Making it up to E(A)LT's: extremely (adaptive) large telescopes

Carlos M Correia

Special thanks to my direct collaborators: Jean-François Sauvage, Benoit Neichel, Thierry Fusco, Olivier Beltramo-Martin, Charlotte Bond, Yoshito Ono
and the HARMONI consortium

Jan 2019

LAM LABORATOIRE D'ASTROPHYSIQUE DE MARSEILLE
extra
Aix*Marseille université
A*Midex Initiative d'excellence Aix-Marseille

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-or-

striving to make stable observations when everything else varies…

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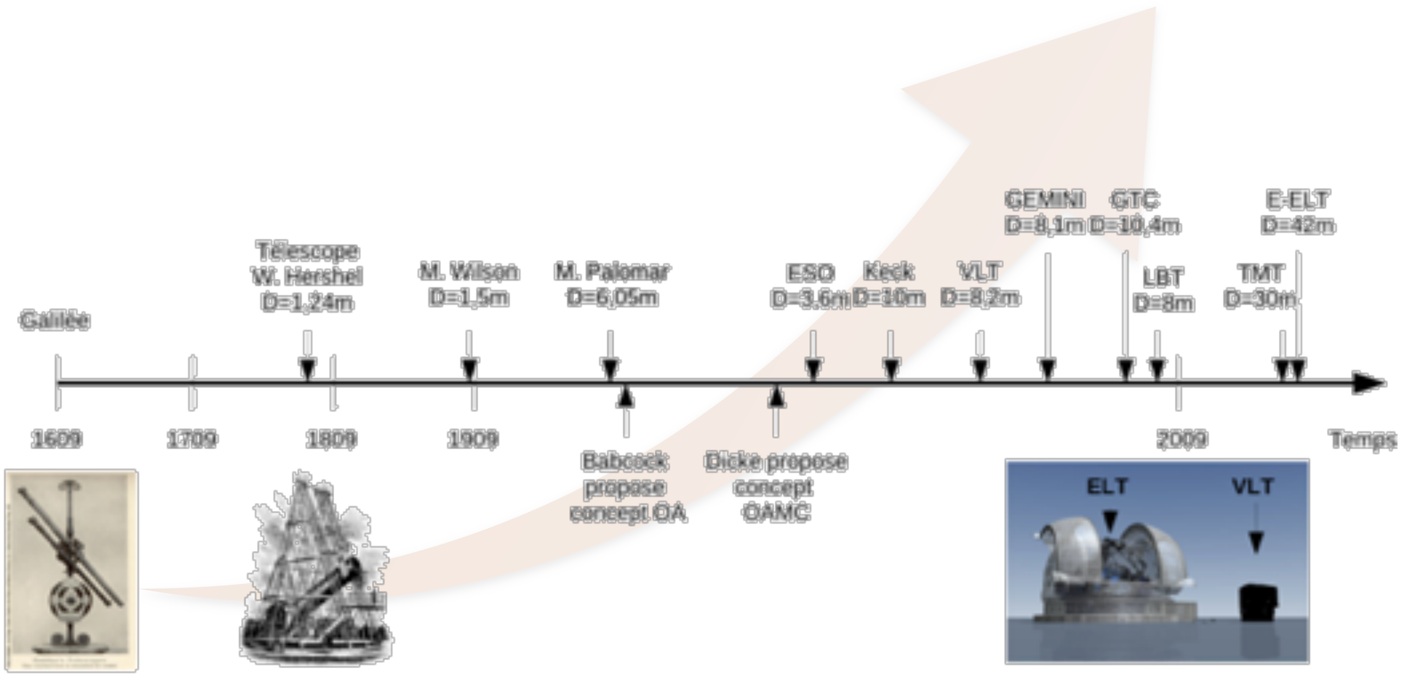
Outline

- Going larger, going faster, doing it better…
  - some of the expected capabilities of GSMTs
- Getting it working in the 1st place
  - Known issues (amongst the unknown…)
- HARMONI
  - 1st light IFU @ ELT
- Putting it all together
  - Scaling it up, nothing simpler!
- How to make sense of the data?
  - Custom data-reduction

#1- Going larger, going faster, doing it better…

Exponential growth…



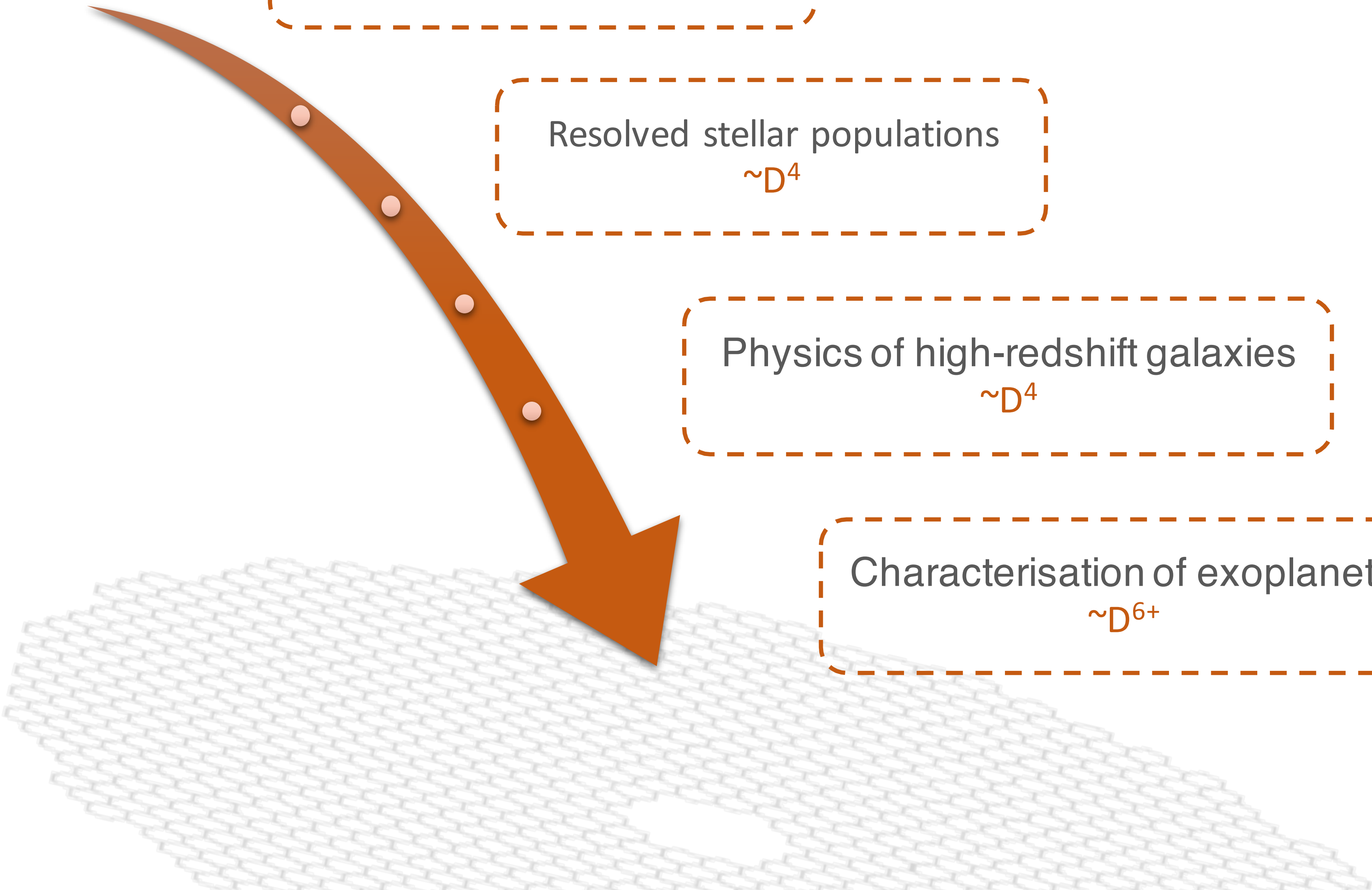
New worlds, new horizons... new telescopes

Cosmic expansion
$\sim D^2$

Resolved stellar populations
$\sim D^4$

Physics of high-redshift galaxies
$\sim D^4$

Characterisation of exoplanets
$\sim D^{6+}$



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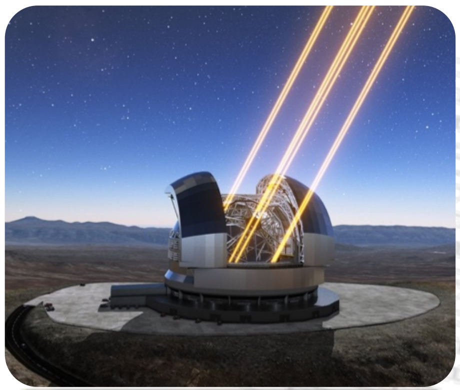
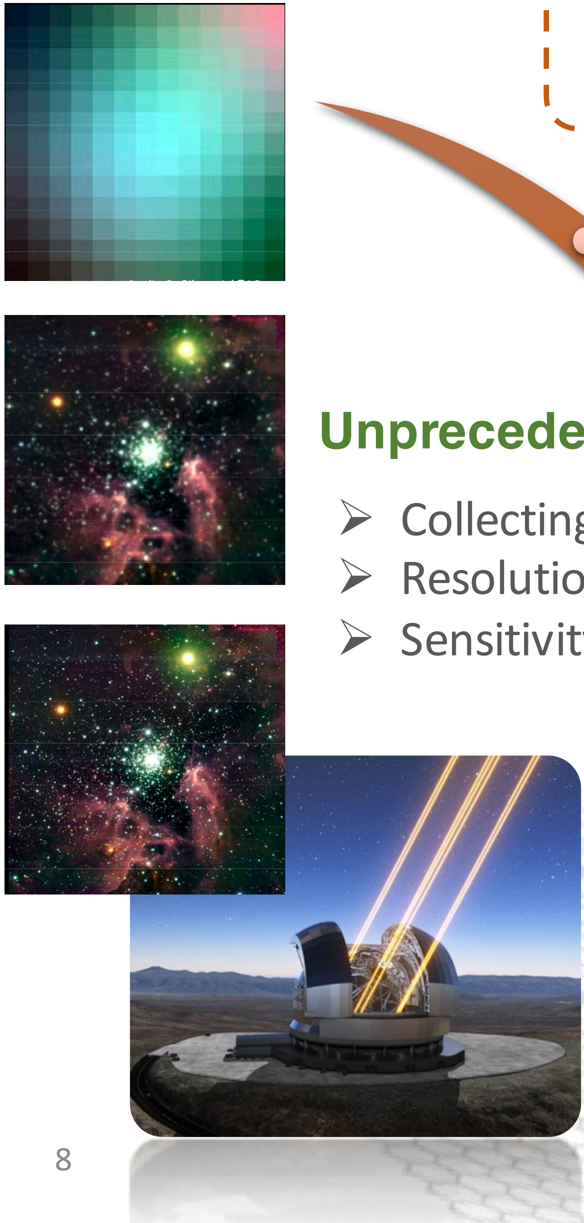
Key Science Drivers
ELT Reference Mission
Prospective INSU
Decadal Survey



ELT: European Extremely Large Telescope

New worlds, new horizons… new telescopes



Unprecedented

- Collecting power
- Resolution
- Sensitivity

Cosmic expansion
$\sim D^2$

Resolved stellar populations
$\sim D^4$

Physics of high-redshift galaxies
$\sim D^4$

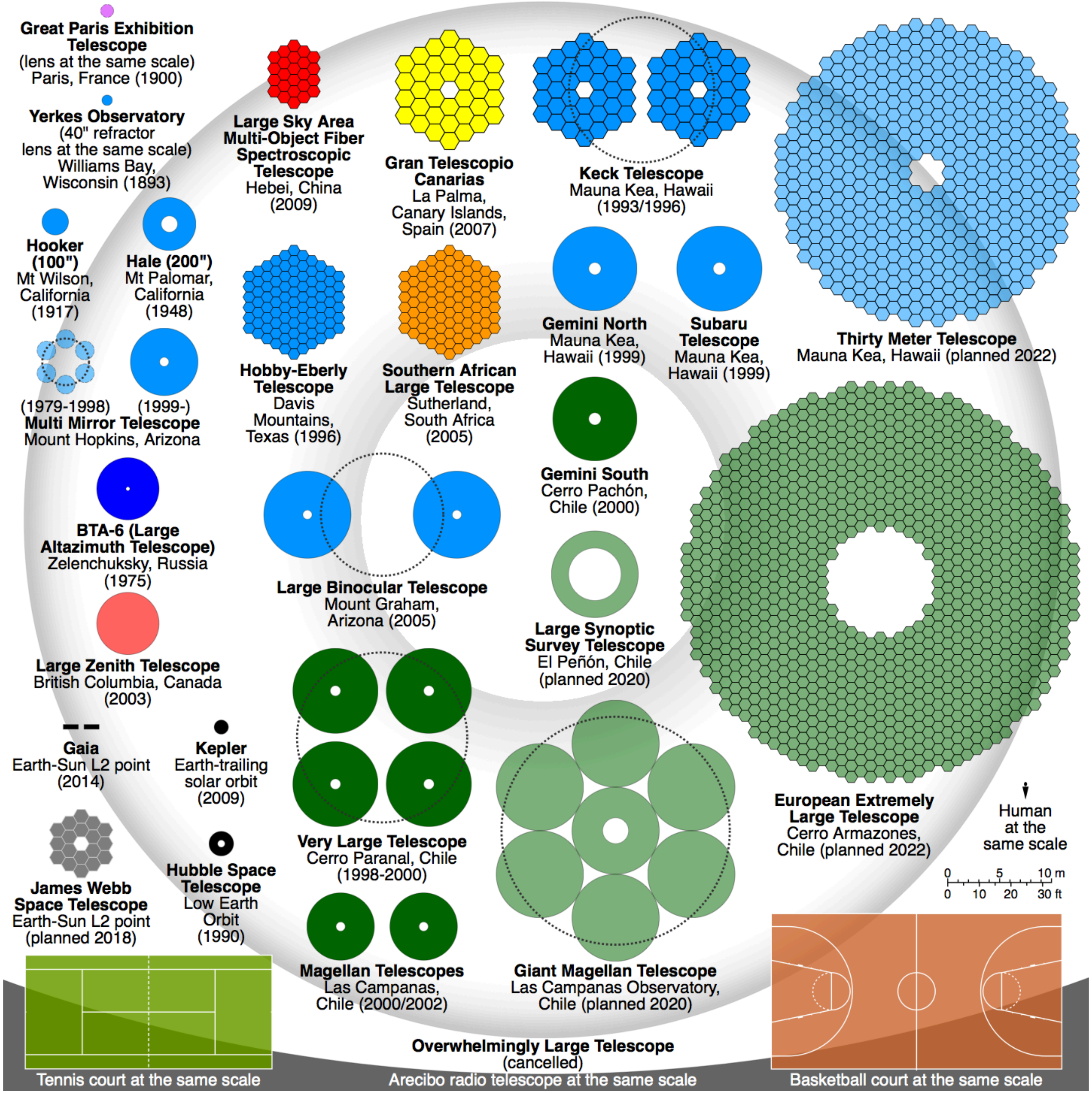
Characterisation of exoplanets
$\sim D^{6+}$

Key Science Drivers

ELT Reference Mission
Prospective INSU
Decadal Survey

ELT: European Extremely Large Telescope

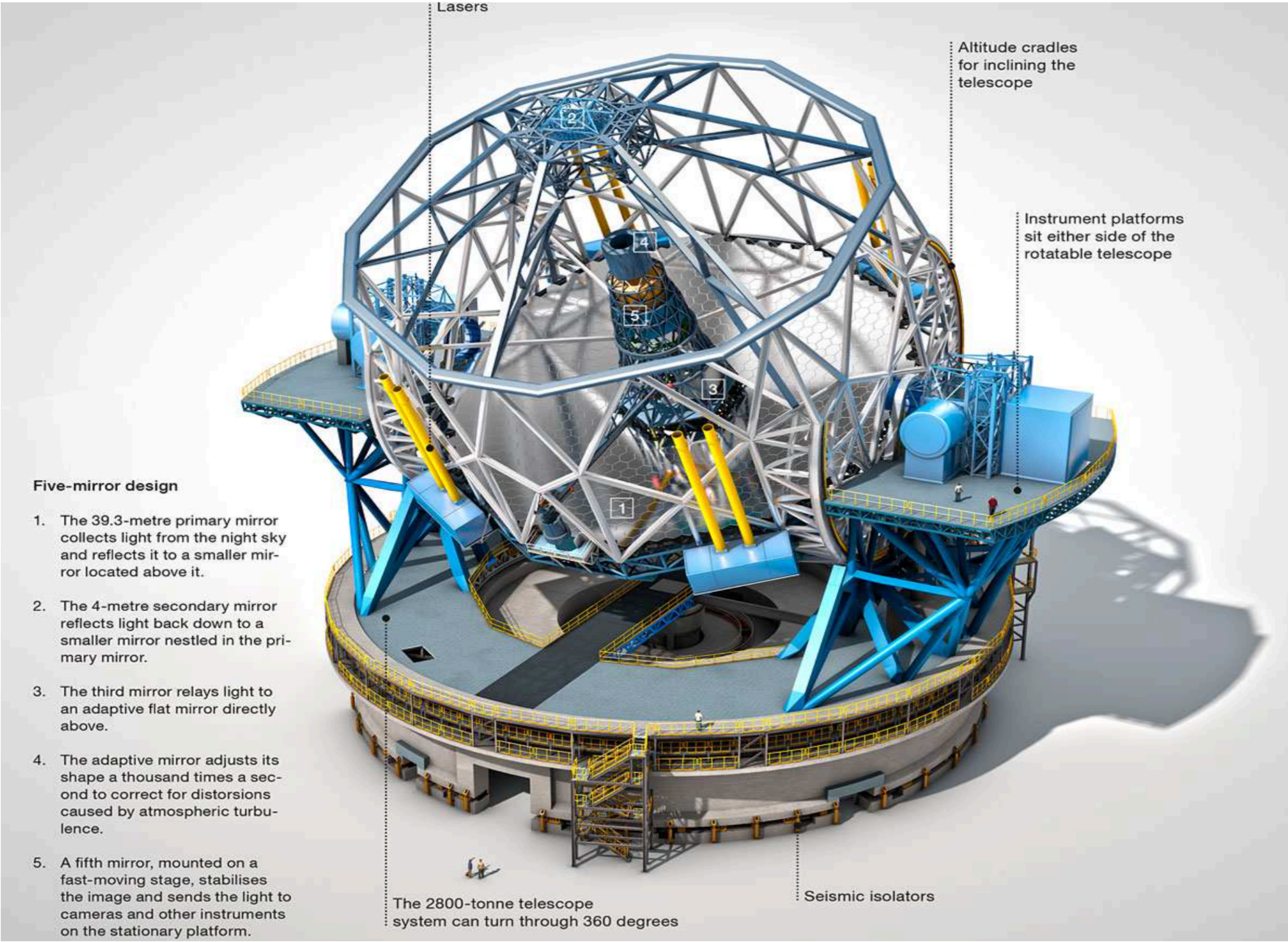
What *Extremely Large* means?


Great Paris Exhibition Telescope
(lens at the same scale)
Paris, France (1900)
Yerkes Observatory
(40" refractor
lens at the same scale)
Williams Bay,
Wisconsin (1893)
Hooker (100")
Mt Wilson, California (1917)
Hale (200")
Mt Palomar, California (1948)
(1979-1998)
(1999-)
Multi Mirror Telescope
Mount Hopkins, Arizona
BTA-6 (Large Altazimuth Telescope)
Zelenchuksky, Russia
(1975)
Large Zenith Telescope
British Columbia, Canada
(2003)
Gaia
Earth-Sun L2 point
(2014)
Kepler
Earth-trailing solar orbit
(2009)
James Webb Space Telescope
Earth-Sun L2 point
(planned 2018)
Hubble Space Telescope
Low Earth Orbit
(1990)
Large Sky Area Multi-Object Fiber Spectroscopic Telescope
Hebei, China
(2009)
Gran Telescopio Canarias
La Palma, Canary Islands, Spain (2007)
Keck Telescope
Mauna Kea, Hawaii
(1993/1996)
Thirty Meter Telescope
Mauna Kea, Hawaii (planned 2022)
Hobby-Eberly Telescope
Davis Mountains, Texas (1996)
Southern African Large Telescope
Sutherland, South Africa
(2005)
Gemini North
Mauna Kea, Hawaii (1999)
Subaru Telescope
Mauna Kea, Hawaii (1999)
Gemini South
Cerro Pachón, Chile (2000)
Large Binocular Telescope
Mount Graham, Arizona (2005)
Large Synoptic Survey Telescope
El Peñón, Chile
(planned 2020)
Very Large Telescope
Cerro Paranal, Chile
(1998-2000)
Magellan Telescopes
Las Campanas, Chile (2000/2002)
Giant Magellan Telescope
Las Campanas Observatory, Chile (planned 2020)
European Extremely Large Telescope
Cerro Armazones, Chile (planned 2022)
Human at the same scale
0 5 10 m
0 10 20 30 ft
Overwhelmingly Large Telescope
(cancelled)
Tennis court at the same scale
Arecibo radio telescope at the same scale
Basketball court at the same scale

#2 - Getting the telescope right…

Towards a working telescope delivering diffraction-limited observations…

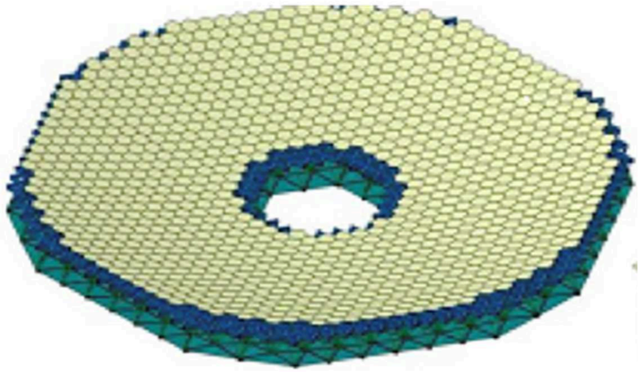
Who heard challenges?

