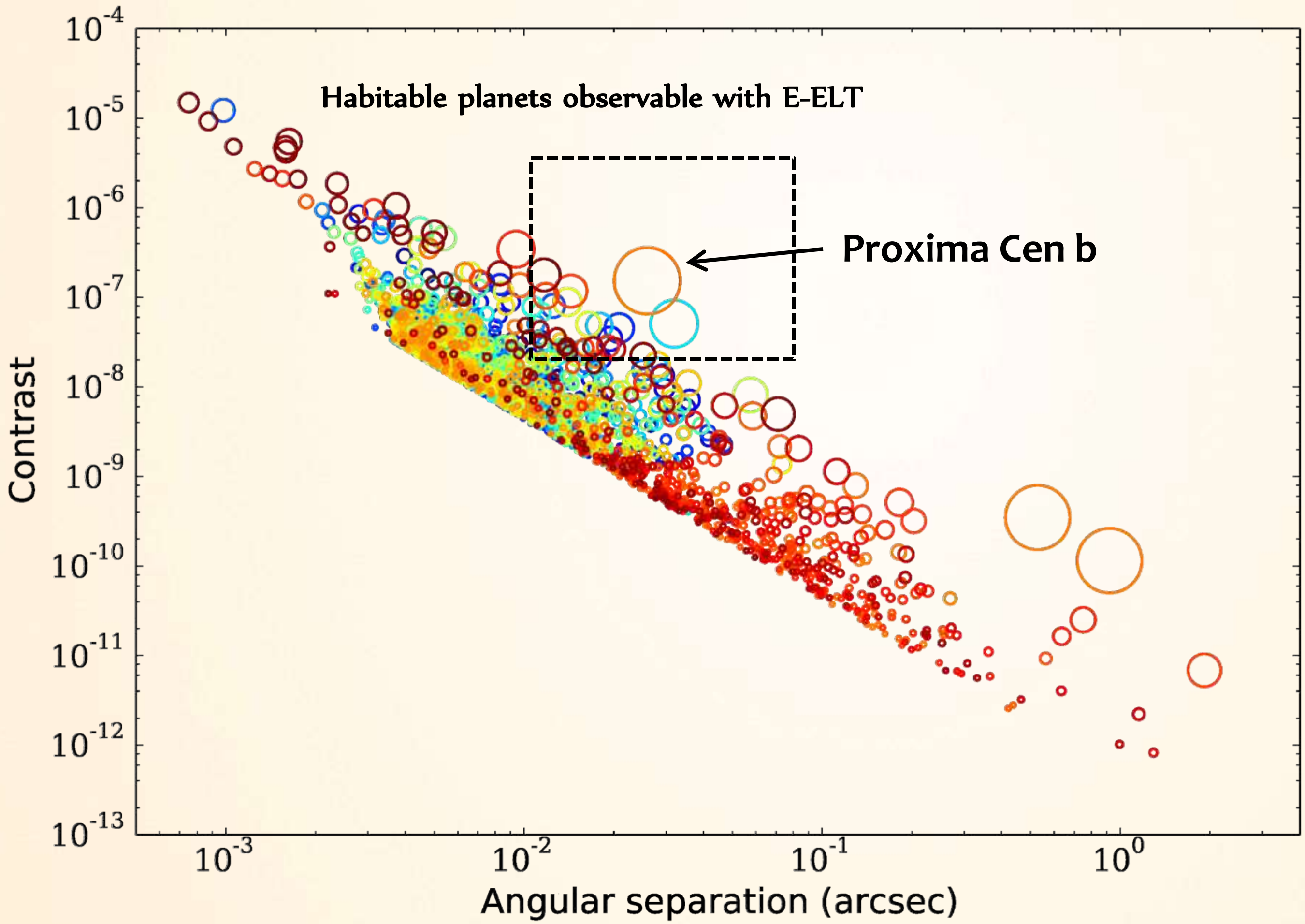
- ❑ Extreme Adaptive Optics (90% Strehl ratio)
- ❑ **Coronagraphy (small inner working angle)**
- ❑ Differential Imaging (ADI, SDI)



SCExAO's on-sky H-band PSF

Habitable planets within the reach of EELT

E-ELT is well suited for imaging habitable exoplanets around M-type stars using the reflected light.



1. **High-angular resolution:**
   H-band: ~ 11 mas

2. **High performance Coronagraphy:**
   Raw Contrast:
   ~ **10^{-5}**
   Inner Working Angle:
   2 λ/D

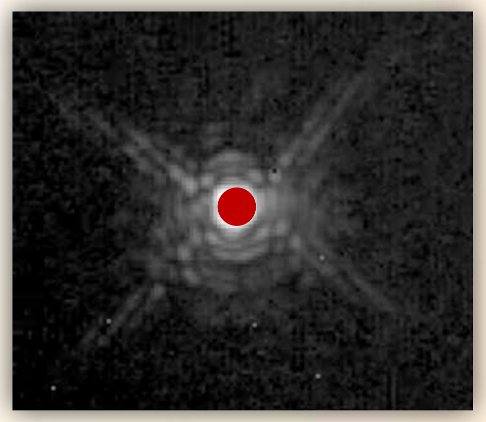
Potential habitable Earth-size exoplanets within 20 pc

Coronagraphy

Key coronagraph requirements:

1. **Raw Contrast:** (10^{-5}) The ratio of the planet light to the star light.
2. **Inner Working Angle:** **(1-2 λ/D)** smallest angle on the sky at which the needed contrast is achieved and the planet light is reduced by no more than 50%.
3. **High throughput:** fraction of planet light in your photometric aperture.
4. **Bandwidth:** The wavelengths at which high contrast is achieved.
5. **Sensitivity:** Contrast is degraded in the presence of aberrations such as **low order** and ***atmospheric dispersion***.

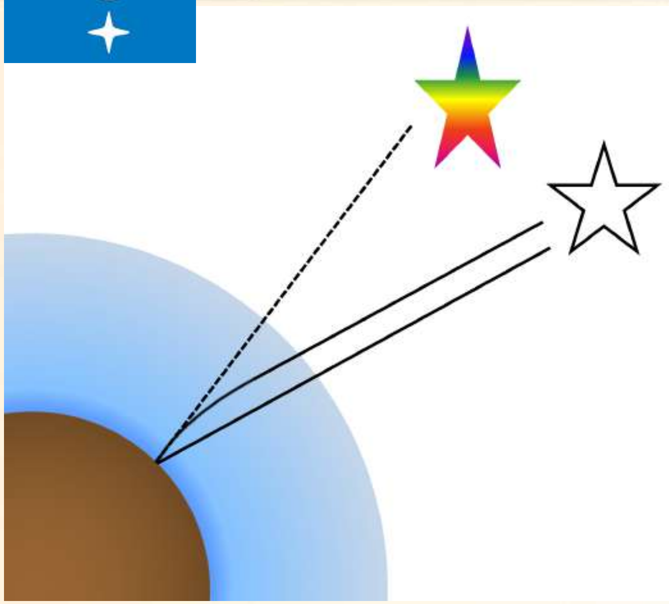
Solar Corona during eclipse.
It has brightness 4×10^{-6} compared to solar photosphere, *Hanaoka et. al. 2012*



Coronagraphic low-order wavefront sensor

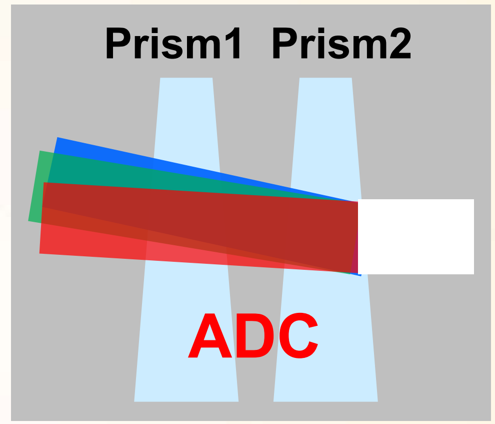
Atmospheric Dispersion and Coronagraphy

Atmospheric Dispersion



Most AO systems employ Atmospheric Dispersion Compensator (ADC) to correct for the atmospheric dispersion.

Zenith angle 33°



Zenith angle 33°

Zheng et al.(2014)

Characterization of the Atmospheric Dispersion Corrector of the Gemini Planet Imager

Pascale Hibon[a], Sandrine Thomas[b], Jennifer Dunn[c], Jenny Atwood[c], Les Saddlemyer[c], Naru Sadakuni[a], Stephen Goodsell[d], Bruce Macintosh[e], James Graham[h], Marshall Perrin[f], Fredrik

Study of the performance of the Atmospheric Dispersion Correctors from VLT/SPHERE.

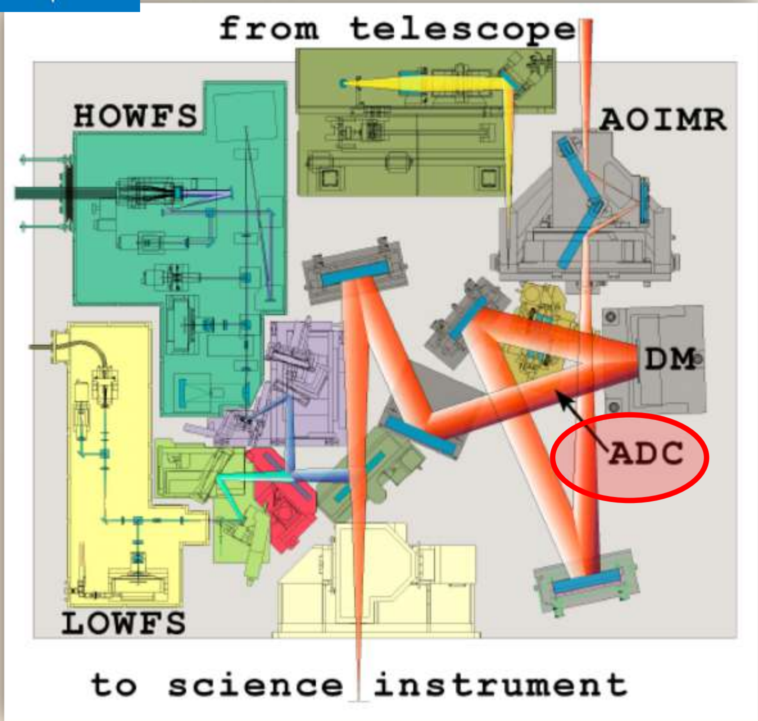
Pascale Hibon[a], Arthur Vigan[b], Kjetil Dohlen[b], Julien Milli[a], Julien Girard[a], Jean-Luc Beuzit[c], and David Mouillet[c]

Residual dispersion < 5 mas
Astrometry < 1 mas

??

