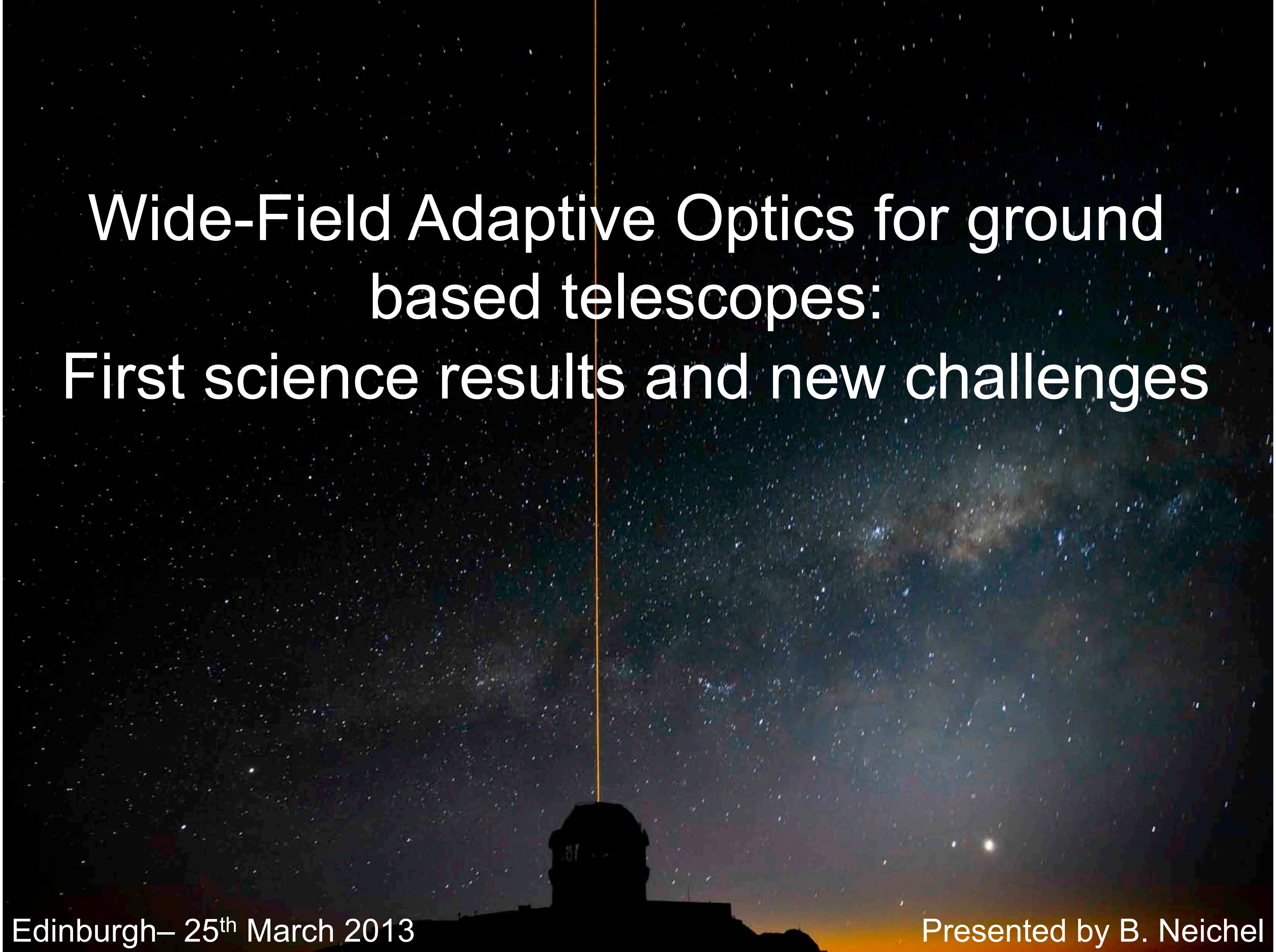


# Wide-Field Adaptive Optics for ground based telescopes: First science results and new challenges

Edinburgh– 25th March 2013

Presented by B. Neichel

# Outline

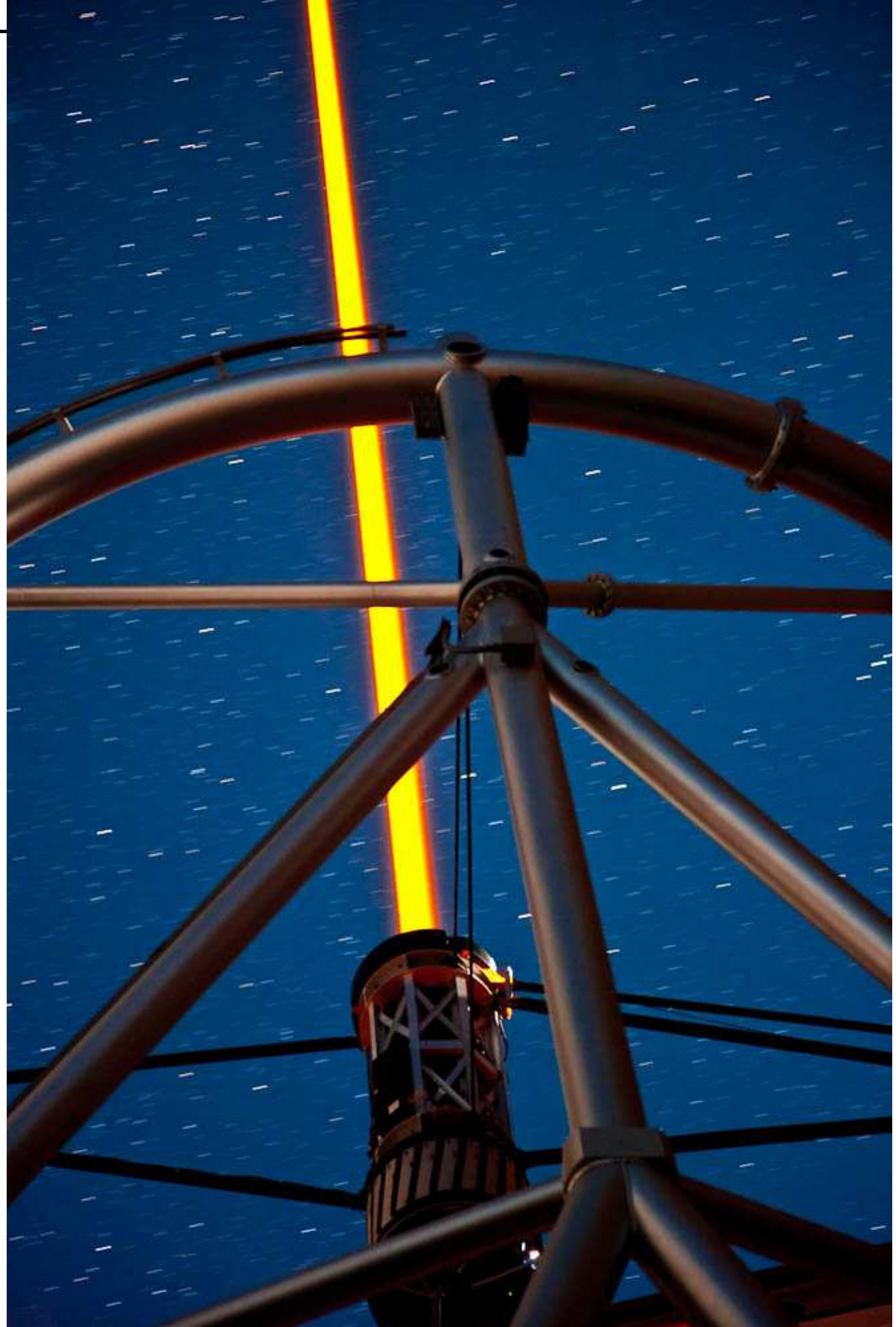
A brief Introduction to Adaptive Optics (AO) and Wide Field AO

GeMS: the Gemini MCAO system

Tomography & Calibrations

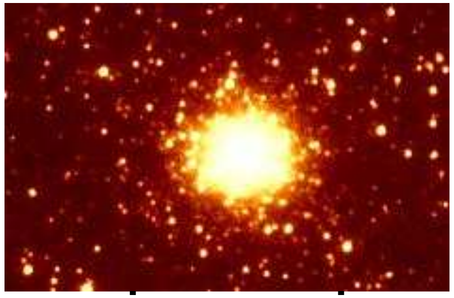
First science results with WFAO

New challenges

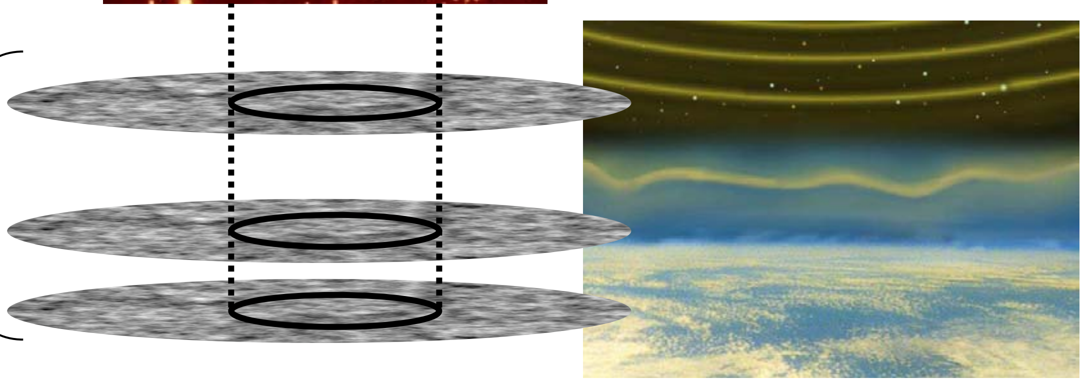


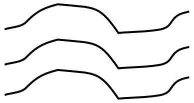
# A brief Introduction to Adaptive Optics (AO) and Wide Field AO (WFAO)