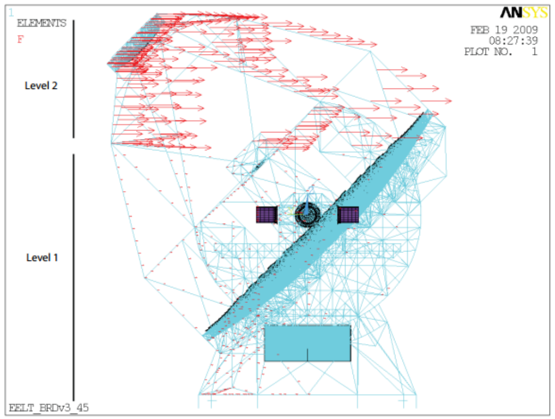


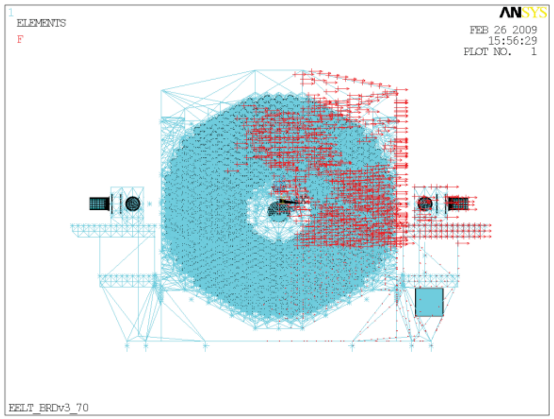
Credits: ESO

ELTs are too large to operate as conventional seeing-limited telescopes

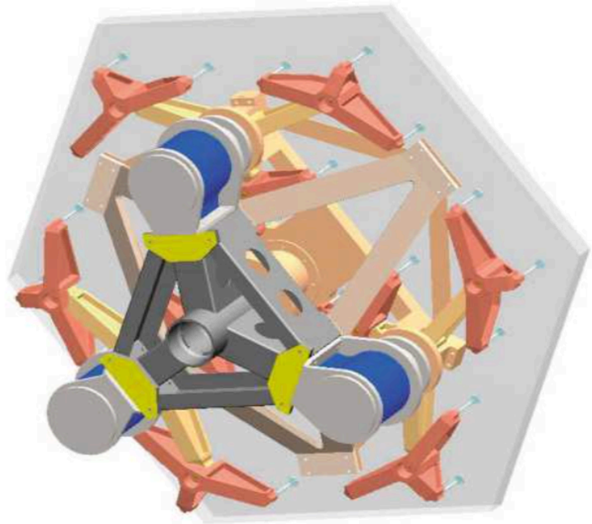
- Active Optics
  - Correct slowly varying opto-mechanical effects
    ~800 segments + 133 spares
    1.4 m wide and 5 cm thick
- Wind-load on the main structure
  - resonances (vibrations)
- **Adaptive Optics**



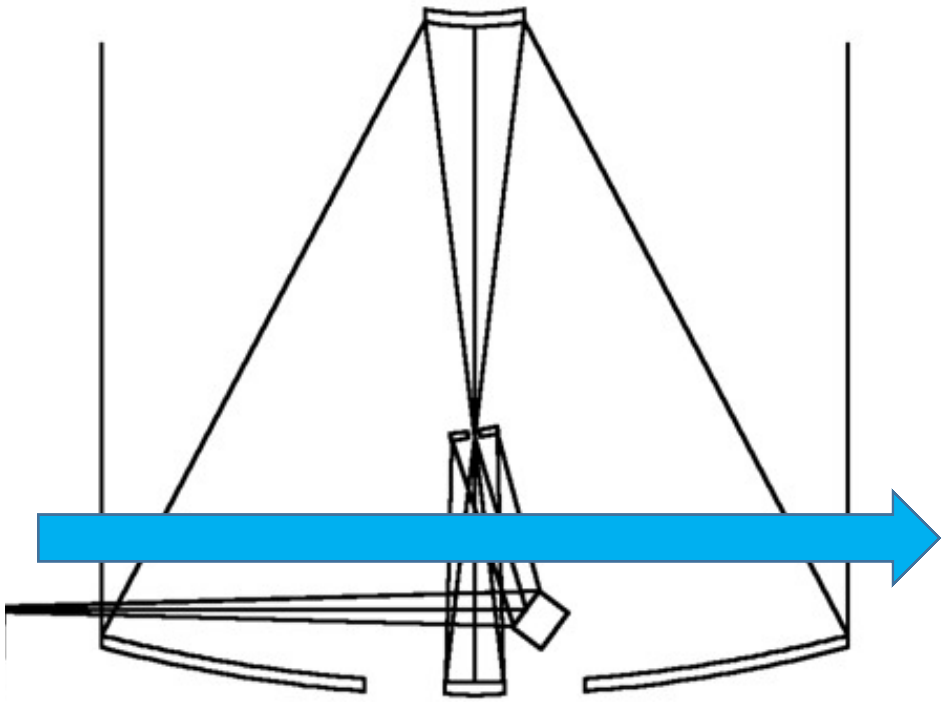


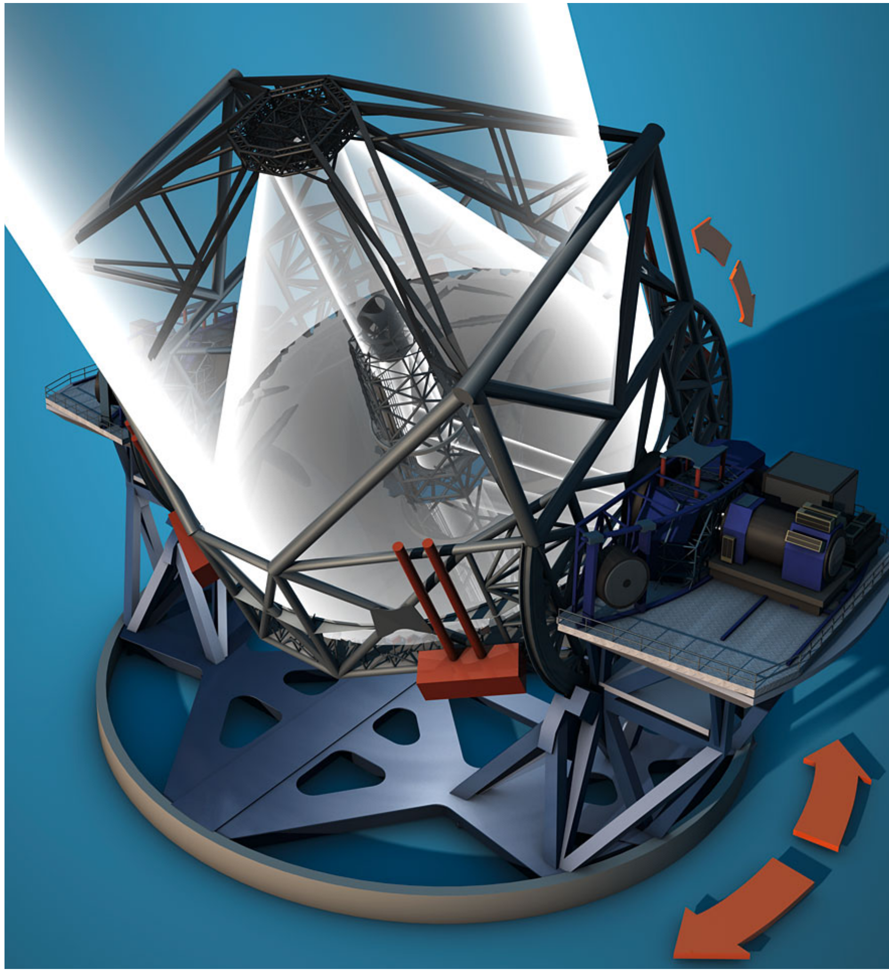


Courtesy: B. Sedghi



Active Optics: Structure-induced turbulence





5km

00m

00m

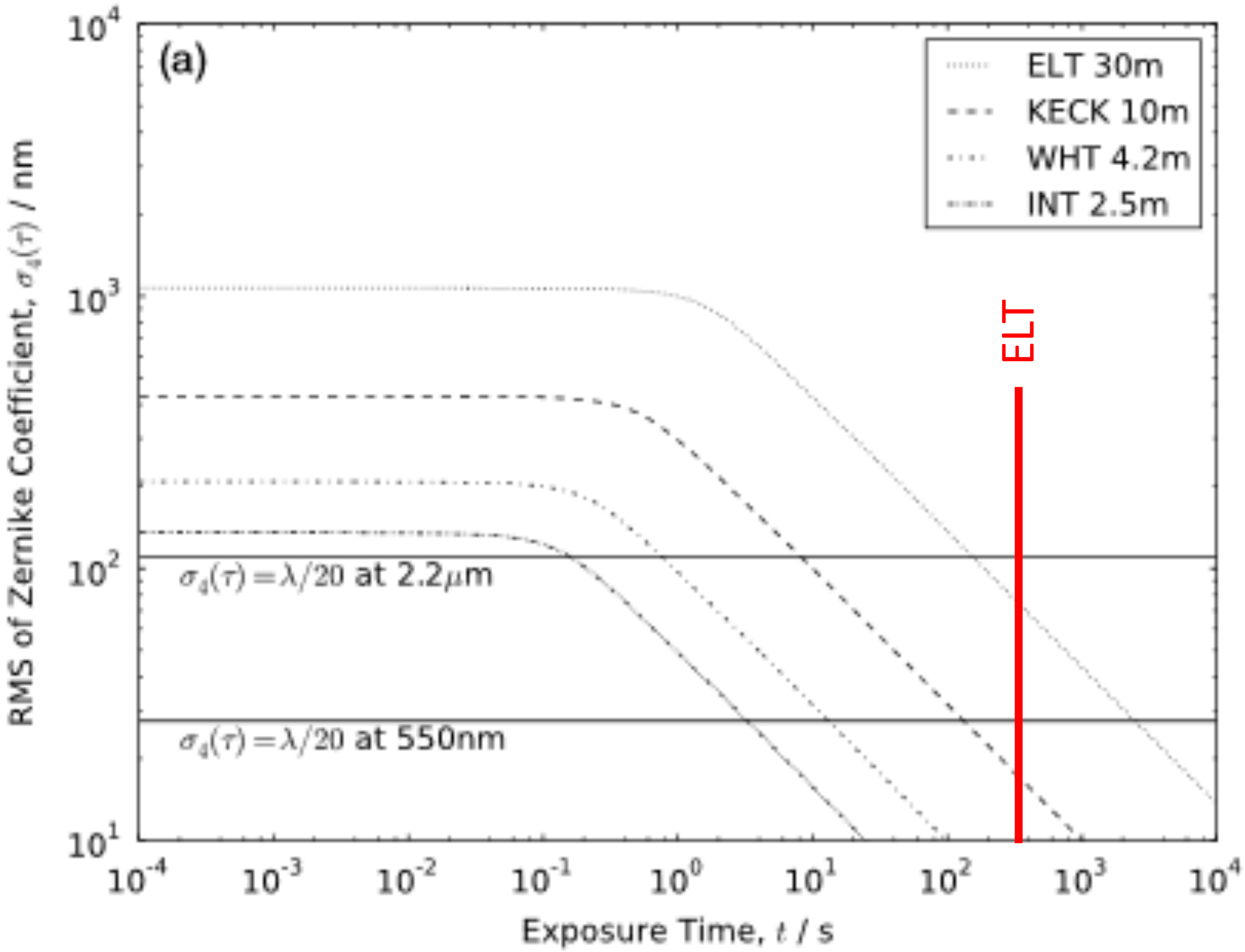
m

.5km

Adapted from Tim Morris

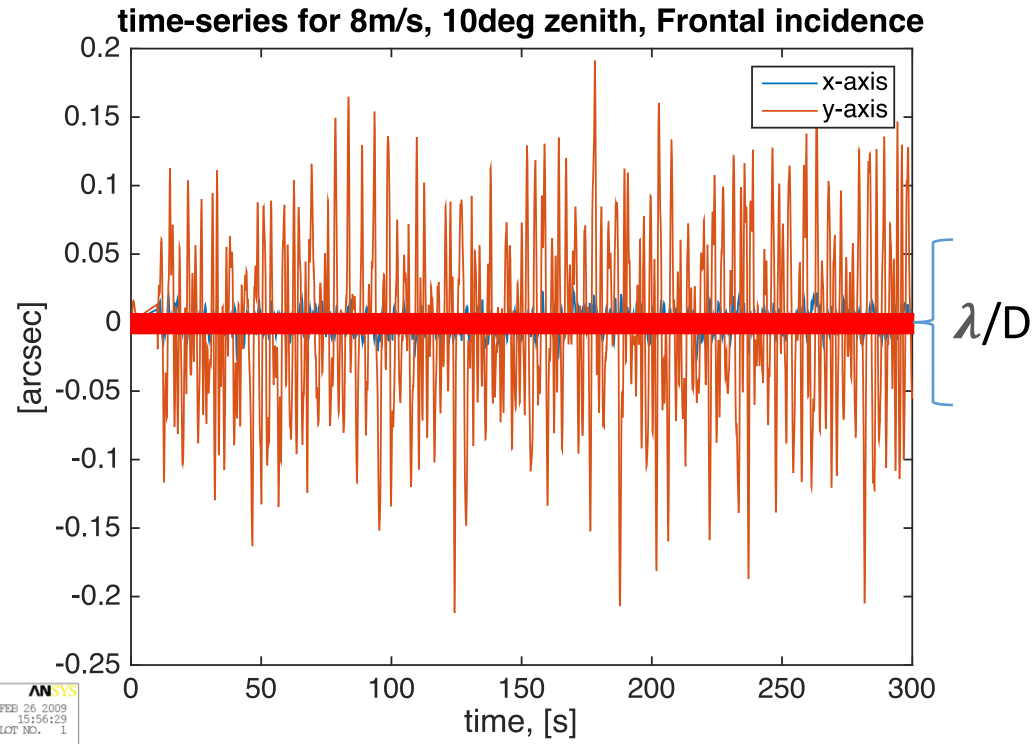
Active Optics

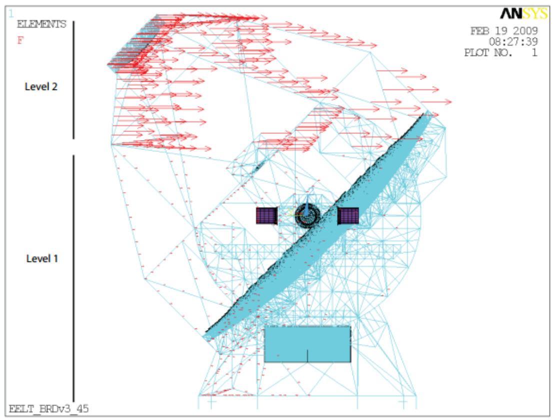
Exposure time required vs RMS focus error for telescopes of various diameters [Gordon et al, Appl. Opt. 50, 27, 2011]

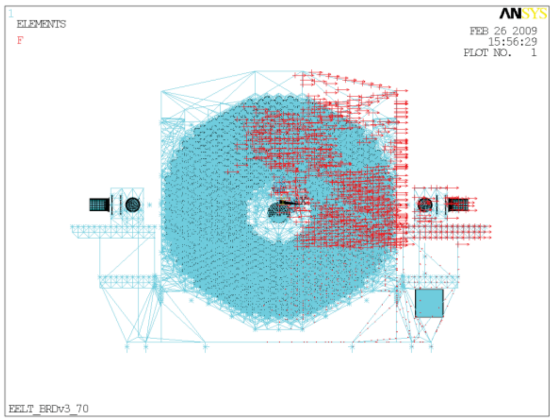


Wind-load on main structure

- Wind load can be 2 orders of magnitude larger than diffraction limit (10mas v. 270 mas rms)
- Real-time correction is needed at all times to counter this nefarious effect



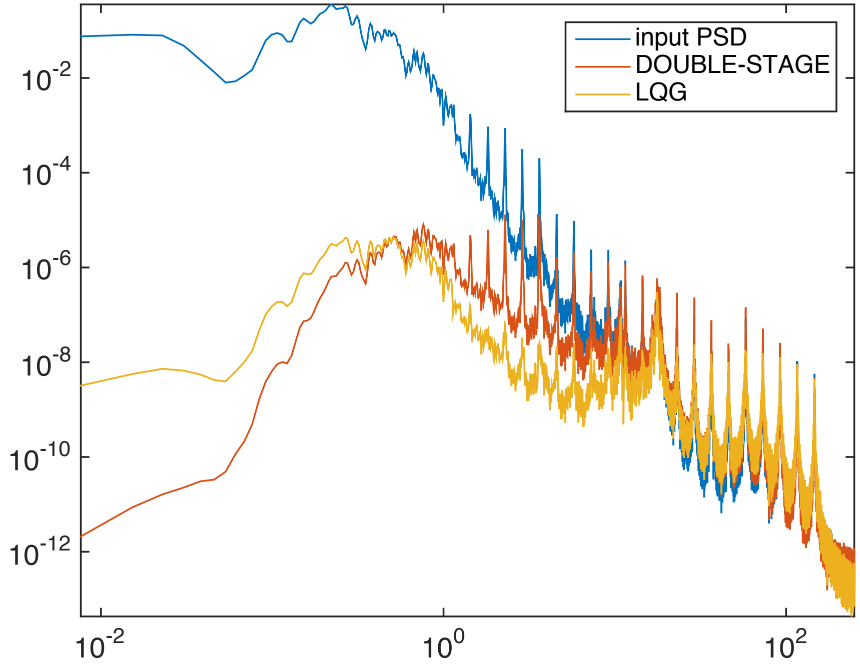


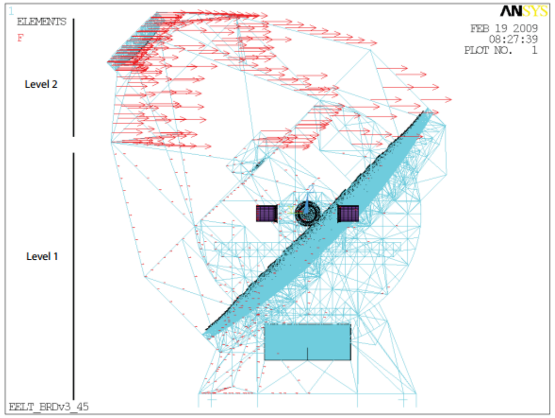


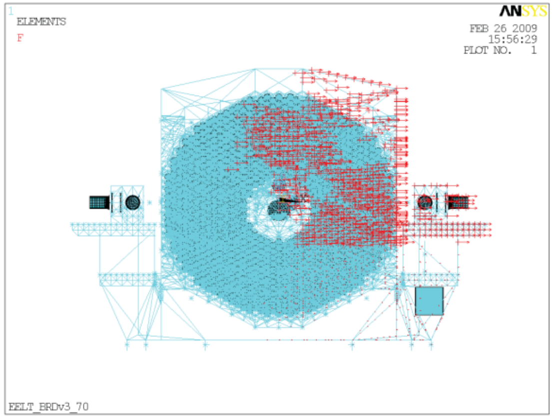
Courtesy: B. Sedghi

Wind-load on main structure

- Wind load can be 2 orders of magnitude larger than diffraction limit (10mas v. 270 mas rms)
- Real-time correction is needed at all times to counter this nefarious effect
- Vibrations may appear (and be quite numerous)





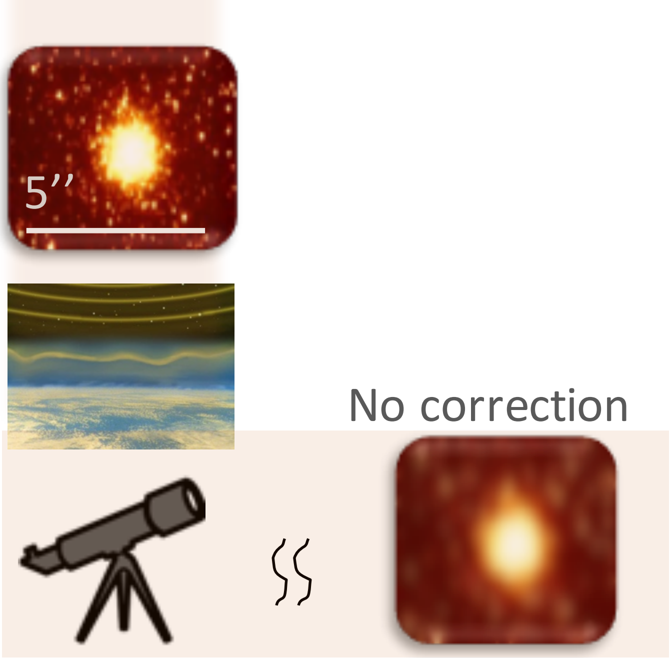


Courtesy: B. Sedghi

Development of specialised damping strategies

Adaptive Optics = resolution + sensitivity

AO = diffraction-limited observations



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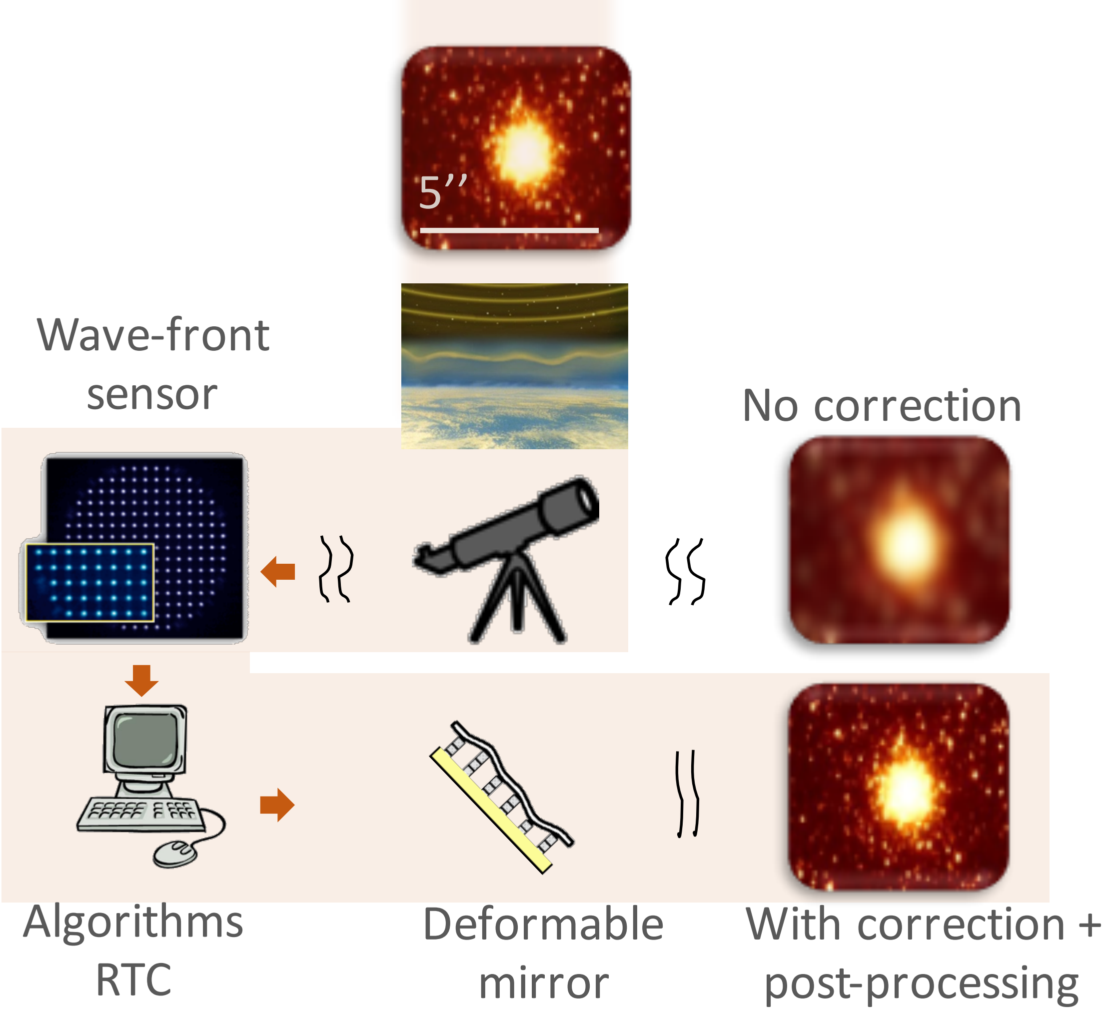