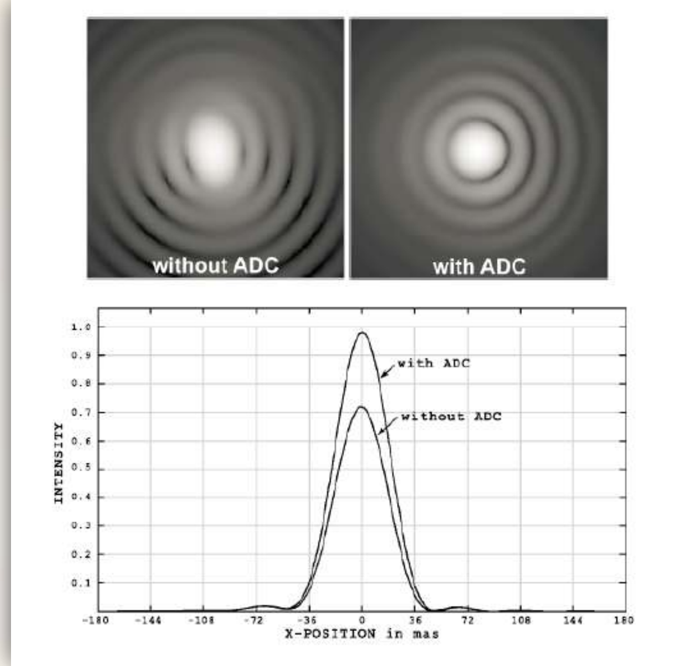
An ADC relying on a look-up table effectively compensates for most of the dispersion, however some residual dispersion remains.

ADC unit at Subaru Telescope



Egner et al. 2010

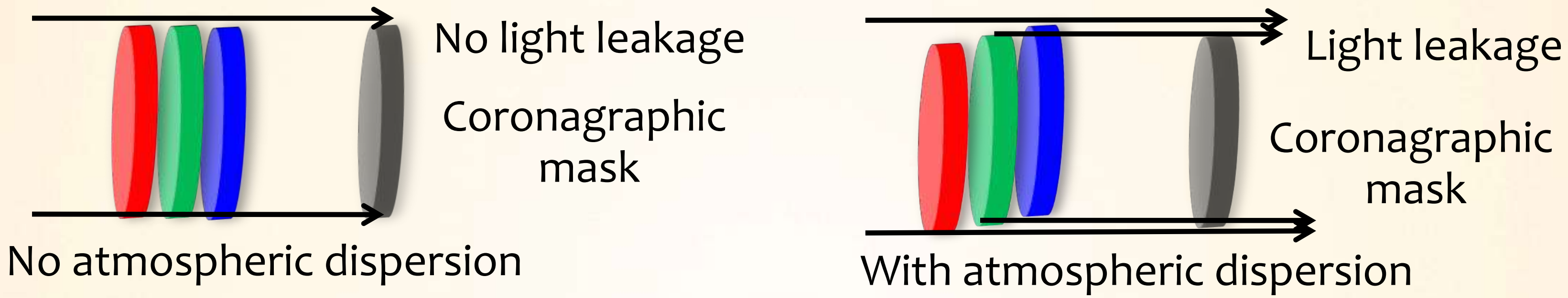
ADC unit for the AO188 of the Subaru Telescope.



Egner et al. 2010

1. H-band PSF, corresponding to zenith distance 60°.
2. PSF elongates by a factor of 1.6
3. Approximately 30% drop in Strehl-ratio

Effect of Atmospheric Dispersion on Coronagraphy

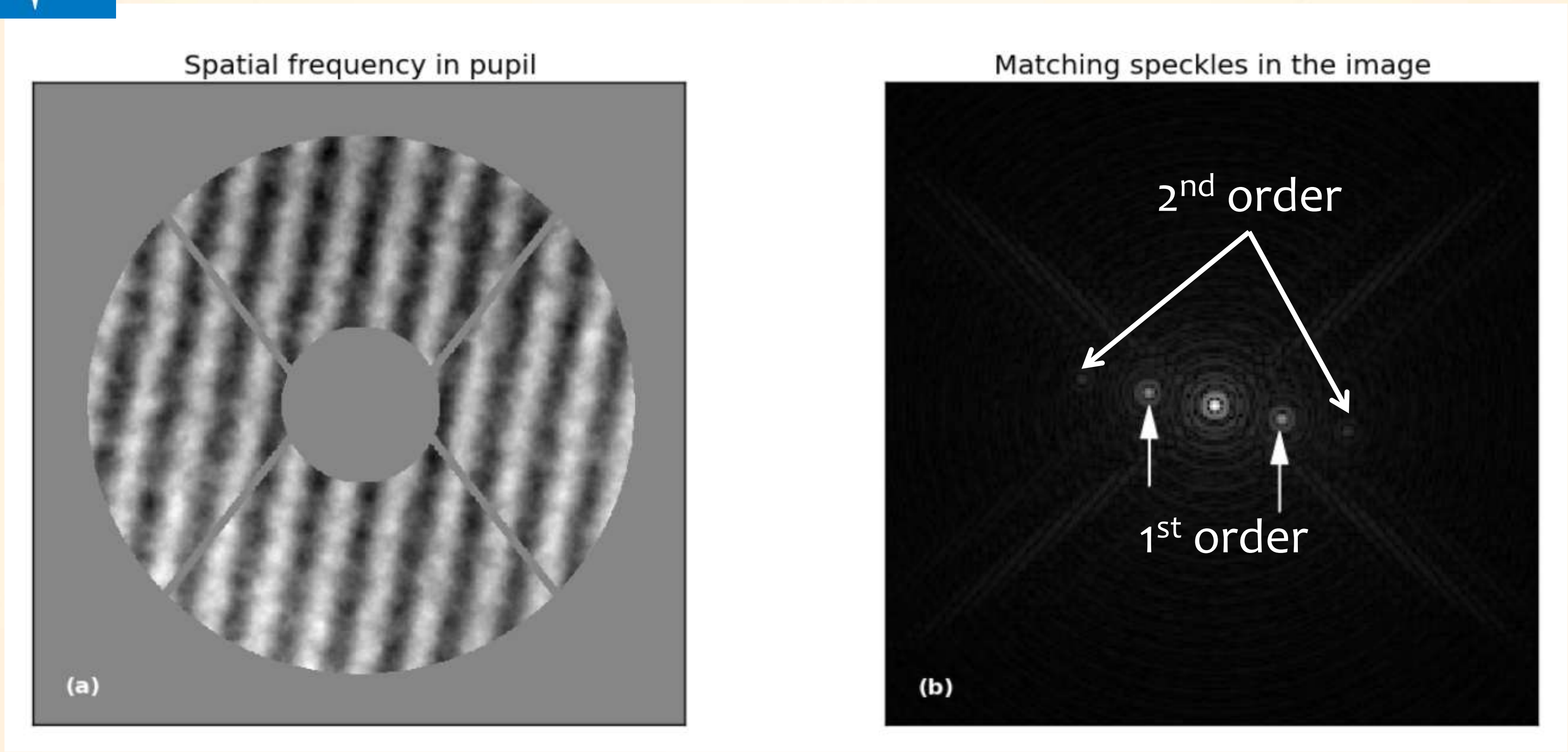


For SCExAO to achieve the desired contrast, PSF shouldn't be spread more than, 1/50th of PSF = 1 mas

For high-performance coronagraphy with E-ELT, residual dispersion requirement:
Measurement precision of 0.1 mas and correction at 0.3 mas level in science band.