# Adaptive Optics

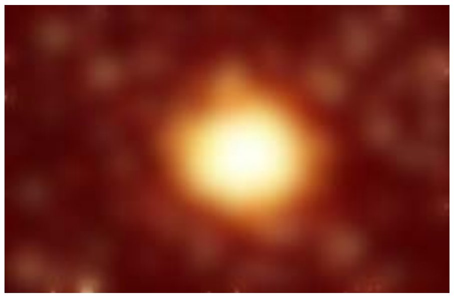


Earth's atmosphere

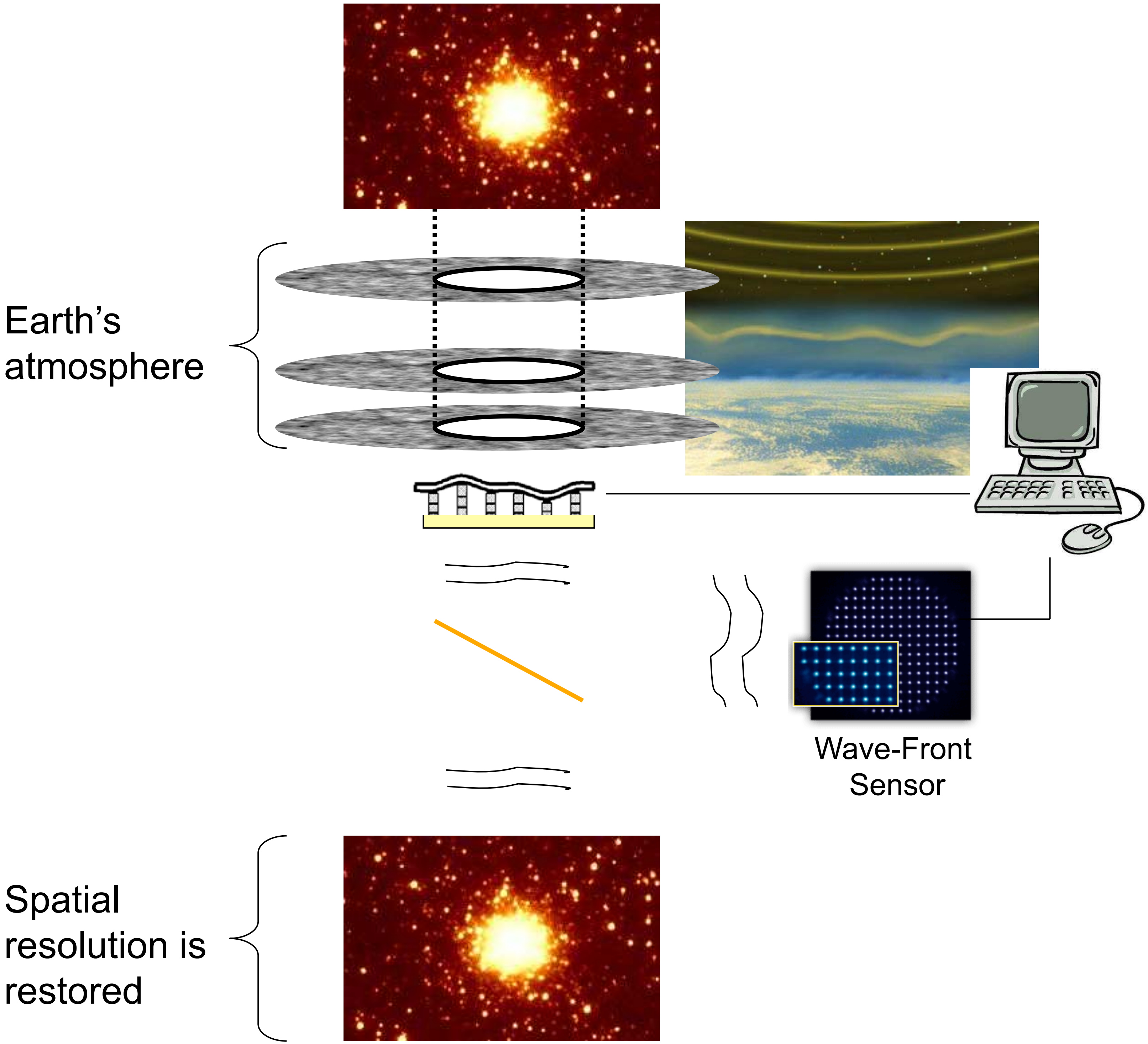




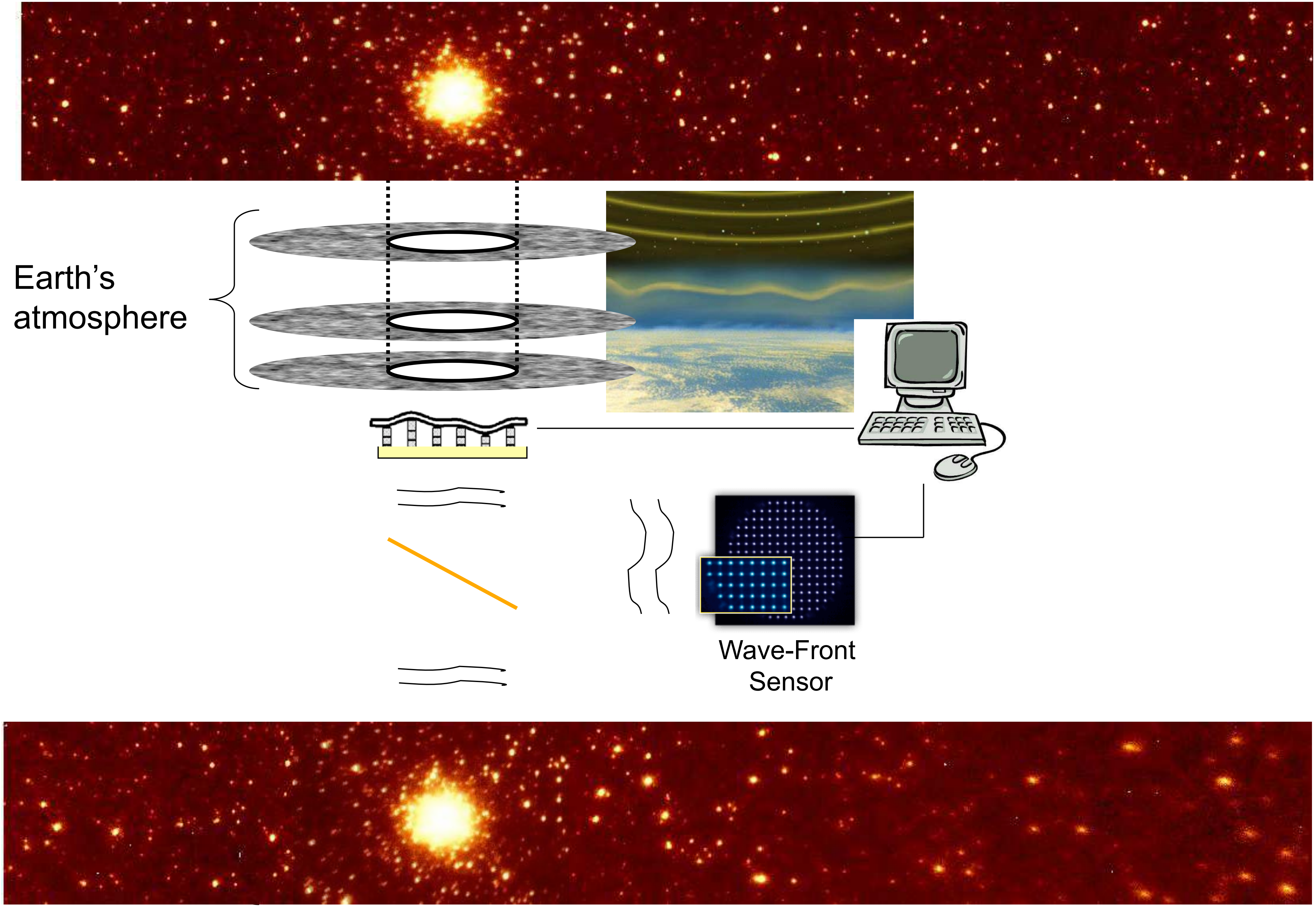
Spatial resolution is lost…



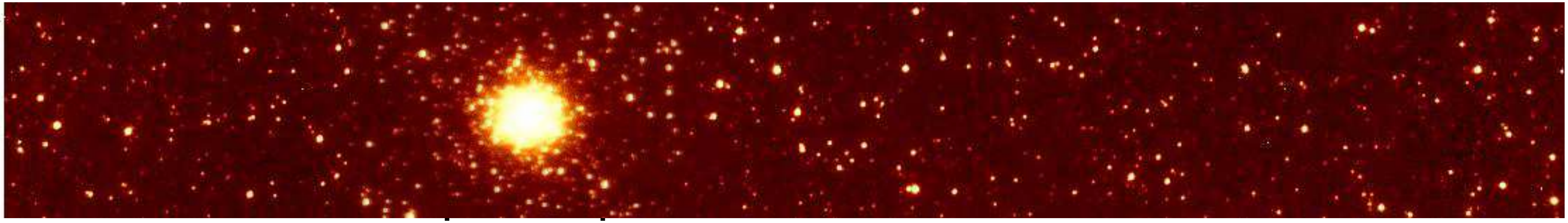
# Adaptive Optics

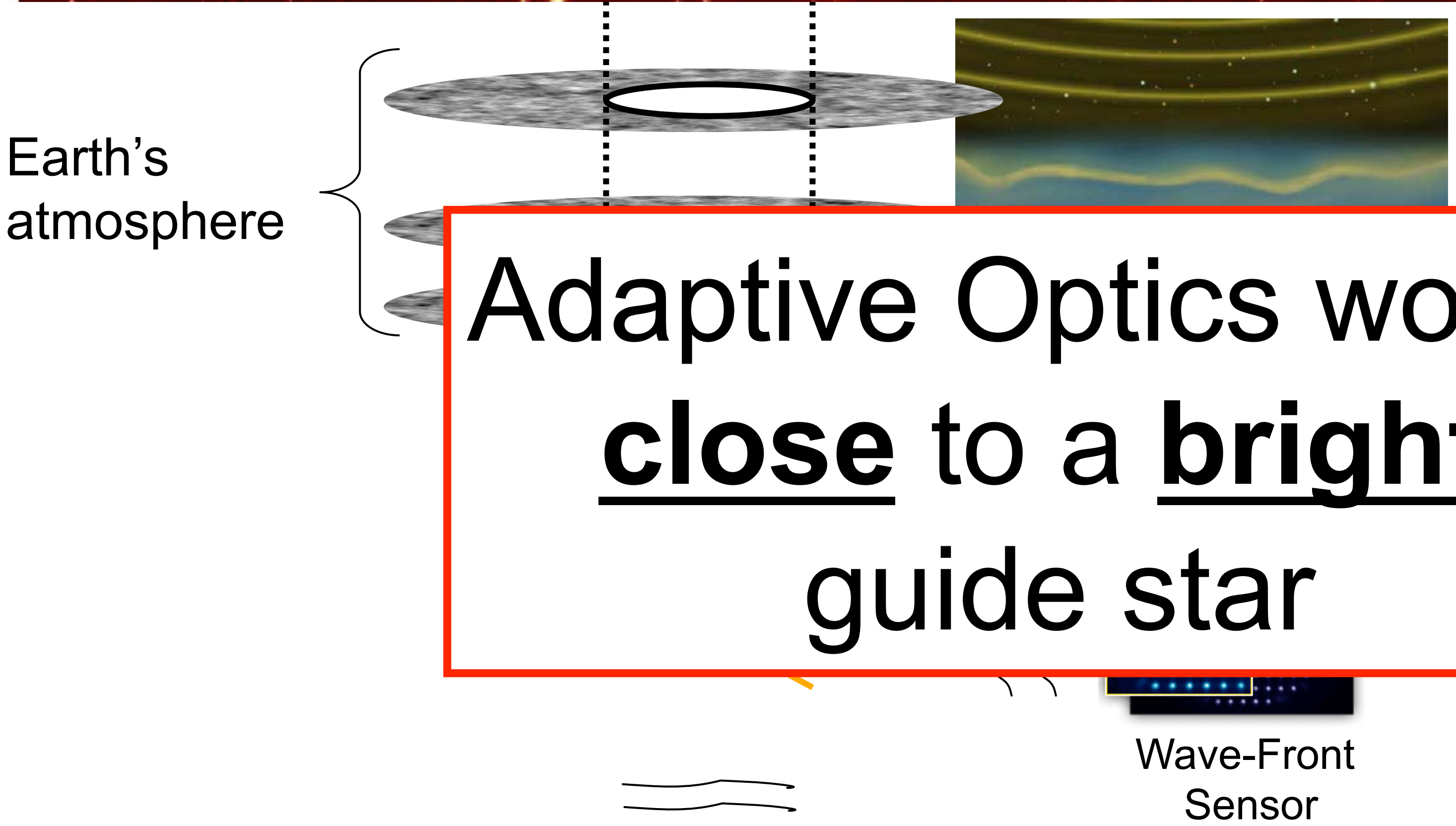


# Adaptive Optics

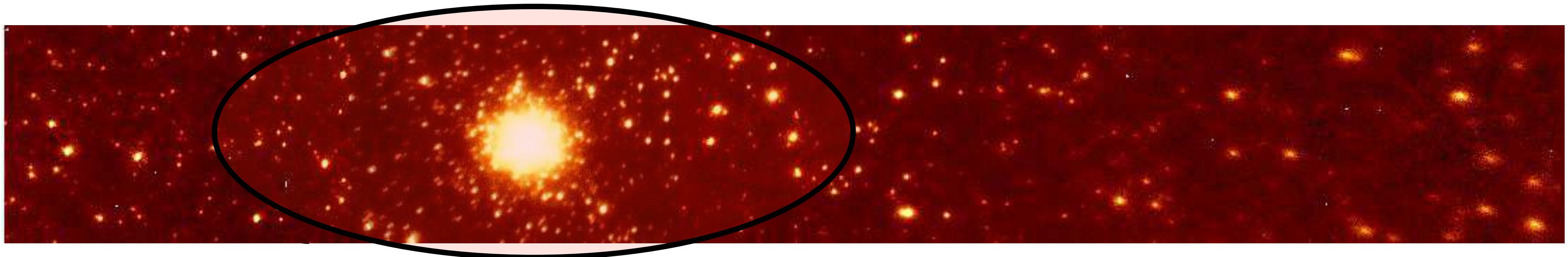


# Adaptive Optics

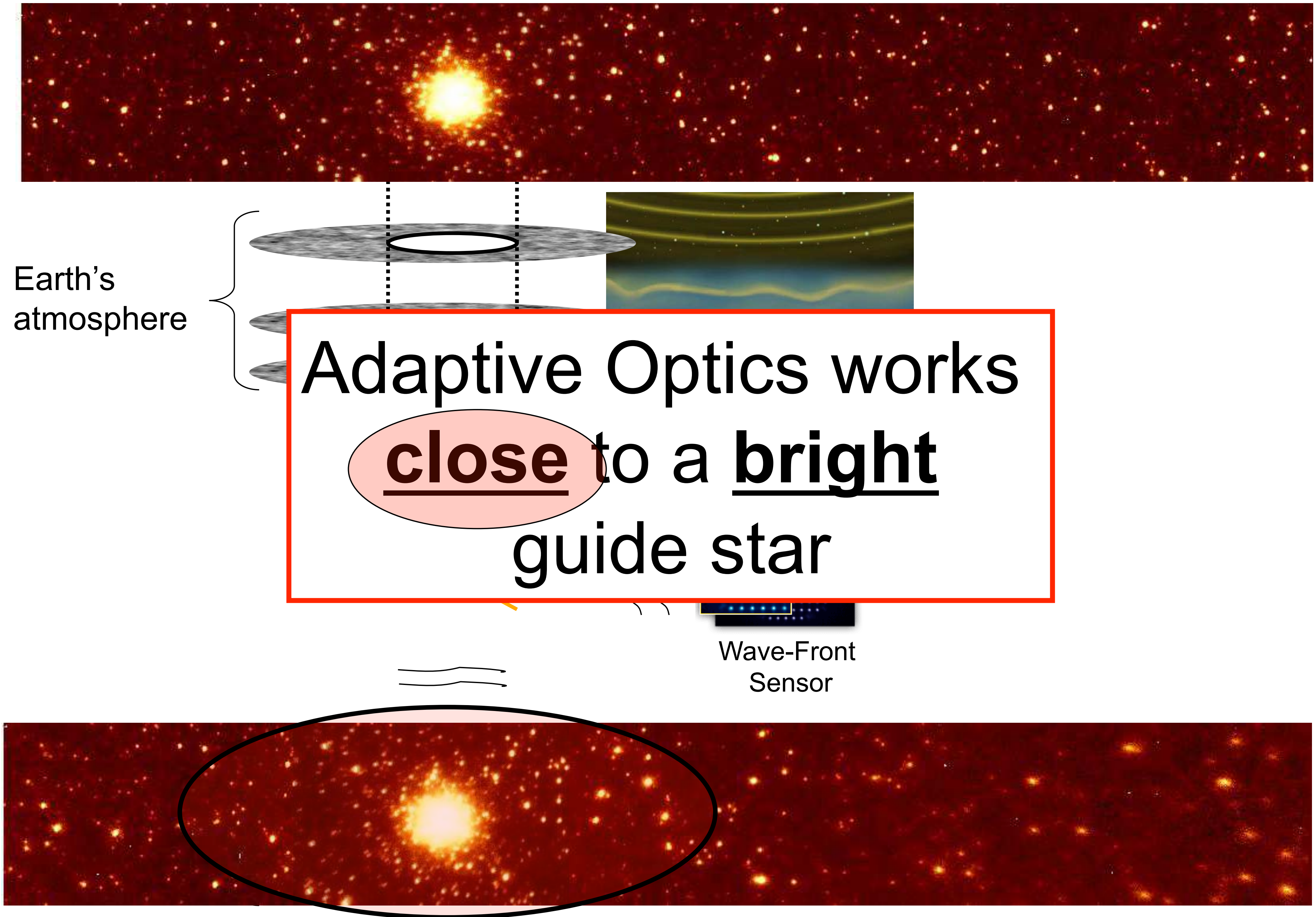





Adaptive Optics works **close** to a **bright** guide star

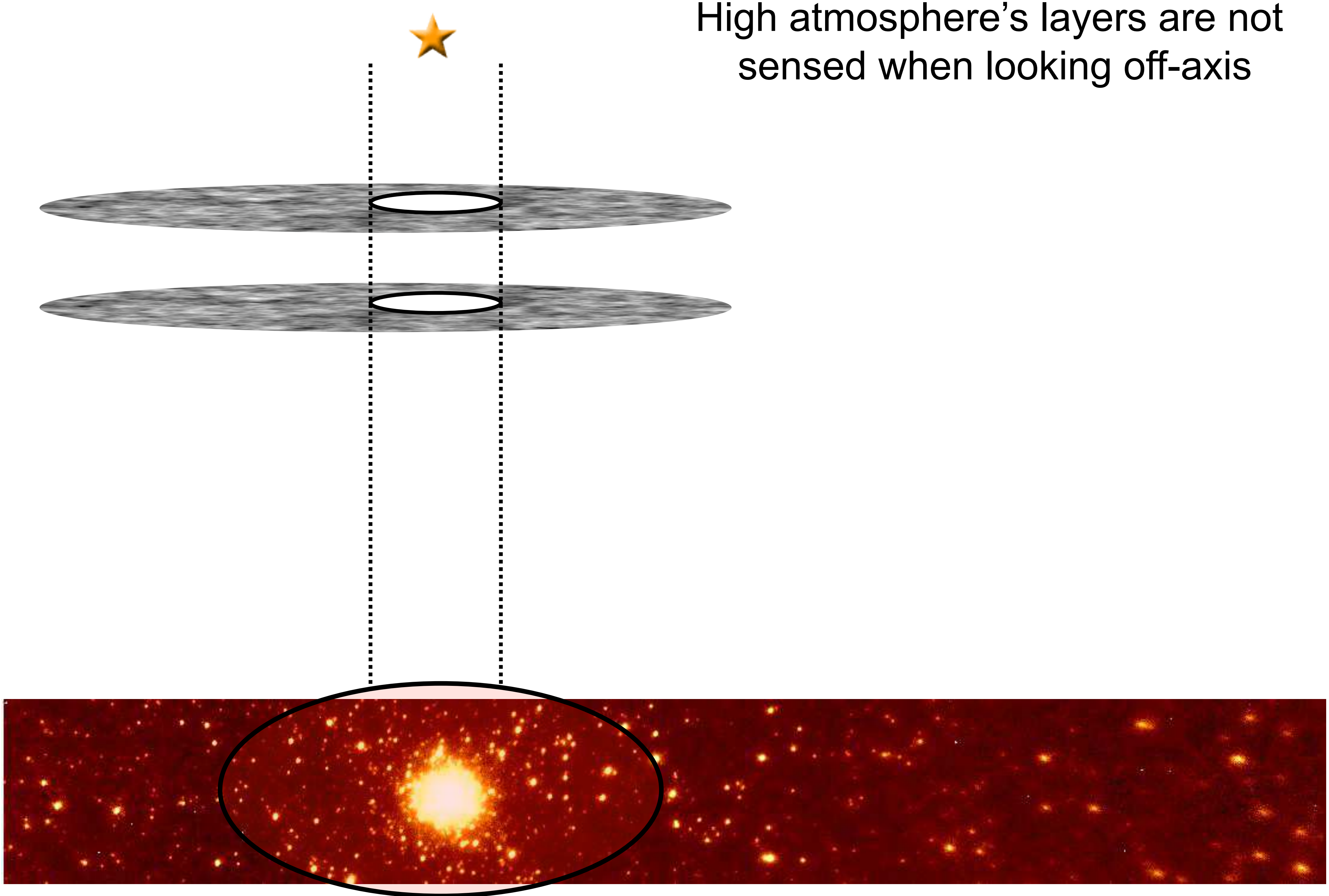


# Adaptive Optics



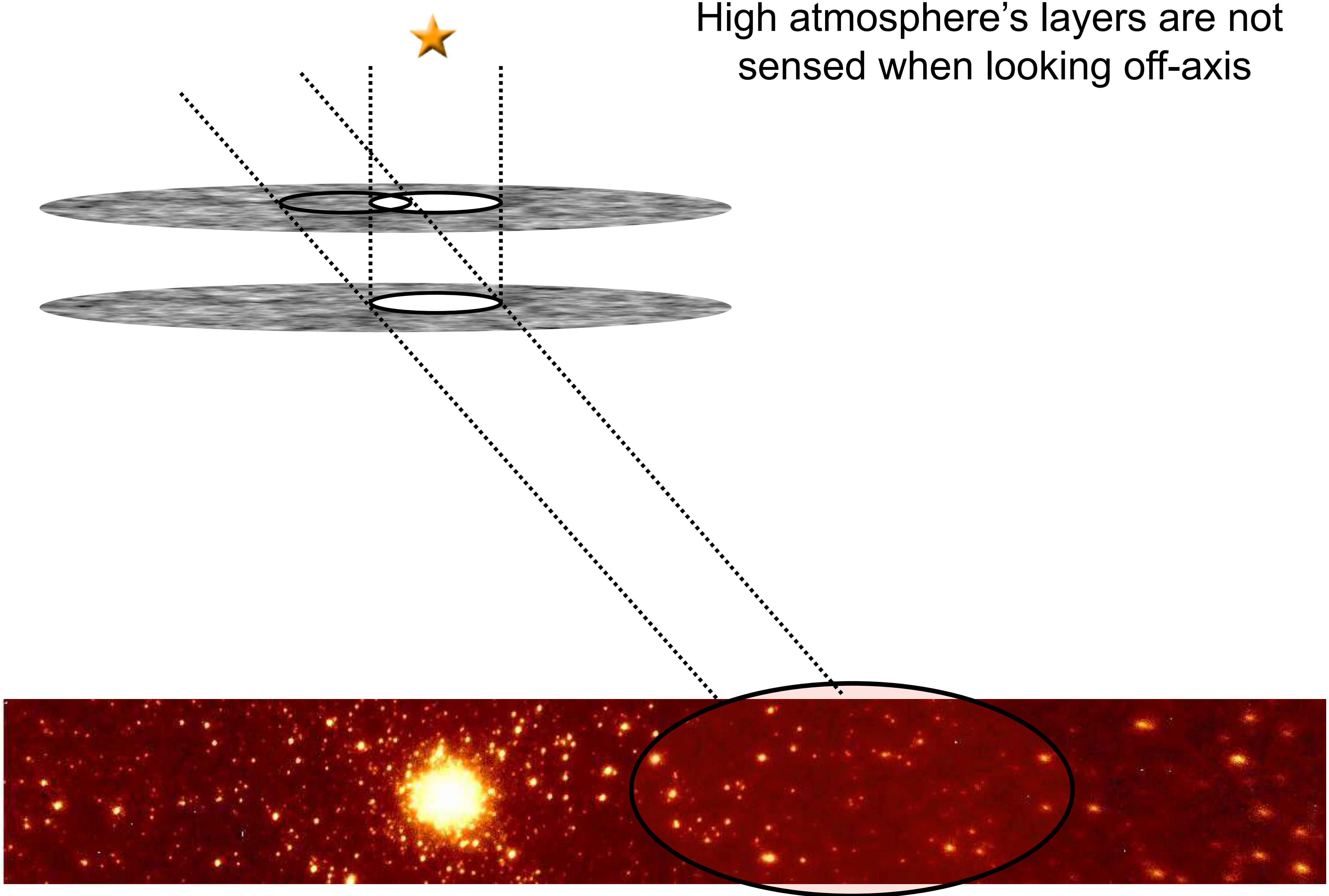
# Anisoplanatism

High atmosphere's layers are not sensed when looking off-axis



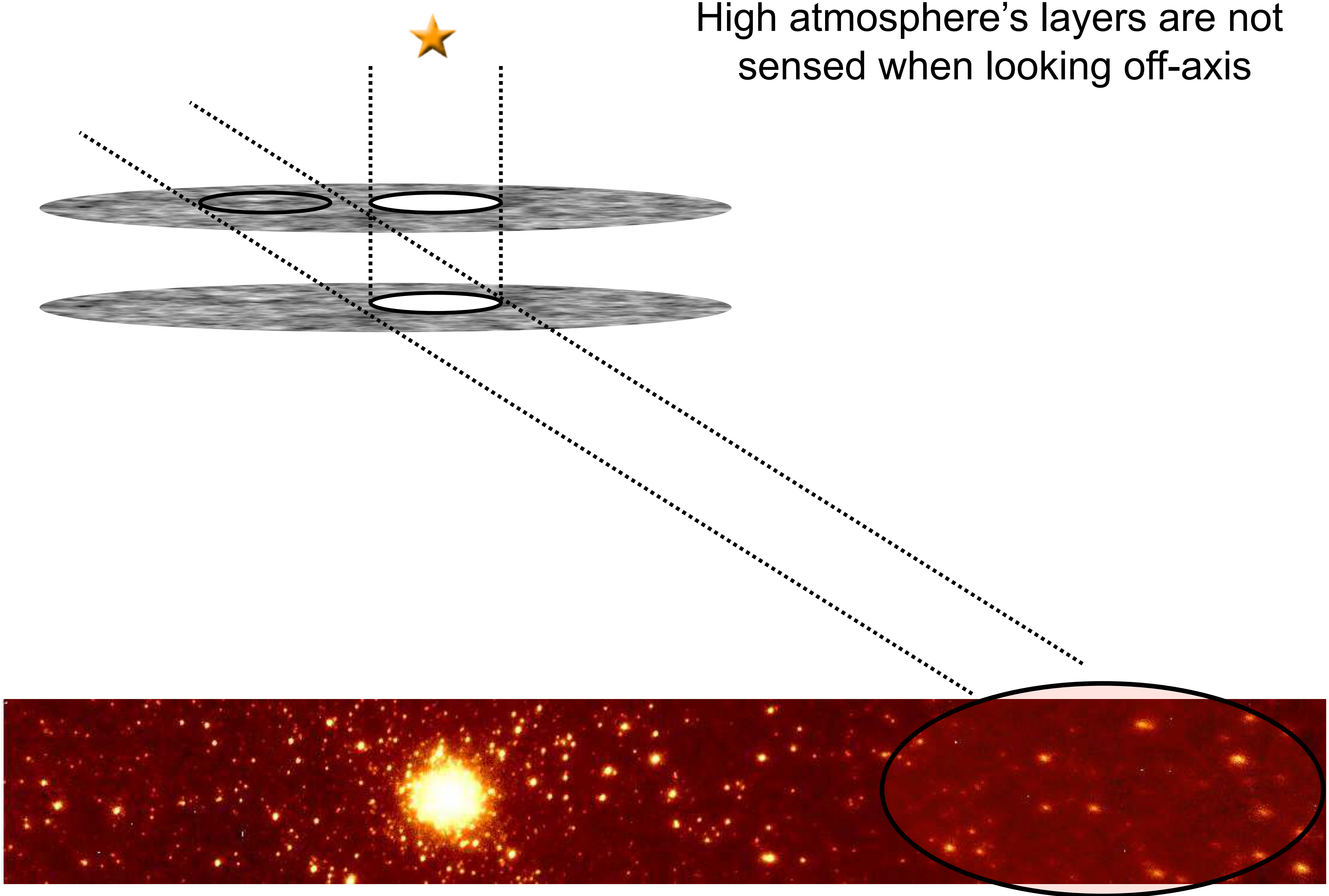
# Anisoplanatism

High atmosphere's layers are not sensed when looking off-axis

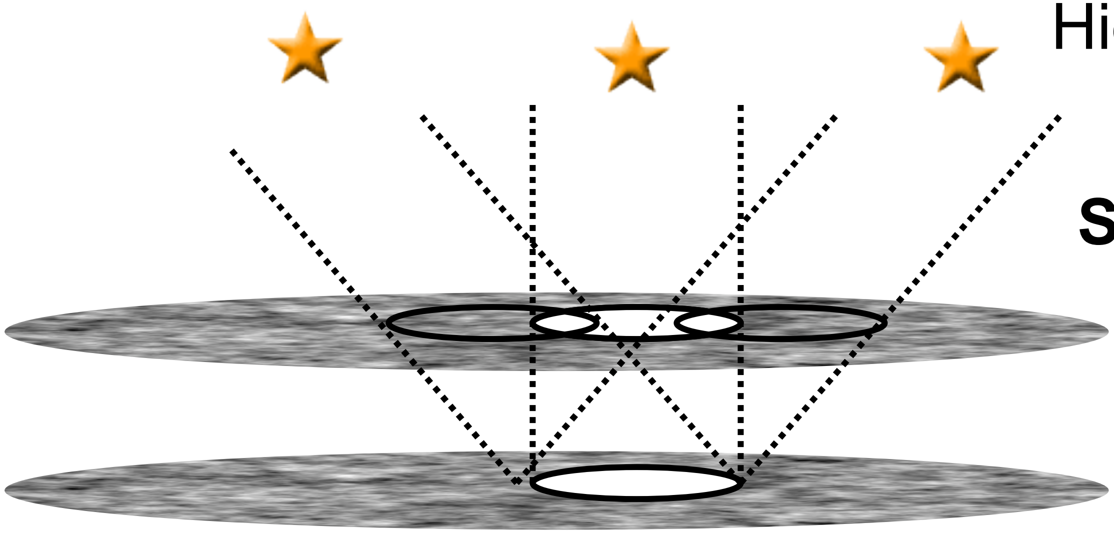


# Anisoplanatism

High atmosphere's layers are not sensed when looking off-axis

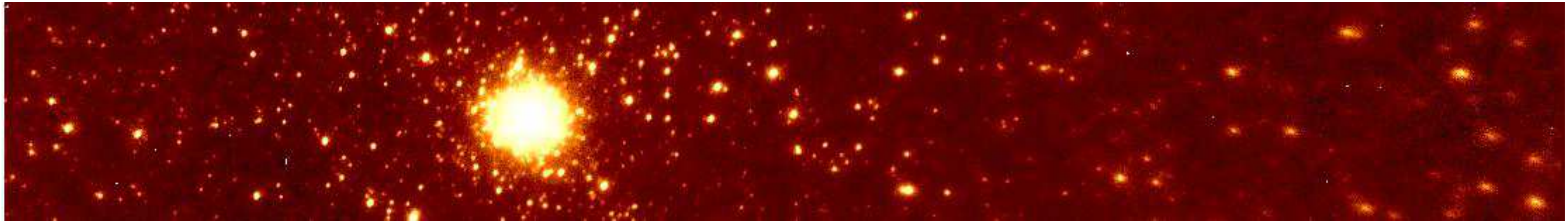


# Tomography

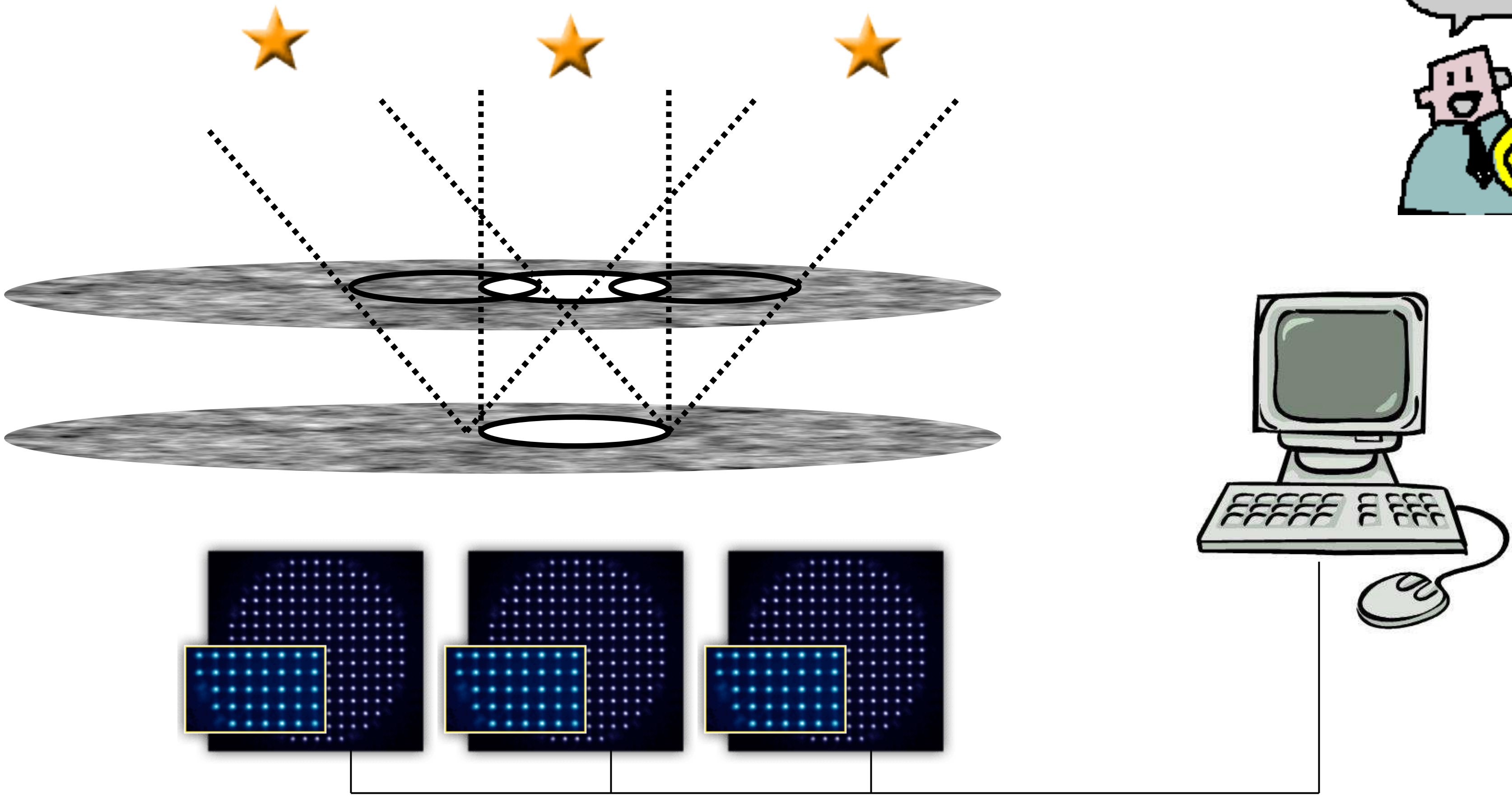


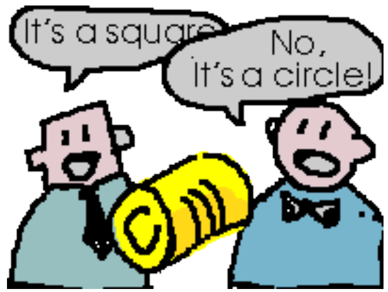
High atmosphere's layers are not sensed when looking off-axis

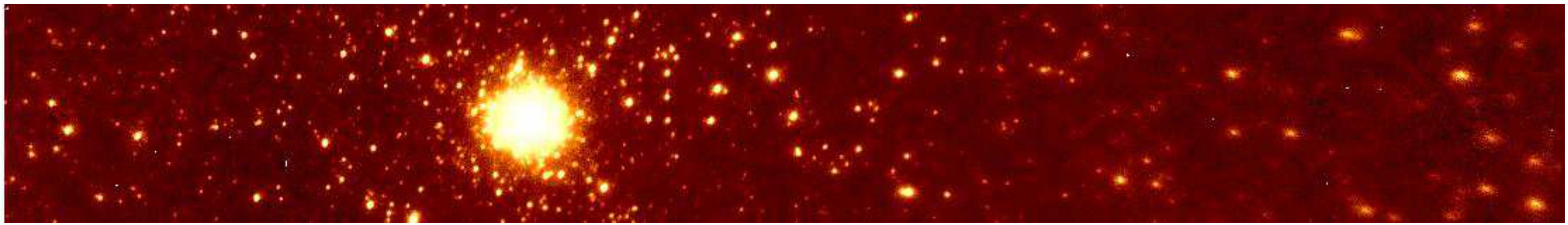
**Solution => Combine off-axis measurements**



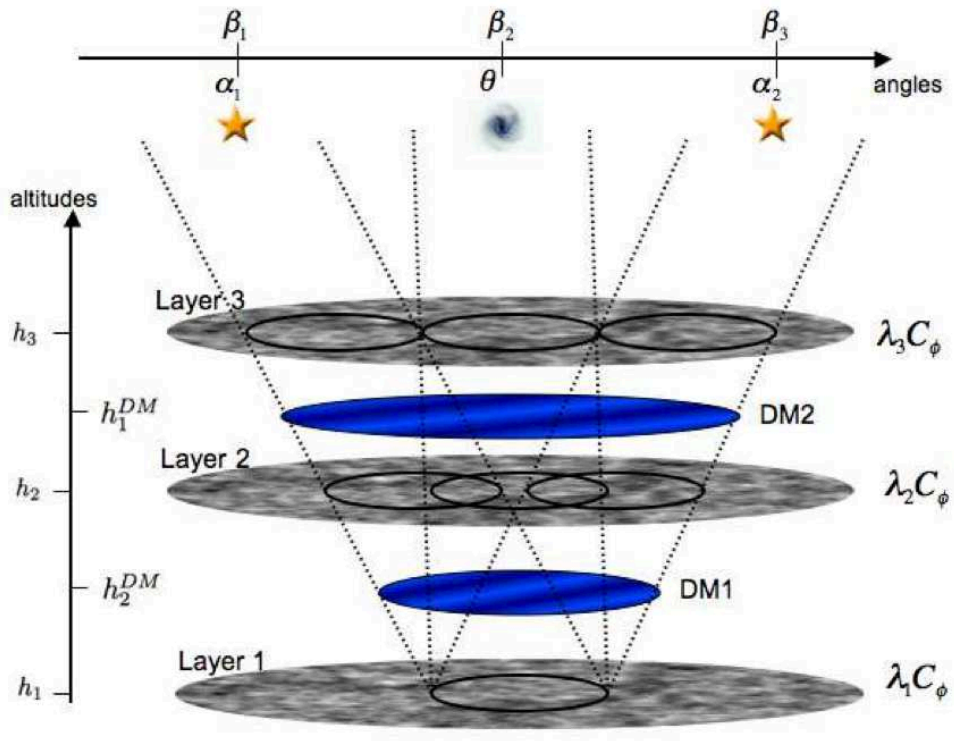
# Tomography

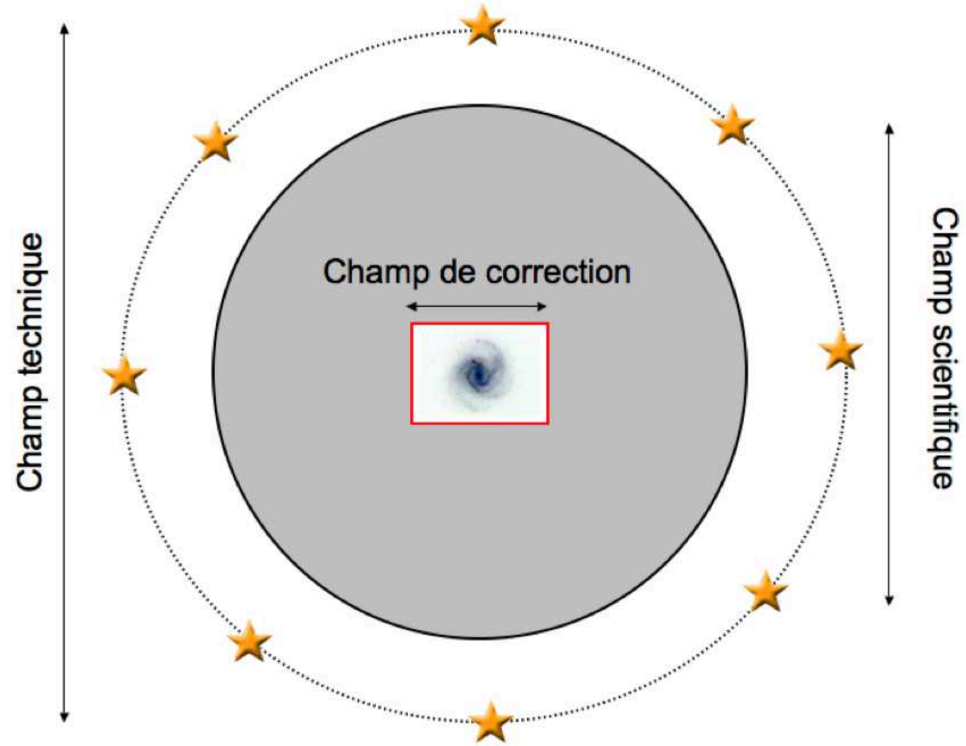




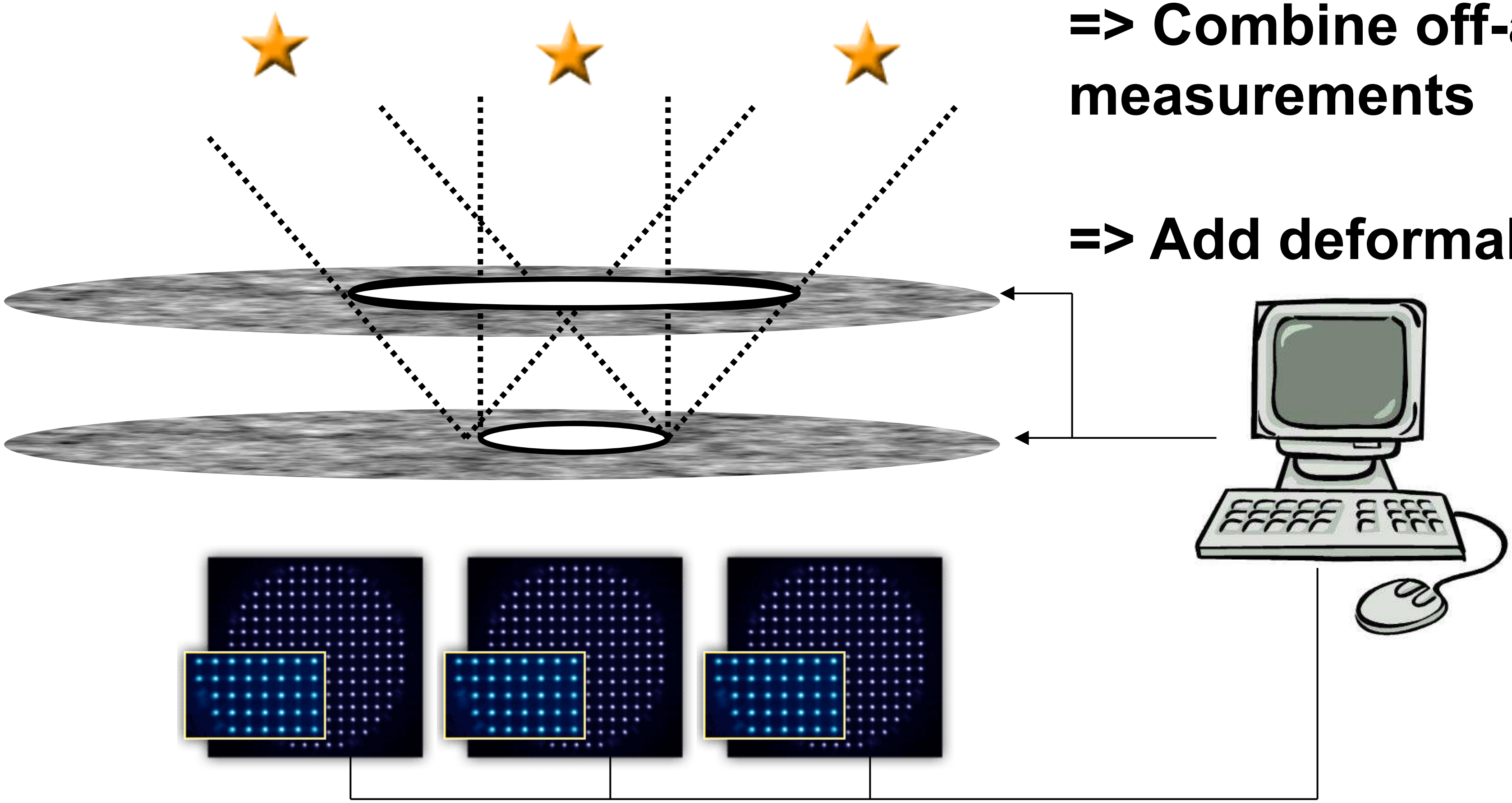
How to combine the WFSs measurements to do the tomography ?