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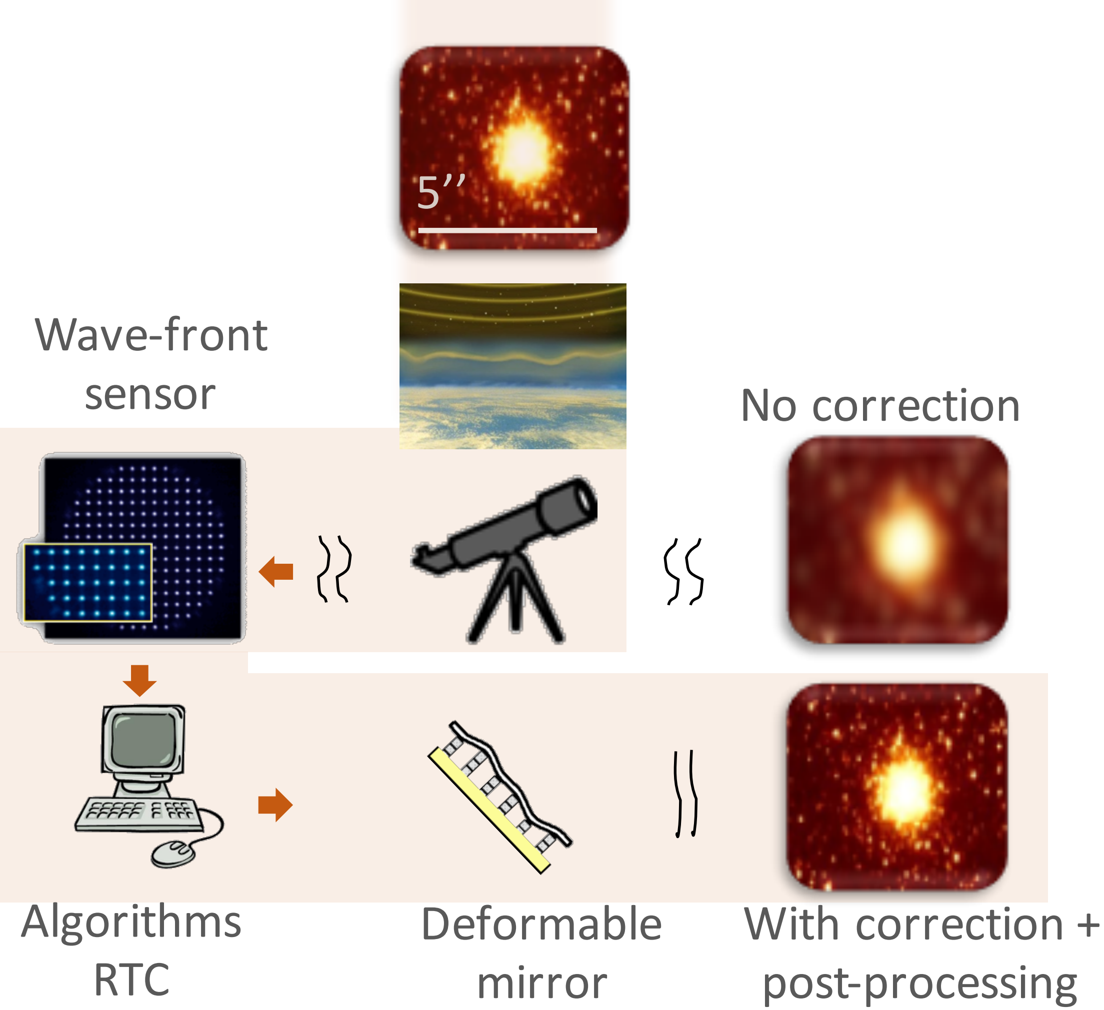
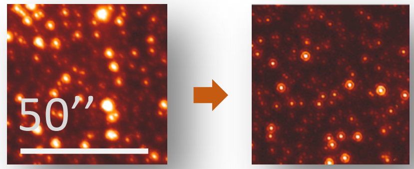


Scientific goals

- 10x corrected field 5'' → 50''



3D tomography

- 10x sky coverage 5% → 50%

Laser Guide Stars

- 10-100x contrast $10^{-6} \rightarrow 10^{-8}$

Nanometric control

Adaptive Optics = resolution + sensitivity

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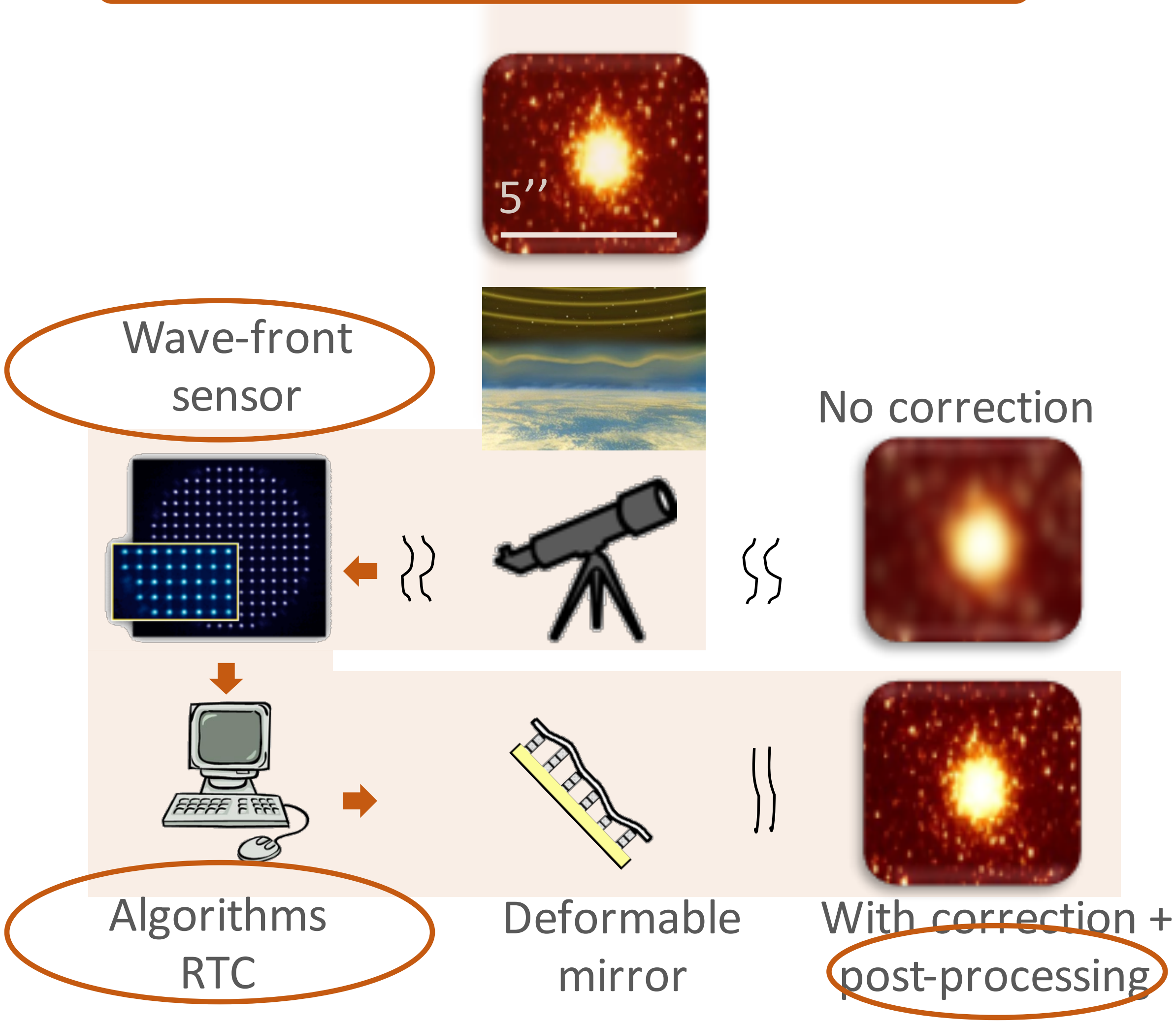

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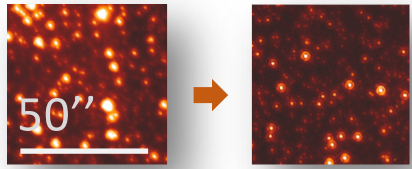


3D tomography

- 10x sky coverage 5% → 50%

Laser Guide Stars

- 10-100x contrast $10^{-6} \rightarrow 10^{-8}$

Nanometric control

ELT= 100% AO

- 10-100x # degrees of freedom

Adaptive Optics: the beating heart of ELTs

Adaptive Giant Segmented Mirror Ground-based Telescopes

Coronagraphic spectro-imagers

>10-8 contrast @ 0.1”

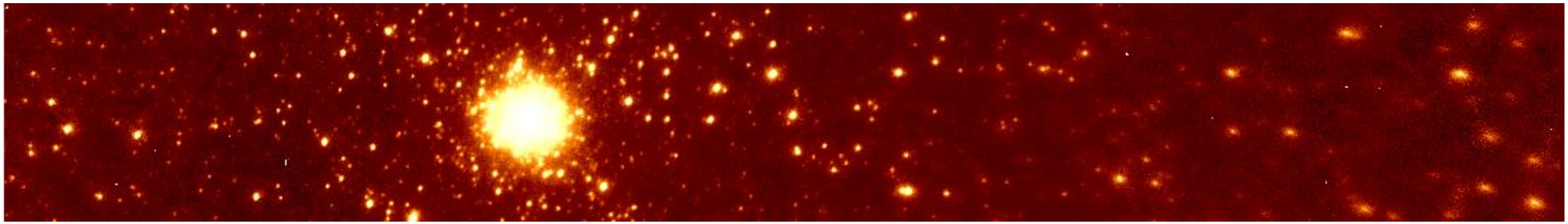
☛ **Ultimate wave-front correction**

Wide-field spectro-imagers

Object kinematics/morphology m~28

☛ **Observe anywhere on the sky**

YET AO works close to bright guide stars



Adaptive Optics: the beating heart of ELTs

↔ **Adaptive Giant Segmented Mirror Ground-based Telescopes**

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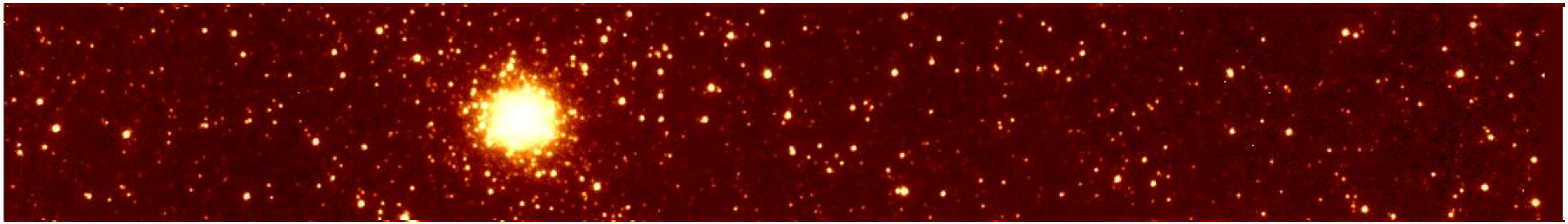


Challenges ⟶ **Key AO research drivers:**

- ➤ Tomography → x10 field
- ➤ Laser guide-stars → 10x sky-coverage
- ➤ Nanometric wave-front precision → 10-100x contrast
- ➤ Very large number of degrees-of-freedom

Sensitivity

Sky-coverage

Data-reduction

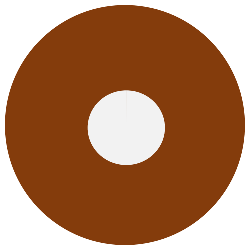
AO is the beating heart of ELTs

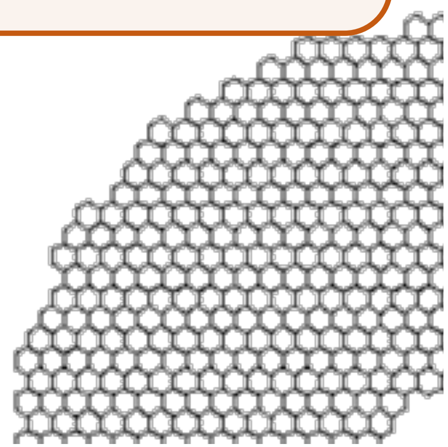
AO mode	FoV	resolution	science case	instrument
Ex-AO	5''	<10mas	exo-planets	HARMONI, PCS, METIS
LTAO	30''	>5mas	Extra-galactic black holes	
SCAO	10''	10mas	Young stars	MICADO, HIRES
MCAO	1'	20mas	Stellar populations	
MOAO	5'	75mas	Galaxy dynamics z<5	MOSAIC
GLAO	10'	100mas	Galaxies z>10	

Better
- *Regular* diffraction-limited observations over larger FoV

Larger
- From 10s -1000s degrees of freedom

At all times
- All instruments are AO assisted



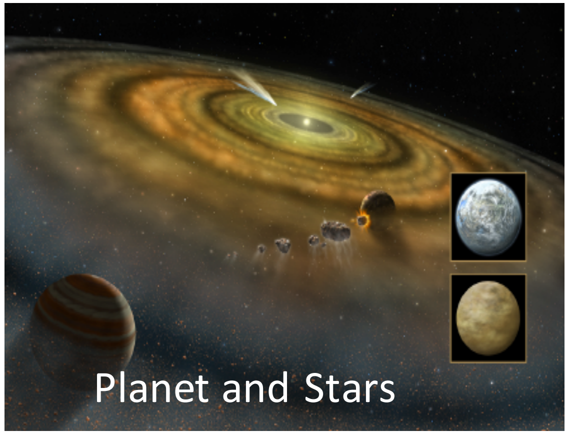


C. M. Correia et al, Making it up to E(A)LLT's, MPIA-Heidelberg, January 2019

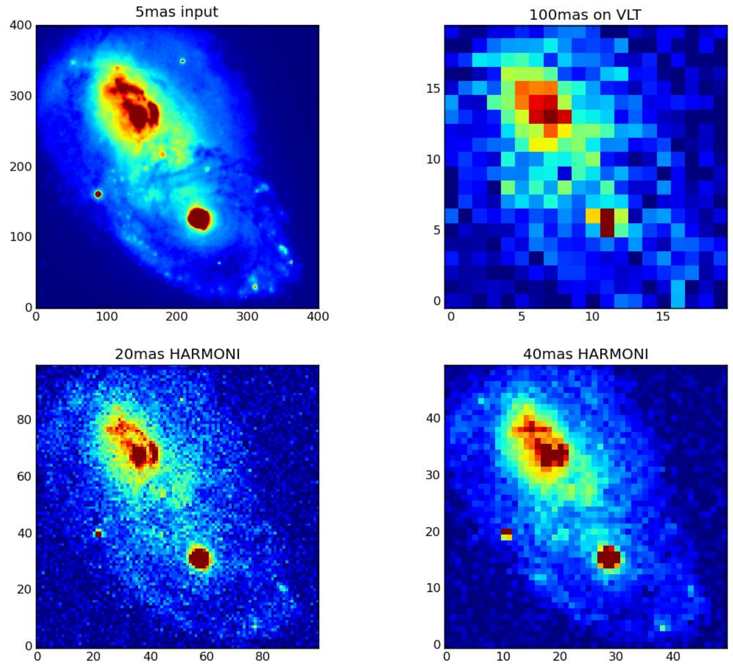
#3 - HARMONI

A Single Field Wide Band Integral Field Spectrograph

HARMONI science cases

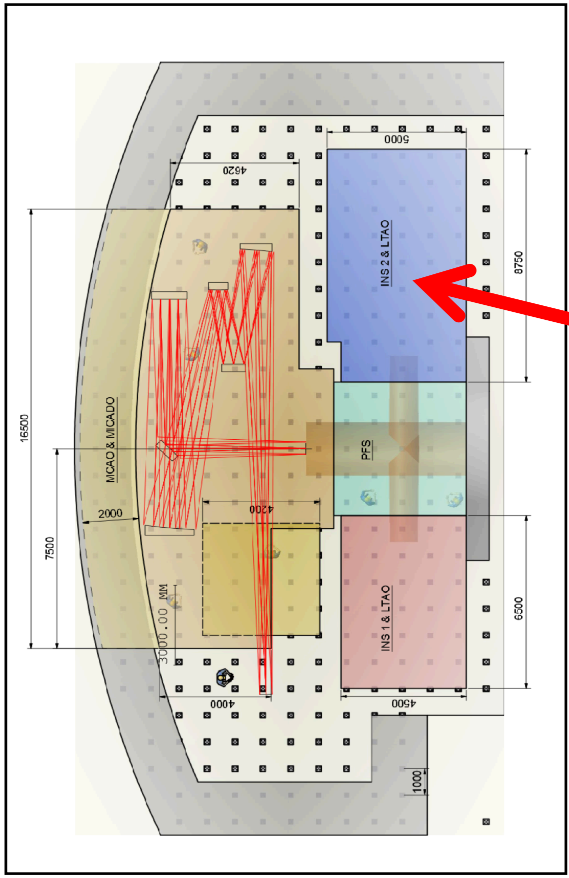


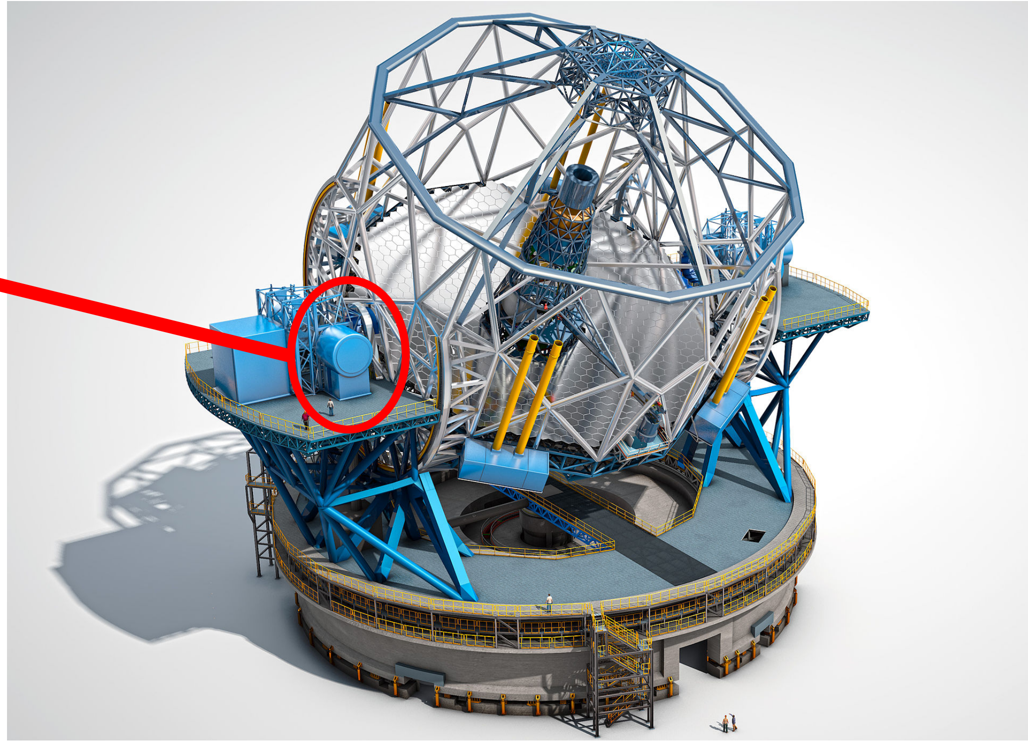
- Extra-solar planets
  - A very powerful tool for direct spectroscopic follow-up, confirmation, and characterization of exo-planets is AO-assisted integral field spectroscopy (IFS)
- Resolved stellar populations
- Galaxies at high redshifts
- Ultra-luminous and luminous infrared galaxies