Concept For Measuring Atmospheric Dispersion

Diffraction of PSF using Deformable Mirror



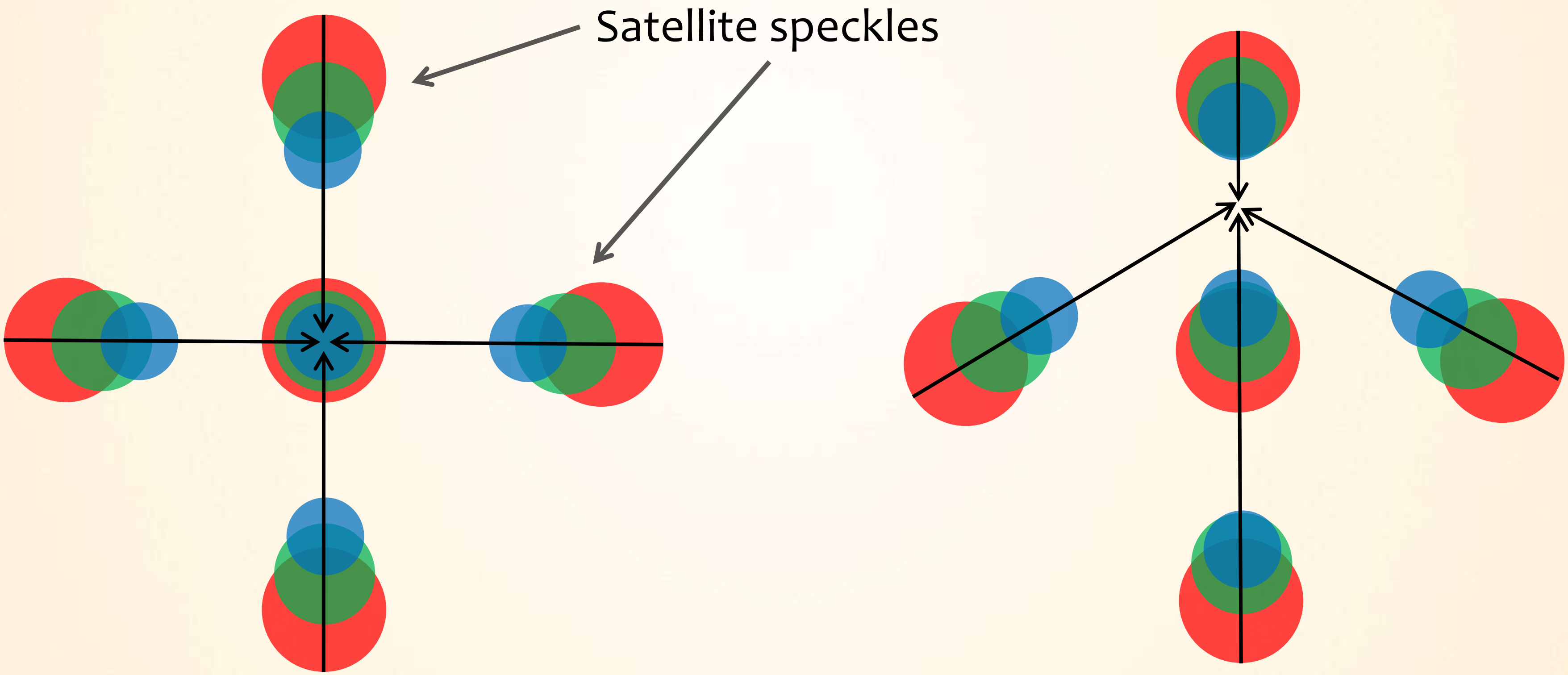
Martinache et al 2014

Deformable mirror with sine wave as a grating

PSF with 1st & 2nd order diffraction, in a narrow band filter

Concept for Measuring Atmospheric Dispersion

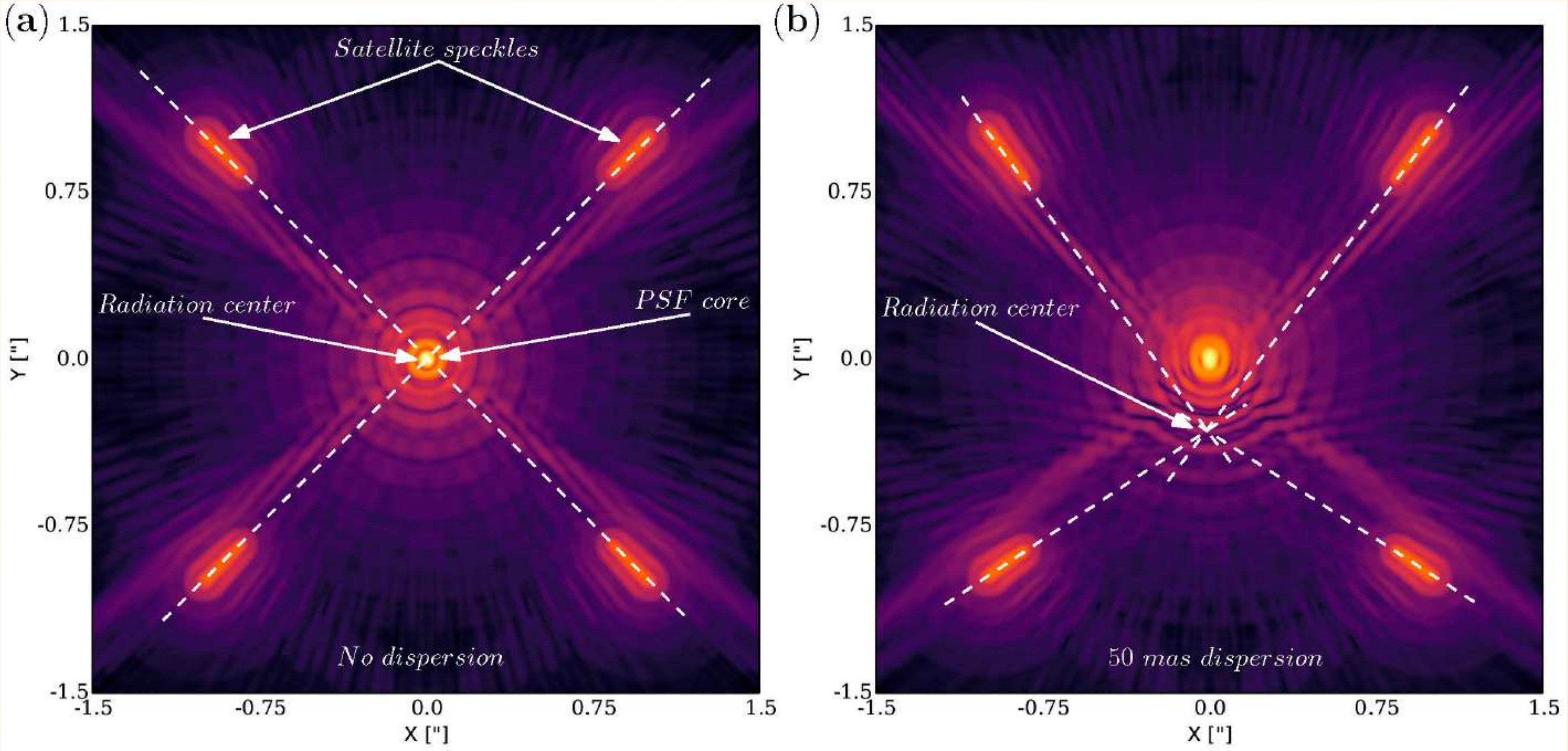
Central PSF can be diffracted using deformable mirror (DM) to produce speckles, which are elongated due to presence of broadband light.



With "NO" Atmospheric Dispersion
(All the wavelength focused at center)

With Atmospheric Dispersion
(wavelengths unfocused at center)

Simulation of PSF with and without Dispersion

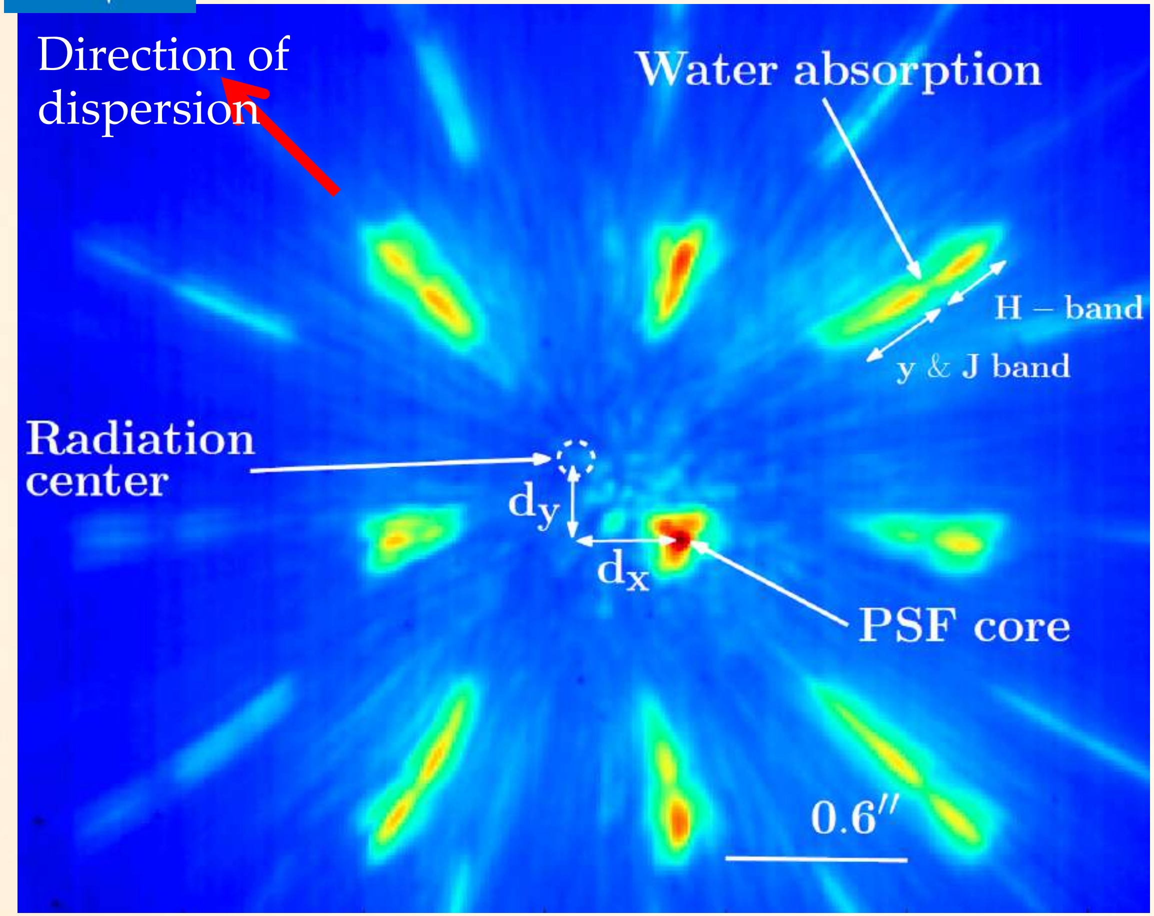


H-band PSF without dispersion

H-band PSF with 50 mas dispersion in y-axis

In the presence of dispersion satellite speckles no longer point towards PSF

On-sky y-H band PSF with Satellite Speckles



Target:
Denebola (Beta leo).
Apparent magnitude 2.113,
Date: 2015/04/02
11:37:18 UTC