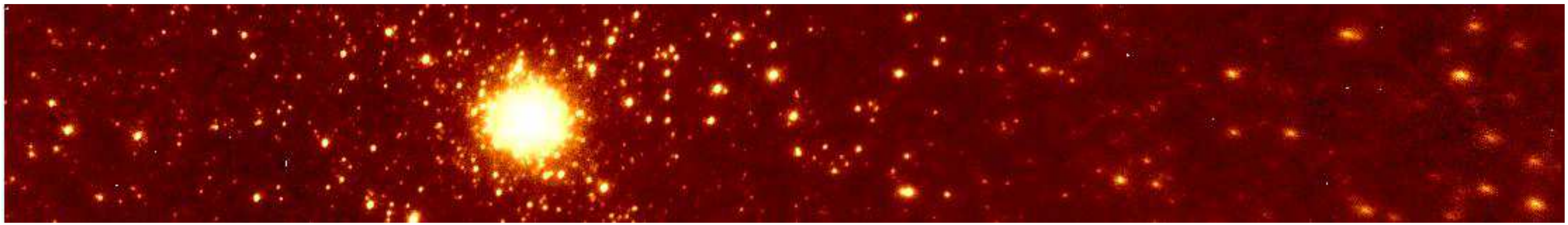

Many different flavors of 3D phase reconstruction:
LSE, MMSE, MV, L&A, FRIM, POLC, Neuronal Network, …

Usually done in 2 steps (1) Reconstruction ; (2) projection

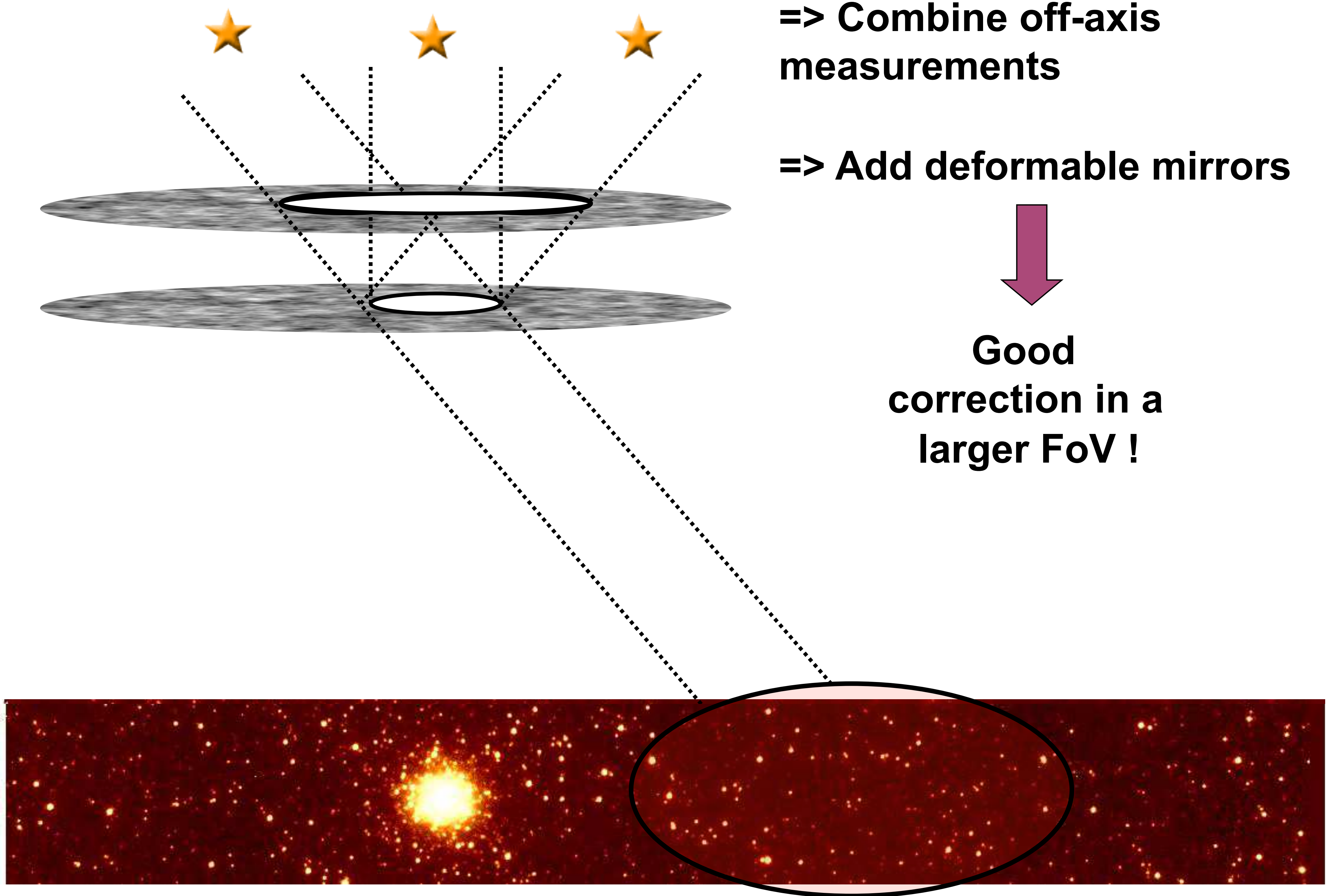


=> Combine off-axis measurements

=> Add deformable mirrors



# MCAO



=> Combine off-axis measurements

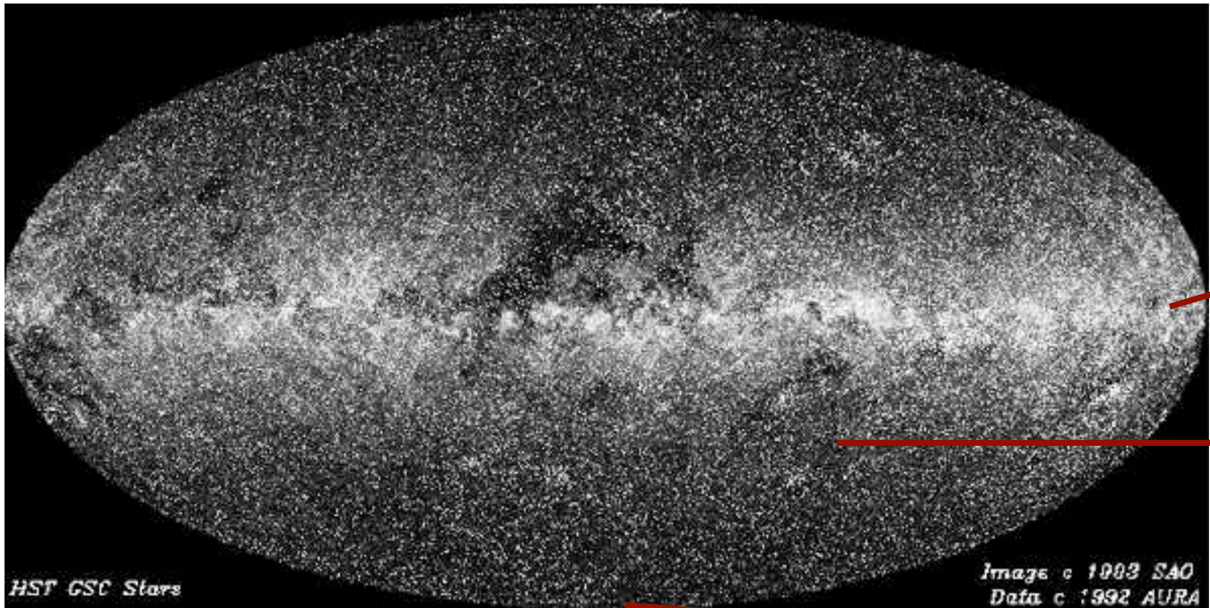
=> Add deformable mirrors

Good correction in a larger FoV !

# Adaptive Optics works **close** to a **bright** guide star

How many Guide Stars are available ?

3 stars with R < 16 in a 2 arcmin FoV

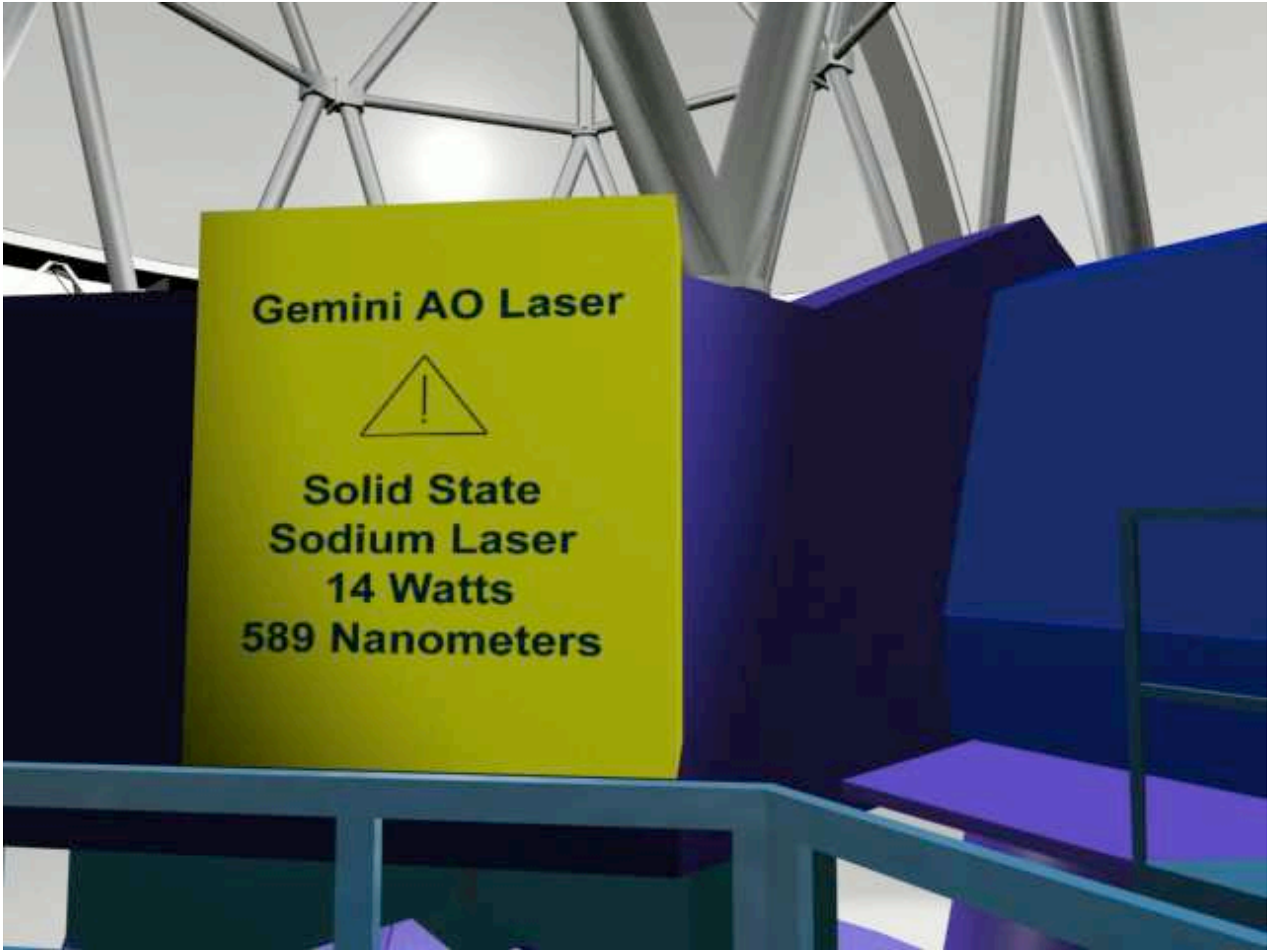



10%

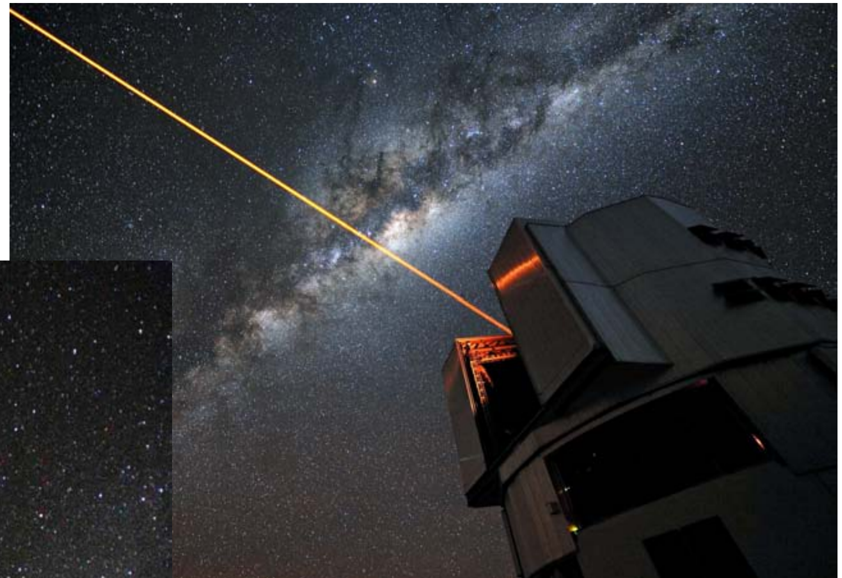
1%

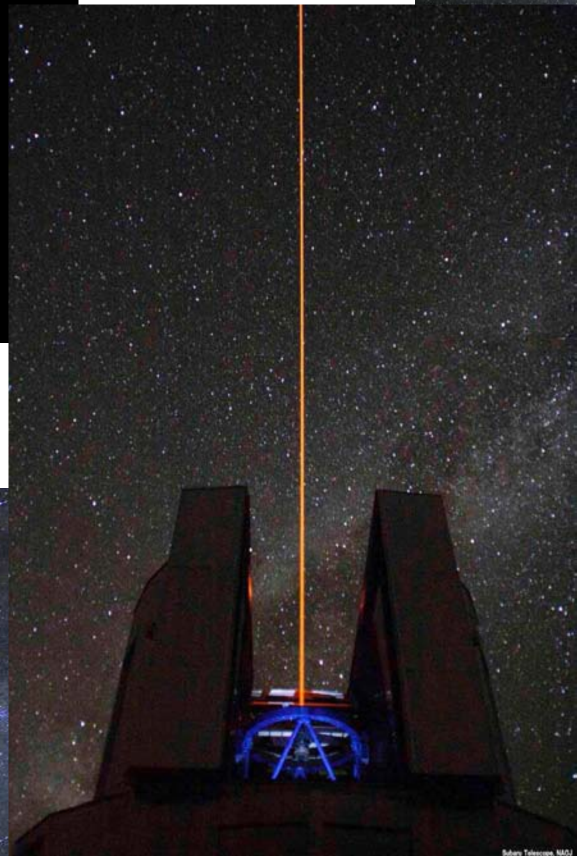
0.1%

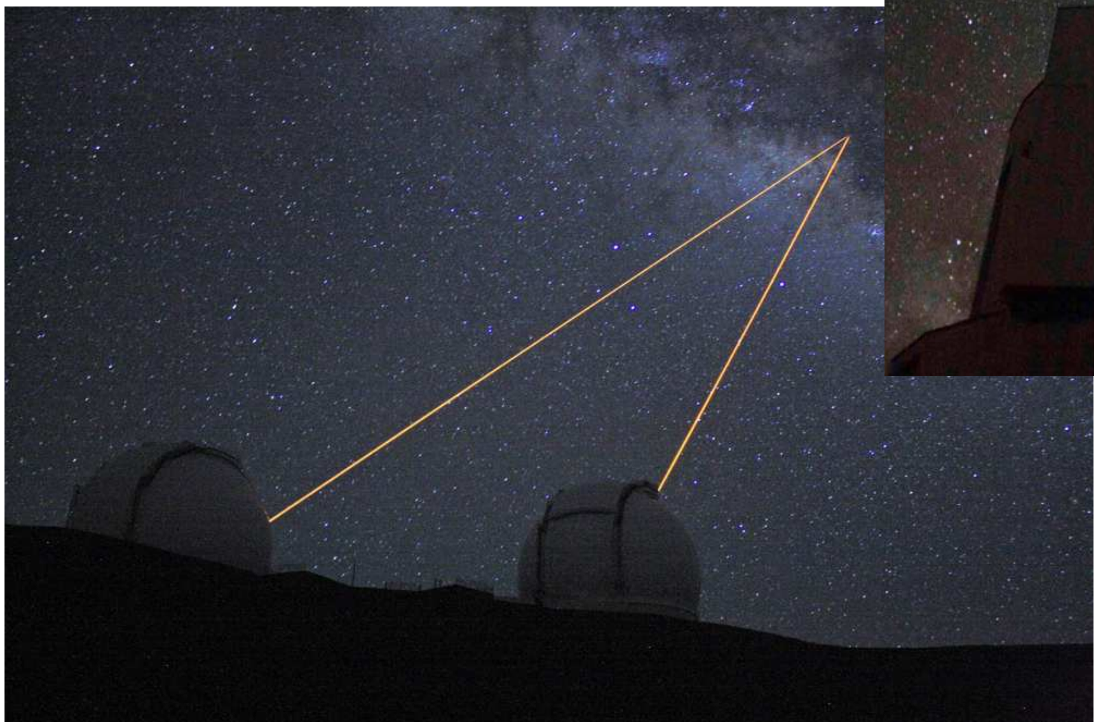
When no guide star are available, we can create one

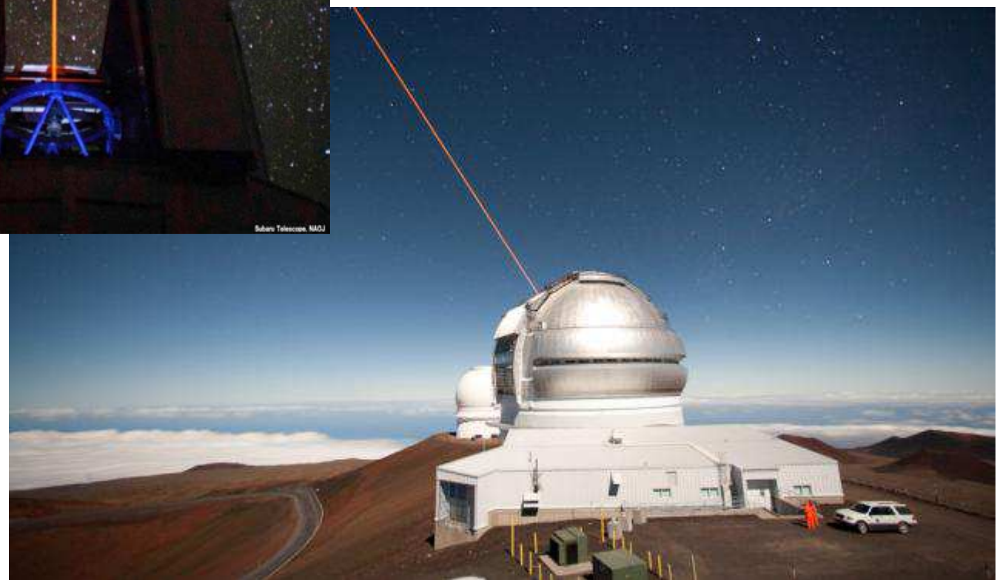


# Laser Guide Star





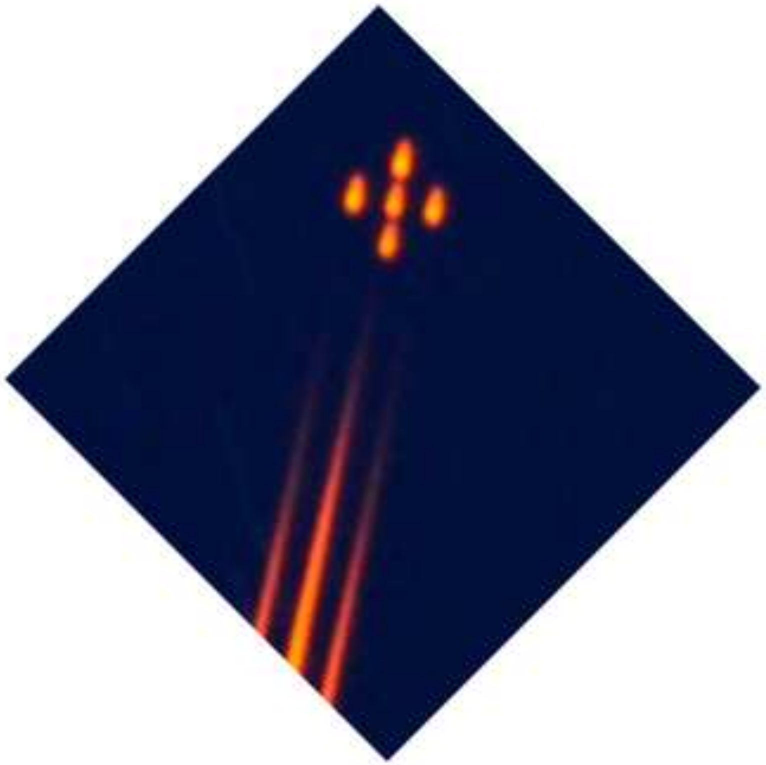



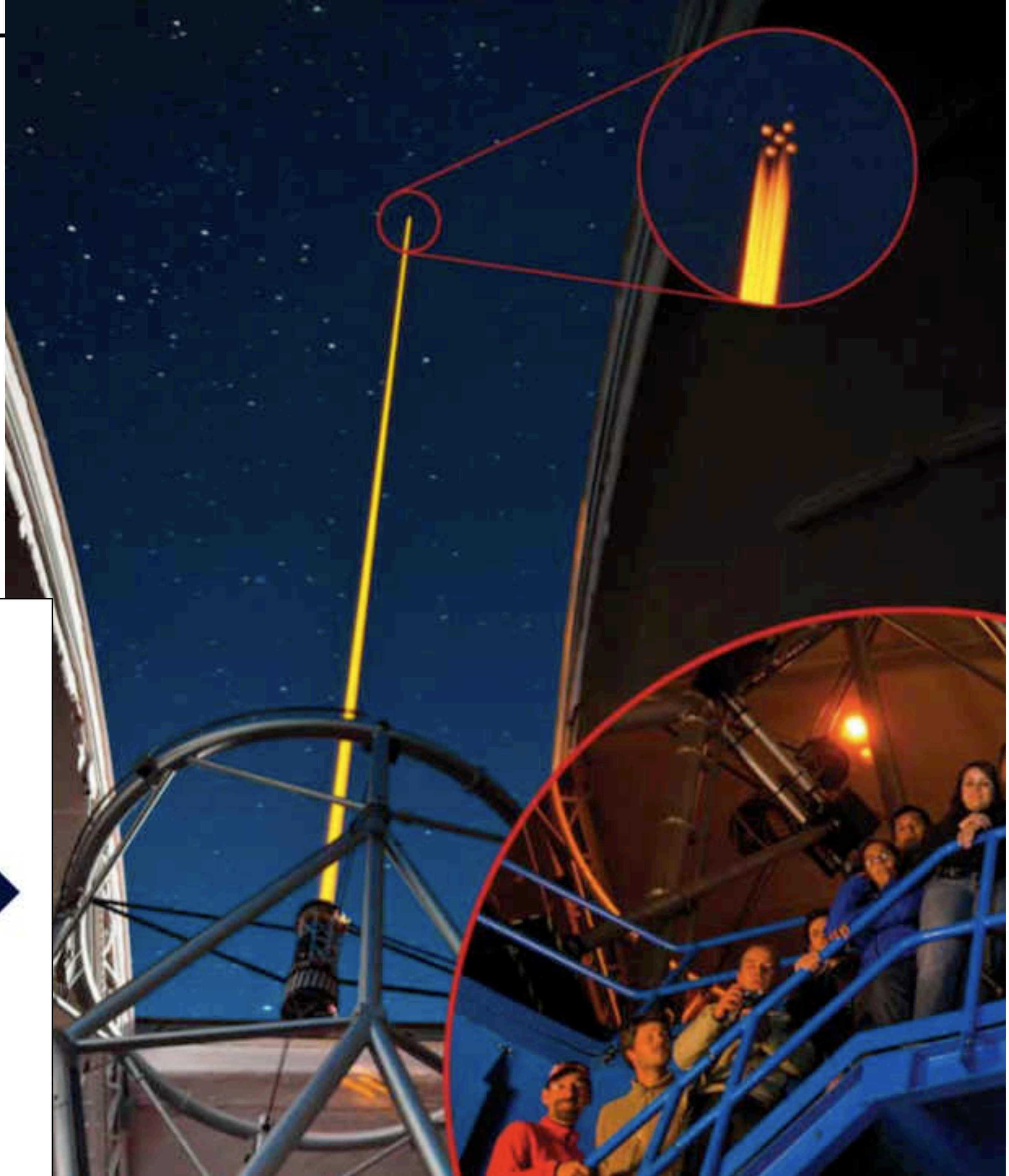


# Laser Guide Star

22 January 2011

First LGS constellation at Gemini South





## - In summary -

Tomography for Astronomy means:

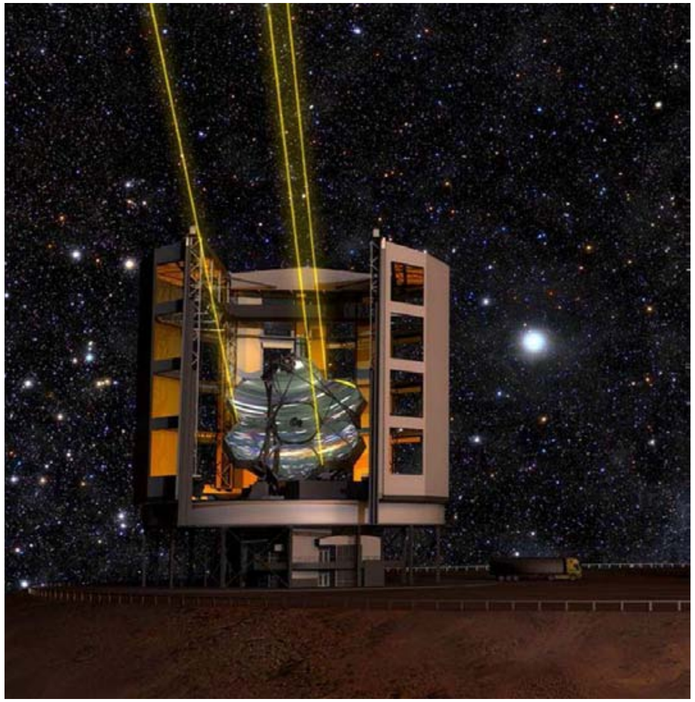
(1) Access to larger FoV
(2) Access to better sky Coverage