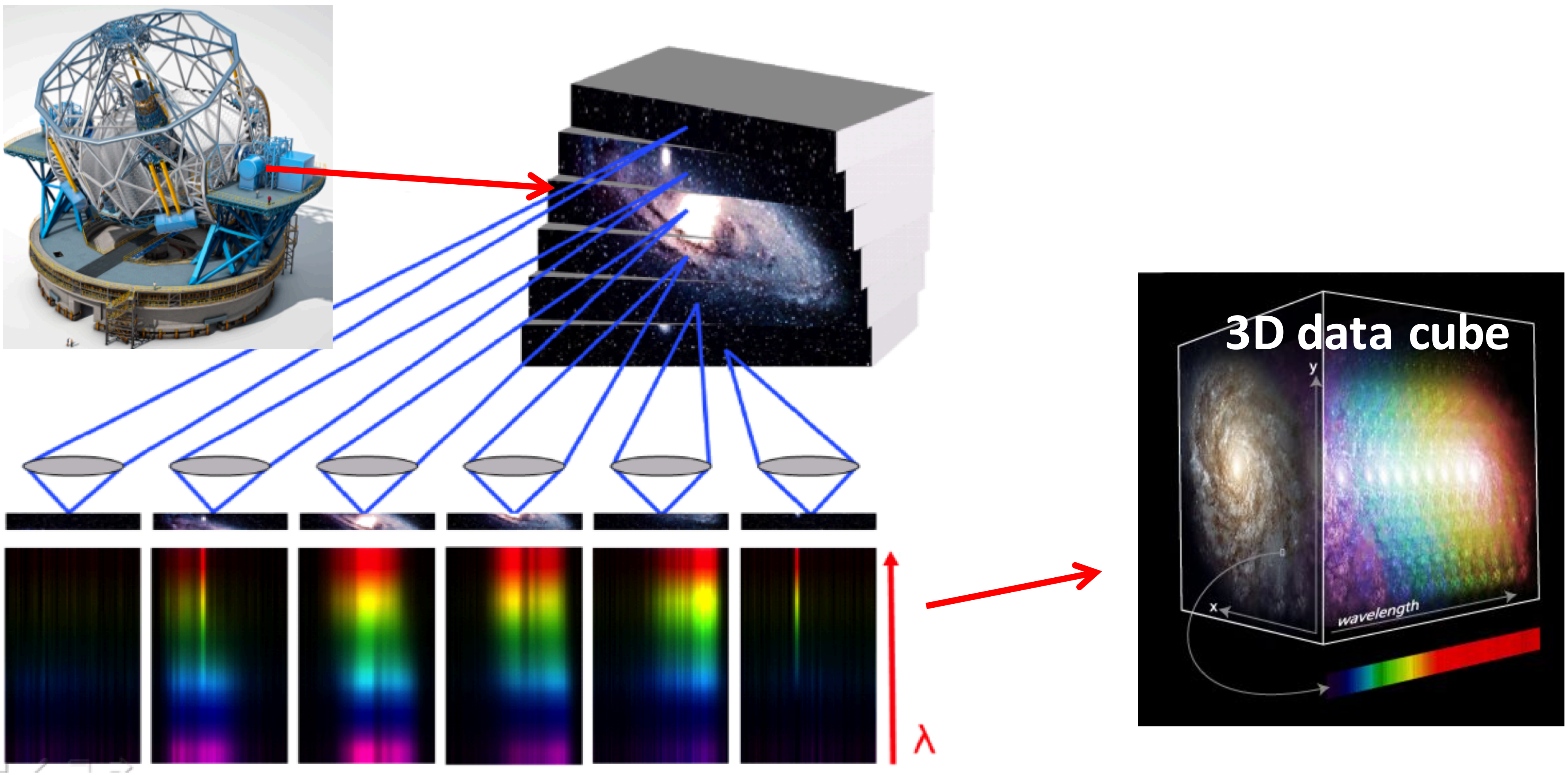
HARMONI

A Single Field Wide Band Integral Field Spectrograph



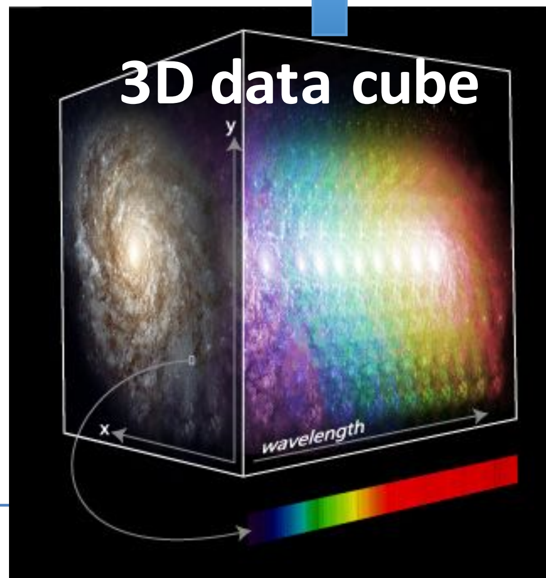


HARMONI = High Angular Resolution - Monolithic - Optical and Near-infrared - Integral field spectrograph

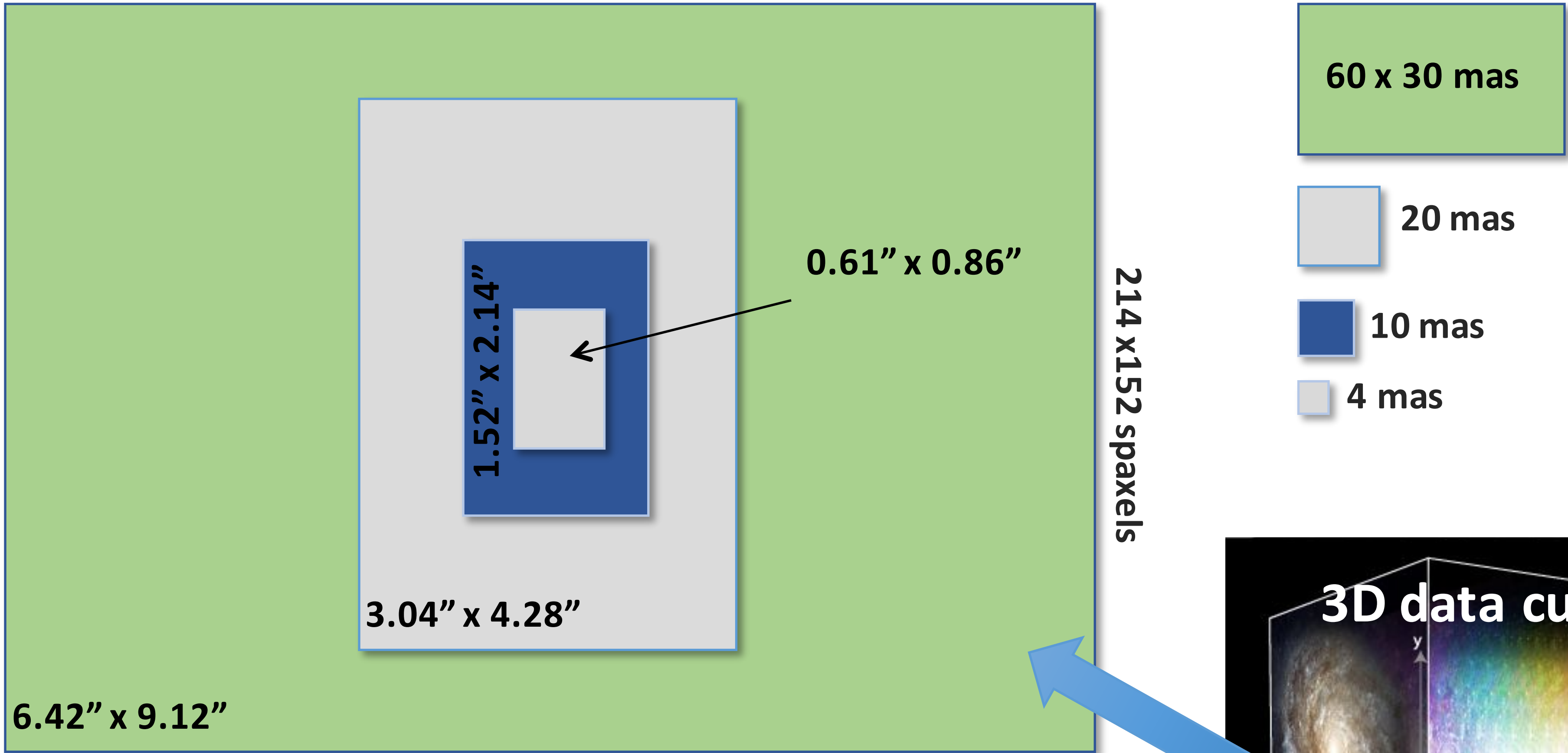


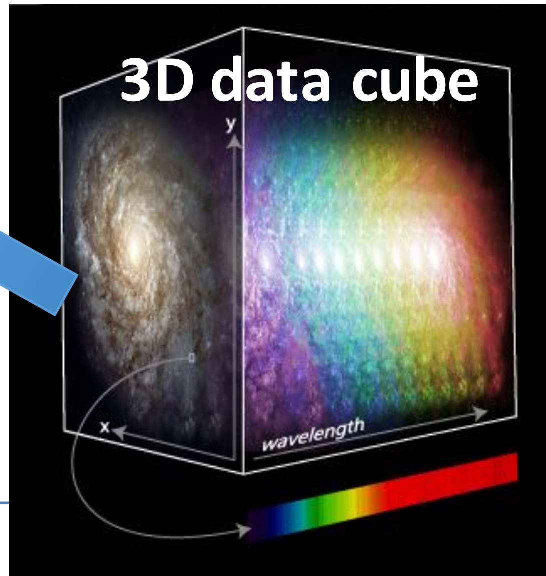
HARMONI = 3 resolving powers

Bands	Wavelengths (µm)	R
"V+R" or "I+z+J" or "H+K"	0.45-0.8, 0.8-1.35, 1.45-2.45	**~3000**
"I+z" or "J" or "H" or "K"	0.8-1.0, 1.1-1.35, 1.45-1.85, 1.95-2.45	**~7500**
"Z" or "J_high" or "H_high" or "K_high"	0.9, 1.2, 1.65, 2.2 (TBD)	**~20000**



HARMONI = 4 spatial scales





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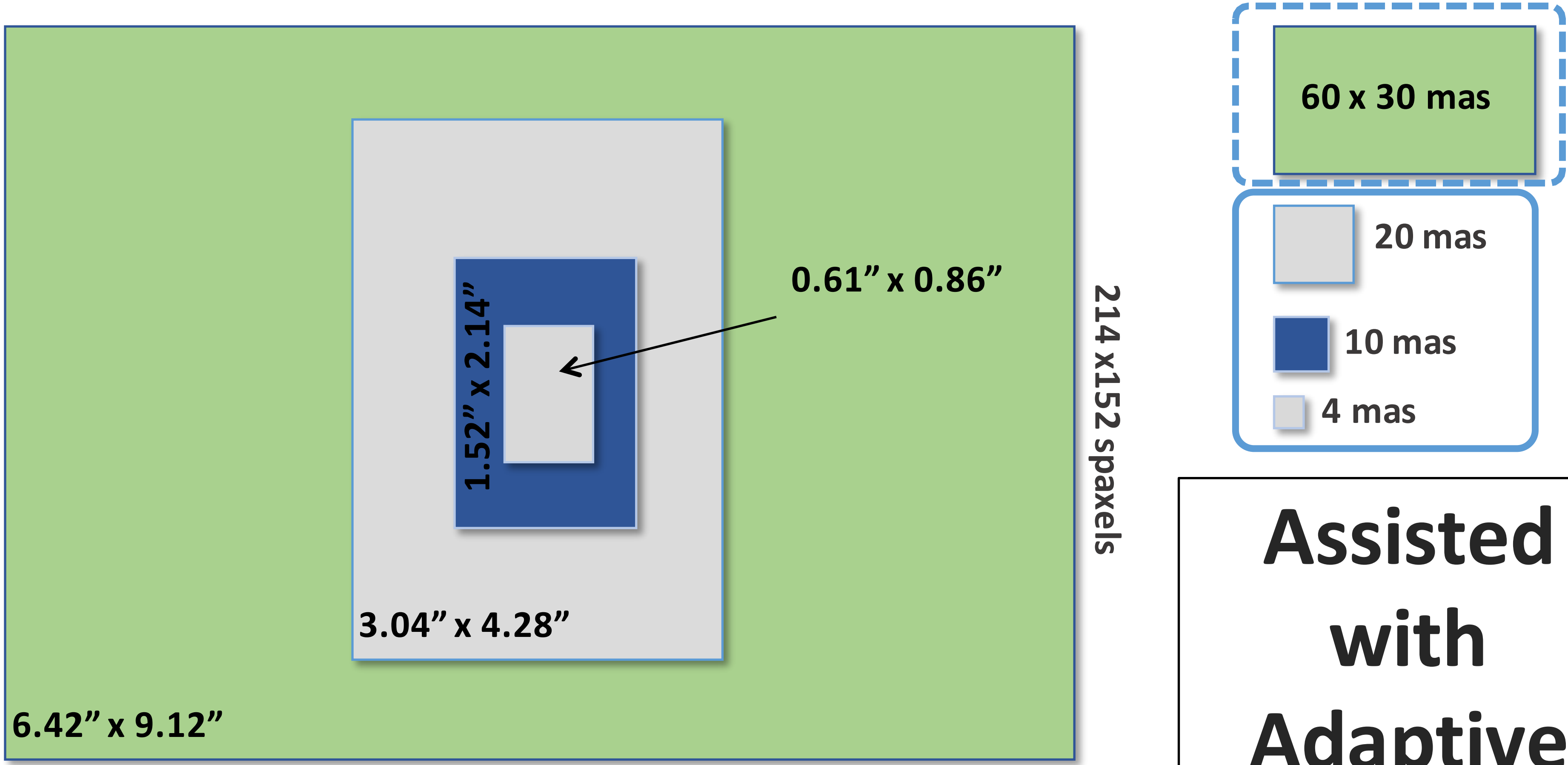
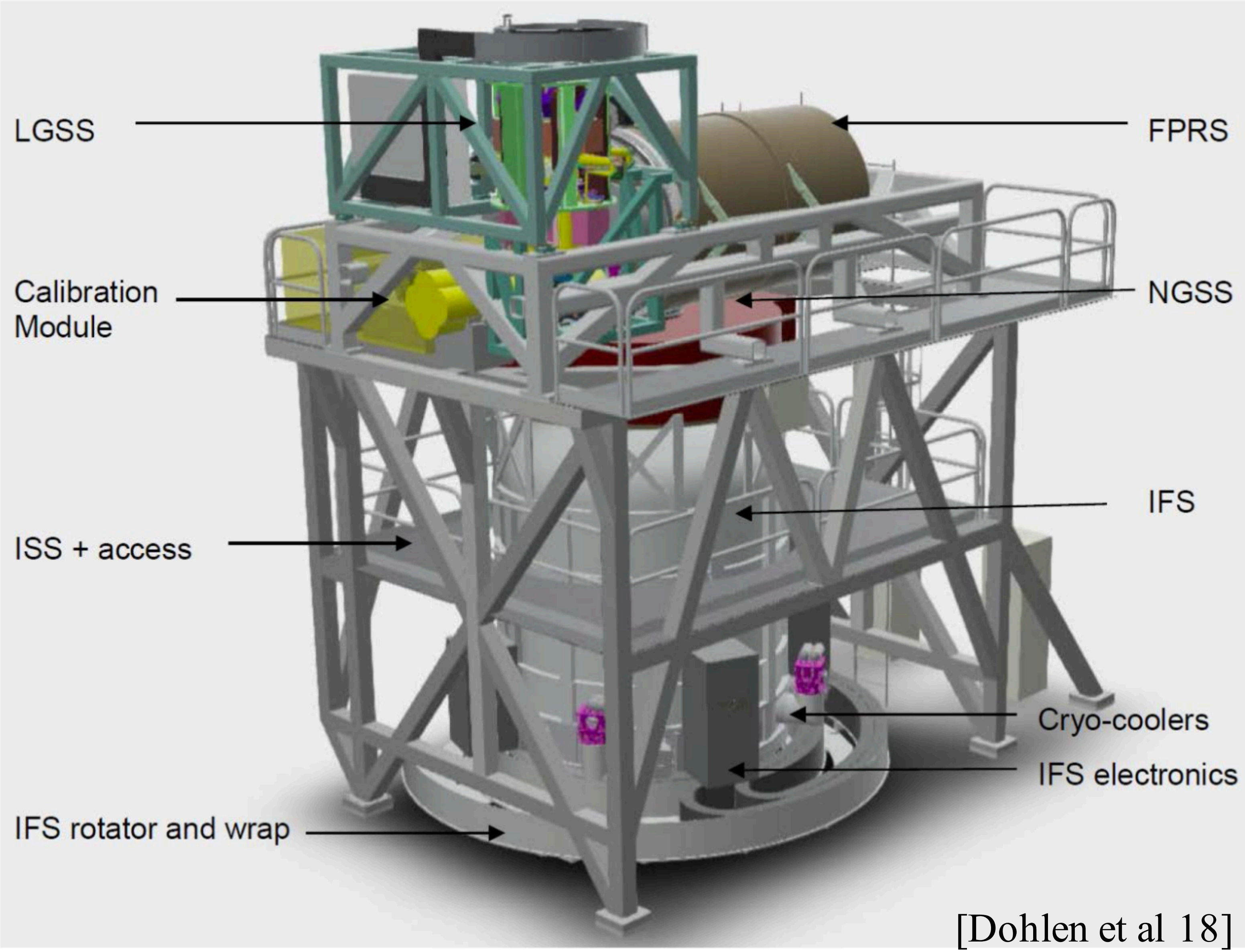


Assisted with Adaptive Optics

3D rendering of the HARMONI instrument indicating major systems and components

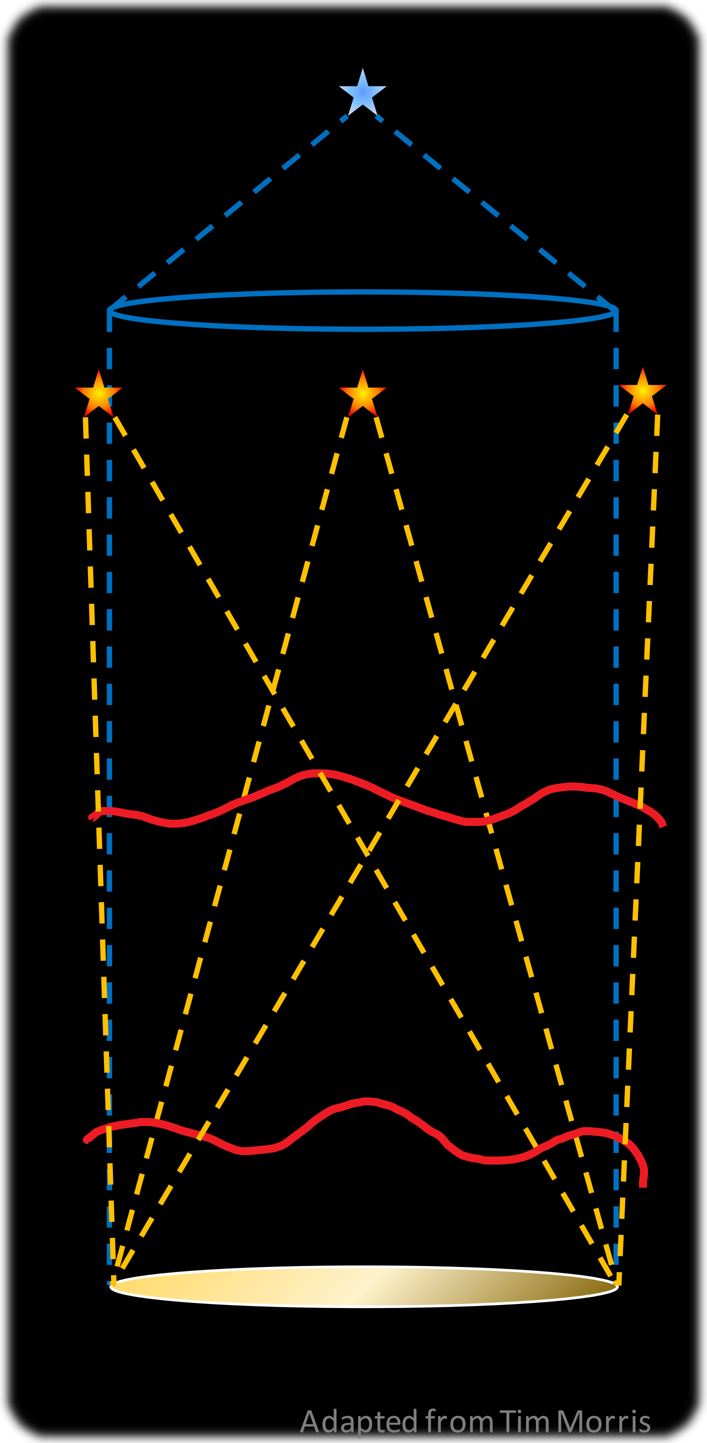


[Dohlen et al 18]

#4 - Putting all the pieces together

Sensing the atmosphere

- Photon-starved AO requires ever more sensitive sensors
  - Focus on Pyramid sensors
- Laser guide stars are required for sky coverage
  - Problem of cone effect gets worse for large telescopes
  - Spot elongation gets worse
- Tomography requires multiple LGSs
  - performance becomes dependent on the vertical distribution of turbulence
- Sensitivity to profile is dependent on
  - Separation of guide stars
  - Diameter of wavefront sensing elements
  - Number of wavefront sensing elements
- Large telescope spiders *ain't a good thing*