Telescope elevation: 43^o

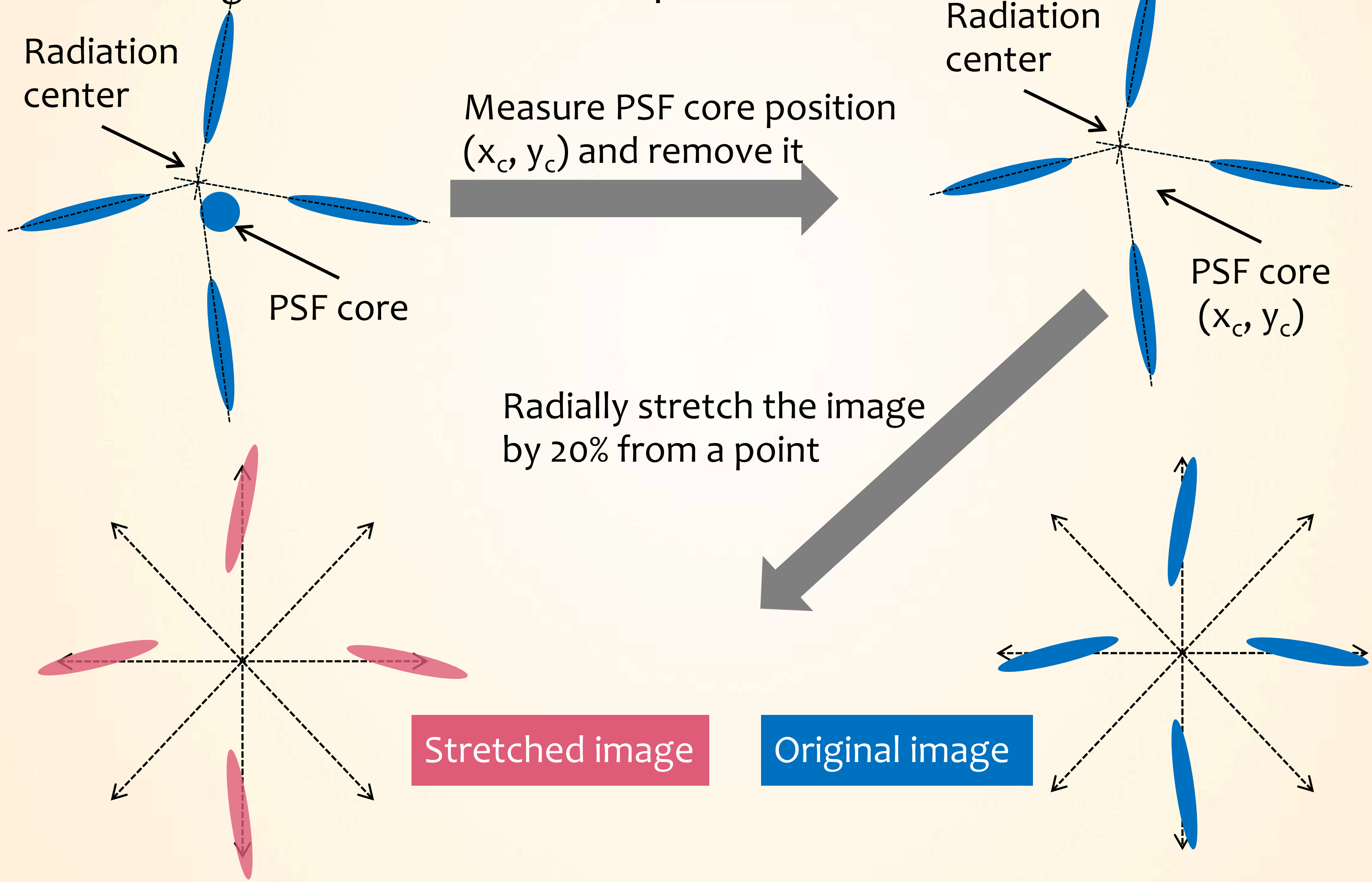
No ADC correction

d_x & d_y measurement, indirectly give us the presence of atmospheric dispersion

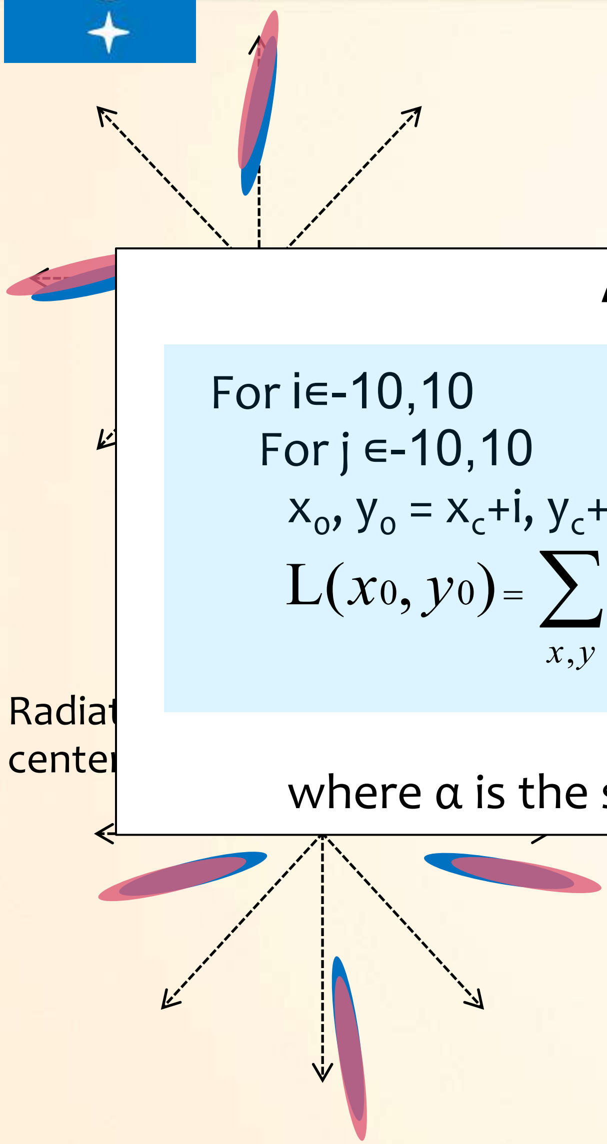
Atmospheric Dispersion can be measured by finding the distance between the radiation center and PSF

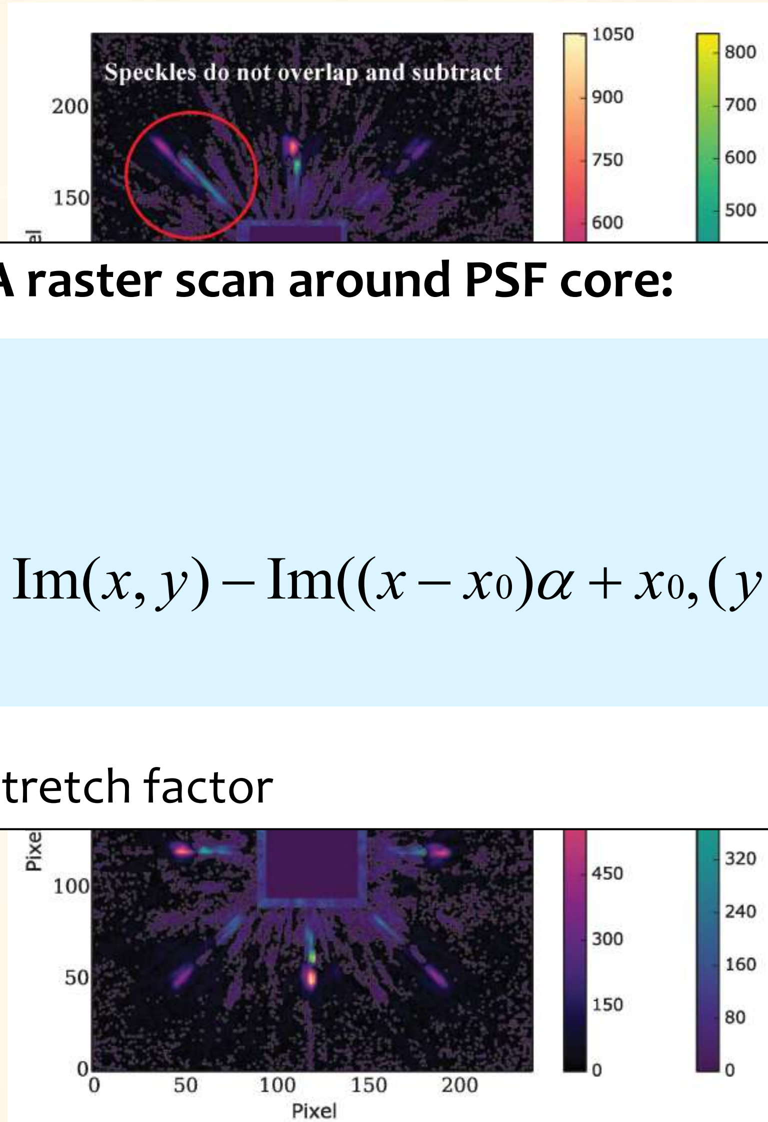
Extraction of Radiation Center

Image with PSF & satellite speckles



Extraction of Radiation Center





A raster scan around PSF core:

For i∈-10,10

For j ∈-10,10

$x_o, y_o = x_c+i, y_c+j$

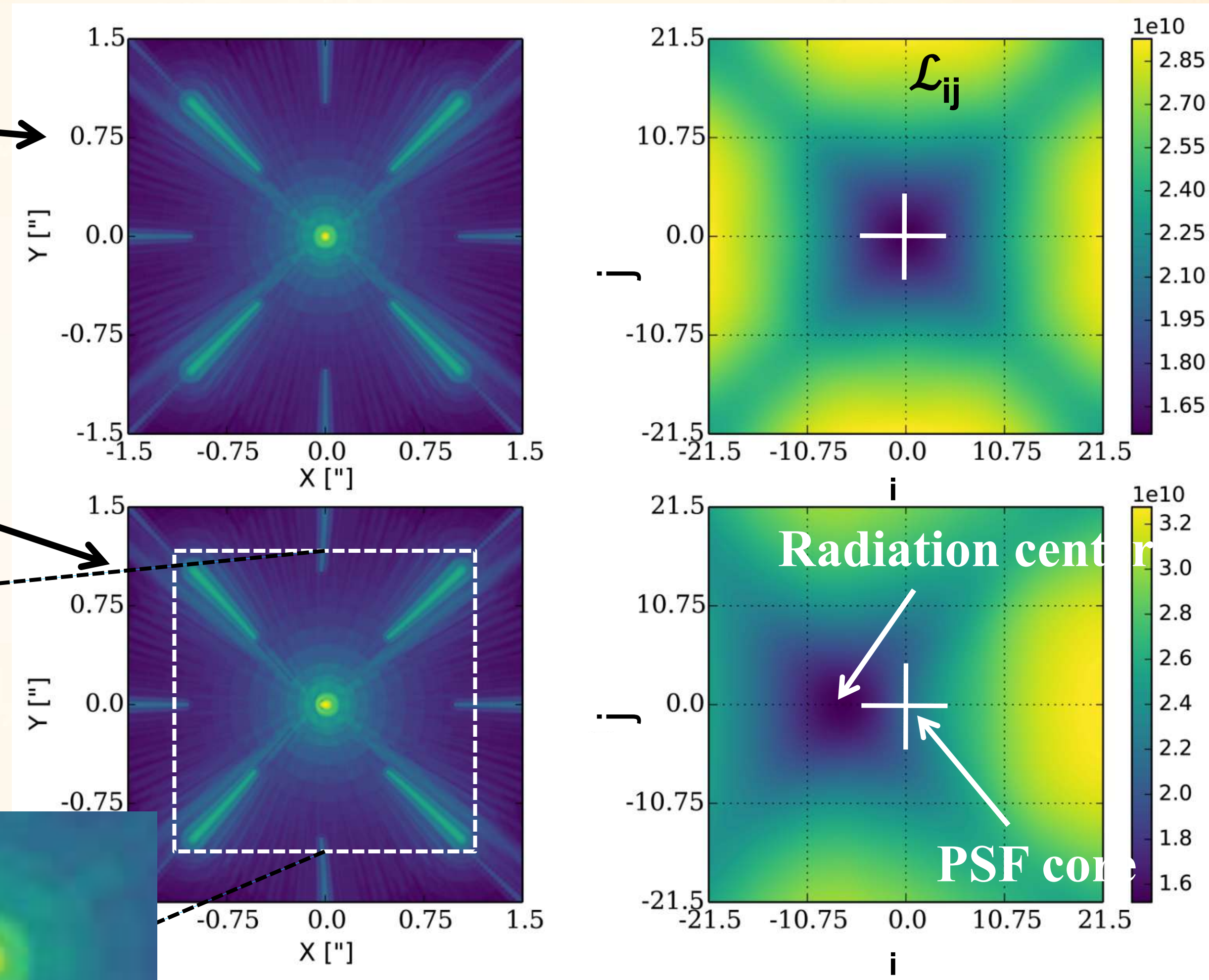
$$L(x_0, y_0) = \sum_{x,y} \left| \mathrm{Im}(x,y) - \mathrm{Im}((x-x_0)\alpha + x_0, (y-y_0)\alpha + y_0) \right|$$

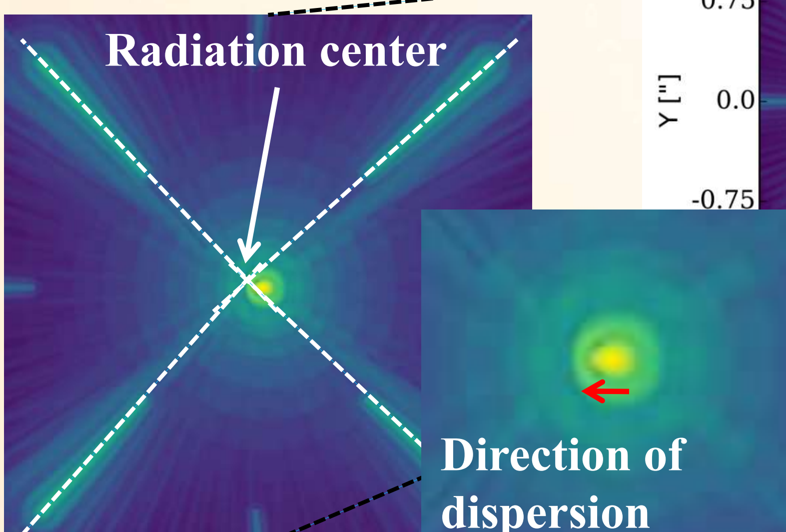
where α is the stretch factor

Radiation center extraction on simulated PSF

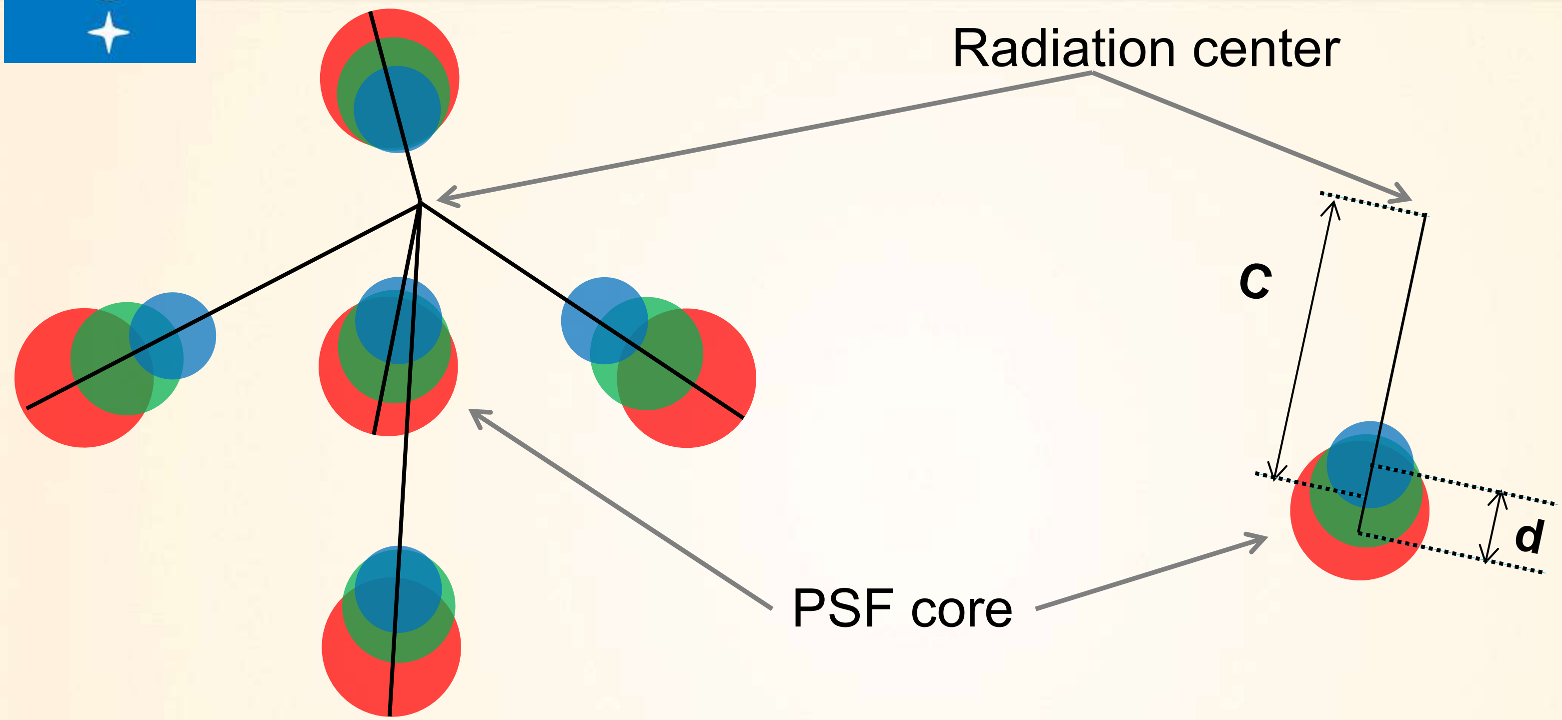
Image with no Dispersion: minimum lies at PSF

PSF with 40 mas Dispersion: minimum lies outside PSF





Relationship between radiation center and dispersion



Using ratio between minimum and maximum wavelength:

$$\frac{C-\frac{d}{2}}{C+\frac{d}{2}} = \frac{const\times\lambda_{min}}{const\times\lambda_{max}}$$

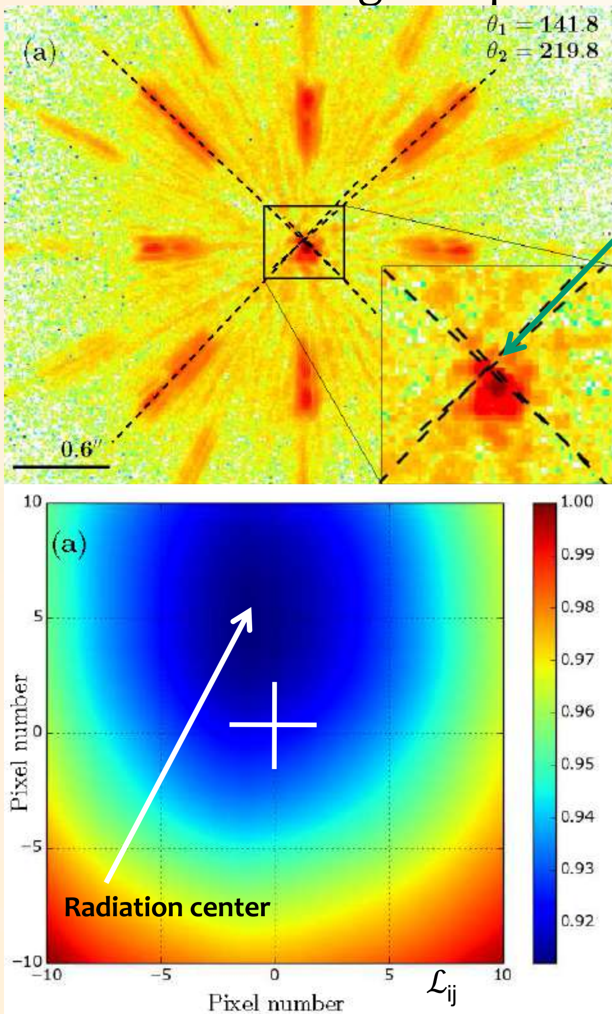
Relationship between offset of radiation center and amount Dispersion:

$$\frac{d}{C} = \frac{2(\lambda_{max}-\lambda_{min})}{\lambda_{max}+\lambda_{min}}$$