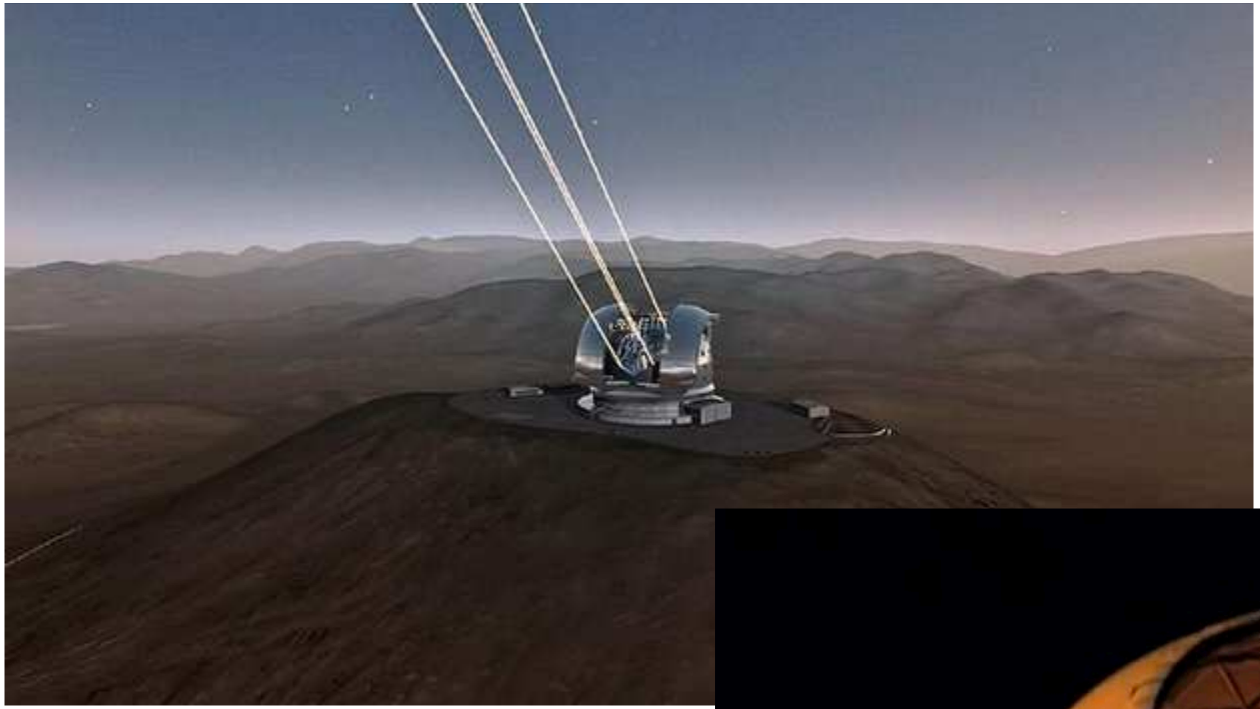
*Where the first AO systems are limited to small and bright objects, new WFAO system opens the way to a multitude of new science cases.*
*(We'll see some nice images at the end of this talk)*

BUT requires LGS

*(We'll see some of the LGS issues latter in this talk)*

All the ELTs are based on multi-LGS WFAO systems

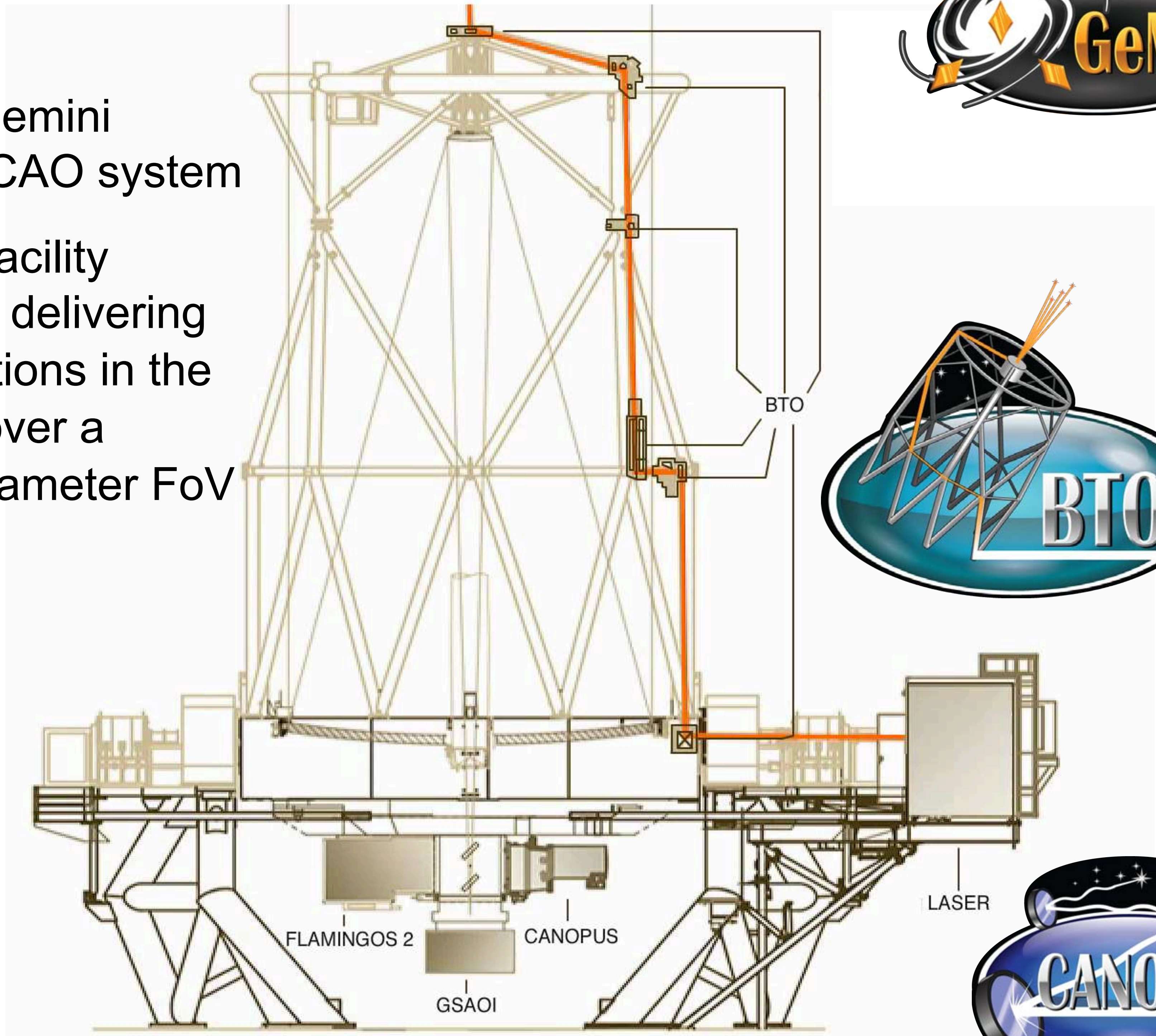




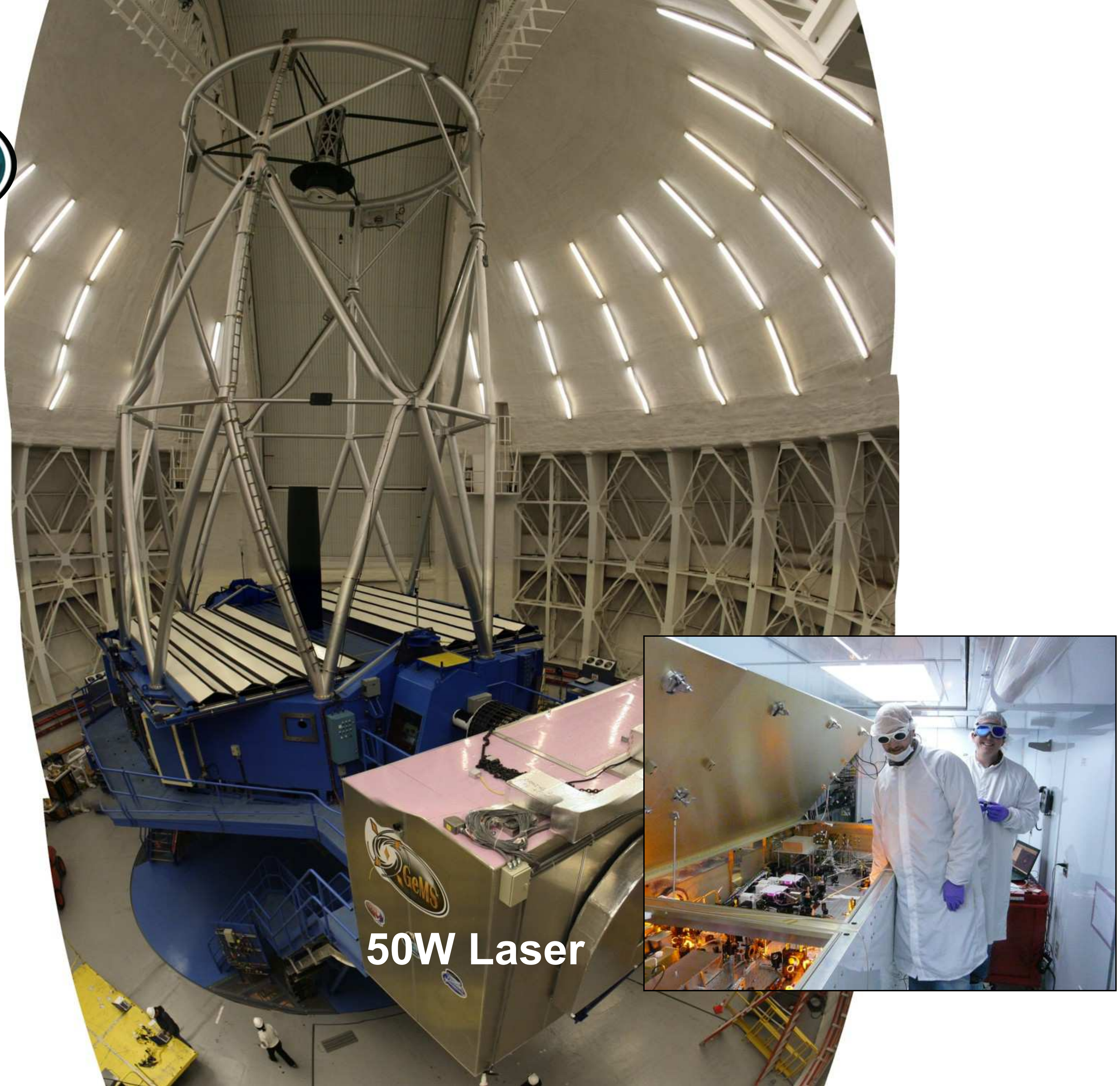
# Introduction to GeMS – The Gemini MCAO system

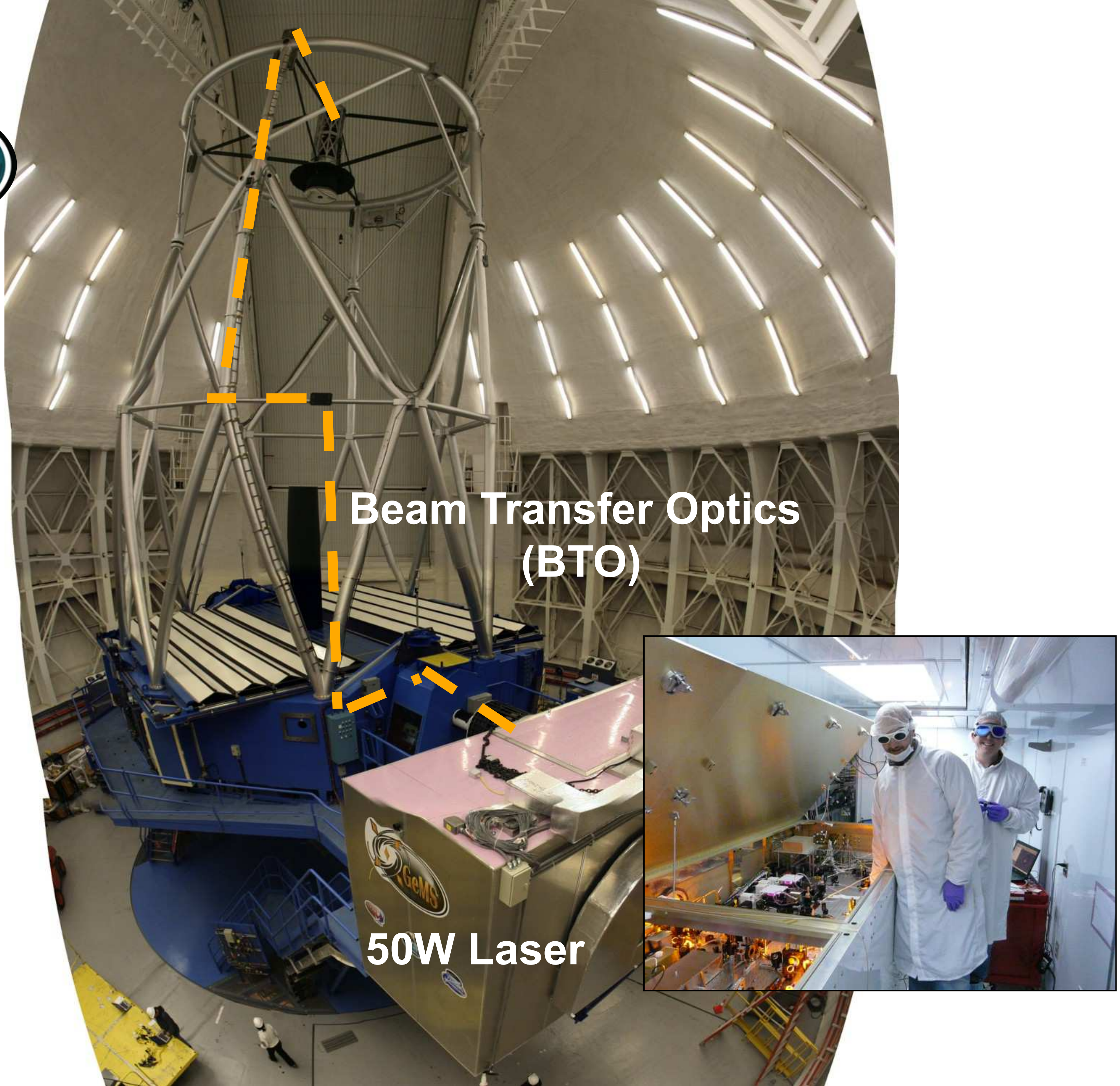
**GeMS** = Gemini (South) MCAO system

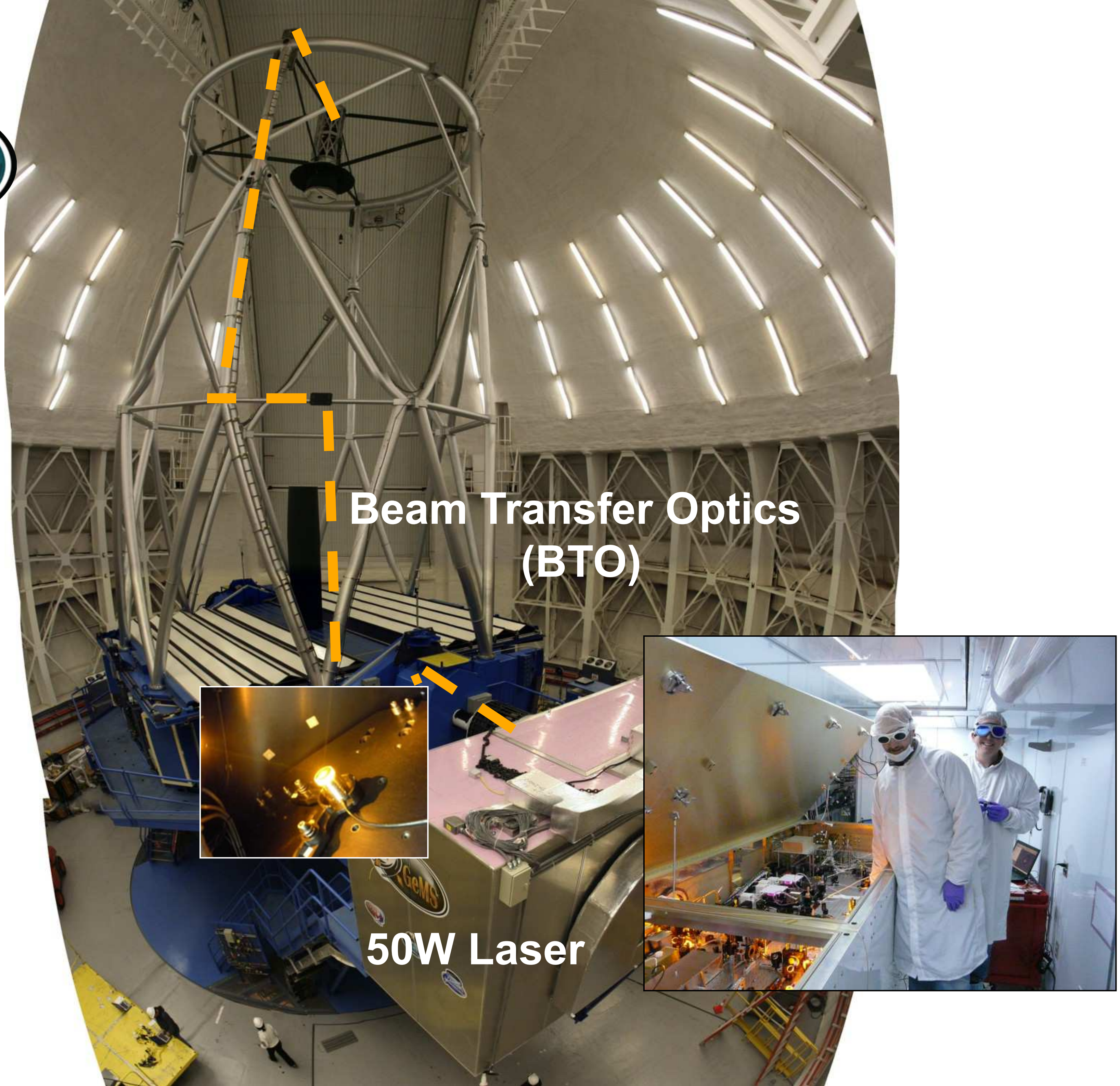
**GeMS** = Facility instrument delivering AO corrections in the NIR, and over a 2arcmin diameter FoV