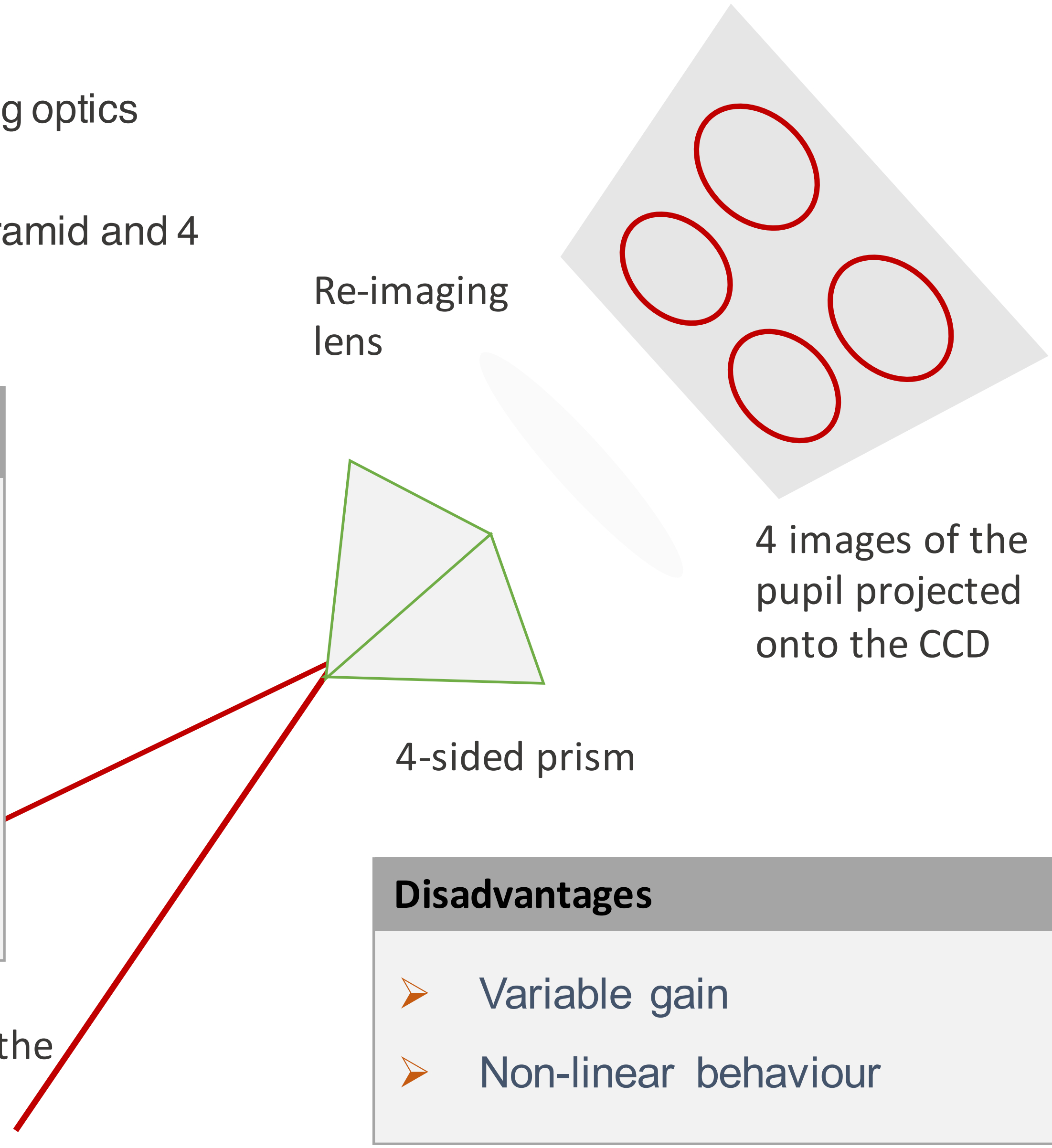


The Pyramid wave-front sensor

- Consists of a 4-sided prism, re-imaging optics and a CCD camera.
- Light focused onto the point of the Pyramid and 4 pupil images projected onto the CCD.

Advantages over Shack-Hartmann

- Potential for increased sensitivity within the correction band.
- Less susceptible to aliasing.
- Flexibility: modulation allows for adjustment of linear range for different conditions at the cost of sensitivity!

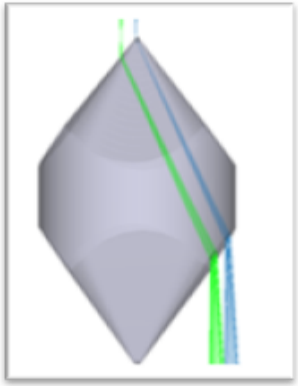


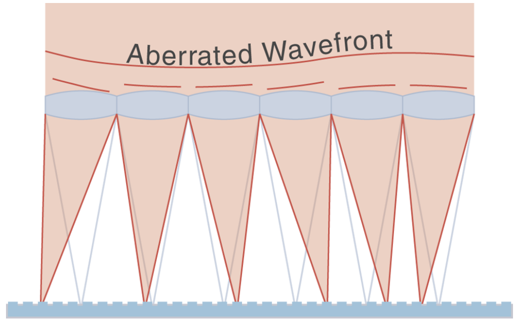
Disadvantages

- Variable gain
- Non-linear behaviour

Pyramid

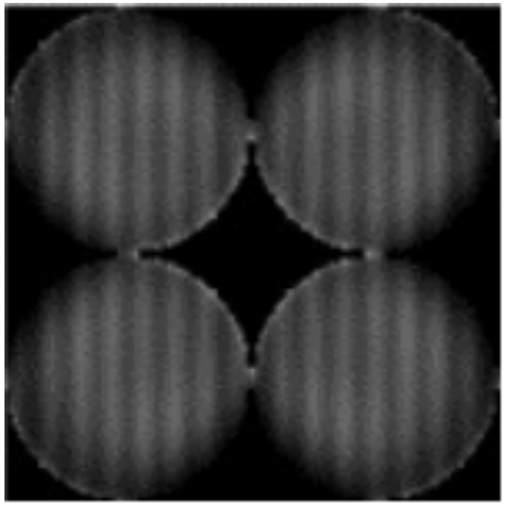
Shack-Hartmann

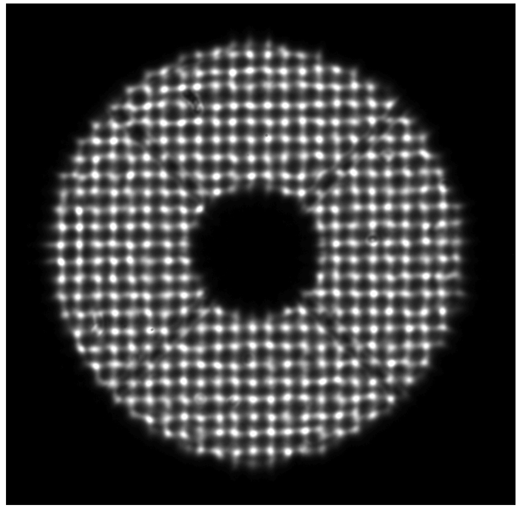




– Round 1 –

Turbulence compensation

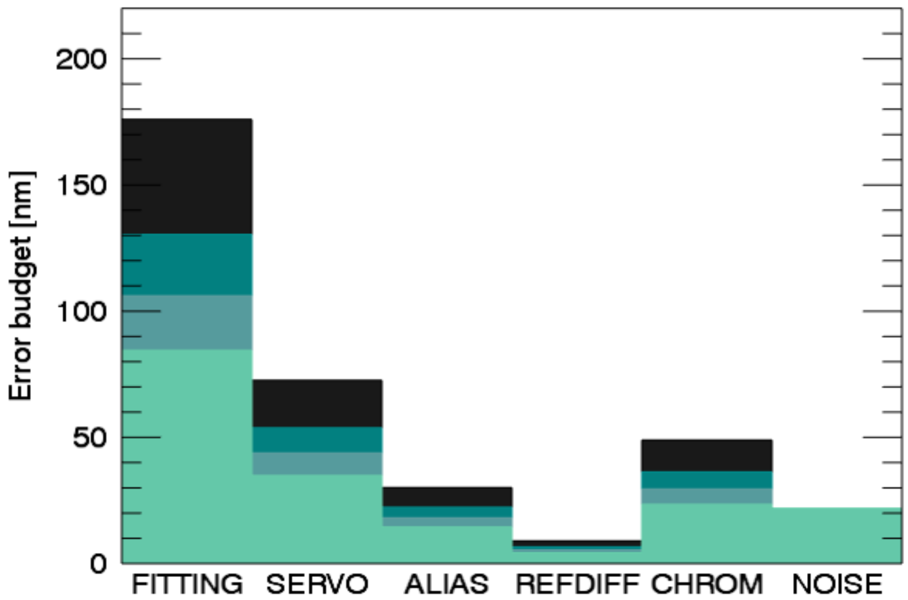


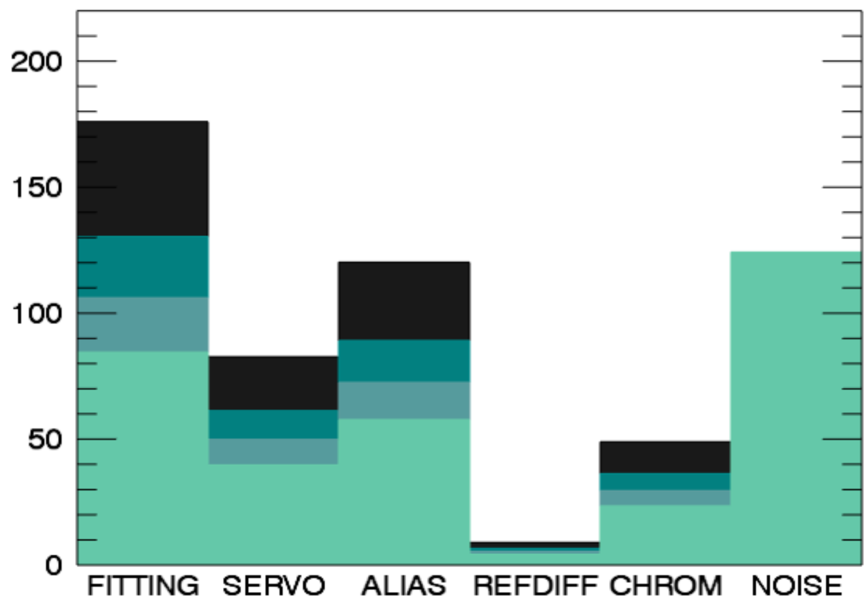


Pyramid

Shack-Hartmann

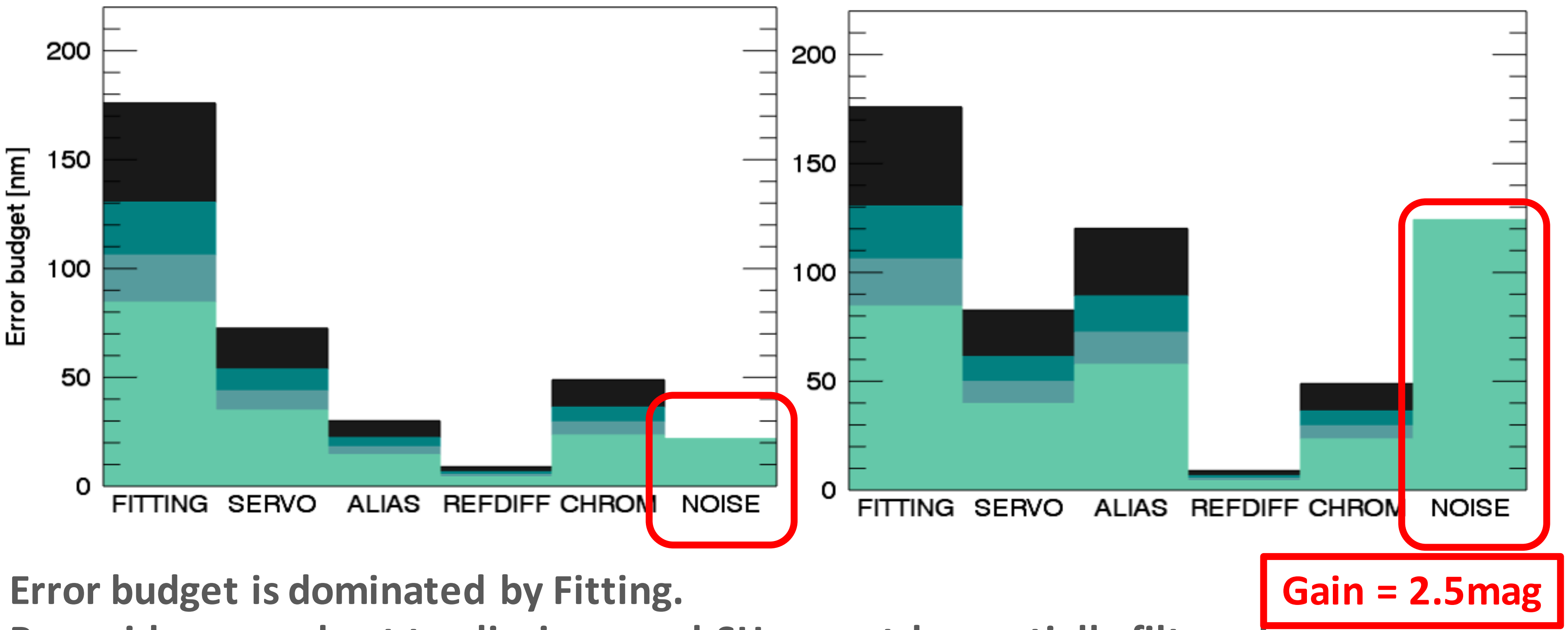
Turbulence compensation





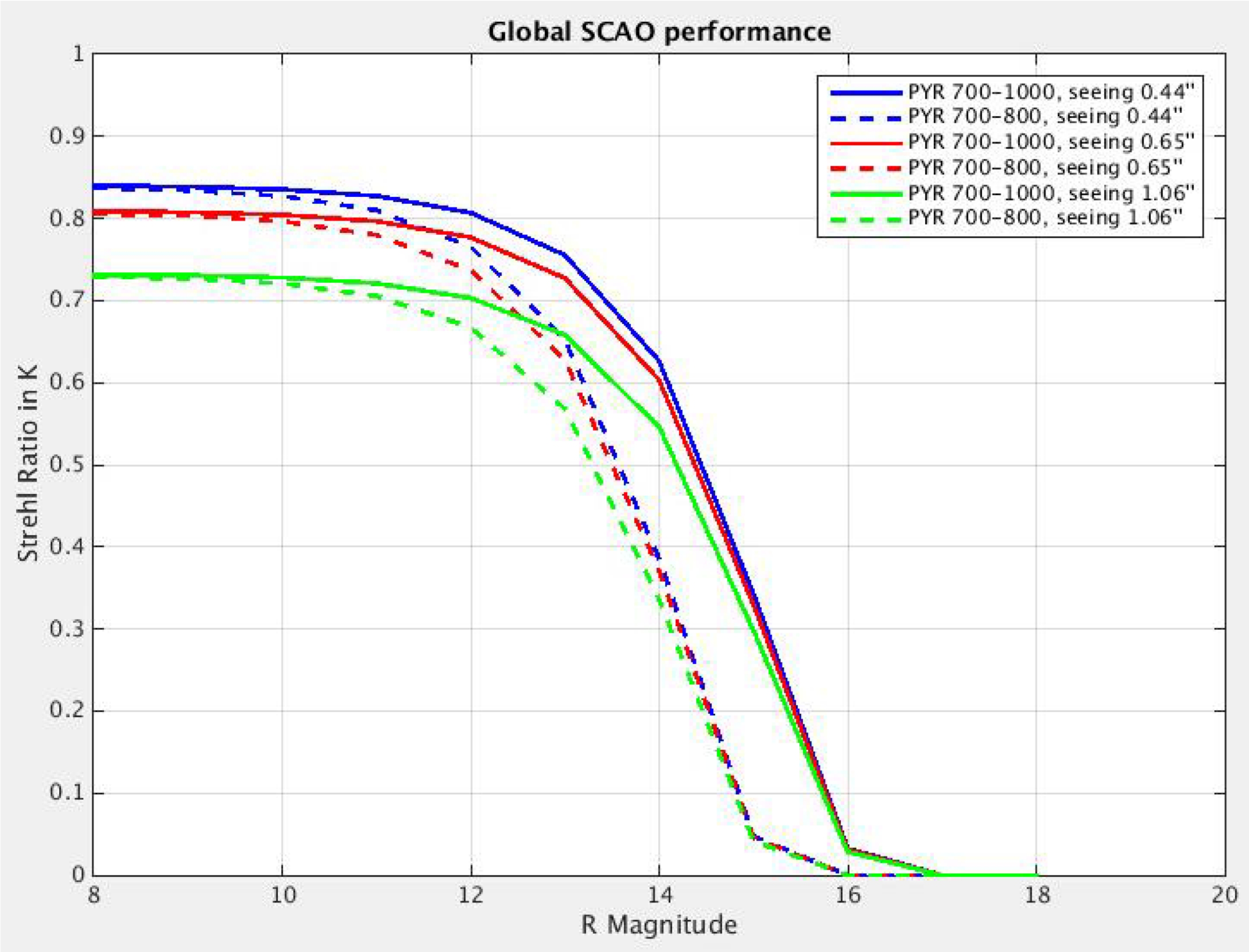
Pyramid　　　　Shack-Hartmann

Turbulence compensation



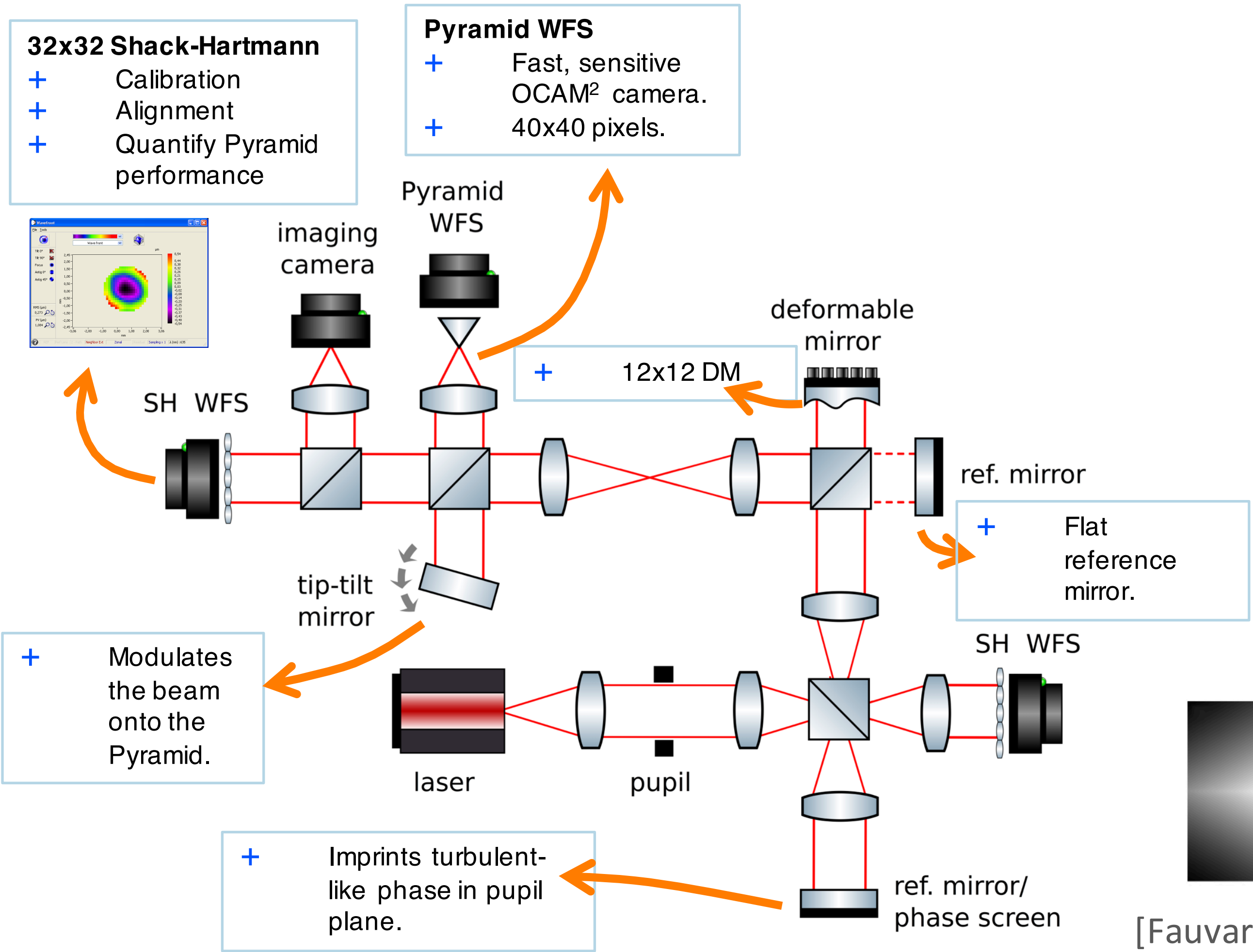
Error budget is dominated by Fitting.
Pyramid more robust to aliasing – and SH cannot be spatially filtered
Pyramid more robust to noise – and can benefit from 0 noise, off-the-shelf, detectors