On-sky Results

PSFs (y-H band) with satellite speckles

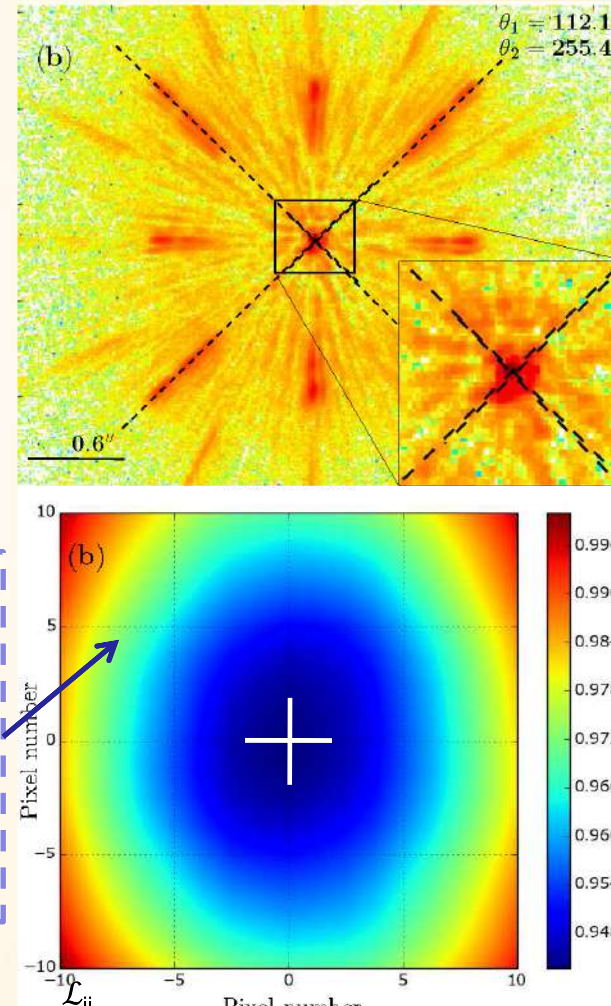
Target: Alpha Ari, apparent magnitude: 2.00, elevation: 85°



Over plotted lines showing speckles don’t point towards the PSF core, which shows presence dispersion

Contour plot: minimum shows the precise location of the radiation center.

PSF location is at (0,0) pixel.

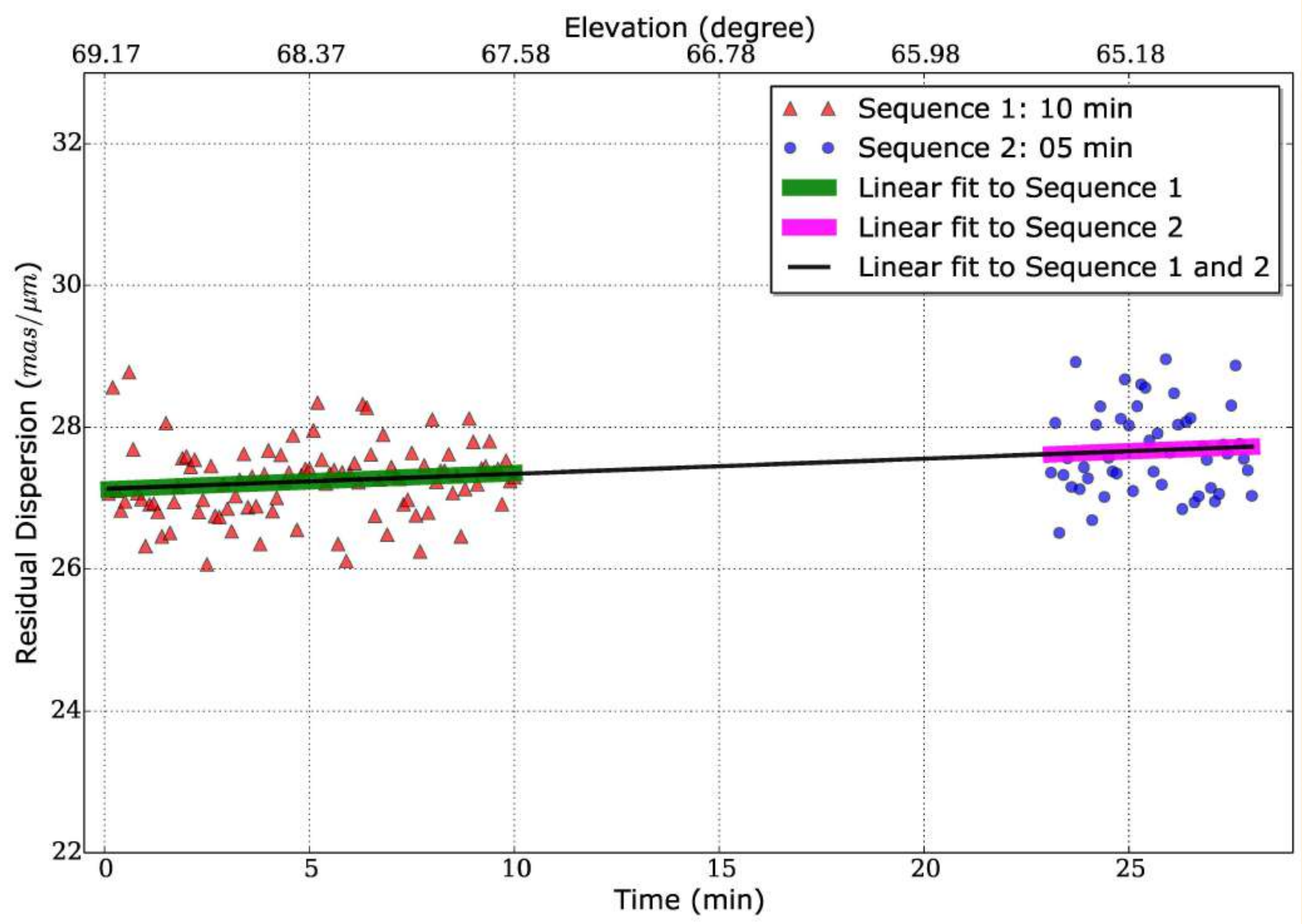


Before Correction

After Correction

Open-loop Residual Dispersion Measurement

Residual dispersion (y-H band) as a function of telescope elevation and time

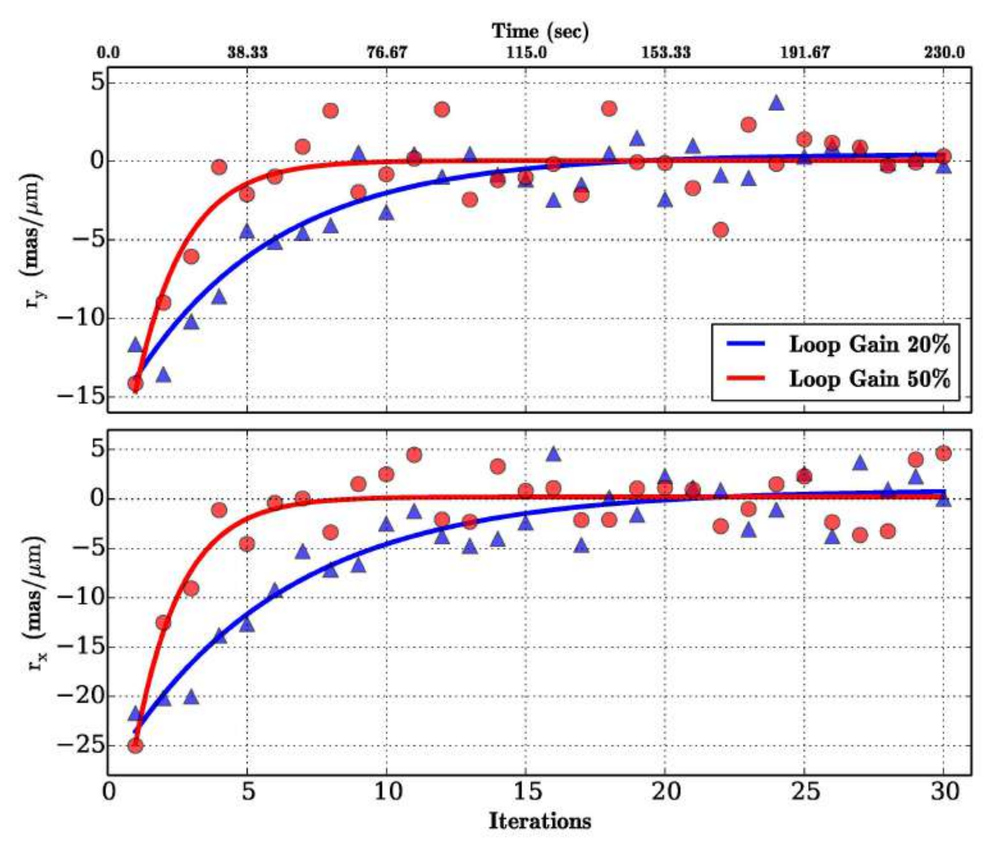


i. During the 30 min observation a small increase in the residual dispersion is observed, because the change in the telescope elevation was not significant.
ii. As long as atmospheric conditions are not varying significantly, correction doesn't need to be applied frequently.