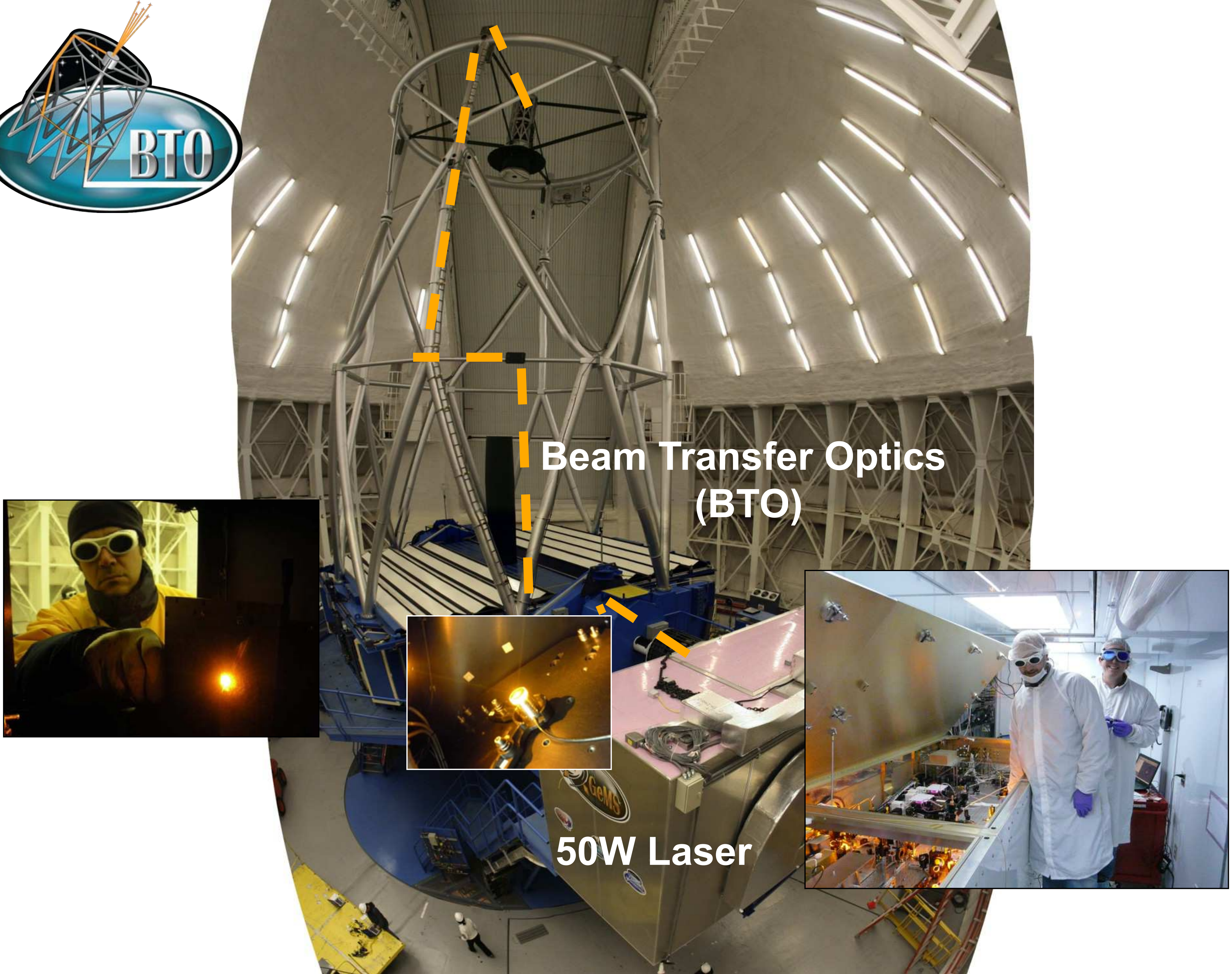


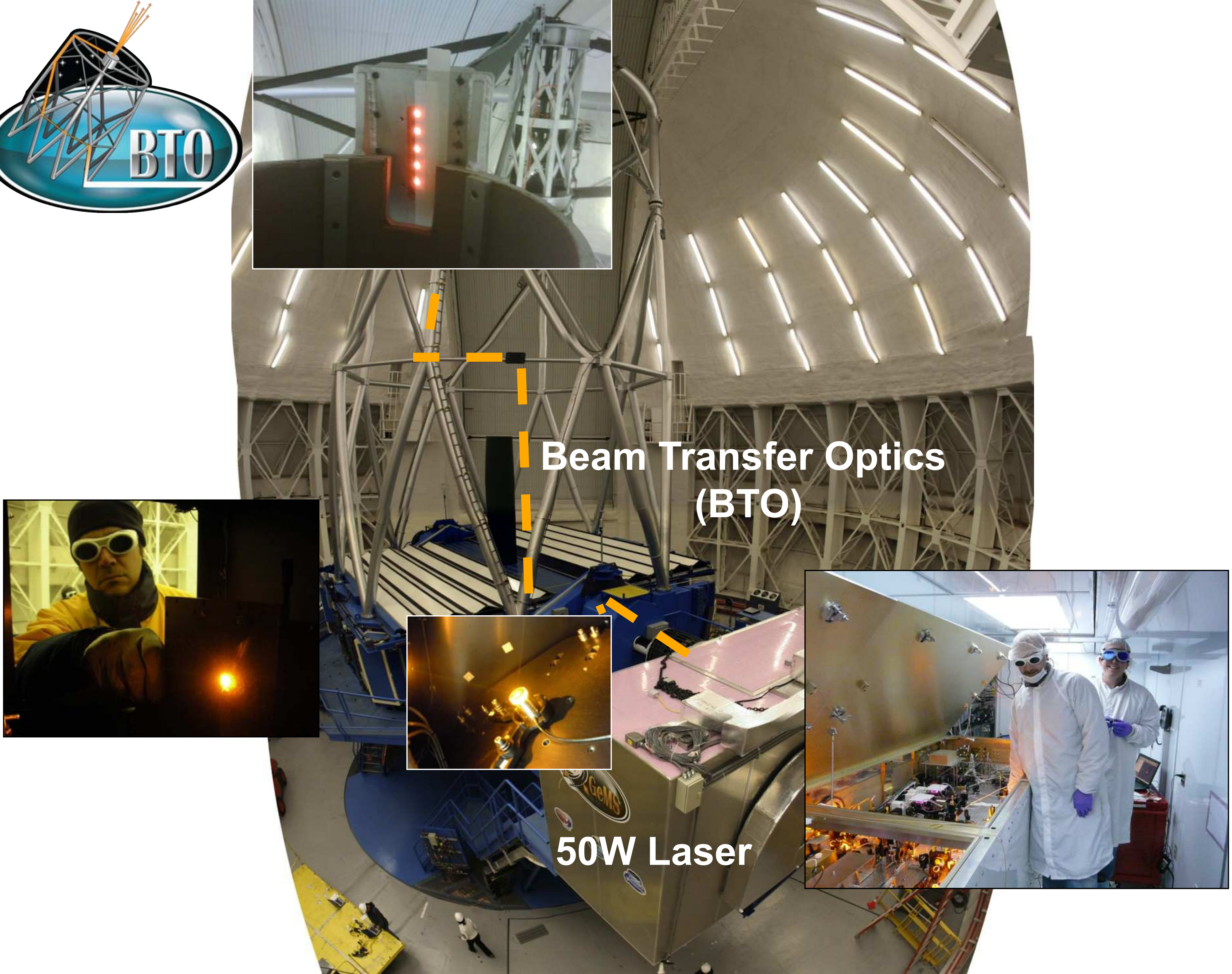
BTO

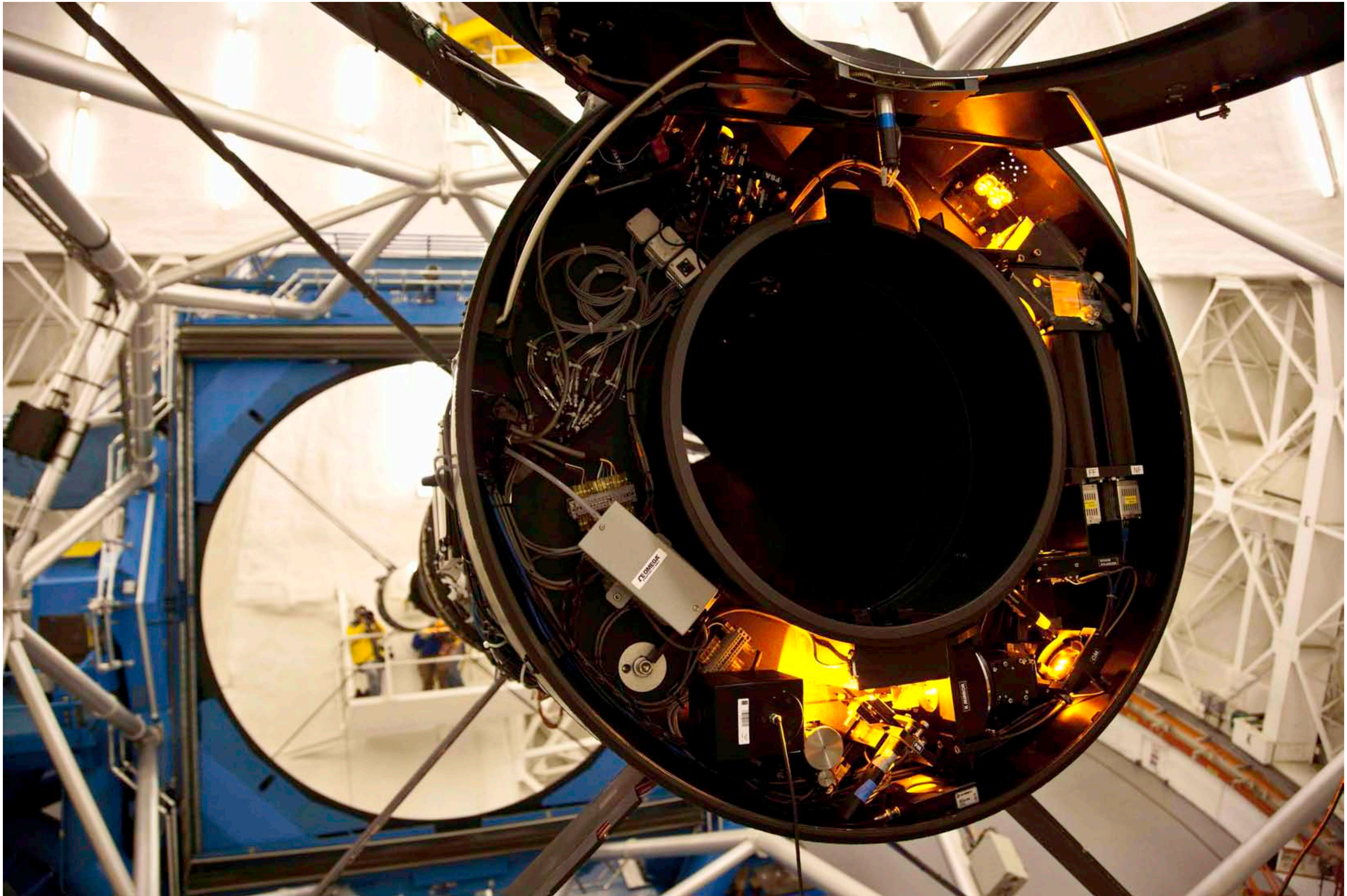

GeMS
50W Laser

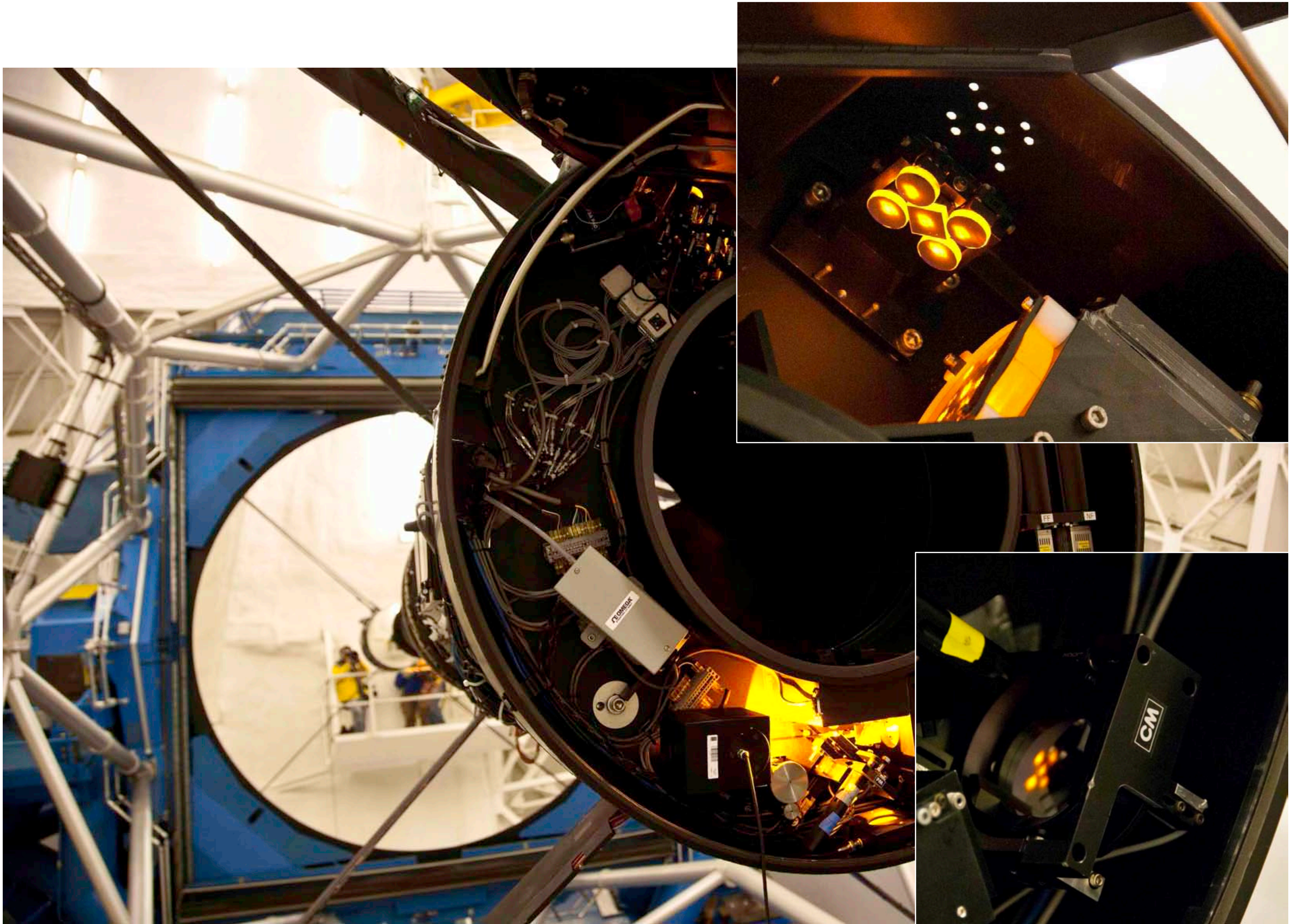

Beam Transfer Optics
(BTO)
GeMS
50W Laser

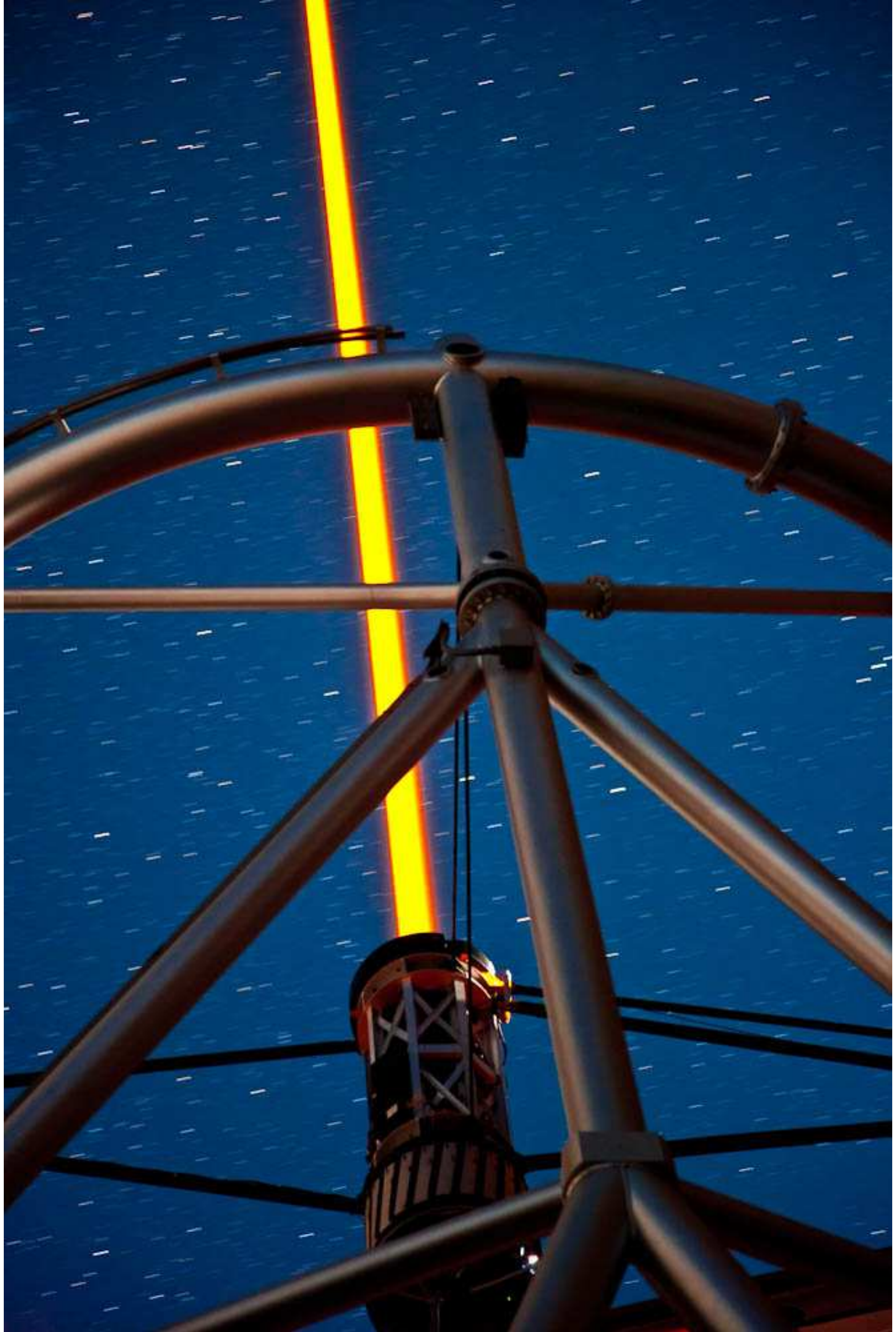

Beam Transfer Optics
(BTO)
50W Laser

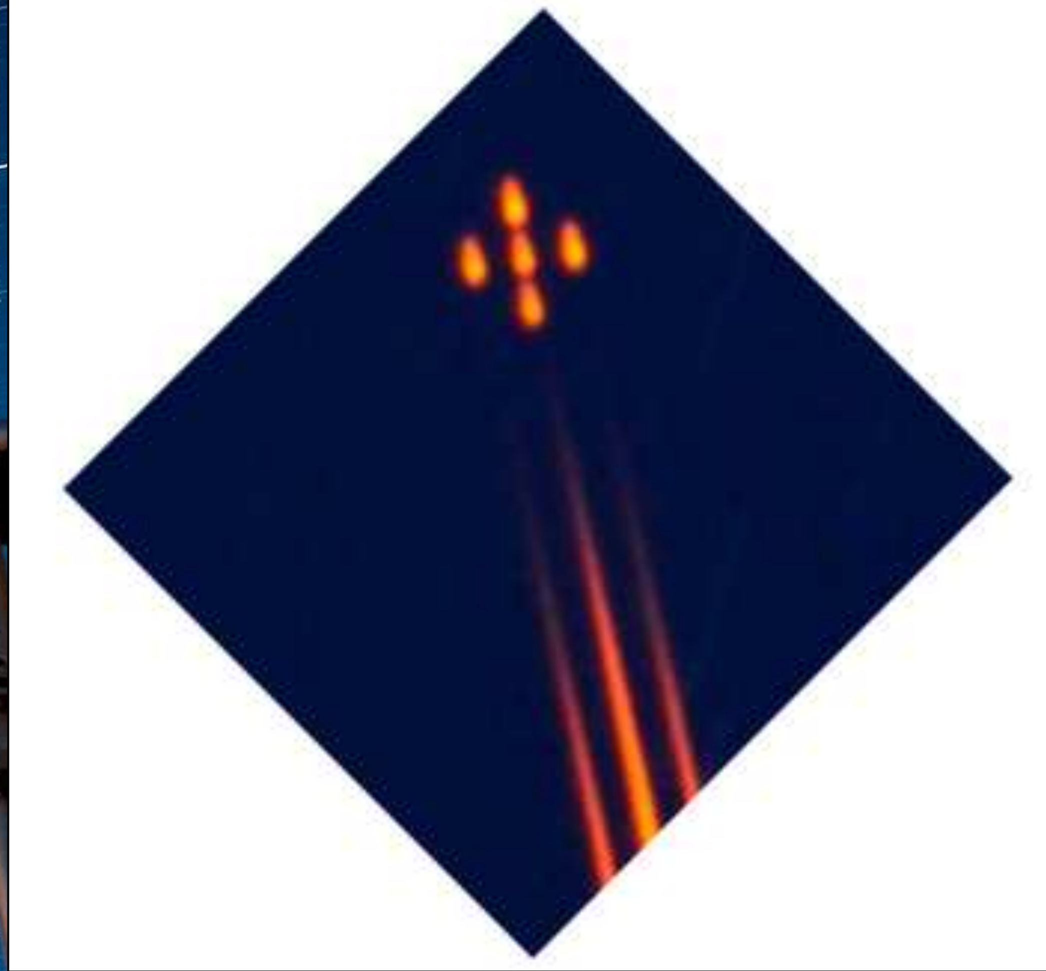

Beam Transfer Optics
(BTO)
50W Laser


Beam Transfer Optics
(BTO)
50W Laser

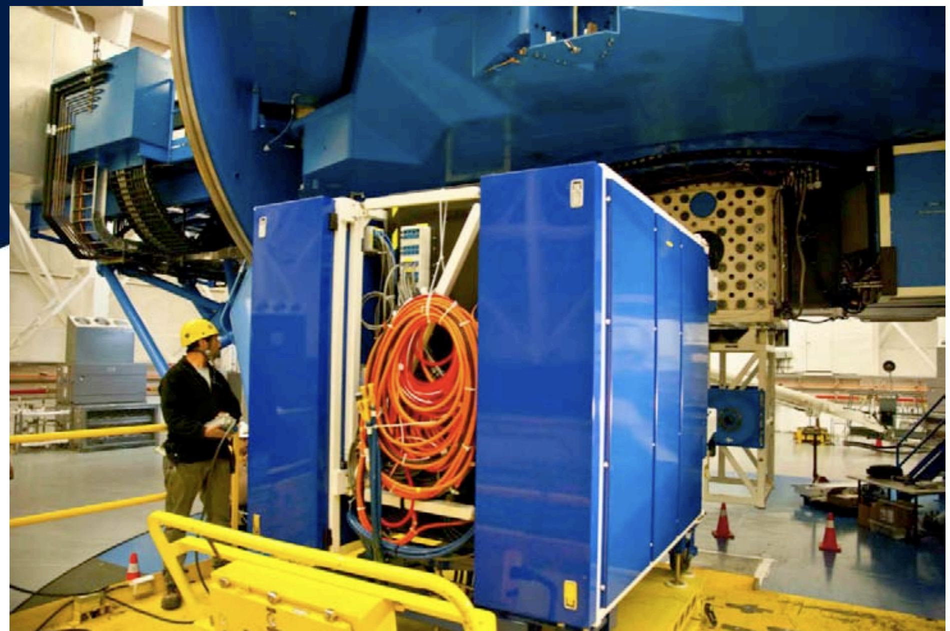

FF
NF


OMEGA
FF
NF
CM





CANOPUS

## GSAOI

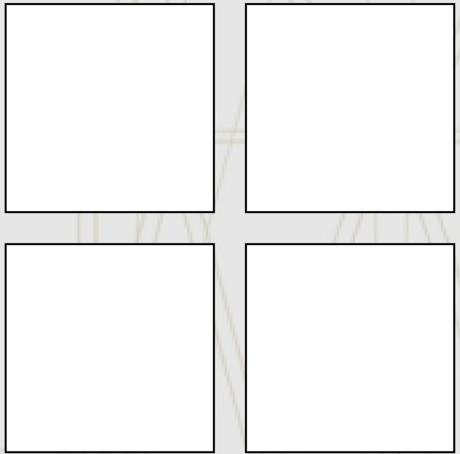
*Near-Infrared wide field imager*

2 x 2 mosaic Rockwell HAWAII-2RG 2048 x 2048 arrays

0.9 - 2.4 μm wavelength

85" x 85" field-of-view

Pix. scale of 0.02"/pixel



## Flamingos-2

*Near-Infrared wide field imager and multi-object spectrometer*

0.95-2.4 μm wavelength

FoV = 120" diameter

Pix. Scale 0.09 arcsec/pix

Long Slit (slit width from 1 to 8 pixels)

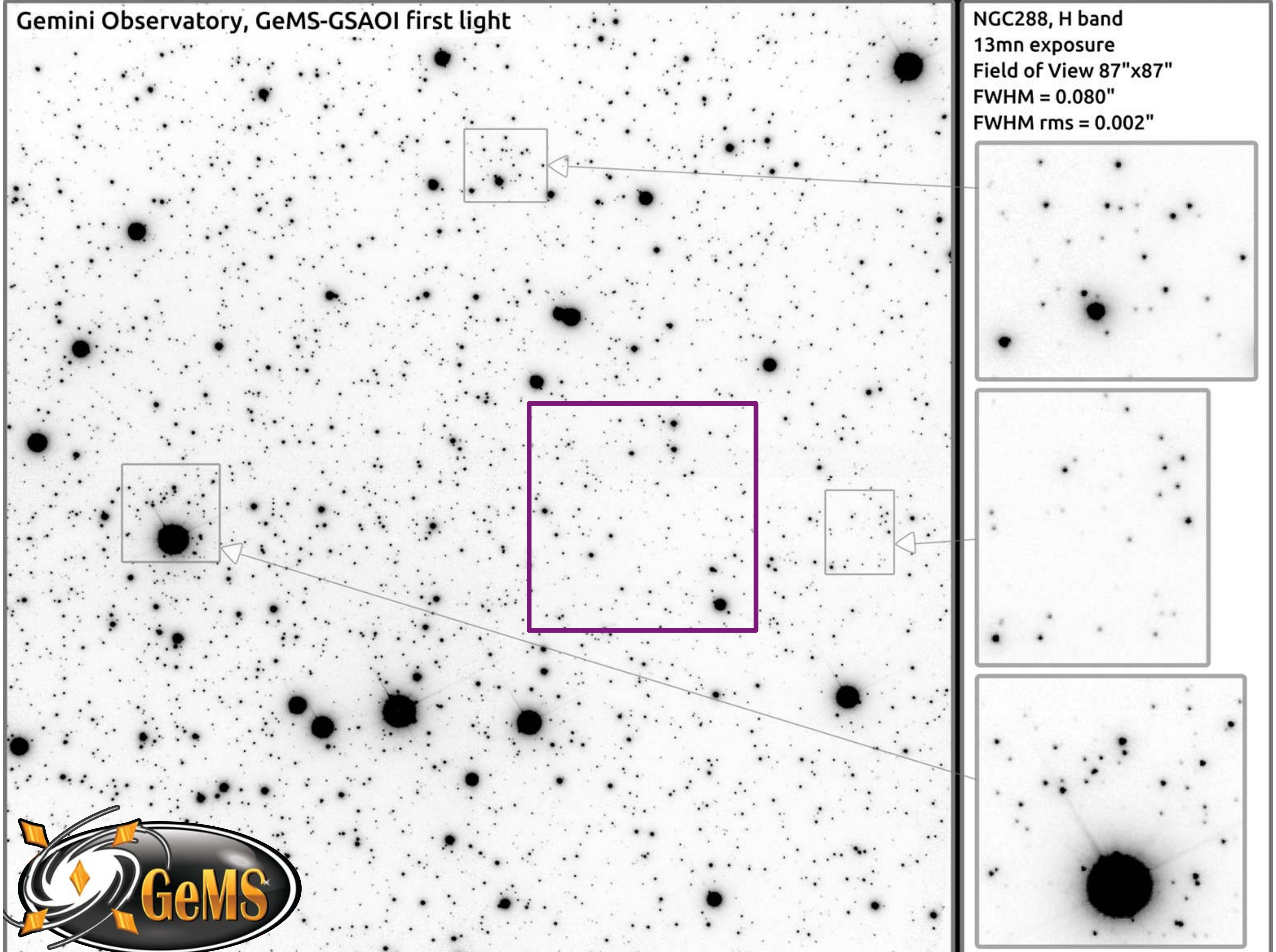
MOS (custom masks)

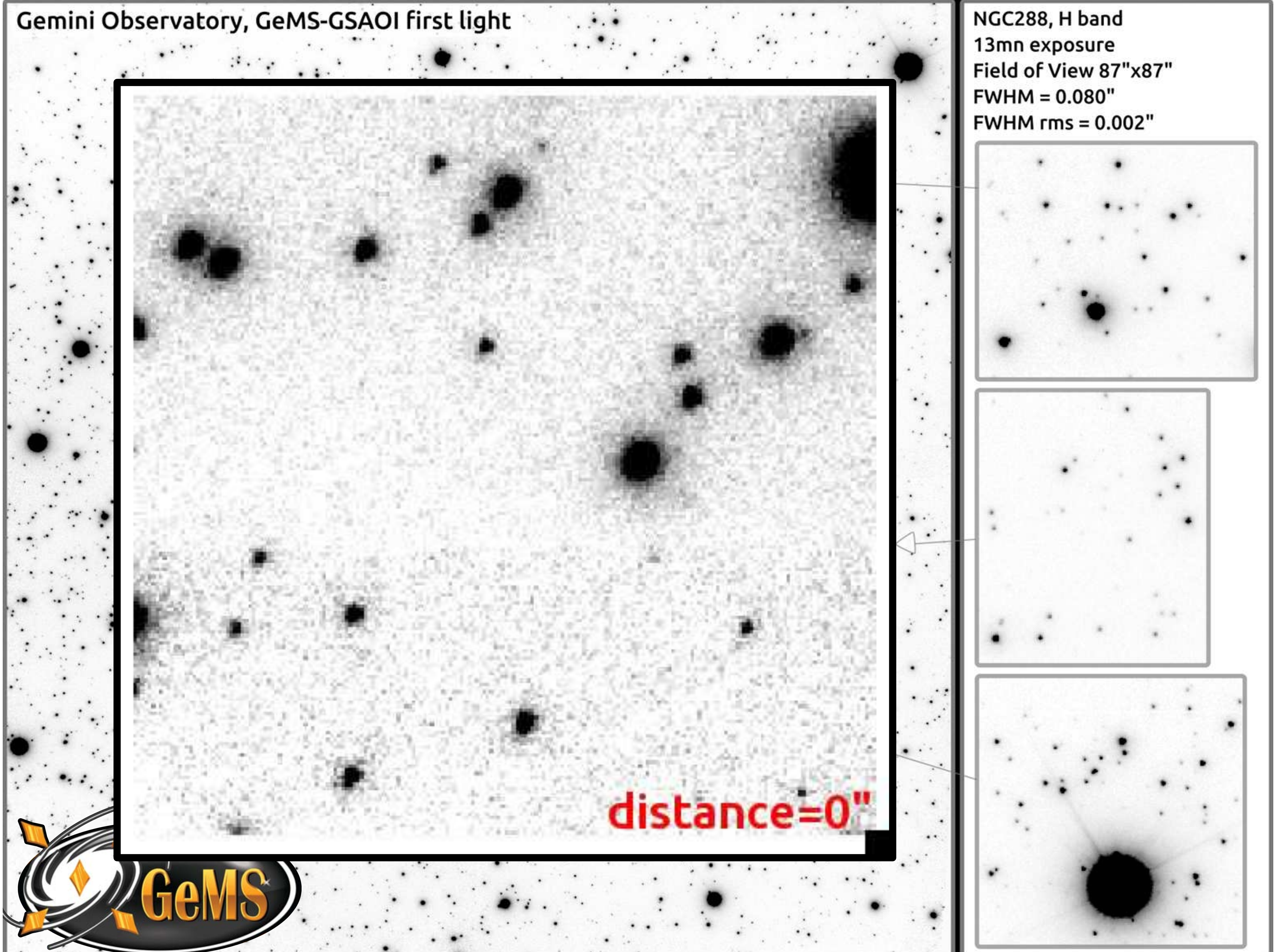
R = 1200-3000

## GMOS

0.36-0.94 μm (New Hamamatsu-Red-Sensitive CCDs) FoV = 2.4 arcminute diameter.
Imaging, long-slit and multi-slit spectroscopy

**Integral Field Unit (IFU)** - pix = 0.1arcsec - FoV = 17arcsec - R150 to 1200


Gemini Observatory, GeMS-GSAOI first light
NGC288, H band
13mn exposure
Field of View 87"x87"
FWHM = 0.080"
FWHM rms = 0.002"
GeMS


Gemini Observatory, GeMS-GSAOI first light
NGC288, H band
13mn exposure
Field of View 87"x87"
FWHM = 0.080"
FWHM rms = 0.002"
distance=0"
GeMS

# GeMS's Tomography Calibrations & Limitations

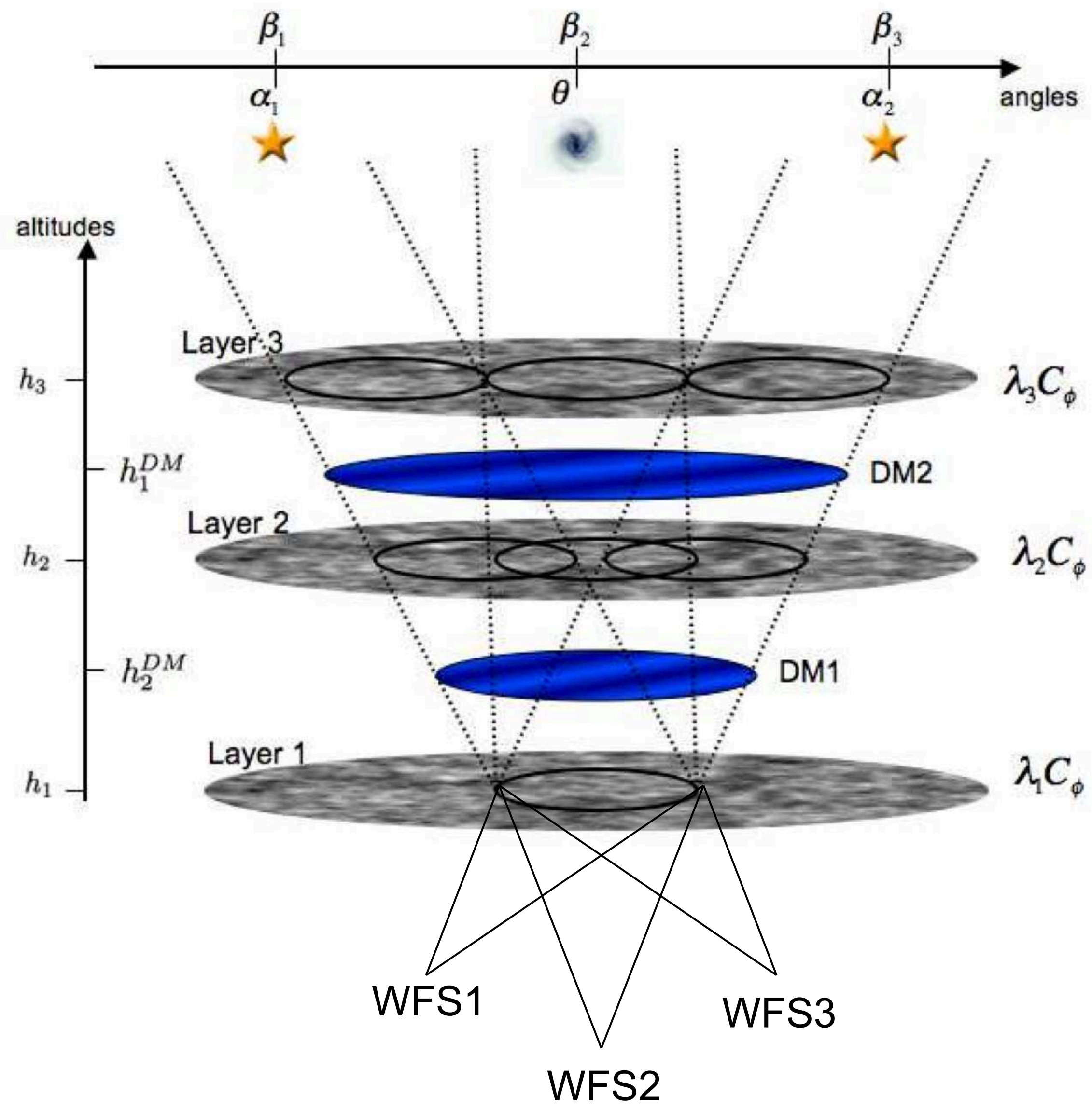
# GeMS's Tomography Calibrations & Limitations