Performance v. magnitude

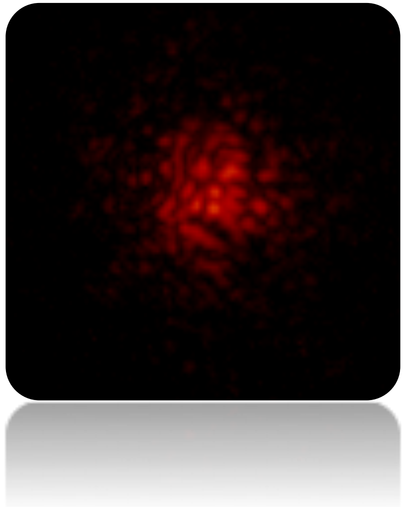


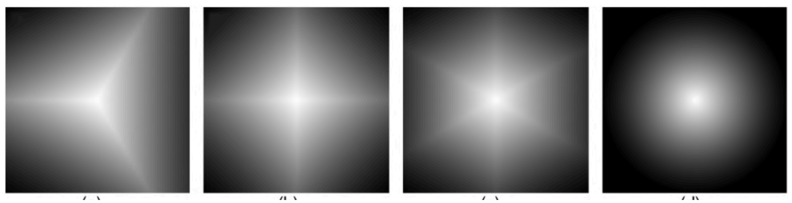
Courtesy: JF Sauvage

Pyramid VS Shack-Hartmann



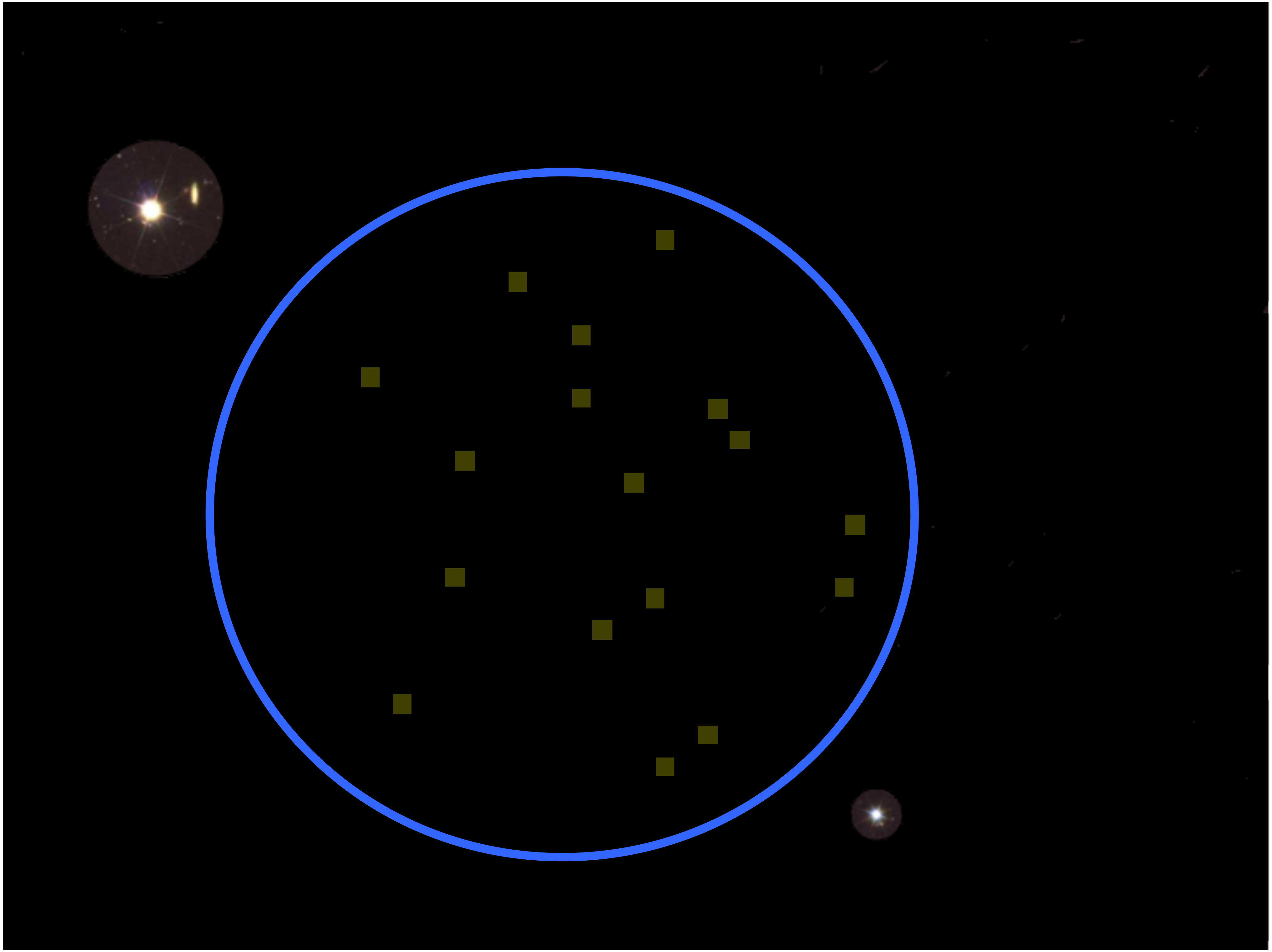
[Bond et al, in prep]



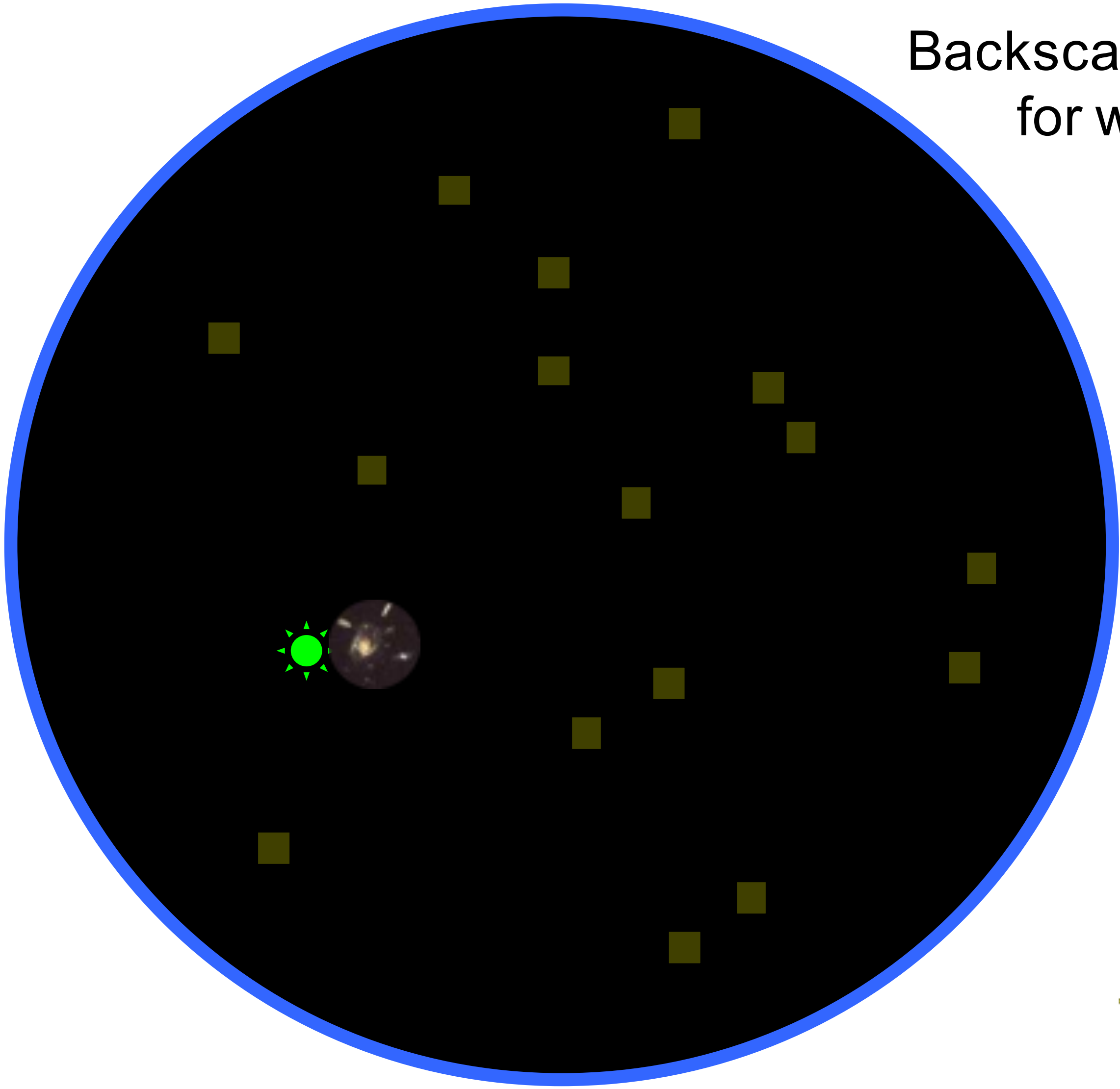


[Fauvarque et al, Fourier based WFSensors, 2015,16,17]

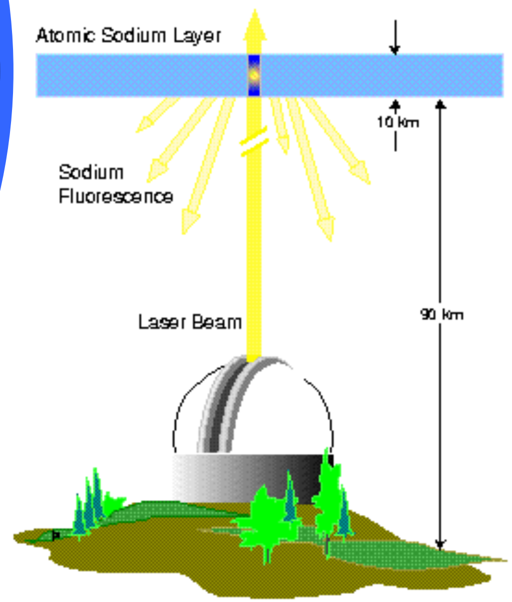
C. M. Correia et al, Making it up to E(A)LLT's, MPIA-Heidelberg, January 2019



Artificial guide-star

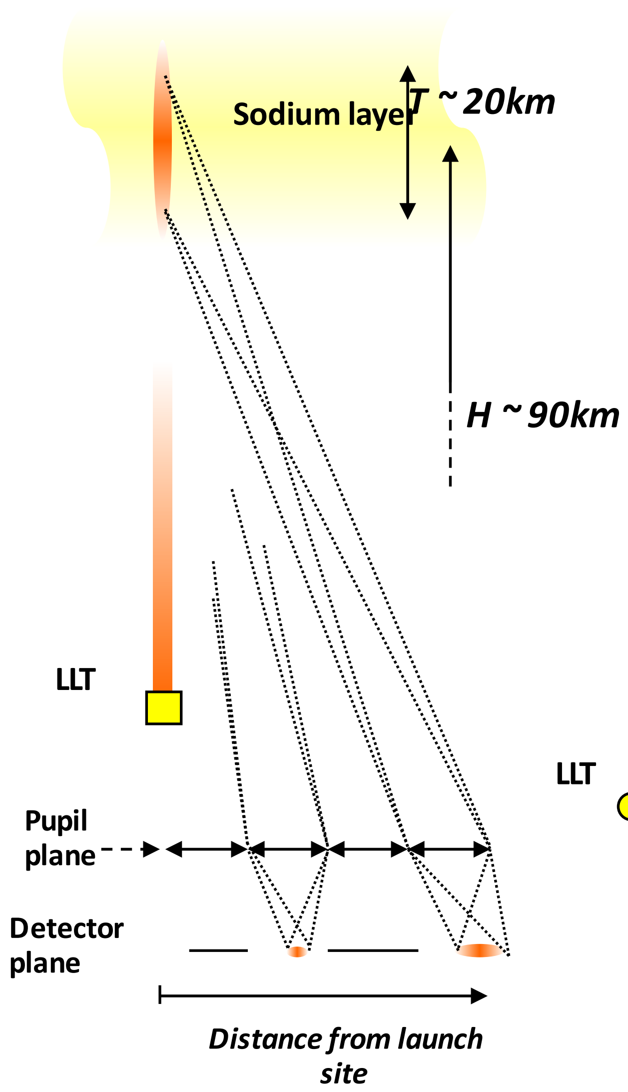


Backscattered light is used for wave-front sensing

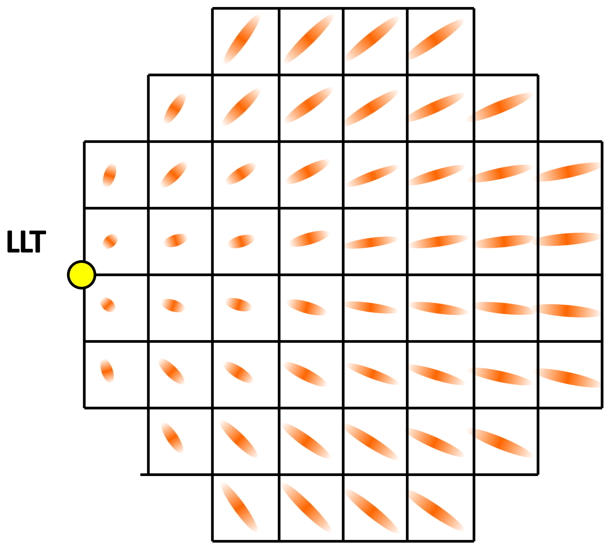


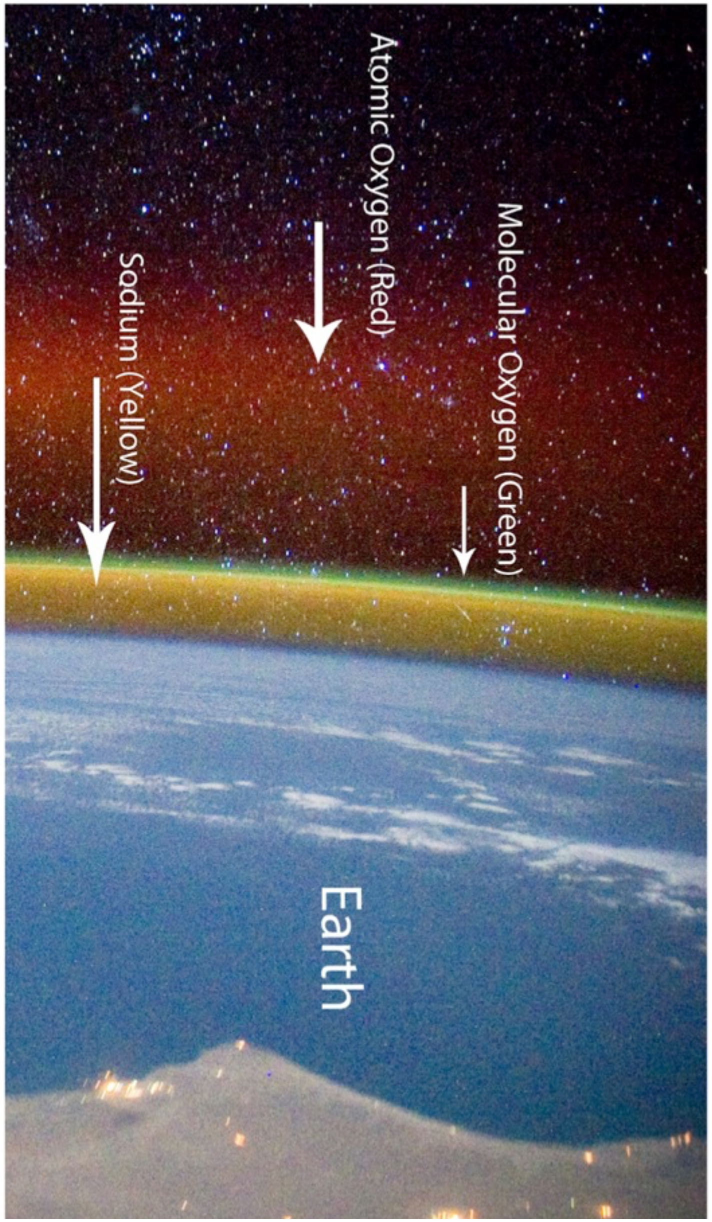
Credits: Conan

LGS Spot elongation



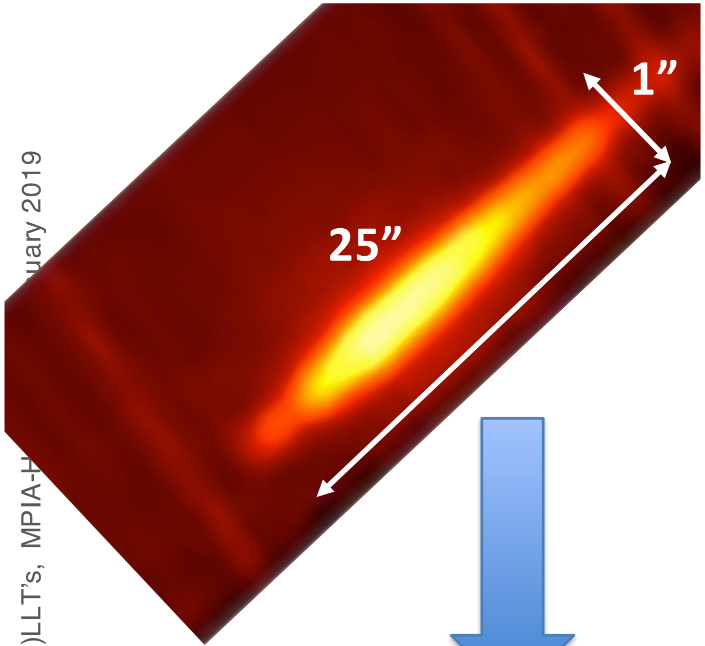
Predicted spot elongation pattern





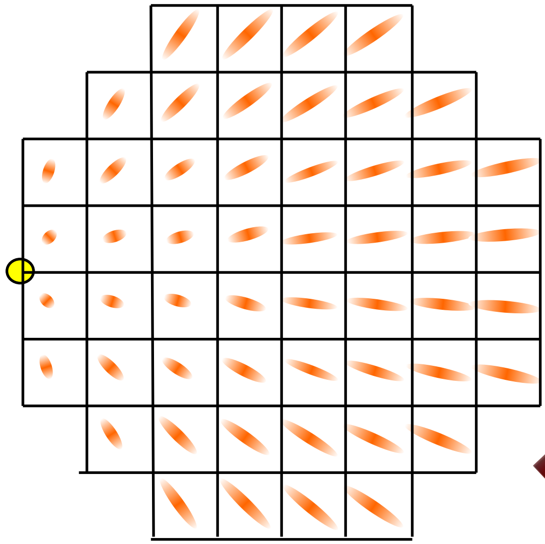
LGS Spot elongation

On a ~40m telescope

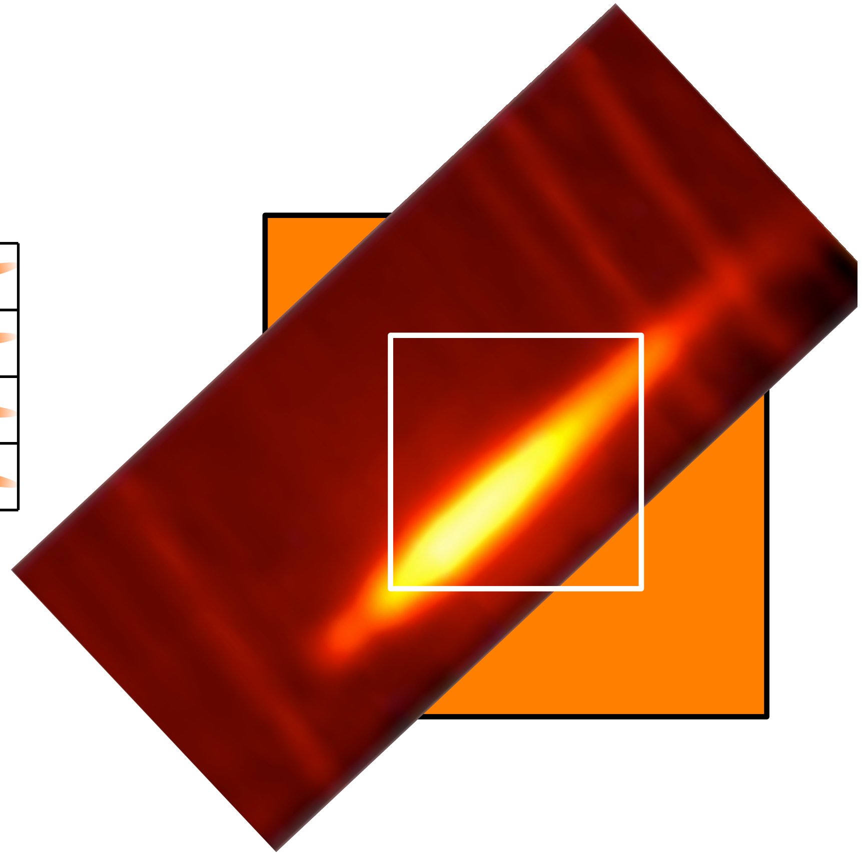


Ideally, we need subapertures with 25x25 pixels of ~1”