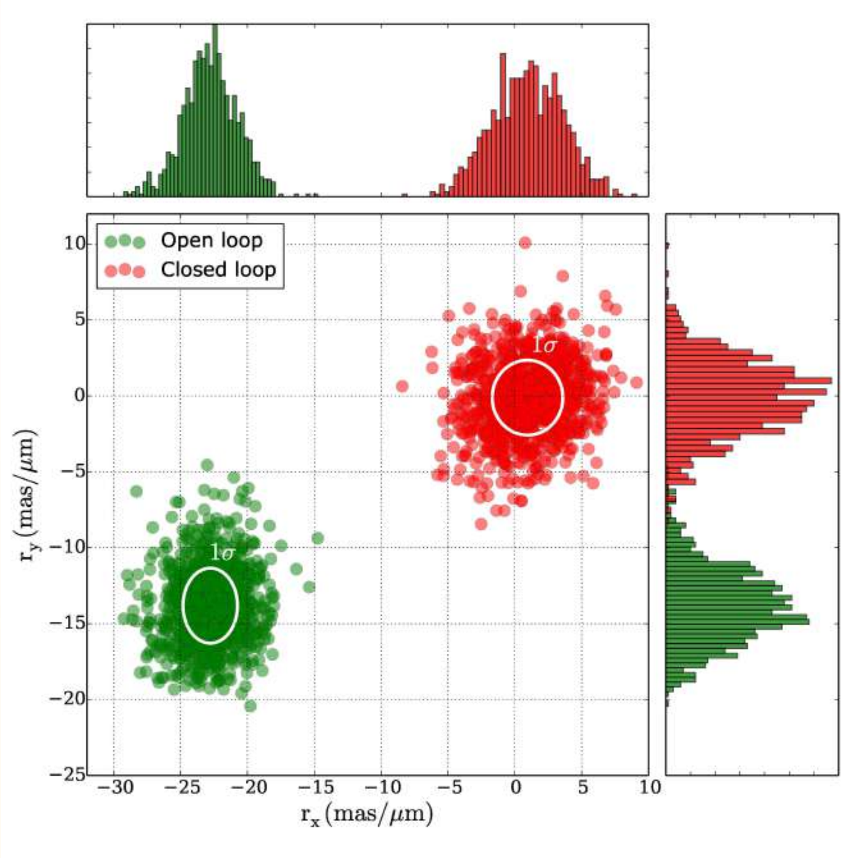
On-sky Closed-loop Results

Target: Beta Andromedae, Apparent magnitude 2.05, Date: 2016/09/19
Telescope elevation: 65°

Closed-loop correction of residual dispersion ($r = r_x + r_y$) for two loop gains of 20% and 50%



Residual dispersion in camera plane, before and after closing the loop



On-sky Results

Target: Beta Andromedae, apparent magnitude 2.05
Date: 2016/09/19
Telescope elevation: 65^0

Residual atmospheric dispersion in y-H band

Before Correction	After Correction
26.64 ± 0.07 mas/μm	0.95 ± 0.08 mas/μm

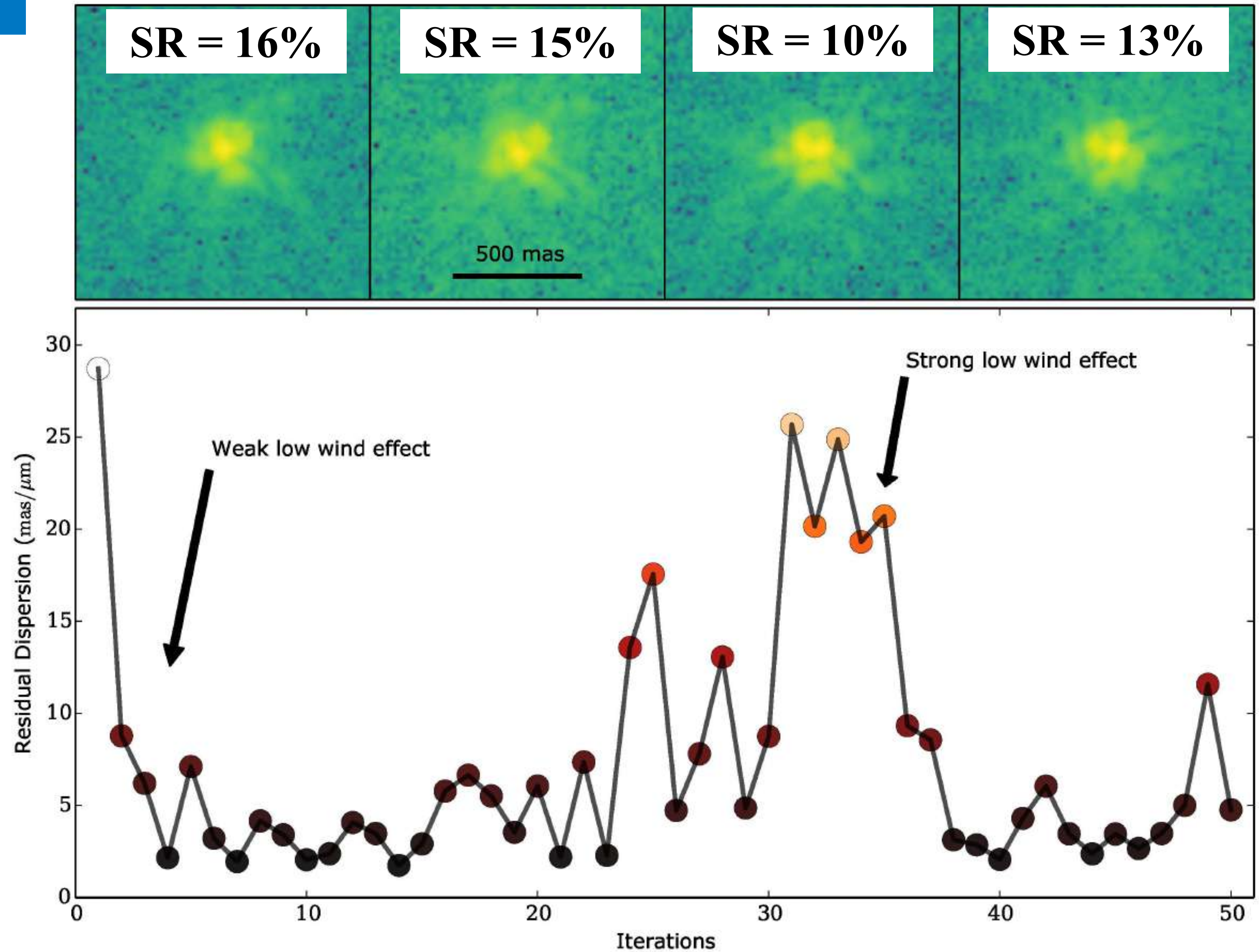
Average of 1000 measurements.
Exposure time: 50 μsec/ measurement

Standard deviation of 1000 measurement

In **H**-band residual dispersion (elongation in PSF) reduced from:
7.99 ± 0.02 mas to 0.28 ± 0.02 mas

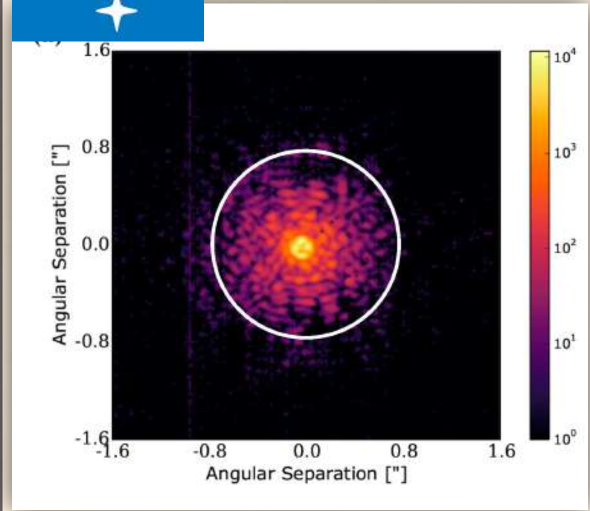
Our requirement: < 1 mas elongation in PSF (H-band)