Tomography is easy, calibrations are difficult…

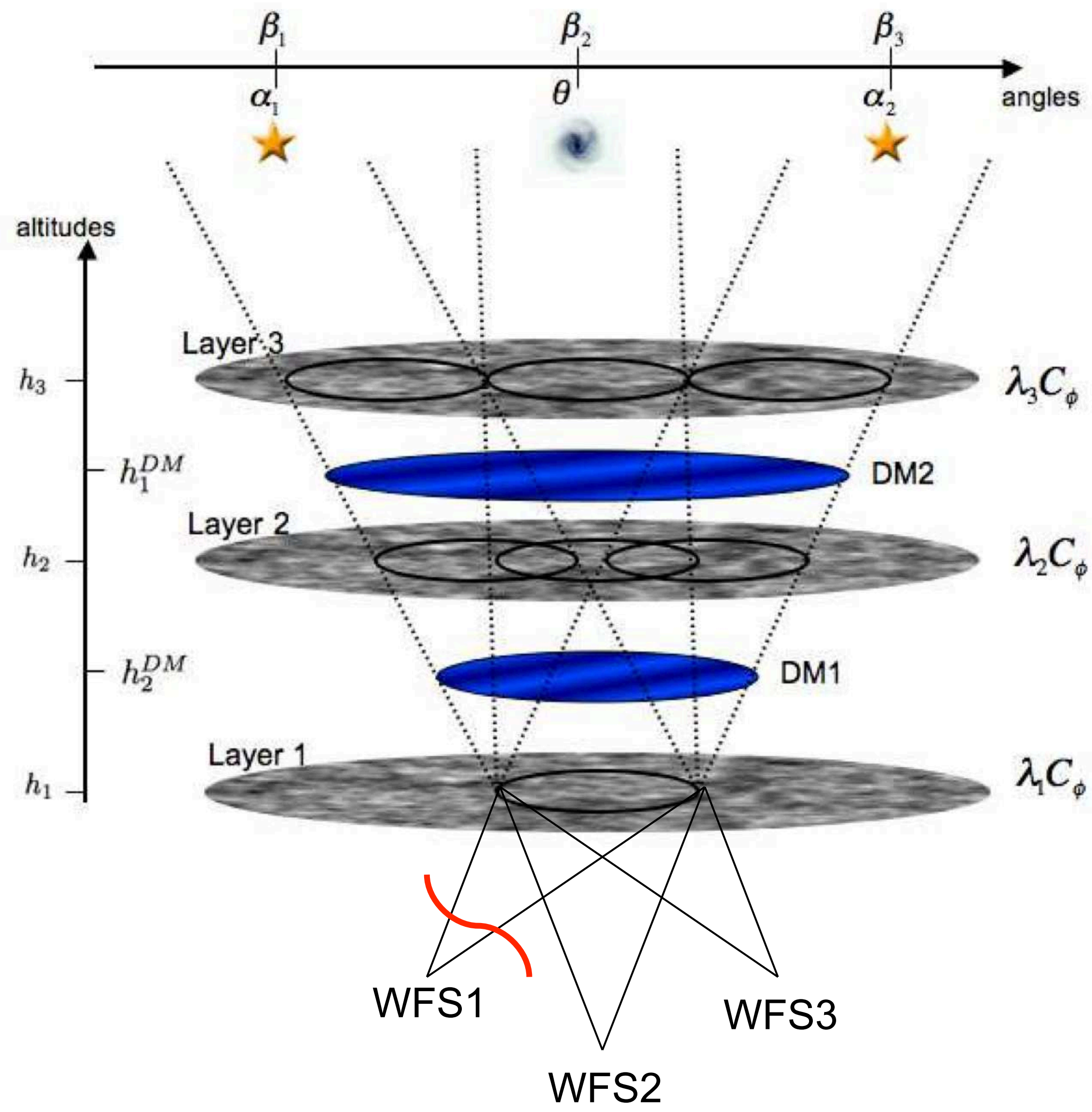
# GeMS’s Tomography Calibrations & Limitations

Tomography is easy, calibrations are difficult…

**Differential aberrations between WFSs**
**Fratricide effect**
**Non-Kolmogorov turbulence**
**Quasi-static aberrations**




Impact of differential aberrations between WFSs




Impact of differential aberrations between WFSs

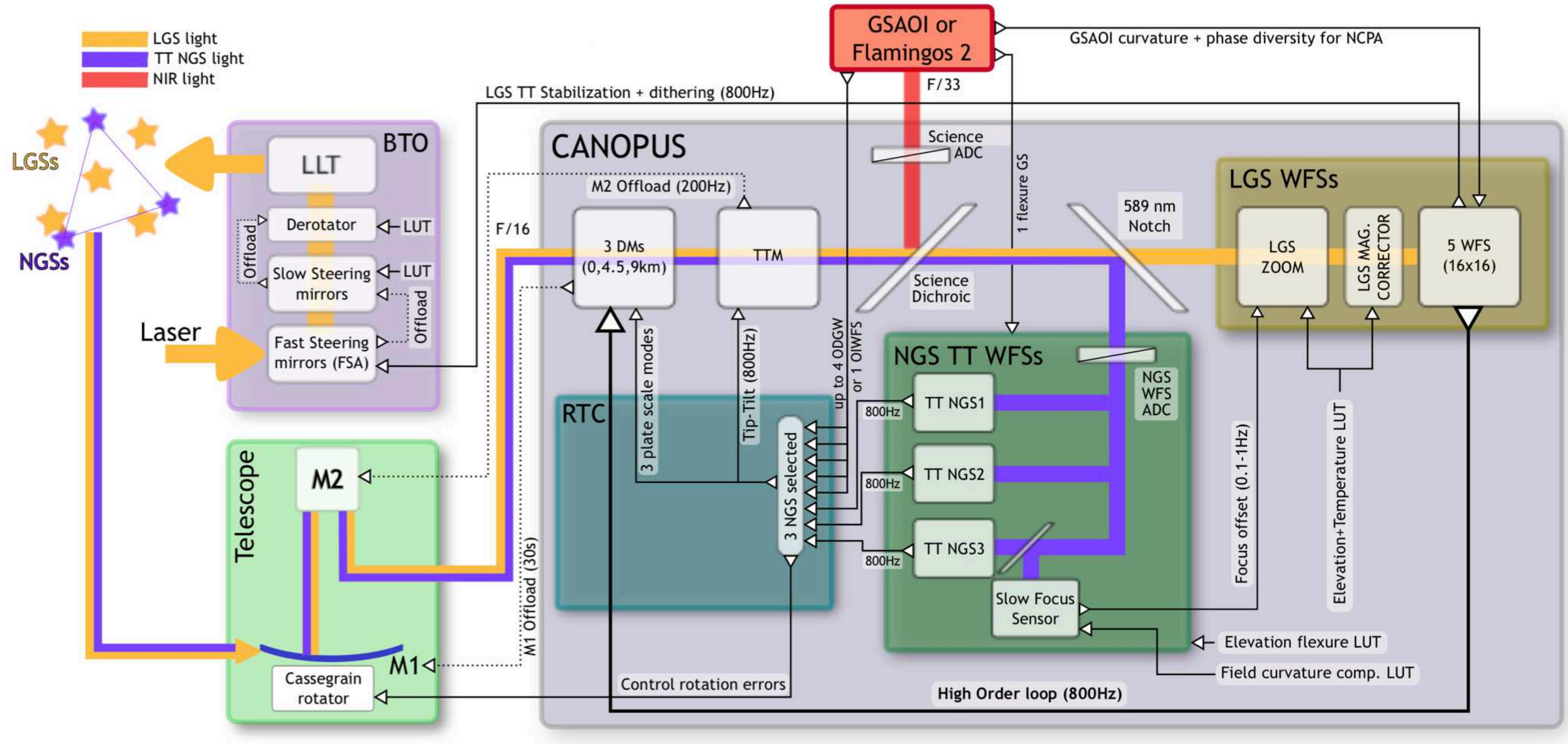
Origin of differential aberrations between WFSs ?

- Registration Look-Up Table
- Static aberrations - Centroiding gains
- Laser Spots
- Differential LGS focus
- Non-linear effects

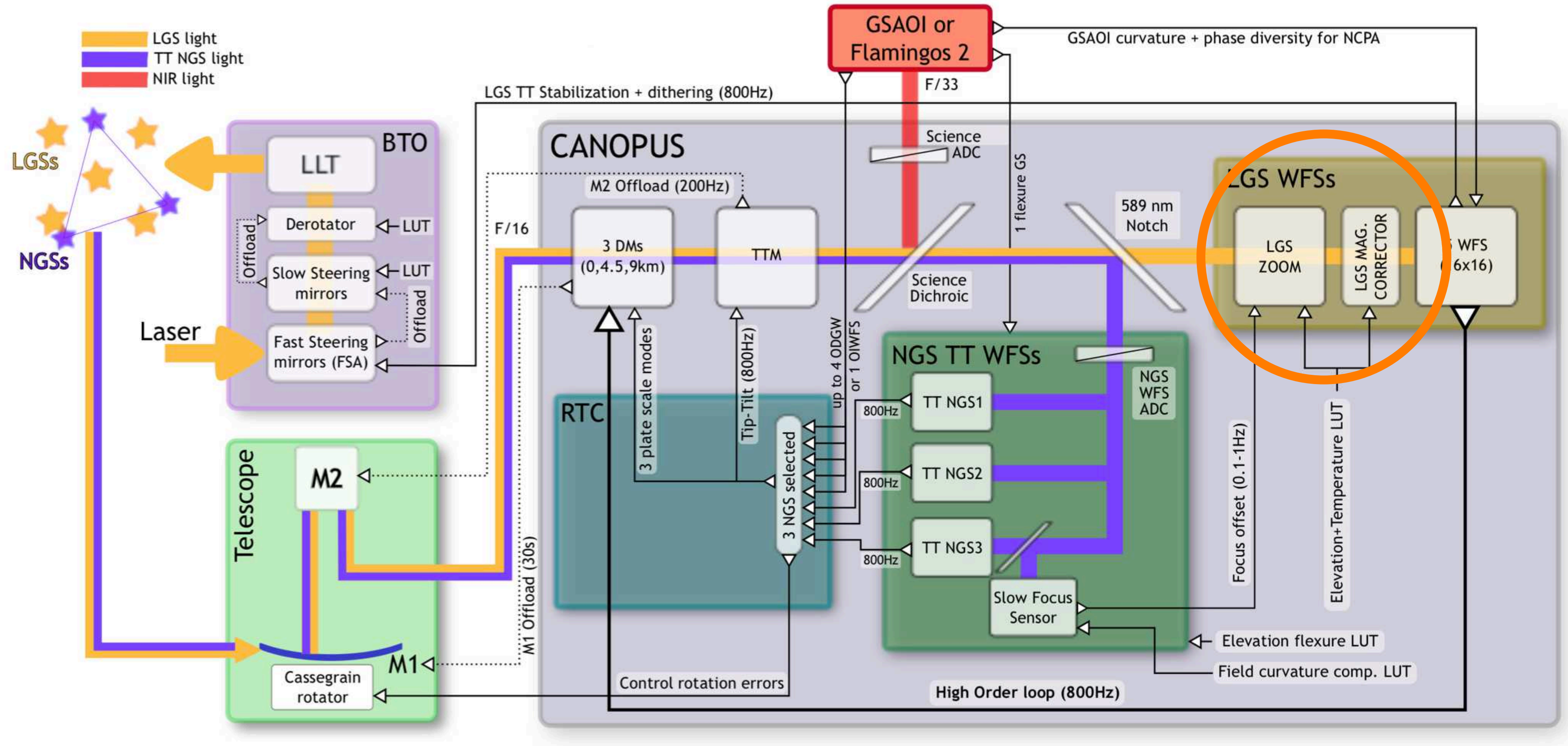
Origin of differential aberrations between WFSs ?

- **Registration Look-Up Table**
- Static aberrations - Centroiding gains
- Laser Spots
- Differential LGS focus
- Non-linear effects

# LUTs are everywhere…

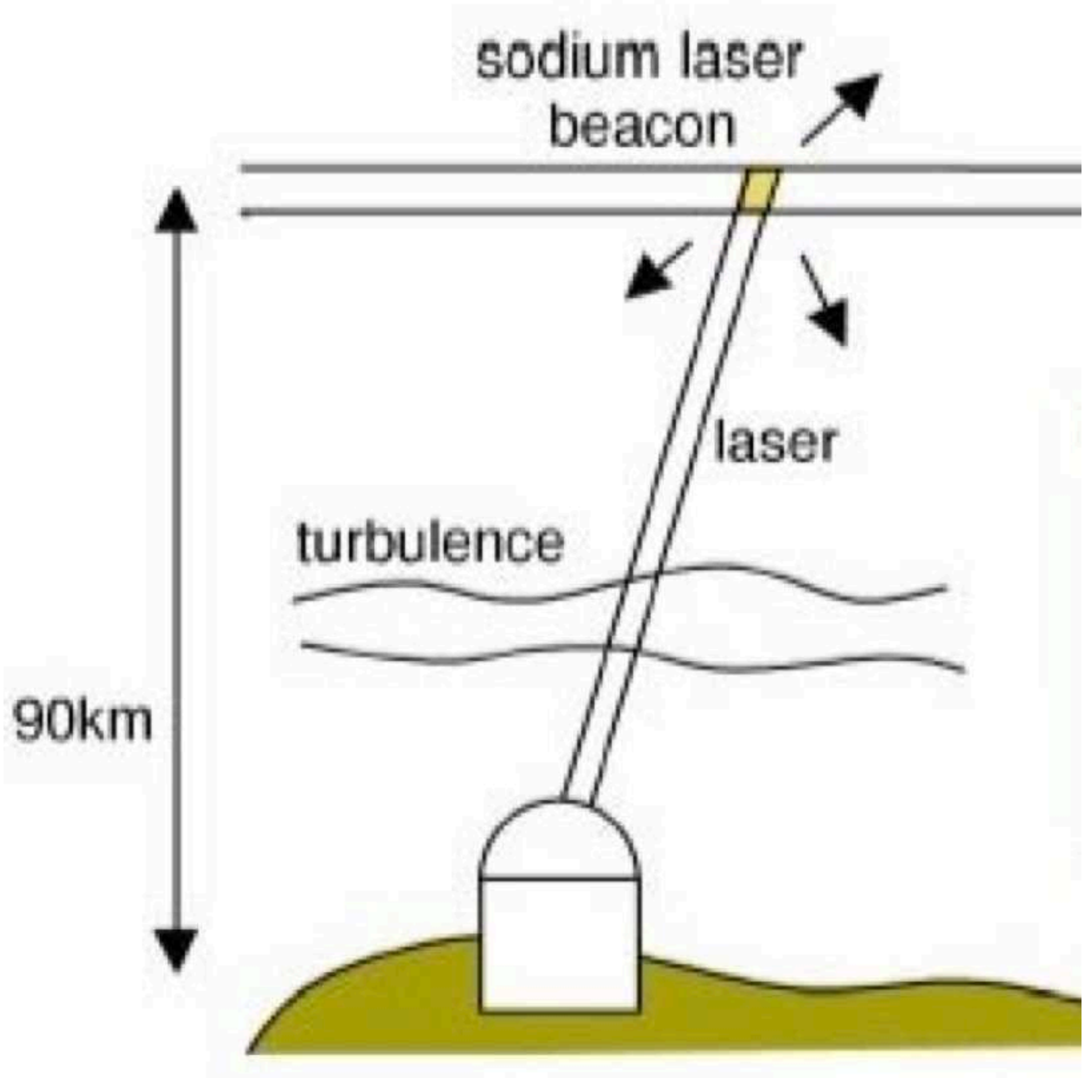


## LUTs are everywhere…

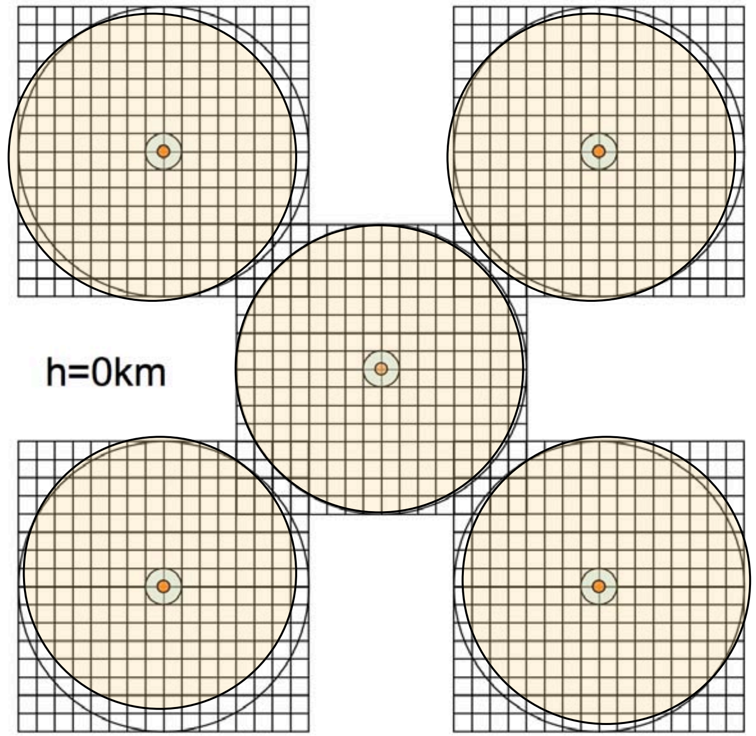



**Ex: LGS WFS zoom mechanisms**

# LGSWFS LUT versus elevation / temperature




When elevation / temperature / flexure change, need to keep the registration and magnification right on each LGSWFS.



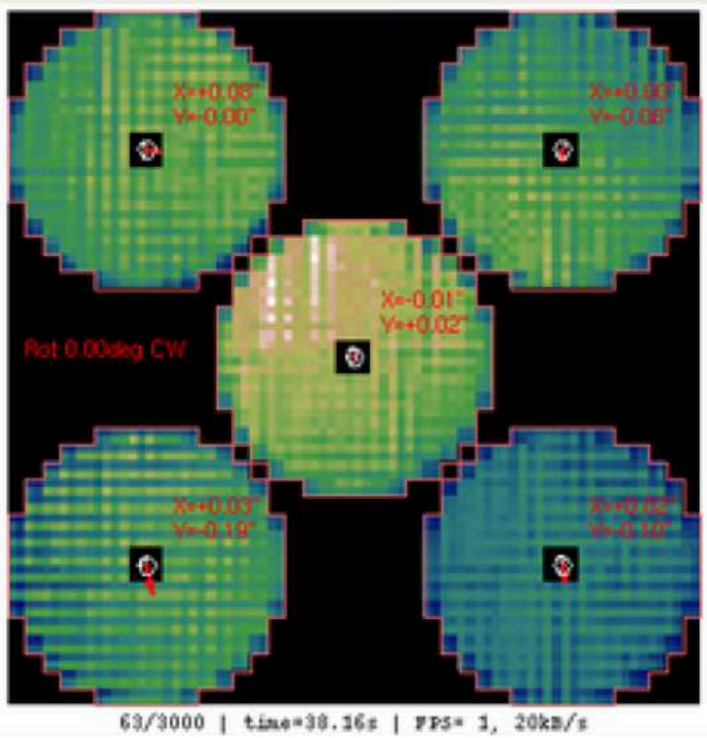
# LGSWFS LUT versus elevation / temperature


LUT is built with calibrations sources moved to different LGS range.

8 mechanisms in the LGSWFS are adjusted to keep registration / magnification right.

# LGSWFS LUT versus elevation / temperature

Need to be done daily when observing.




```
++++++++++++++++++++++++++++++++++++++++++++++++++++++
Average pupil magnification error = 0.04%
 Past values = (0.07 0.04 )
++++++++++++++++++++++++++++++++++++++++++++++++++++++
BUSY, waiting..
Adjusting the AOM LGS stepper LUT a0 coefficients
zoomB, current=32283, shoud be=32234, adjustment=49.1
zoomC, current=41104, shoud be=40995, adjustment=108.9
magX, current=87376, shoud be=87745, adjustment=-369.1
magY, current=68661, shoud be=67786, adjustment=875.3
pwfs1=R3, current=31313, shoud be=32519, adjustment=-1205.5
pwfs2=R5, current=41825, shoud be=42529, adjustment=-703.8
pwfs3=R4, current=49988, shoud be=41013, adjustment=8975.1
pwfs4=R2, current=44300, shoud be=43528, adjustment=771.8
Updated Model coefs written in /media/mcao-rtc/spotfind/lgs_stepper_coefs.dat
```

No ways to check while observing, " Trust the LUT "
(Can do some on-sky checks, but "science destructive")

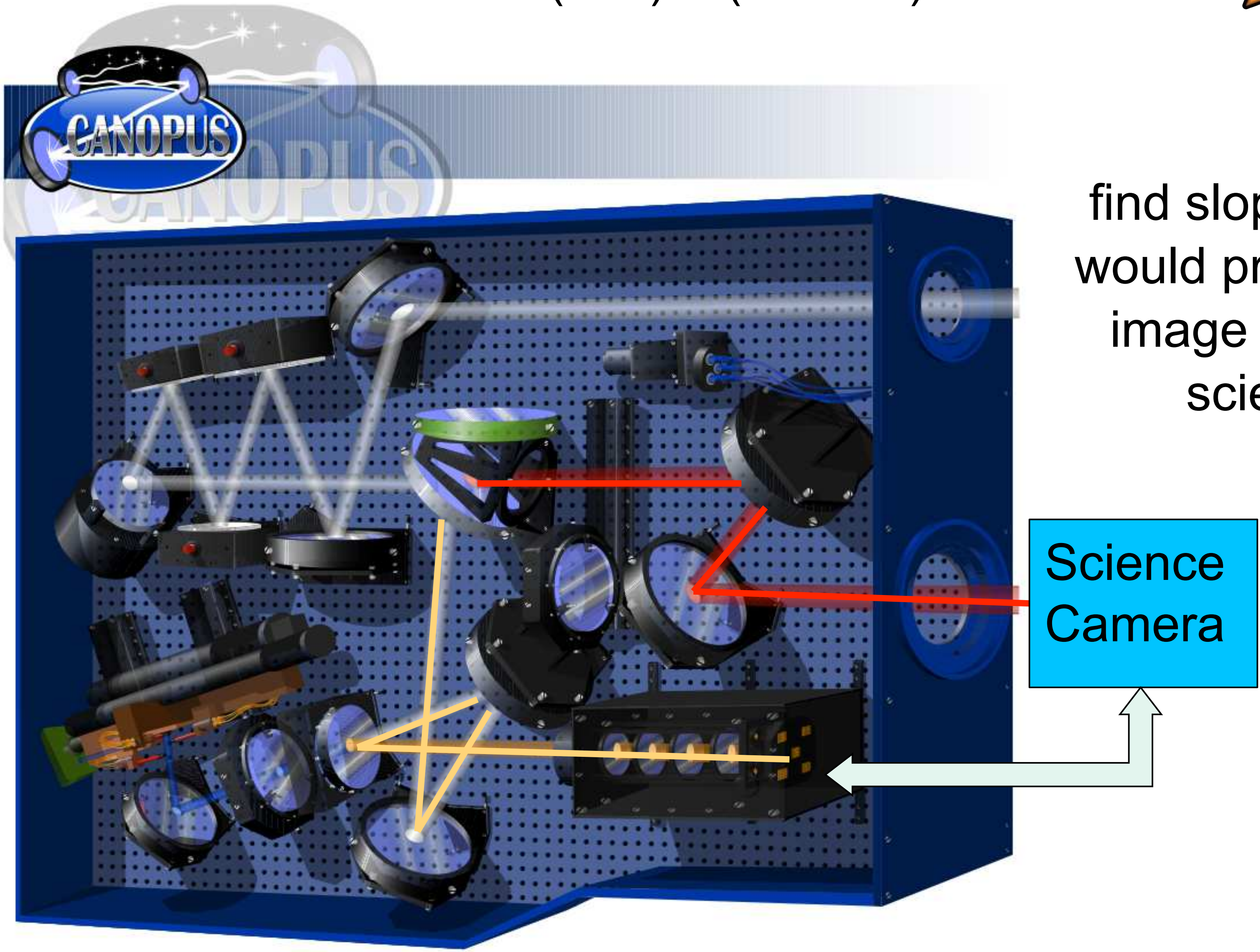
Would require non-destructive, on-line calibration tools !

(Cf. ESO AOF ?)

Origin of differential aberrations between WFSs ?

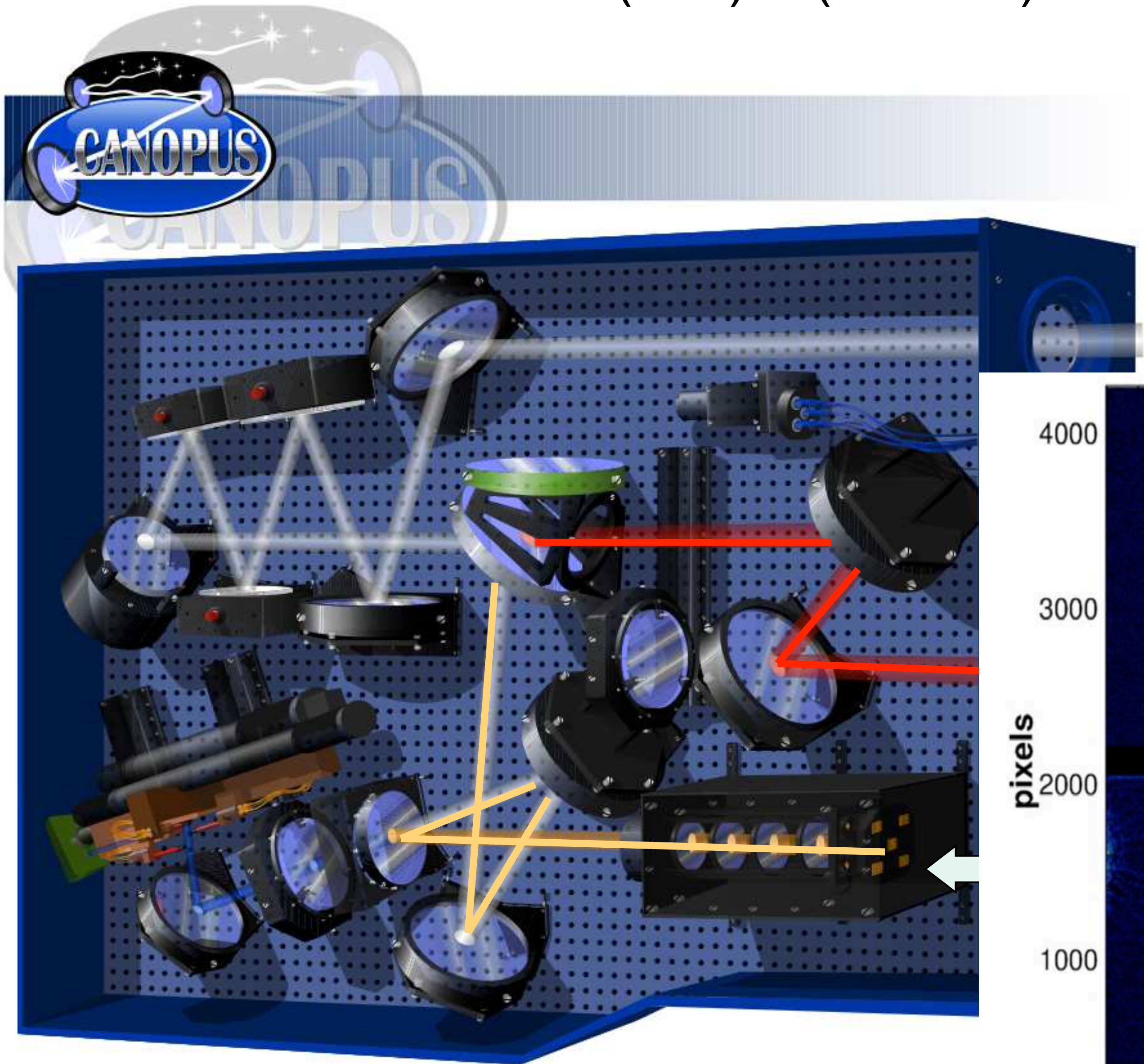
- Registration Look-Up Table
- **Static aberrations**
- Centroiding gains - Laser Spots
- Differential LGS focus
- Non-linear effects

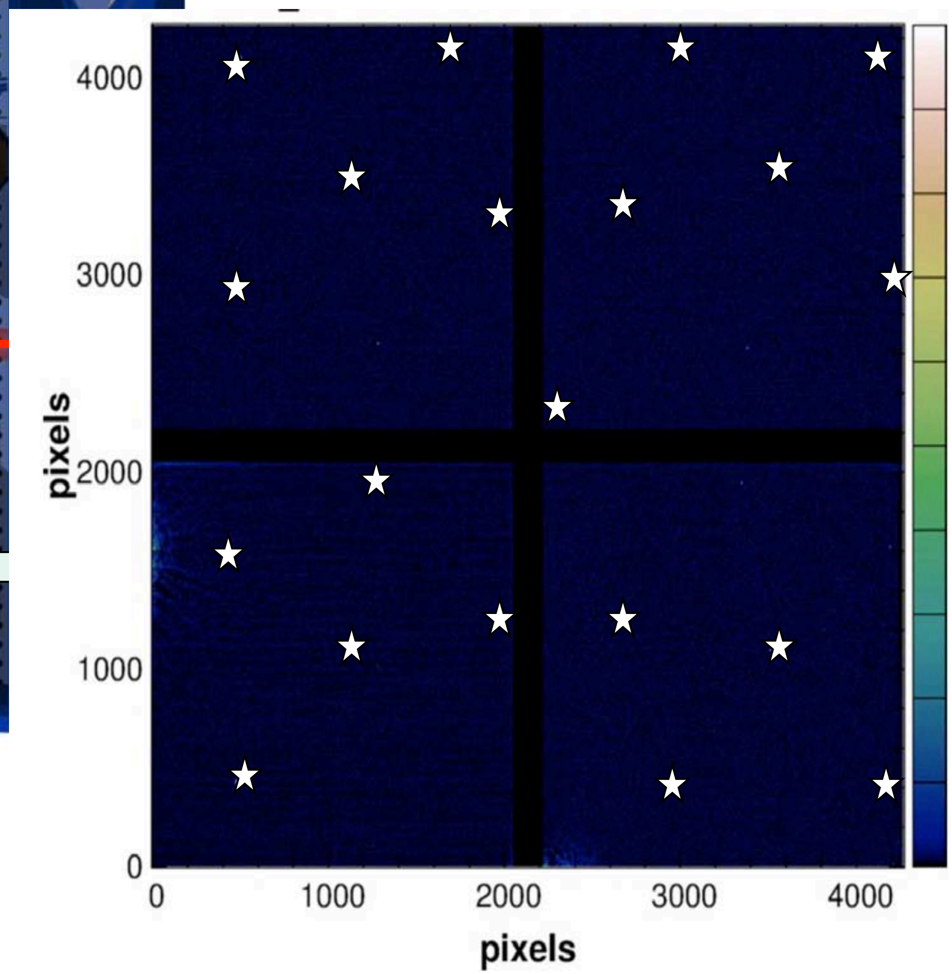
No NCPA == SR of 50 (±10)% (H-band) in the field.