For 80x80 subapertures, we need 2000 x 2000 pixels



Most likely, we will have no more than 10x10 pixels

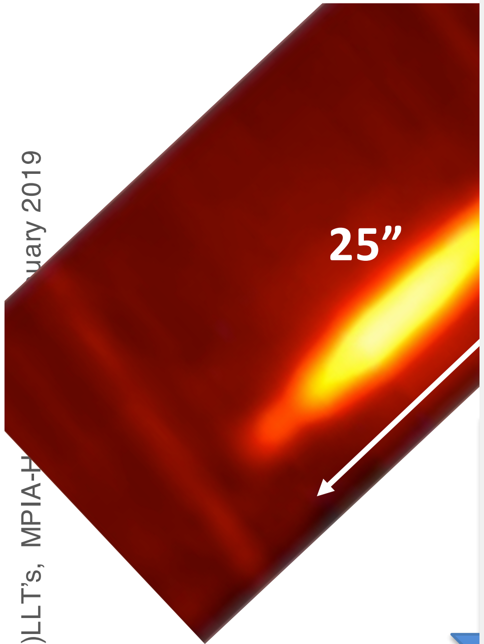


Strong truncation

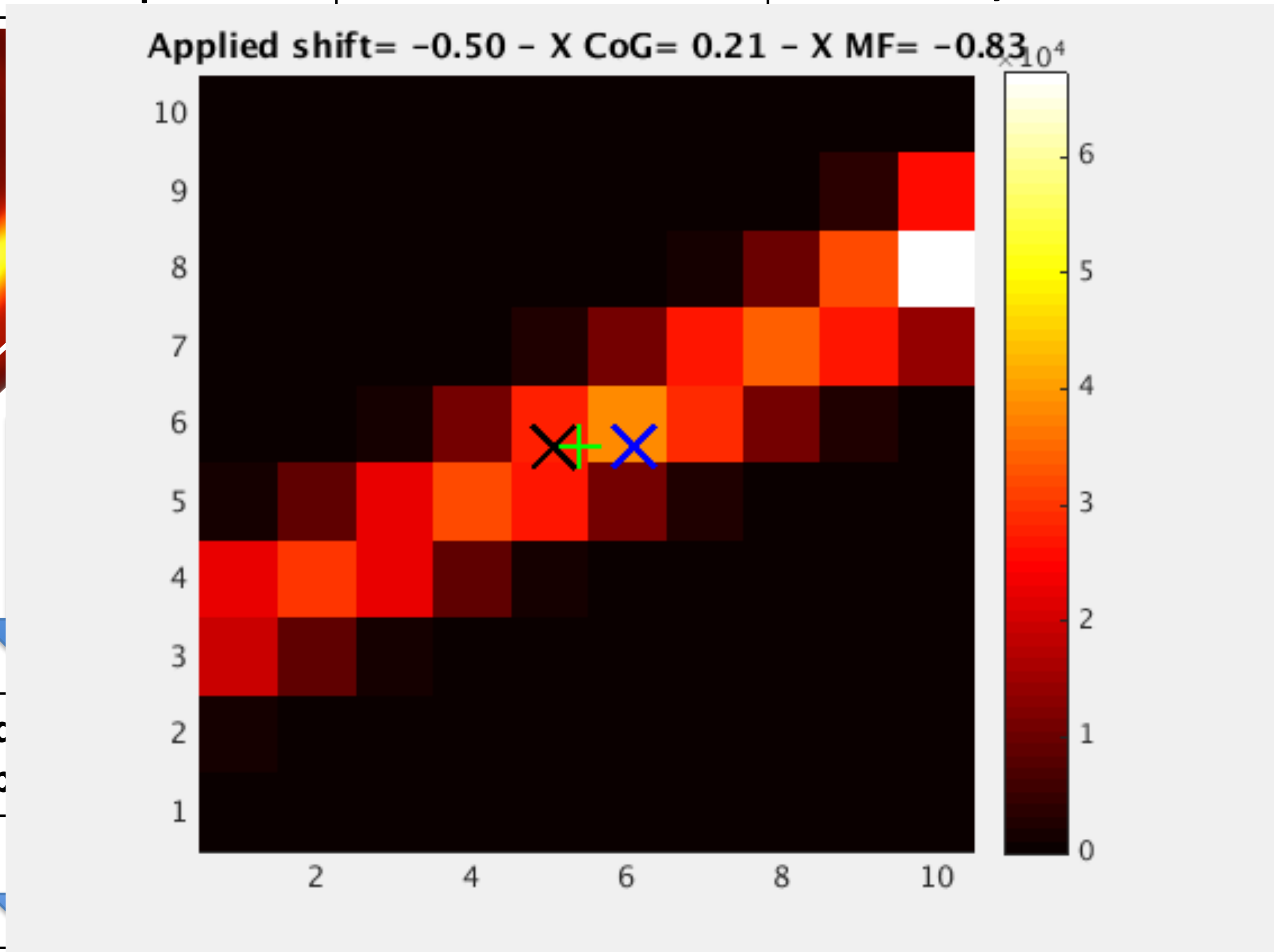
C. M. Correia et al, Making it up to E(A)LLT's, MPIA-H… …uary 2019

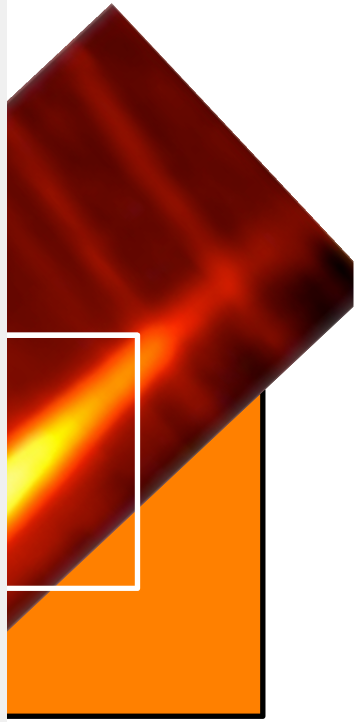
LGS Spot elongation

On a ~40m telescope



Most likely, we will have no more





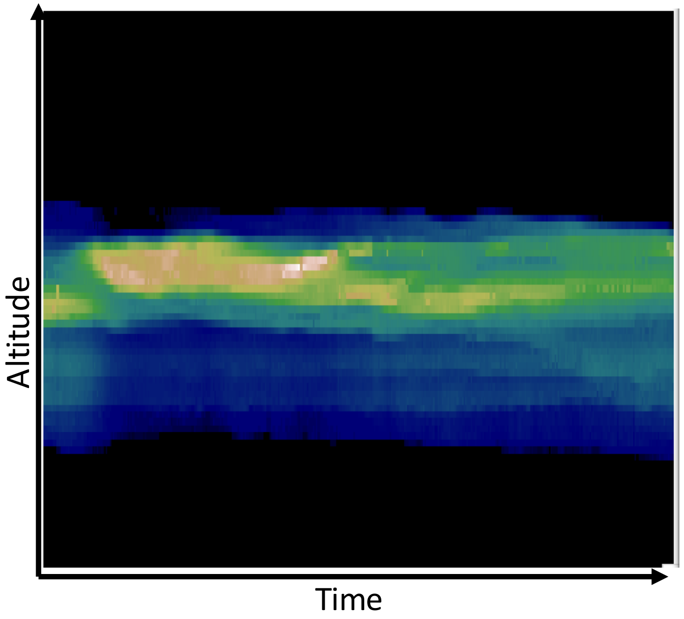
Ideally, we need
25x25 p

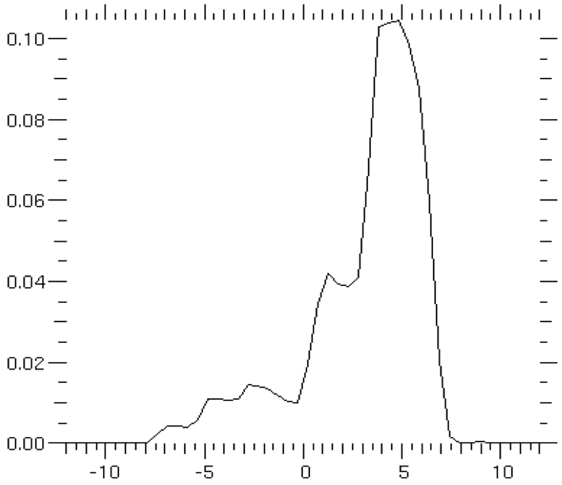
For 80x80 subapertures, we need
2000 x 2000 pixels

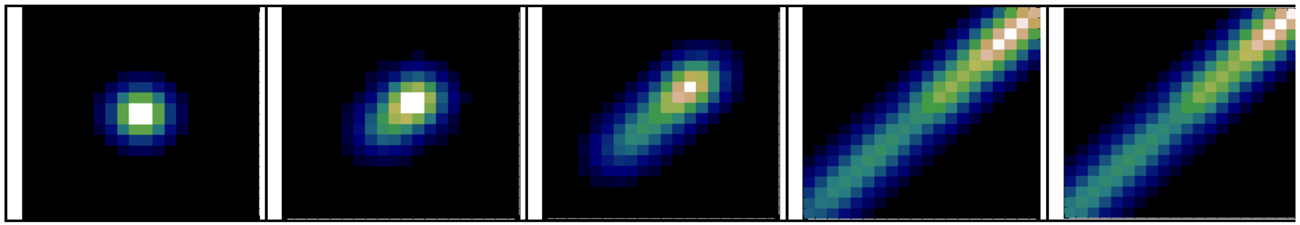
Strong truncation

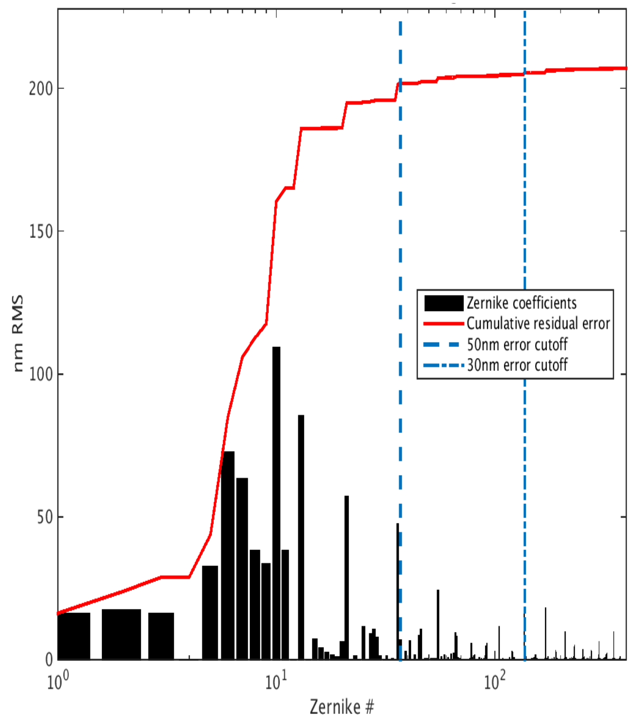
Impact of truncation on LTAO

- 6 LGS
- No turbulence
- MMSE reconstructor









(histogram = avg ; red = cumulative of avg ; blue = 30nm and 50nm cutoff)

Need for a Truth Sensor but aberrations are mostly low order
=> 10x10 subapertures on a truth sensor should be enough…

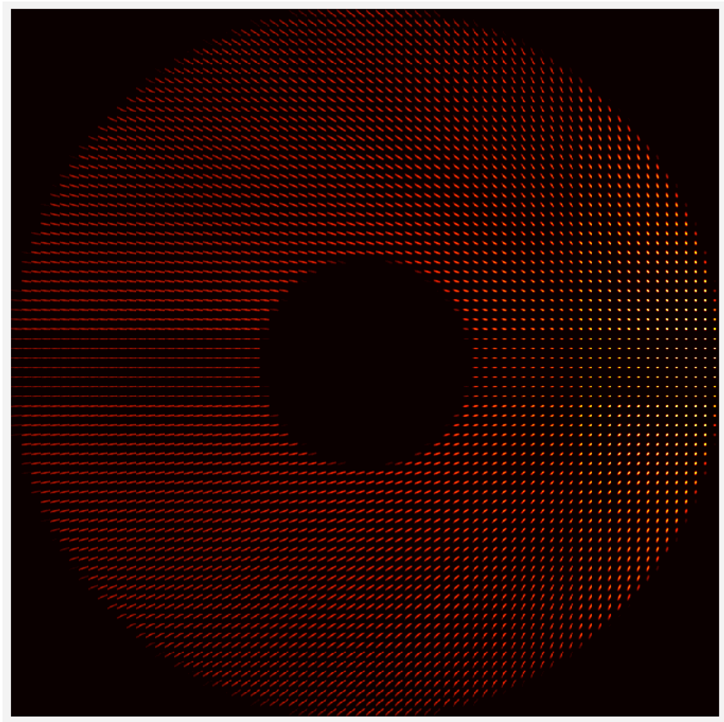
Tomography with large #degrees-of-freedom

- How to solve the problem?

$$\boldsymbol{s_\alpha} = \boldsymbol{G\varphi} + \boldsymbol{\eta}$$

$$\boldsymbol{\varphi} = \boldsymbol{R s_\alpha}$$

$$\boldsymbol{R} = \left(\boldsymbol{G}^T \boldsymbol{C}_{\boldsymbol{\eta\eta}}^{-1} \boldsymbol{G} + \boldsymbol{C}_{\boldsymbol{\varphi\varphi}}^{-1}\right)^{-1} \boldsymbol{G}^T \boldsymbol{C}_{\boldsymbol{\eta\eta}}^{-1}$$



Tomography with large #degrees-of-freedom

- How to solve the problem?

$$\boldsymbol{s_\alpha} = \boldsymbol{G\varphi} + \boldsymbol{\eta}$$
$$\boldsymbol{\varphi} = \boldsymbol{R s_\alpha}$$

$$\boldsymbol{R} = \left(\boldsymbol{G}^T \boldsymbol{C}_{\eta\eta}^{-1} \boldsymbol{G} + \boldsymbol{C}_{\varphi\varphi}^{-1}\right)^{-1} \boldsymbol{G}^T \boldsymbol{C}_{\eta\eta}^{-1}$$

  - …when the number of measurements is ~50000
  - …the number of actuators is ~5000
  - …the loop-frequency is >1 kHz?

~ Tera Floating-point operations per second

[Ono et al, JOSA-A, 2018]

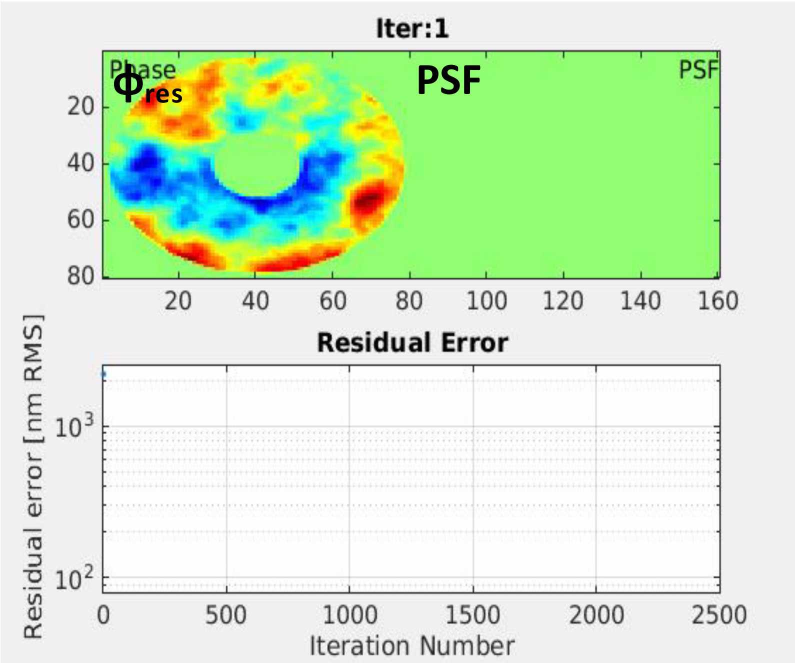
Motivation: Impact of spiders & M4

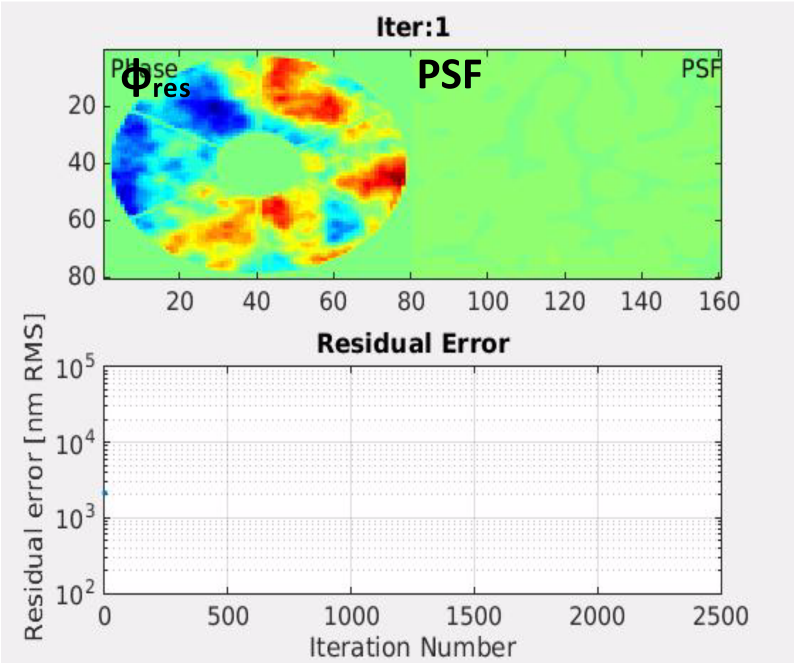
No spiders & continuous DM

- Good performance
  - 100 nm RMS residual error
- Good stability
  - ± 4 nm

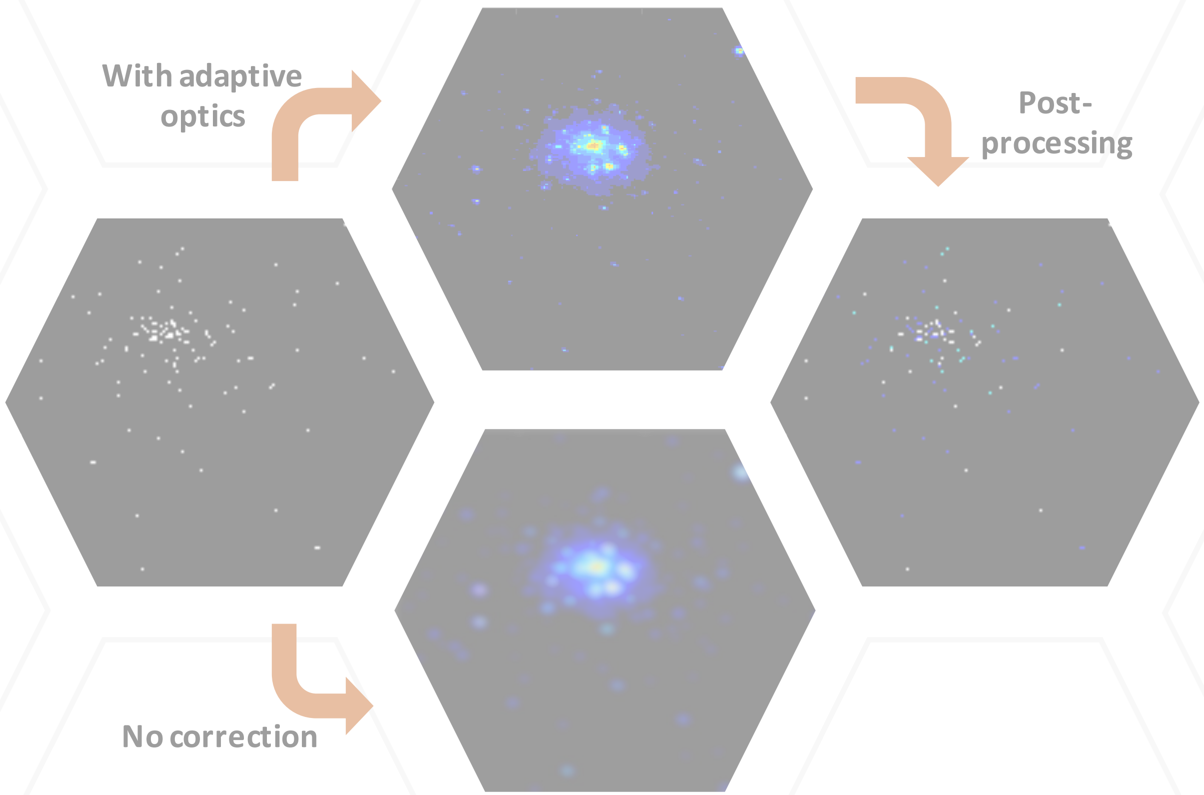
Spiders & M4

- Very poor performance
- Poor stability
  - ➢ Large residual piston between petals > ±5 waves





[Schwartz et al, AO4ELT/SPIE and others…]



How to make sense of the data?