Closed-loop Correction in the Presence of Strong Low-order Aberration

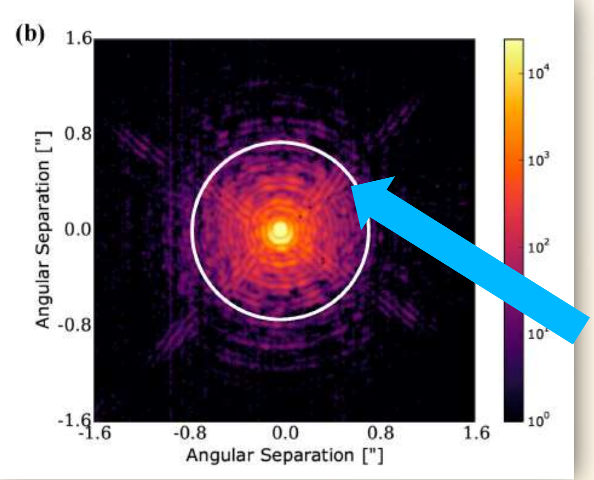


Flux Suppression Using Coronagraph

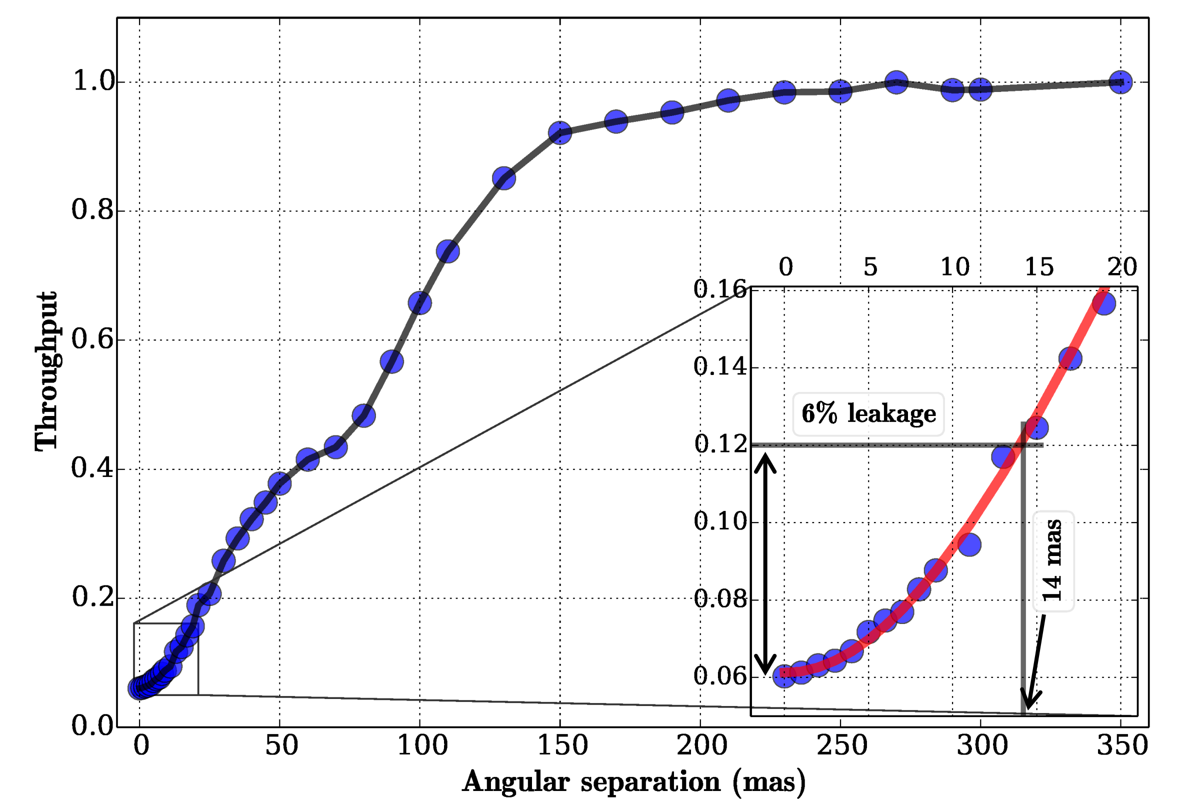
Lab Measurements for Vortex Coronagraph



Aligned vortex coronagraph

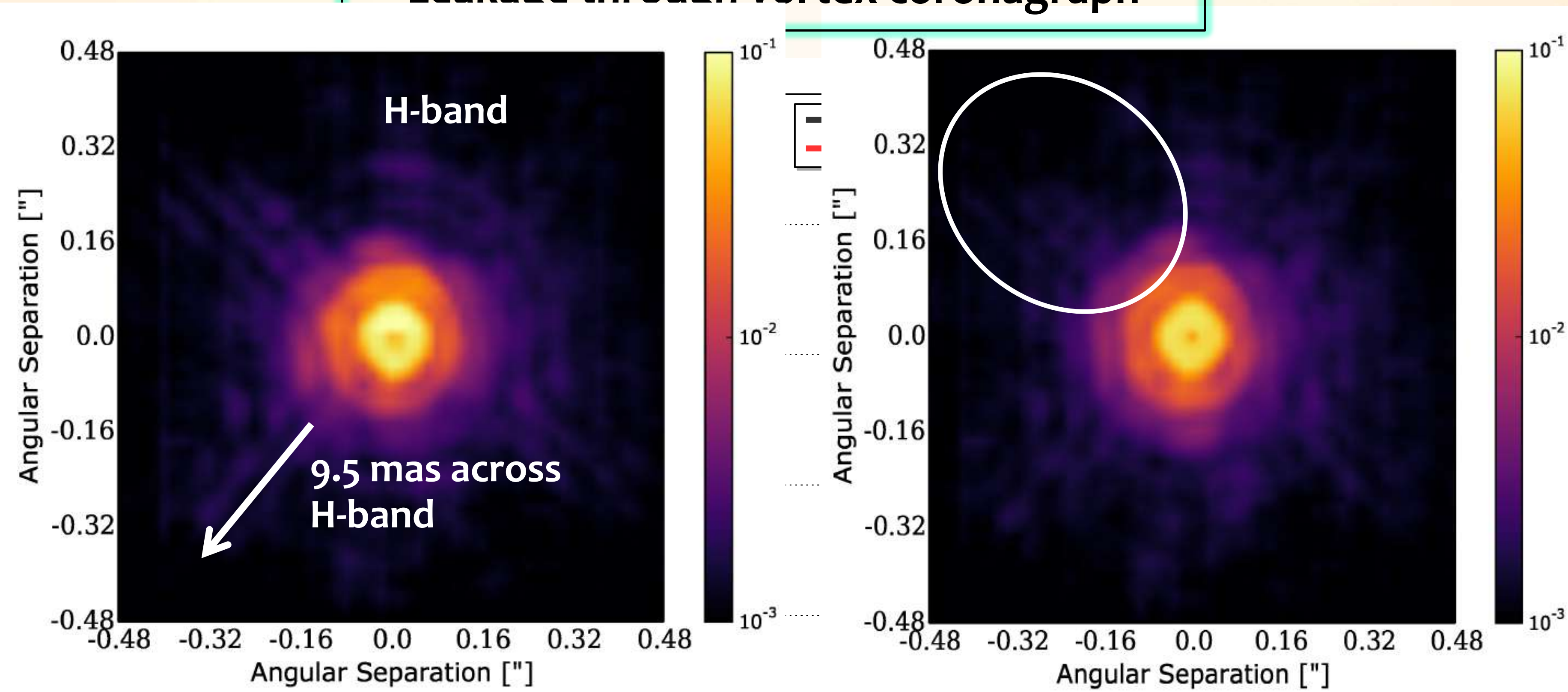


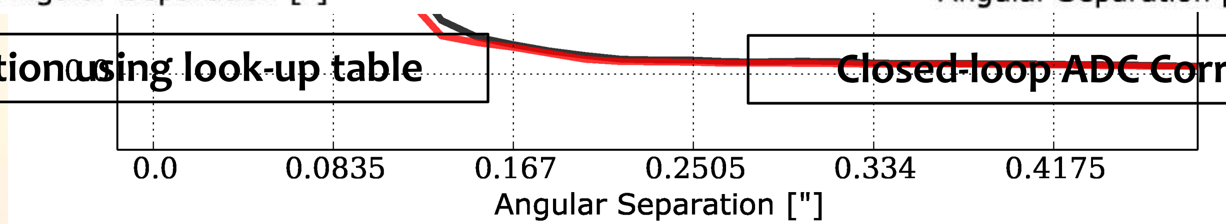
Vortex coronagraph 40 mas tip



On-sky Results

Leakage through vortex coronagraph



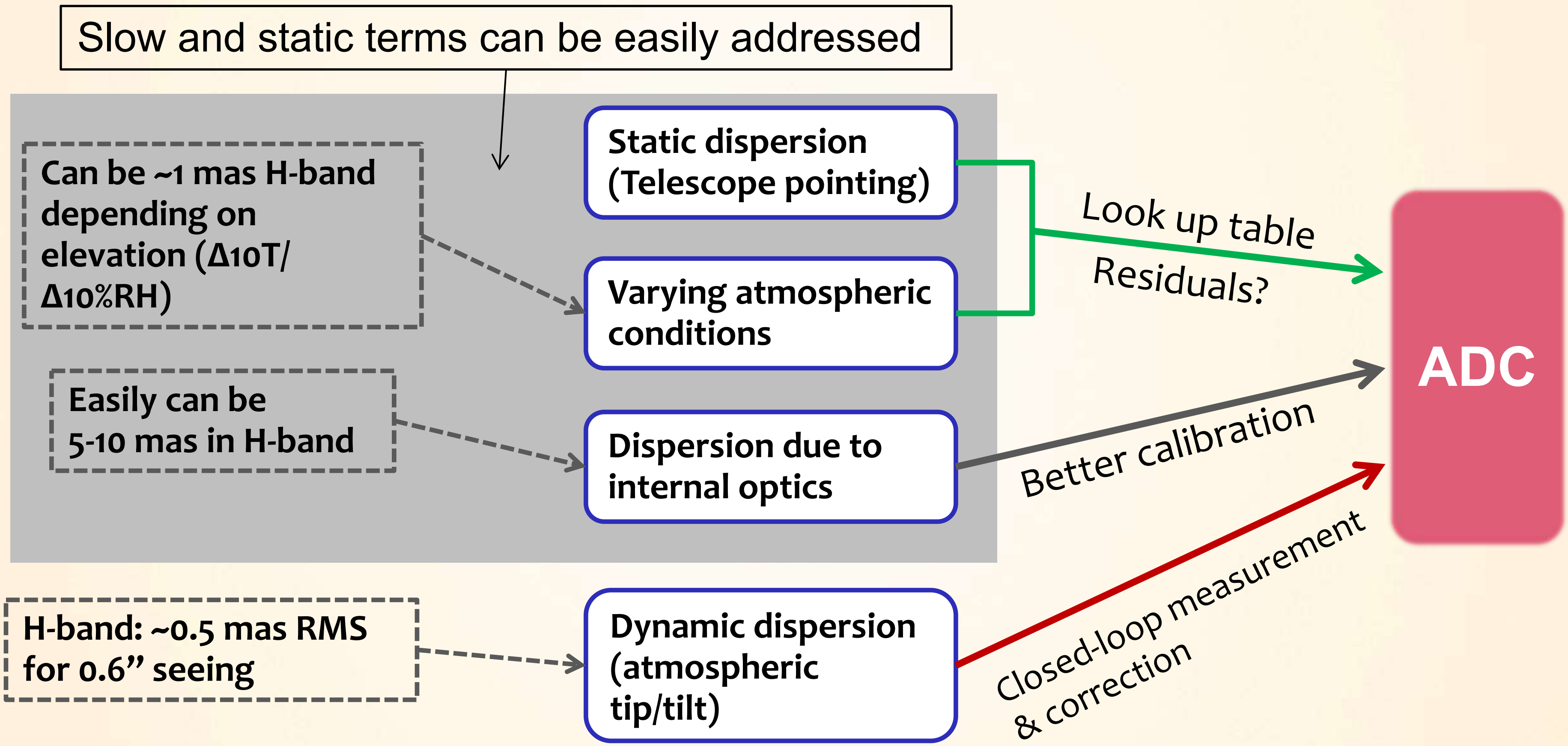


ADC correction using look-up table

Closed-loop ADC Correction

Wavefront correction using PyWFS and LLOWFS was applied

Various Sources of Dispersion



Thank you