Goal:
find slope offsets that would provide the best image quality in the science path.

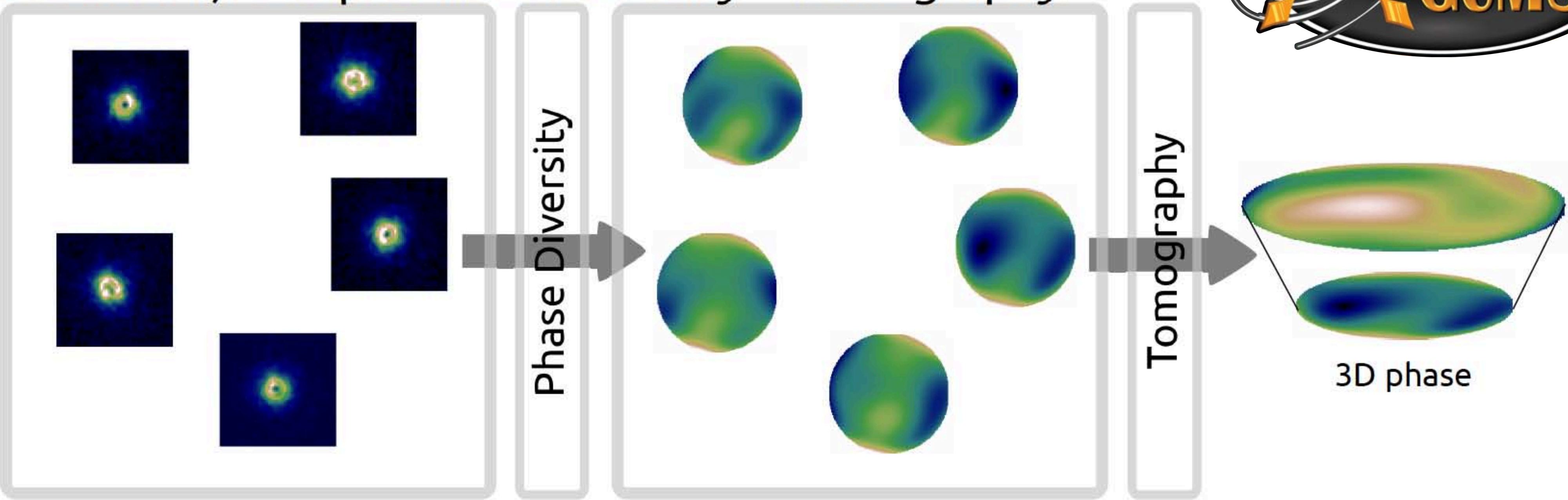
No NCPA == SR of 50 (±10)% (H-band) in the field.



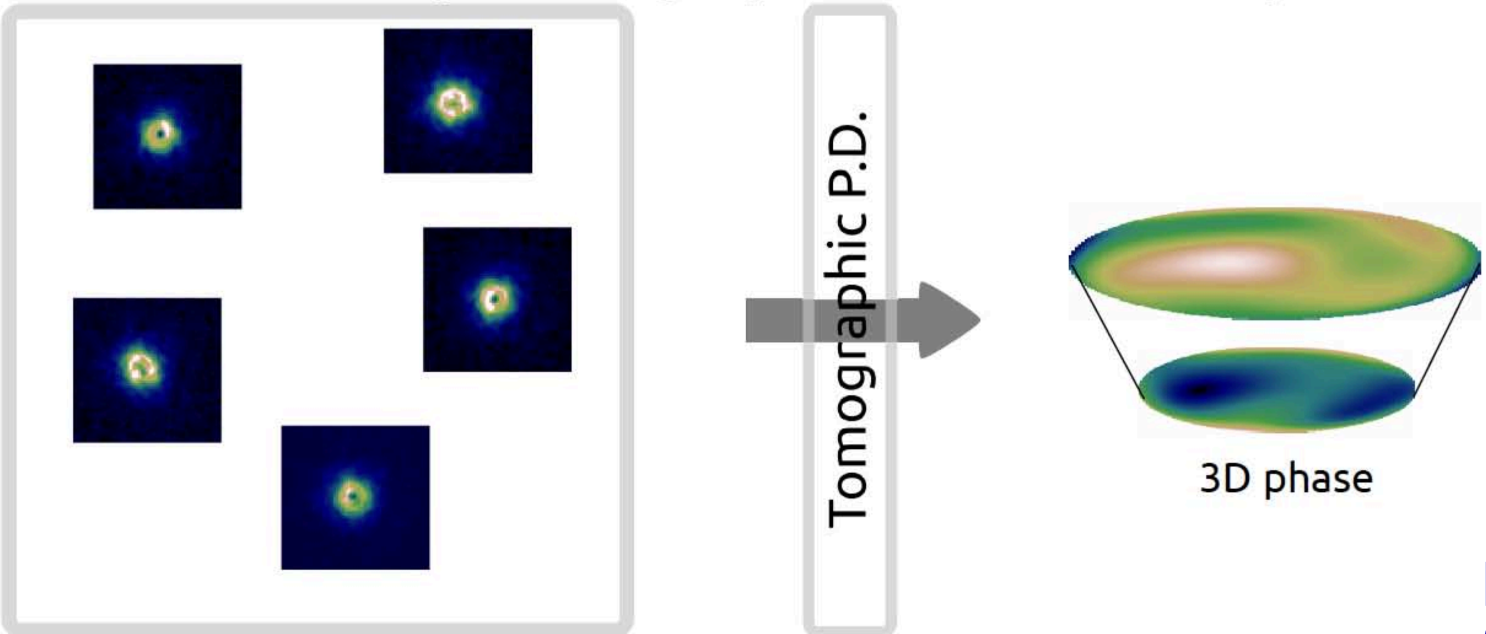



## Static tomography for NCPA

### Method 1, 2 steps: Phase Diversity + Tomography

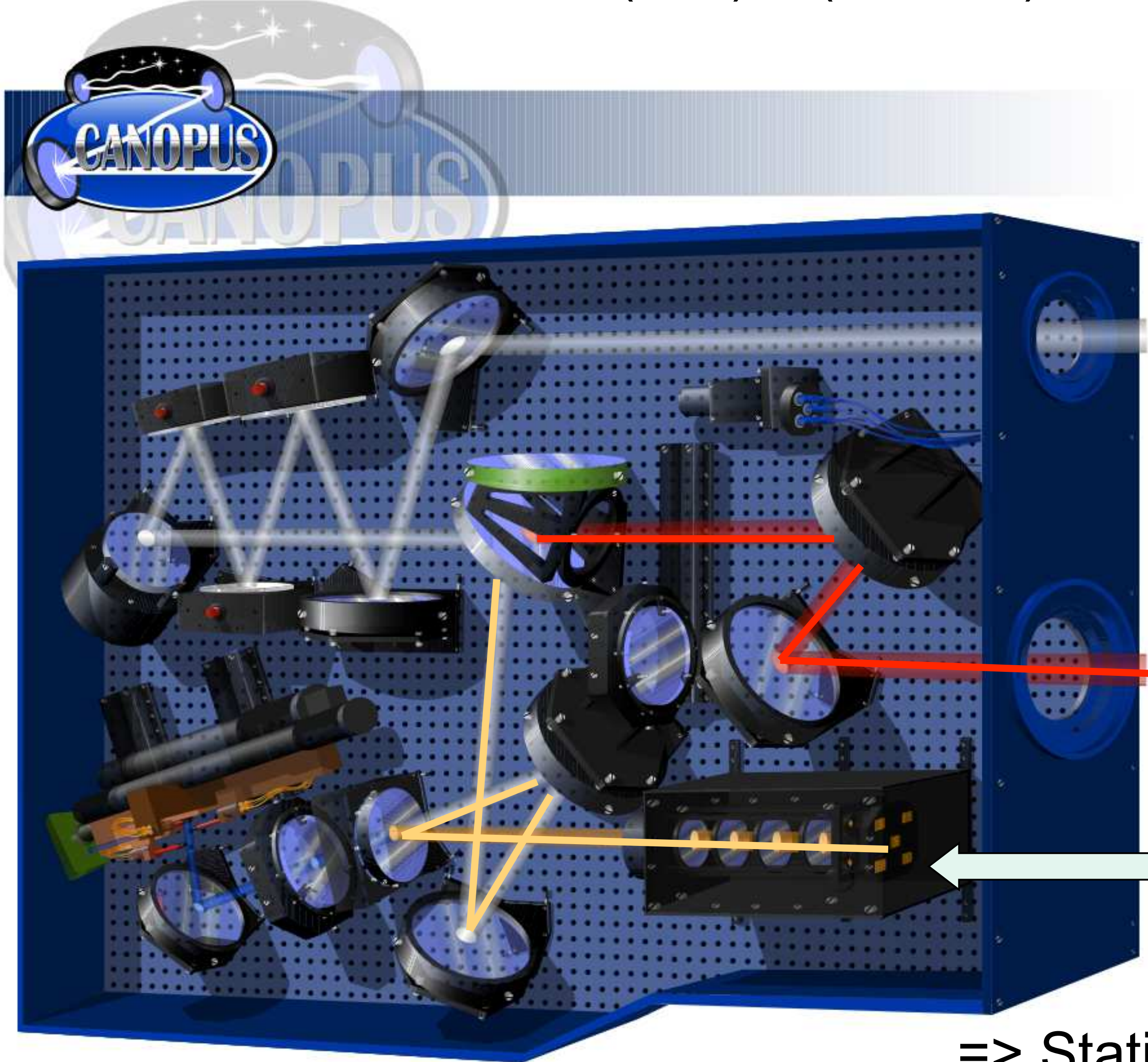



### Method 2, 1 step: Tomographic Phase Diversity




[Rigaut et al. AO4ELT2
Gratadour et al. AO4ELT2]

No NCPA == SR of 50 (±10)% (H-band) in the field.




Goal:
find slope offsets that would provide the best image quality in the science path.

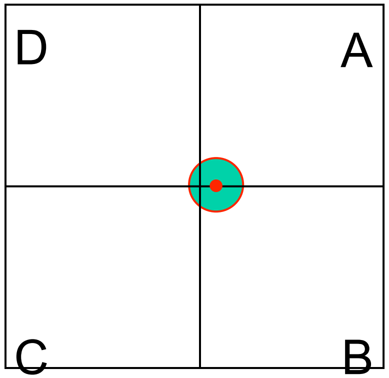
=> Static differential aberrations between WFS should be absorbed by NCPA.

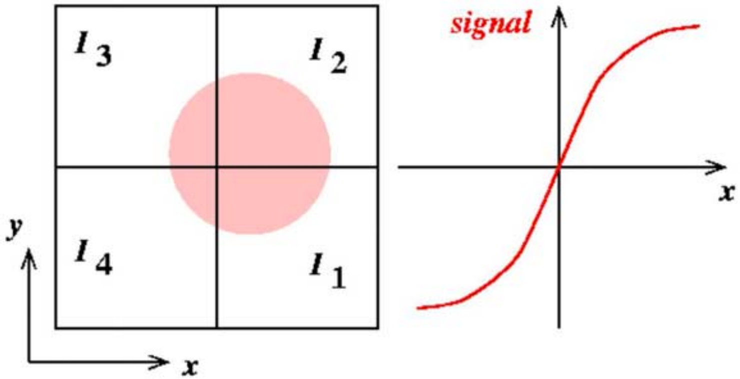
Origin of differential aberrations between WFSs ?

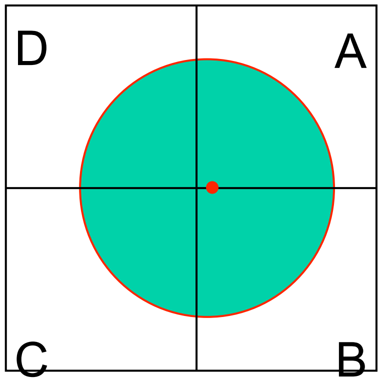
- Registration Look-Up Table
  - Static aberrations
- **Centroiding gains - Laser Spots**
  - Differential LGS focus
  - Non-linear effects

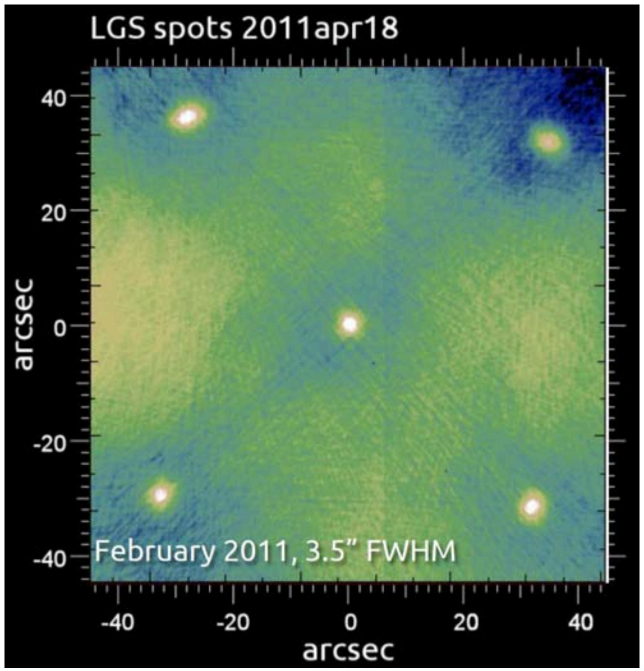
# Quad-cells transfer function & centroid gain

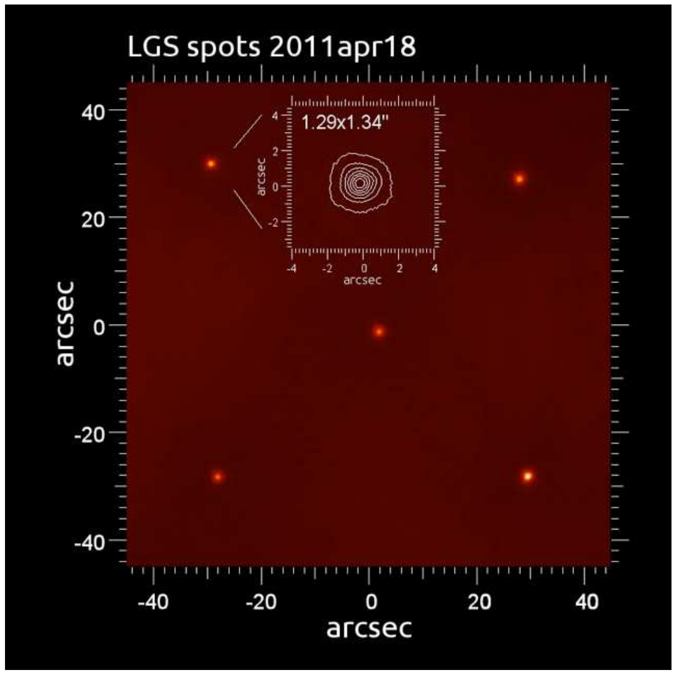
Centroid gain depends on spot size.
Spot size changes with seeing / sodium layer characteristics



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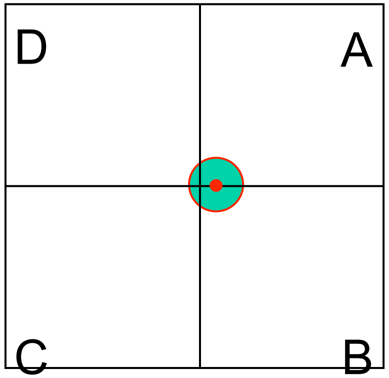
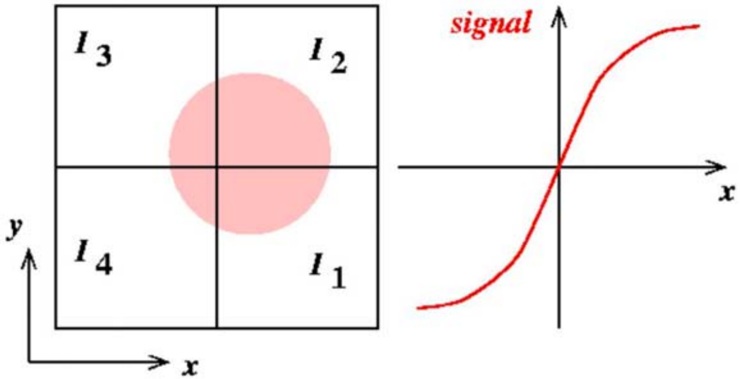
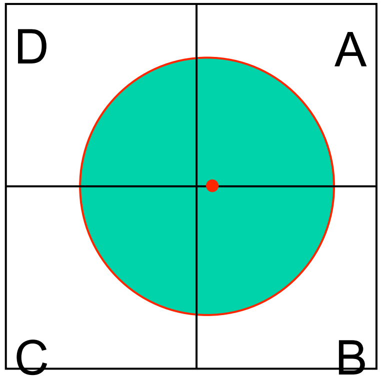


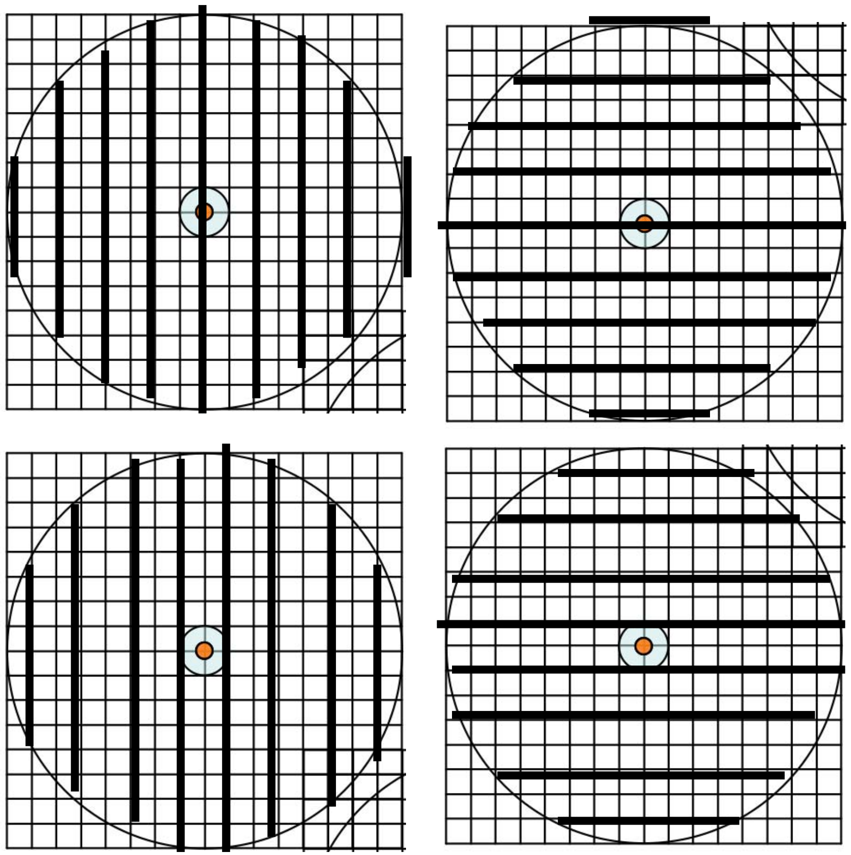

An error on the centroid gains can produce:

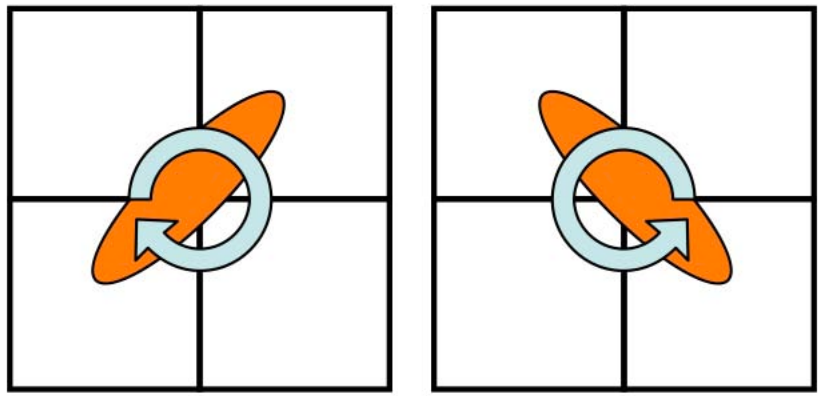
- Wrong loop gain in CL (minor effect) (What in OL ?)
- Wrong NCPA (major effect if NCPA are large)
- Differential aberrations between the WFSs and wrong tomography

**=> Centroid gains need to be calibrated on-line**

## Quad-cells transfer function & centroid gain
=> Centroid gains need to be calibrated on-line

Method: Apply a "sine wave" on the DM at a given frequency and do a lock-in detection.





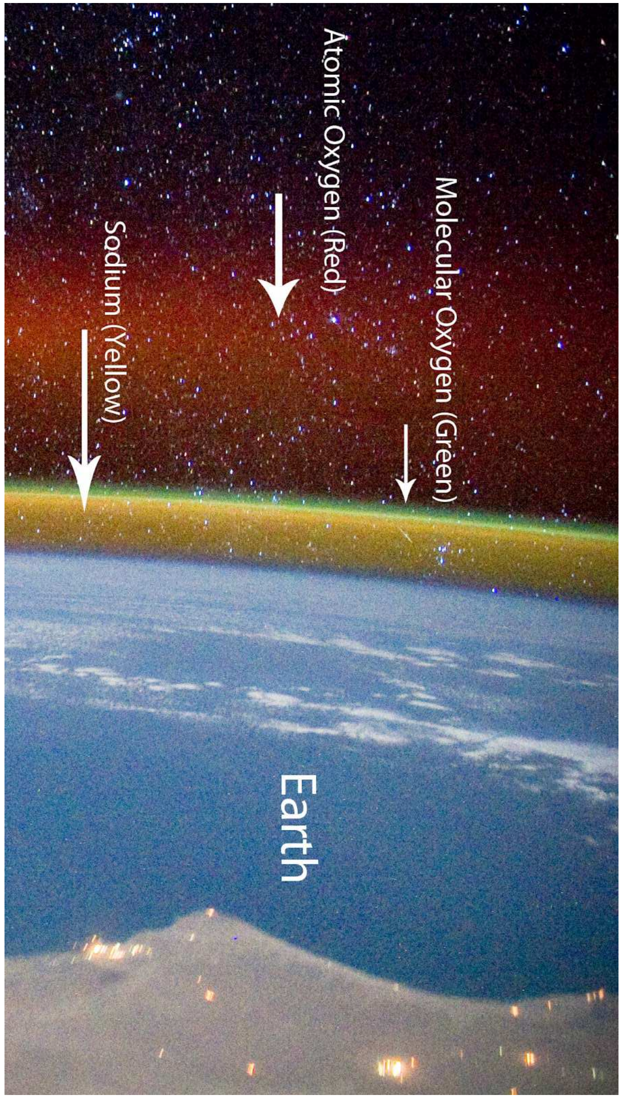
- Insensitive to vibrations
- Not (really) seen by the WFSs, so not corrected
- Small amplitude required (20nm rms)
- Would create satellite spot on the images, but lost in noise.

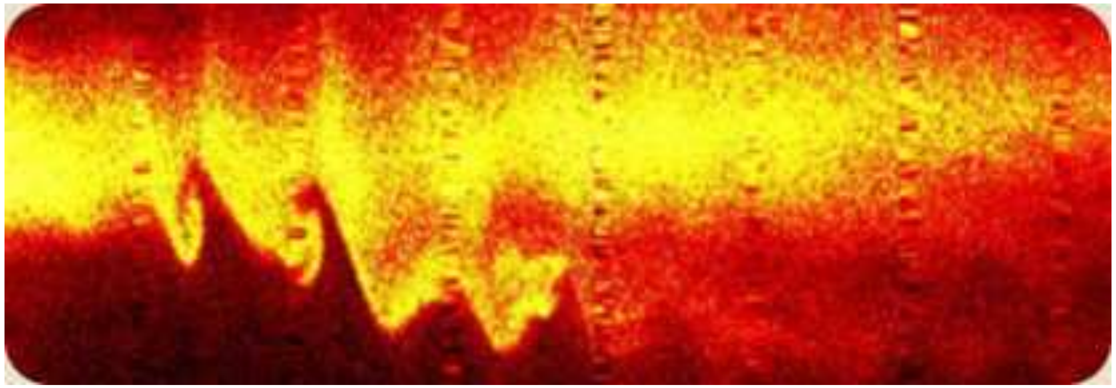
Seems to be working, but no direct way to cross-check results

Origin of differential aberrations between WFSs ?