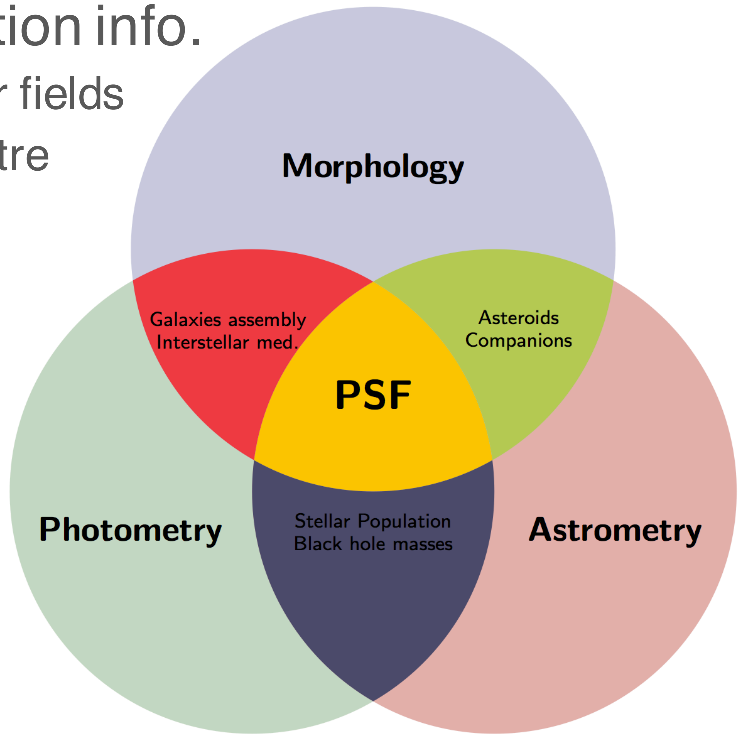
Extraction of precise photometric and astrometric data

Post-processing AO-assisted observations

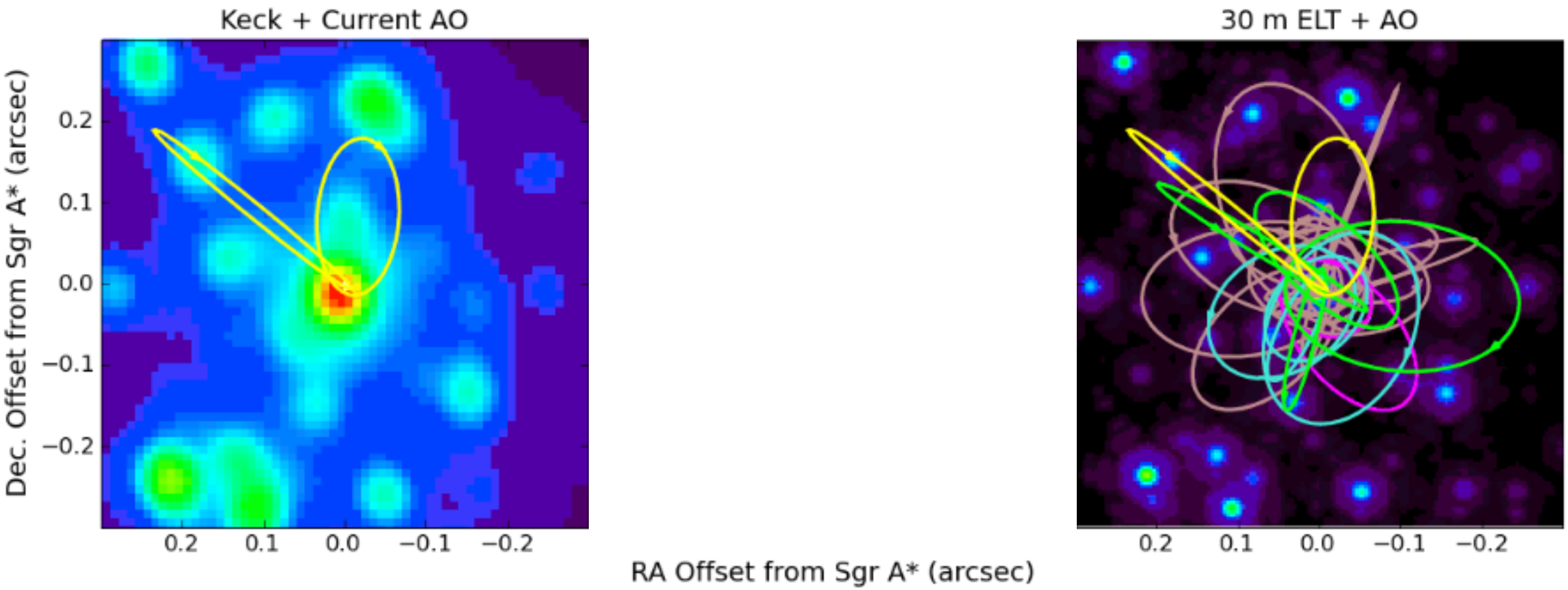
- Observations are a convolution of a PSF (h) and (o) object

$$i = h * o + n$$

- Importance of PSF knowledge for astronomical AO observations
  - Essential to retrieve high angular resolution info.
    - Photometry and astrometry in crowded stellar fields
    - Precision orbit estimation at the Galactic Centre
      - SO-2 (2016-2020)
  - General relativity tests
  - Gravitational lensing
  - Deconvolution of extended objects
  - High resolution spectroscopy
  - (IFS data cube reduction)



Angular resolution



http://www.astro.ucla.edu/~ghezgroup/gc/pictures/Future_GCorbits.shtml

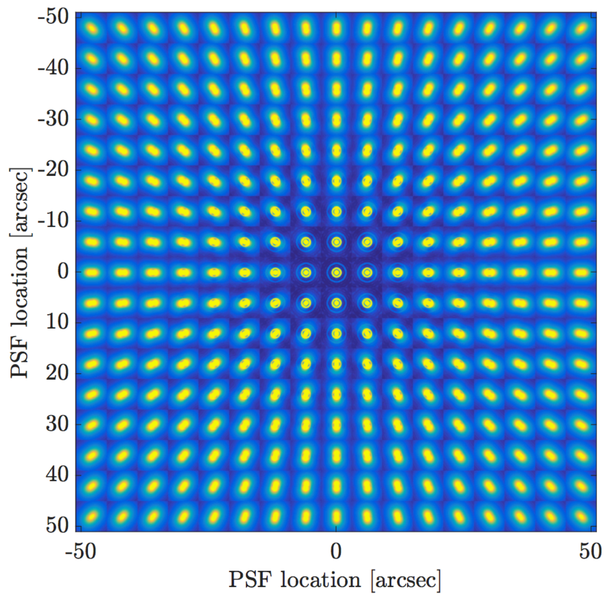
From Prof. Andrea Ghez/UCLA using the W. M. Keck Telescopes

PSF variability

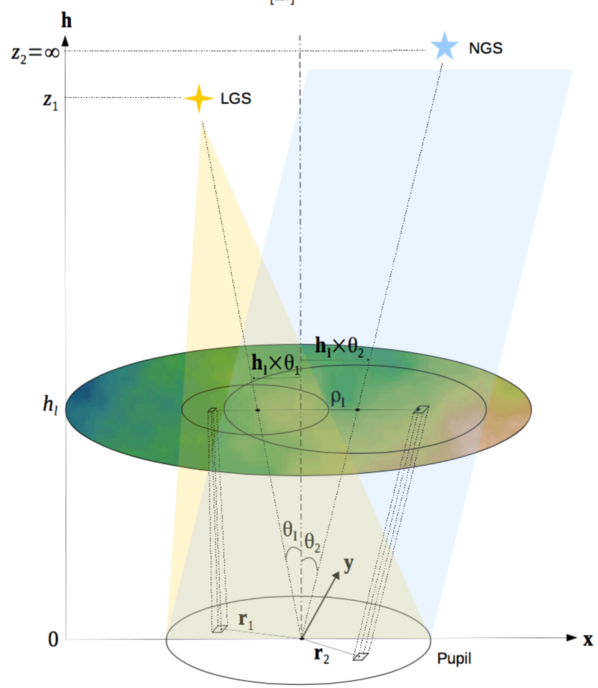
- The PSF doesn't stay still ☺

$$\boldsymbol{h}(\boldsymbol{\rho}, \boldsymbol{\theta}, \boldsymbol{t}, \boldsymbol{\lambda})$$

  - Varies with time and field angle
- Where do we get it from?
  - Observations? Buf if…
    - Too faint objects?
    - Extended objects?
    - Badly resolved?
    - Nearby point source? $\Delta t, \Delta\theta$
  - The AO telemetry?
  - Both?



[h!]



PSF structure

- The PSF doesn't stay still ☺

$$\boldsymbol{h(\rho, \theta, t, \lambda)}$$

  - Varies with time and field angle
- Where do we get it from?
  - Observations? Buf if…
    - Too faint objects?
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    - Nearby point source? $\Delta t, \Delta\theta$
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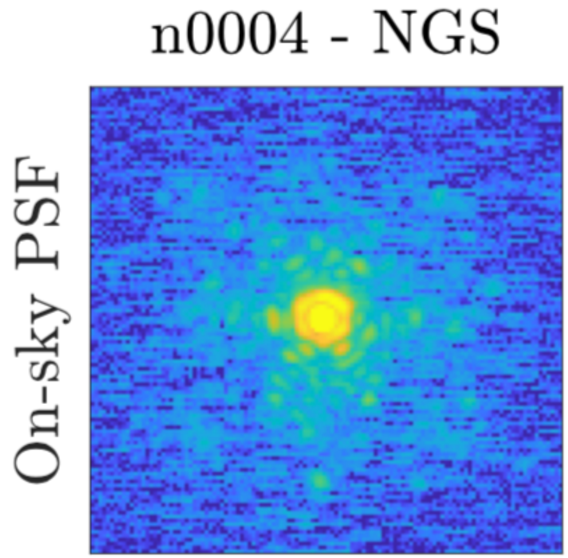

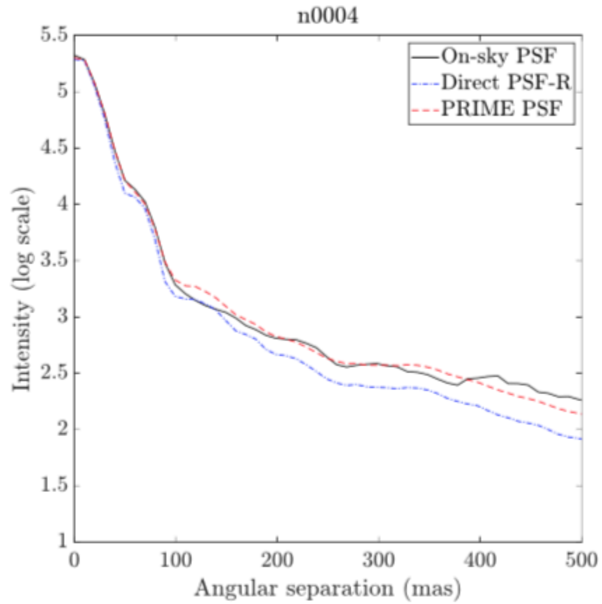

[Beltramo-Martin 19, submitted]

PSF structure

- The PSF doesn't stay still ☺

$$\boldsymbol{h(\rho,\theta,t,\lambda)}$$

  - Varies with time and field angle
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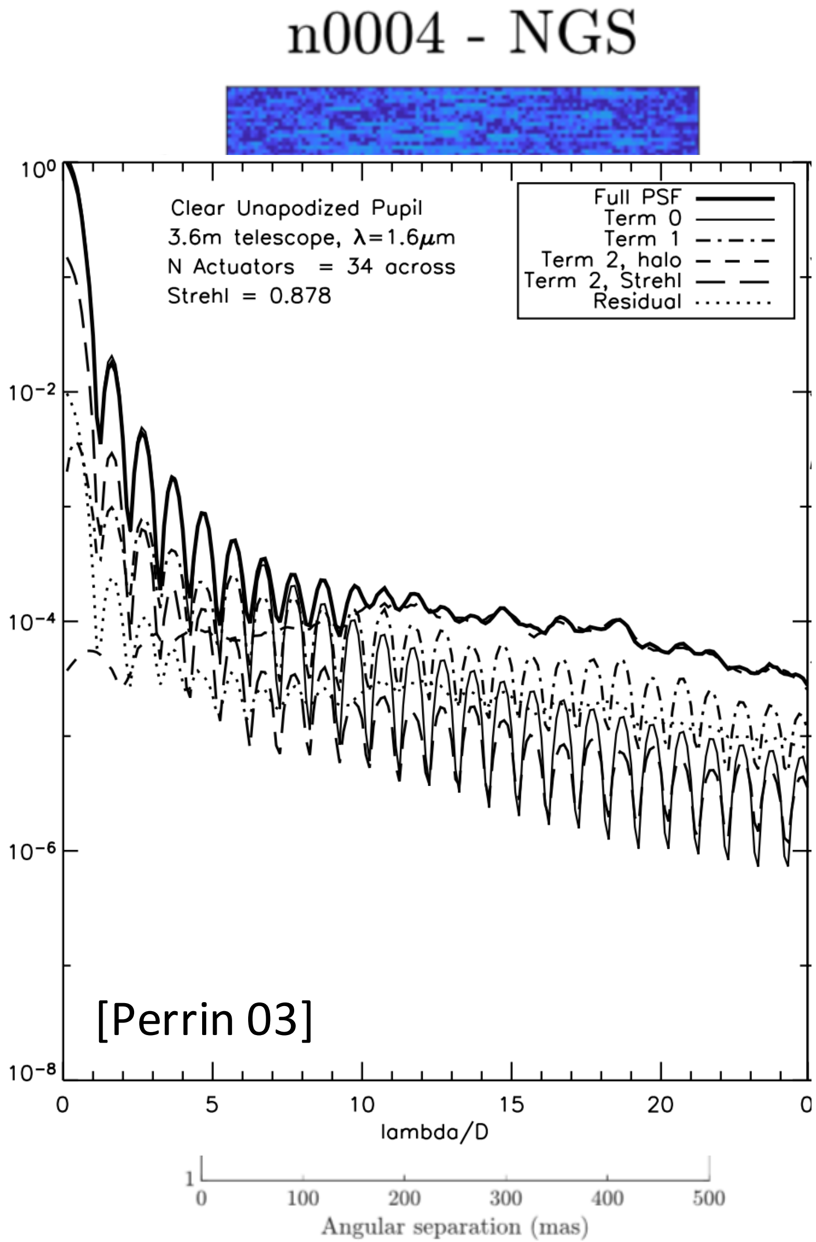
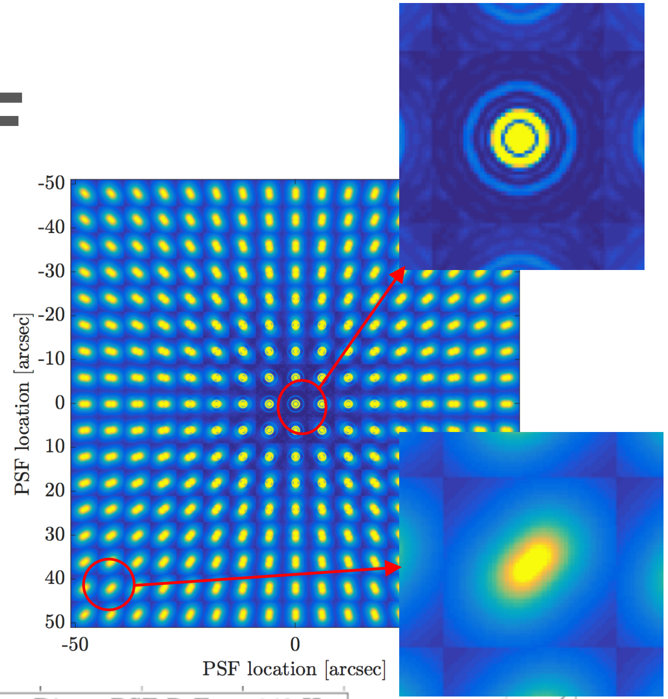
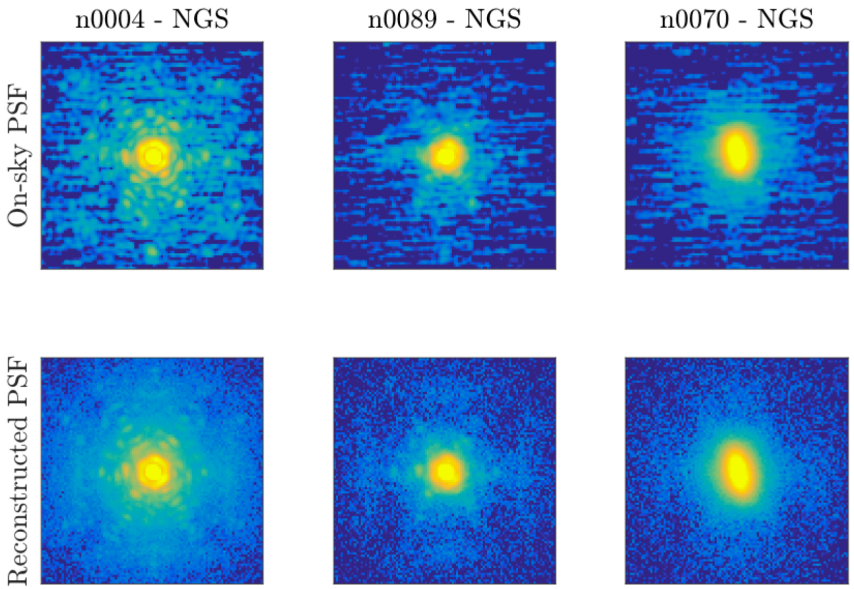


Hybrid telemetry+focal plane PSF reconstruction

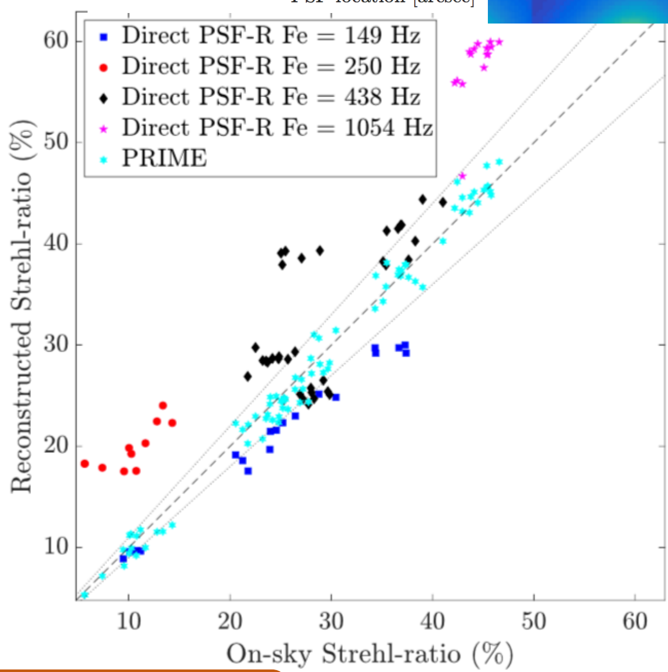


- Principle: use anisoplanatim signature to estimate vertical distribution of turbulence
- Reconstruct all terms in

$$\langle \boldsymbol{\varepsilon}_{||}\boldsymbol{\varepsilon}_{||}^T \rangle = R(\langle \mathbf{gg}^T \rangle - \langle \boldsymbol{\eta\eta}^T \rangle + \langle \mathbf{rr}^T \rangle)R^T + \langle \mathbf{aa}^T \rangle$$



[Beltramo-Martin et al, in prep]



[Beltramo-Martin et al, in prep]

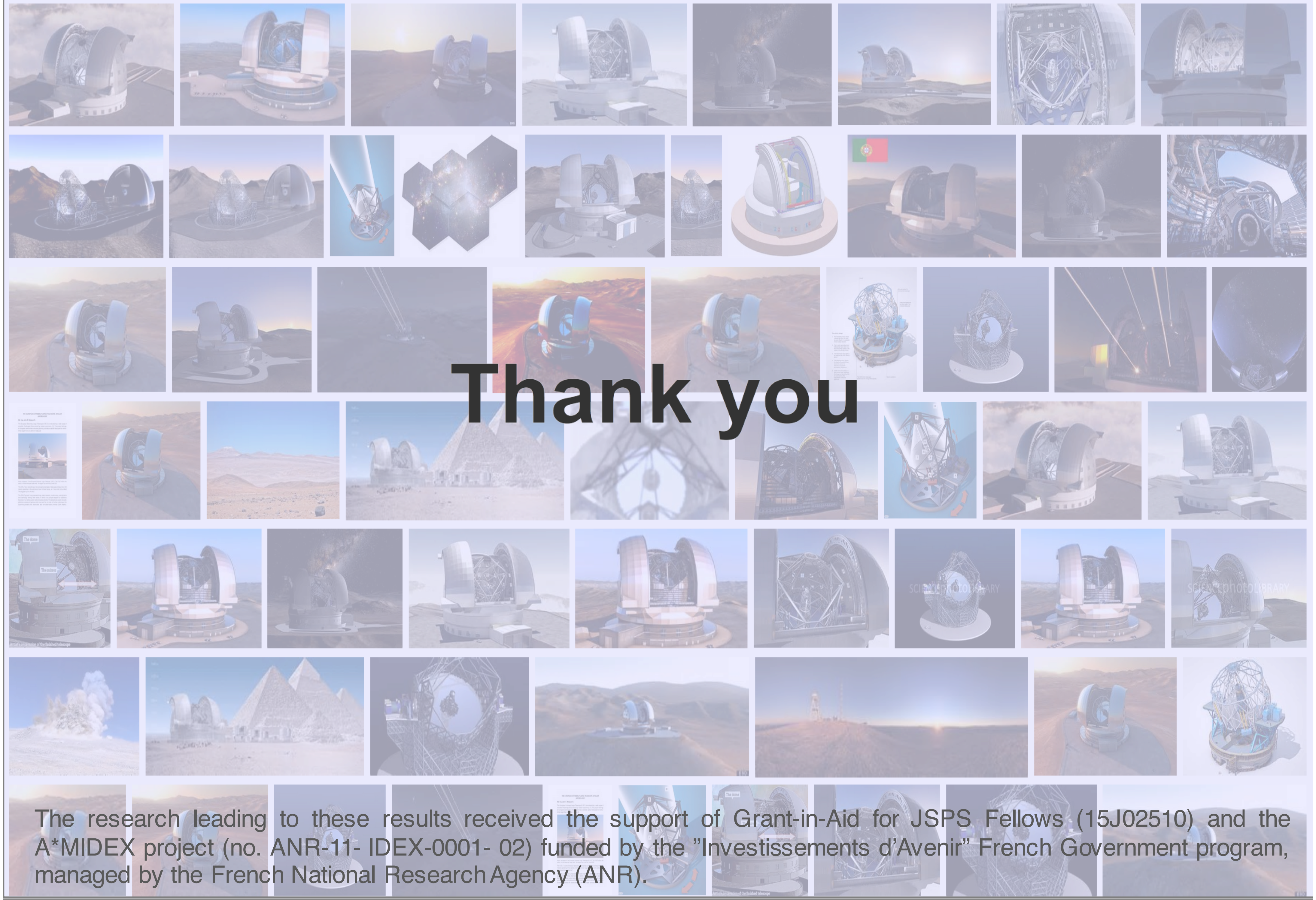
Huge drop in SR & FWHM dispersion

Summary

- ELT too large to operate in conventional seeing-limited mode
  - Adaptive (pre-focal) correction needed all the time

- All AO modes have been demonstrated on smaller telescopes (+ science with tomographic AO @ MUSE NFM)

- Scaling up from the VLT brings about new challenges
  - Wave-front sensing (quest for sensitivity)
    - ➜ novel wave-front sensors and sensing strategies
  - Tomography and real-time control (quest for sky coverage)
    - ➜ advanced control to deal with spurious signals and unprecedented data rates
    - ➜ need for auto-calibration on-sky
  - Data-reduction (quest for precision photometry and astrometry)
    - ➜ development of hybrid telemetry&focal plane approaches



Thank you

The research leading to these results received the support of Grant-in-Aid for JSPS Fellows (15J02510) and the A*MIDEX project (no. ANR-11- IDEX-0001- 02) funded by the "Investissements d'Avenir" French Government program, managed by the French National Research Agency (ANR).