- Registration Look-Up Table
- Static aberrations
- Centroiding gains - Laser Spots
- **Differential LGS focus**
- Non-linear effects

# Differential focus introduced by Na-layer transversal variations



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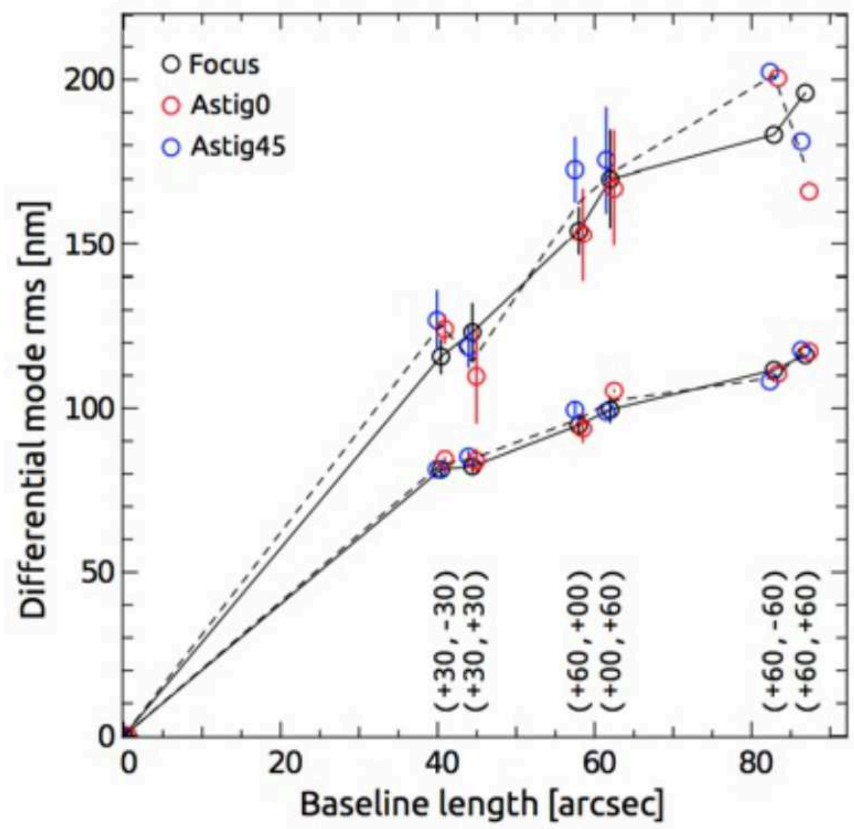
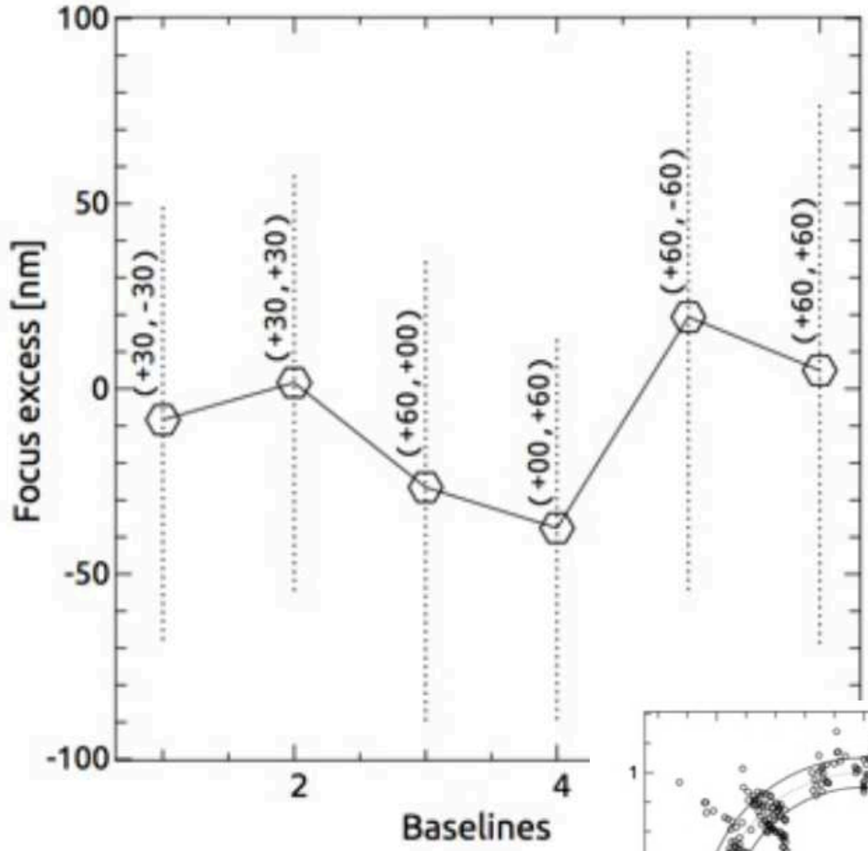
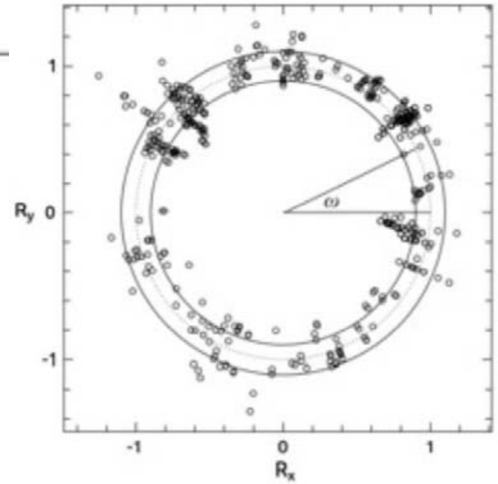


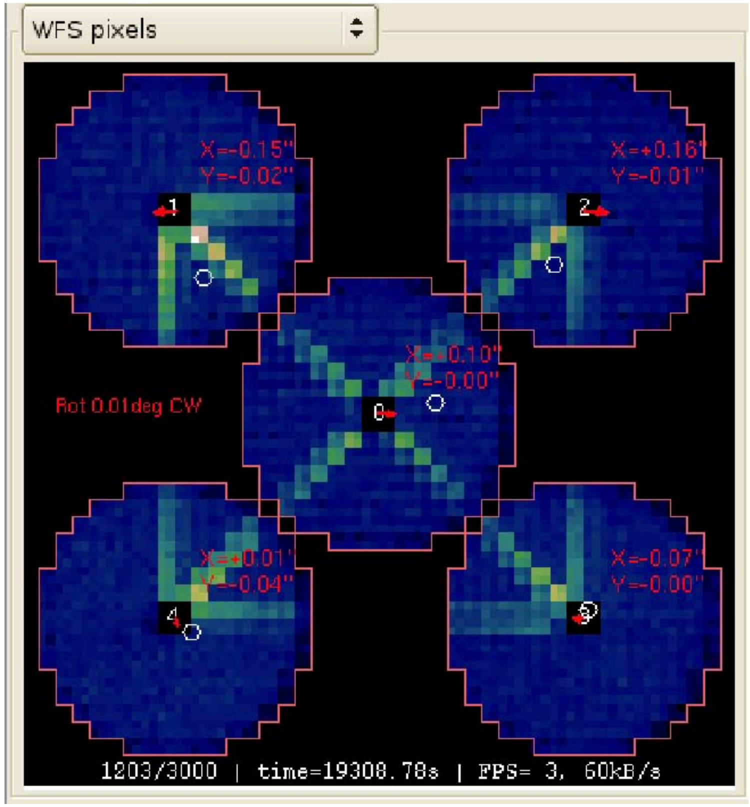




For 8m, differential focus does not seem to be an issue.
But large error bars.
Could be few hundreds of nm for 30-m telescopes

Origin of differential aberrations between WFSs ?

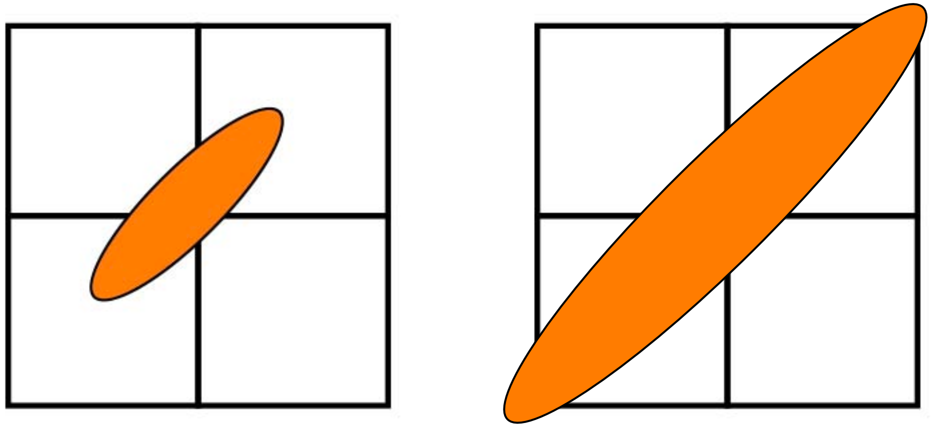
- Registration Look-Up Table
- Static aberrations
- Centroiding gains - Laser Spots
- Differential LGS focus
- **Non-linear effects**

# Non-linear effects



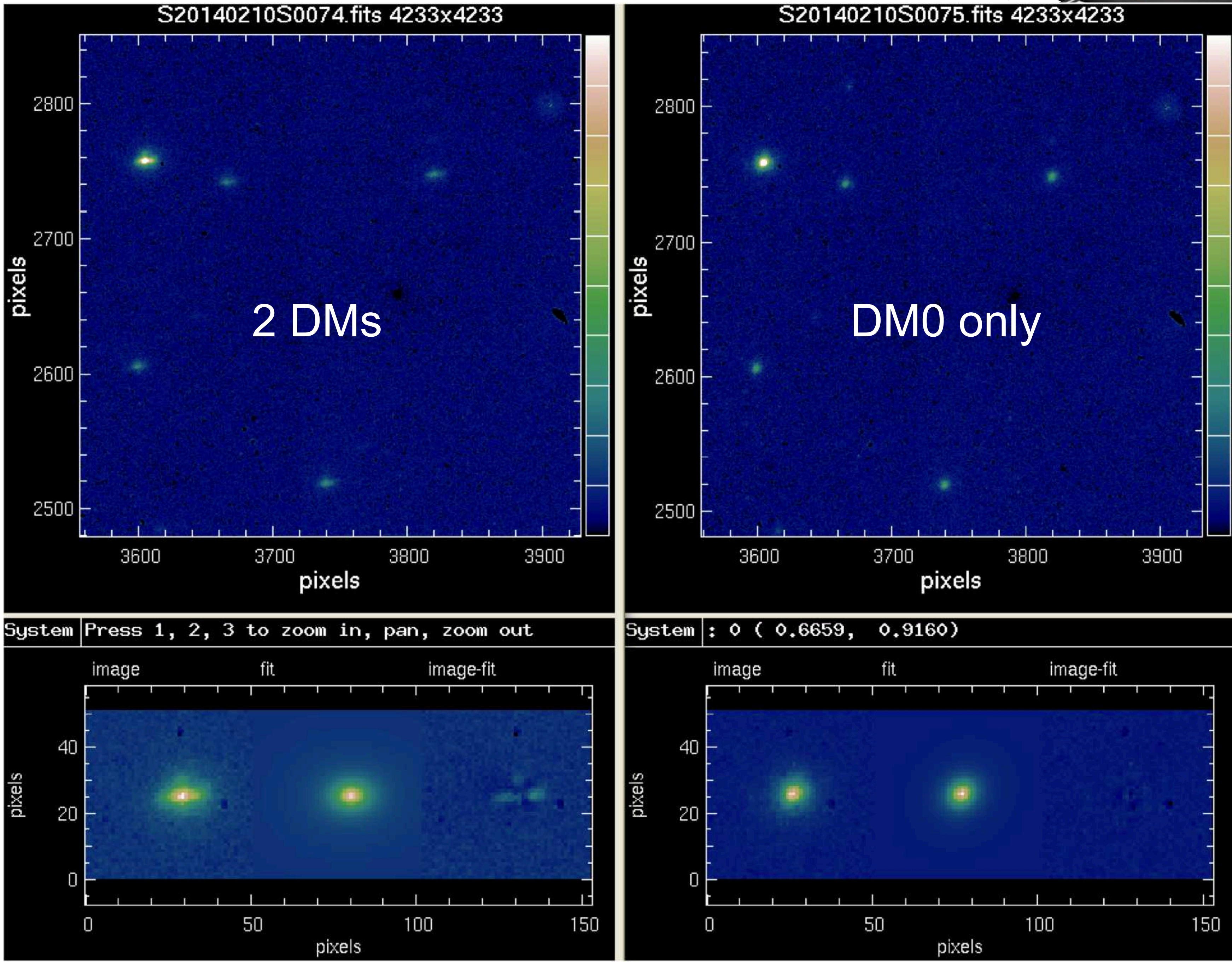

Lasers not properly centered

LGS spot Clipping ?



Field stop Vignetting ?

# And telescope field aberrations !!



# GeMS's Tomography Calibrations & Limitations

Tomography is easy, calibrations are difficult…

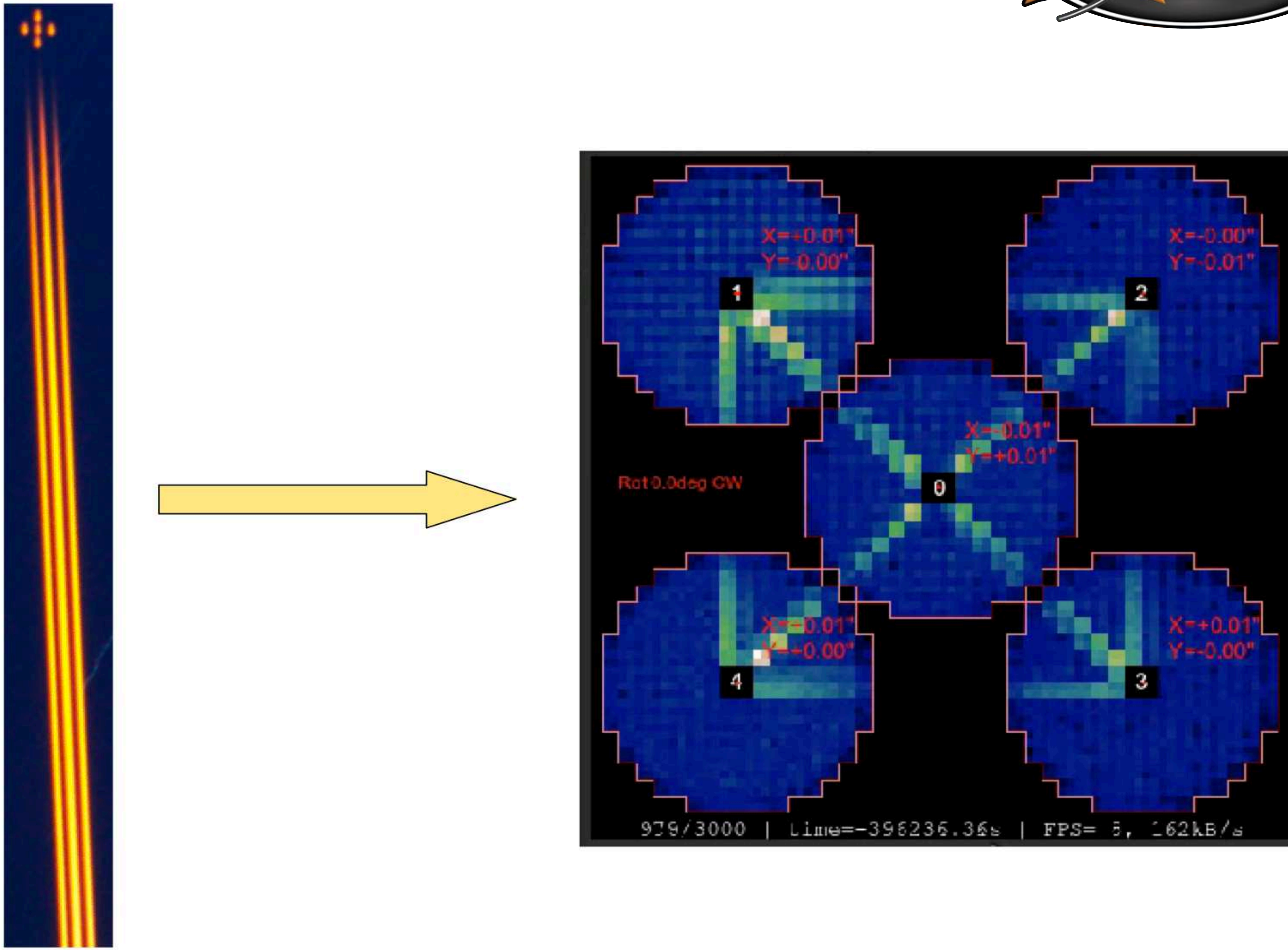
**Differential aberrations between WFSs**

**Fratricide effect**

**Non-Kolmogorov turbulence**

**Quasi-static aberrations**

# Fratricide Effect



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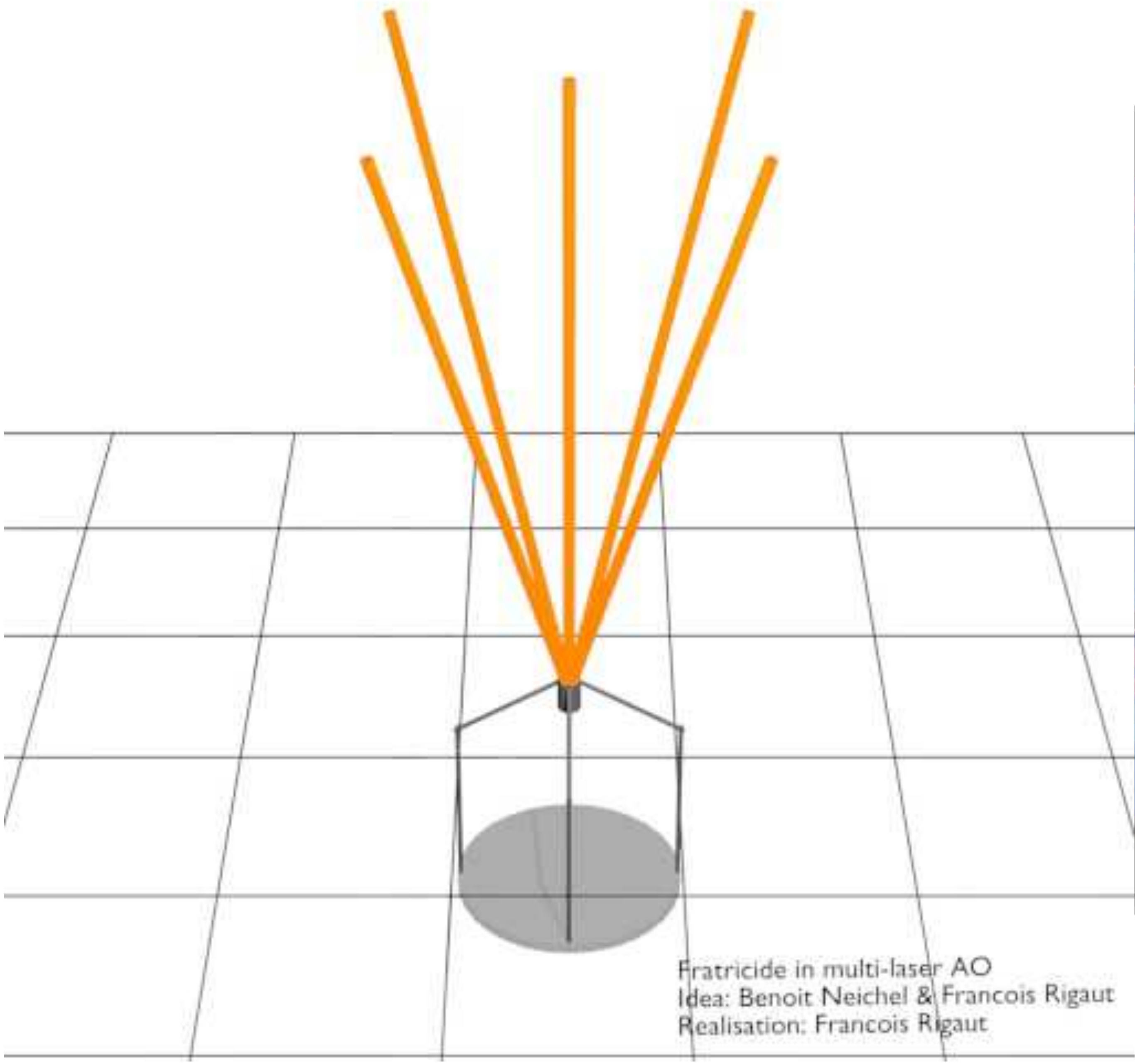
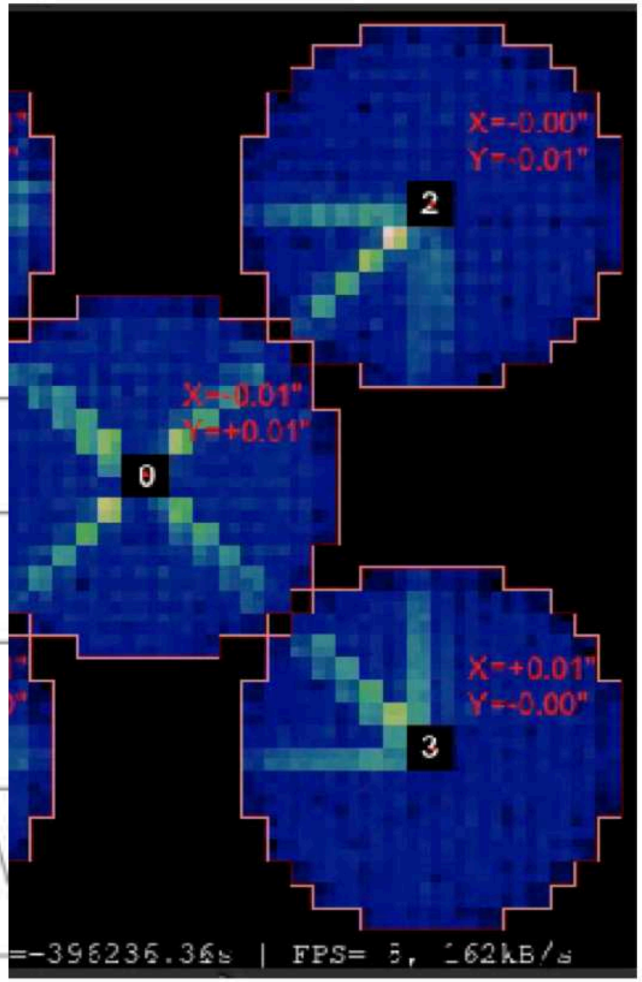
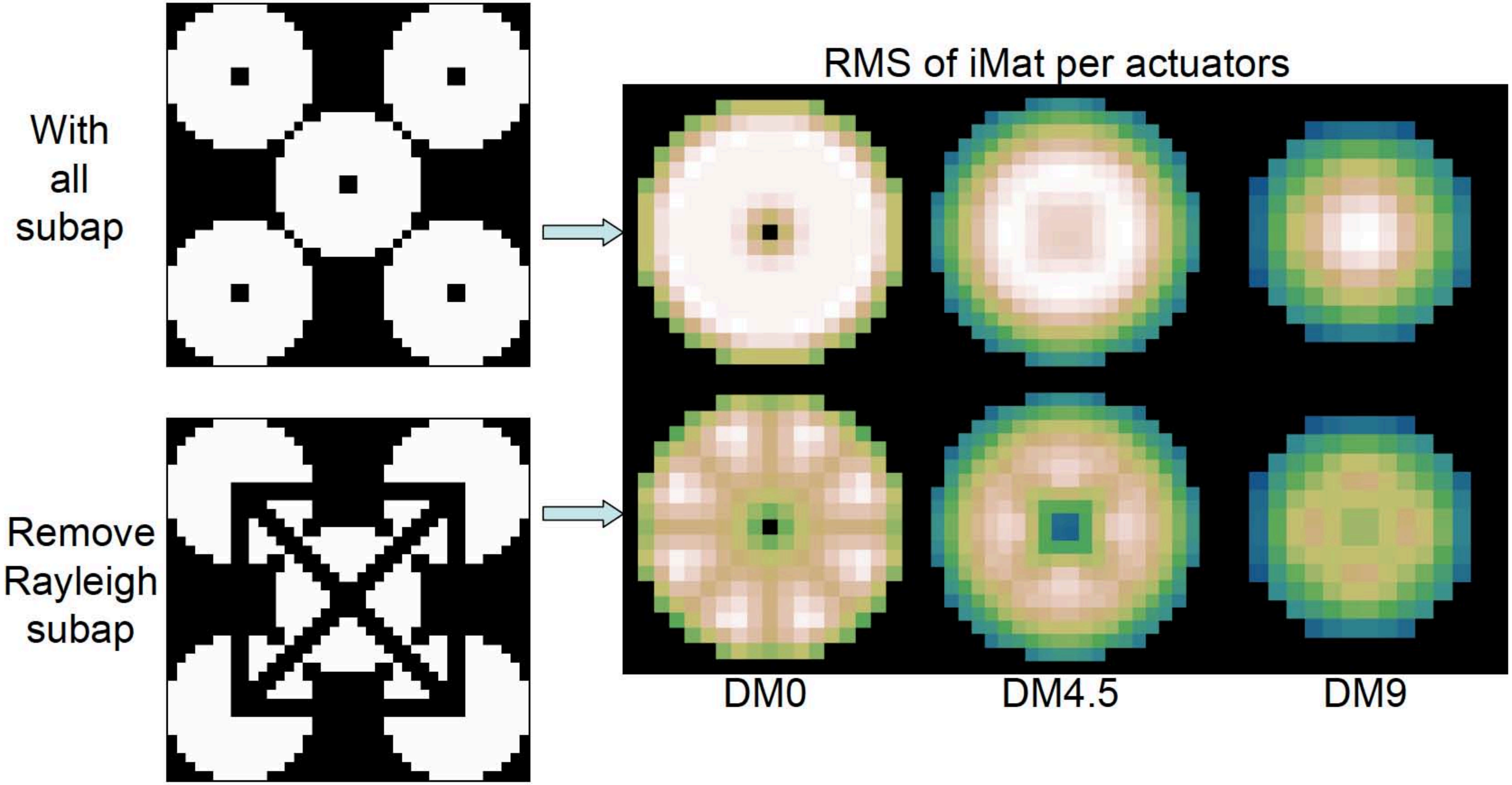


224 subapertures lost (~20% of the subapertures !)



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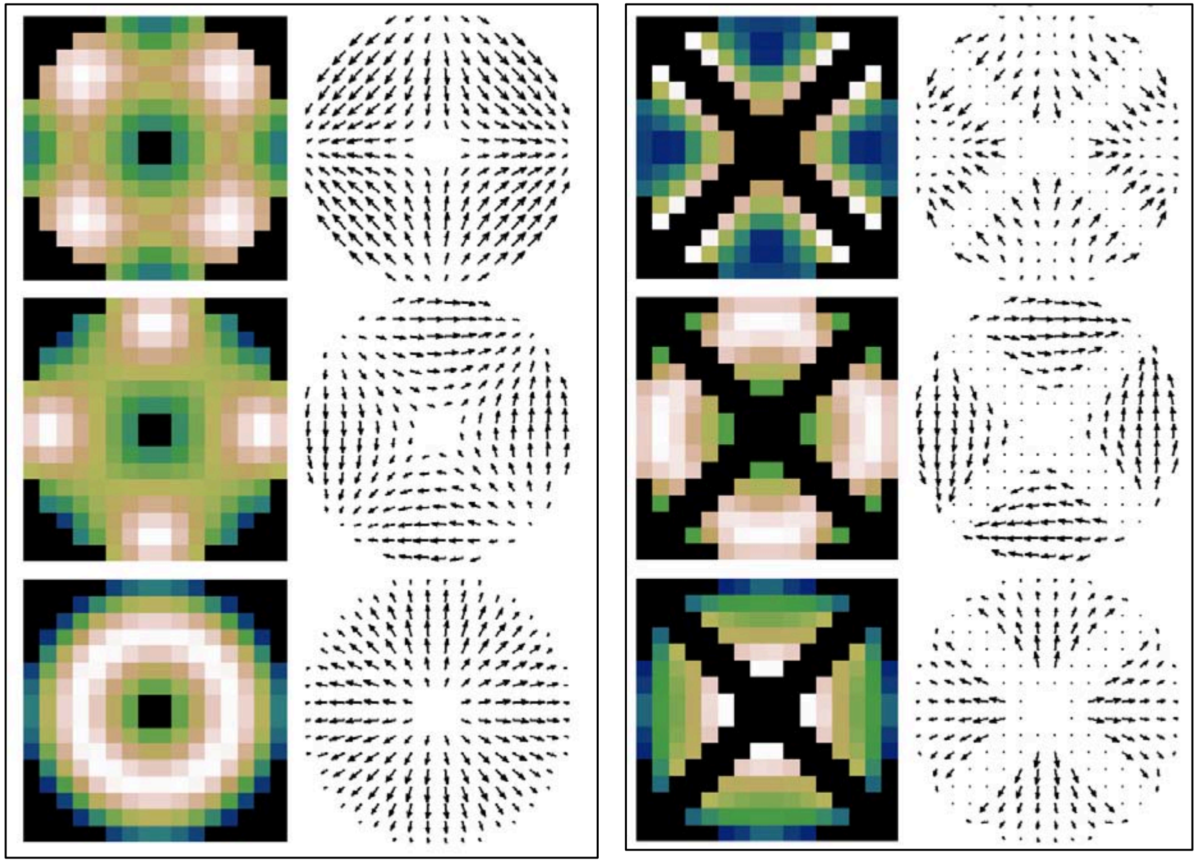
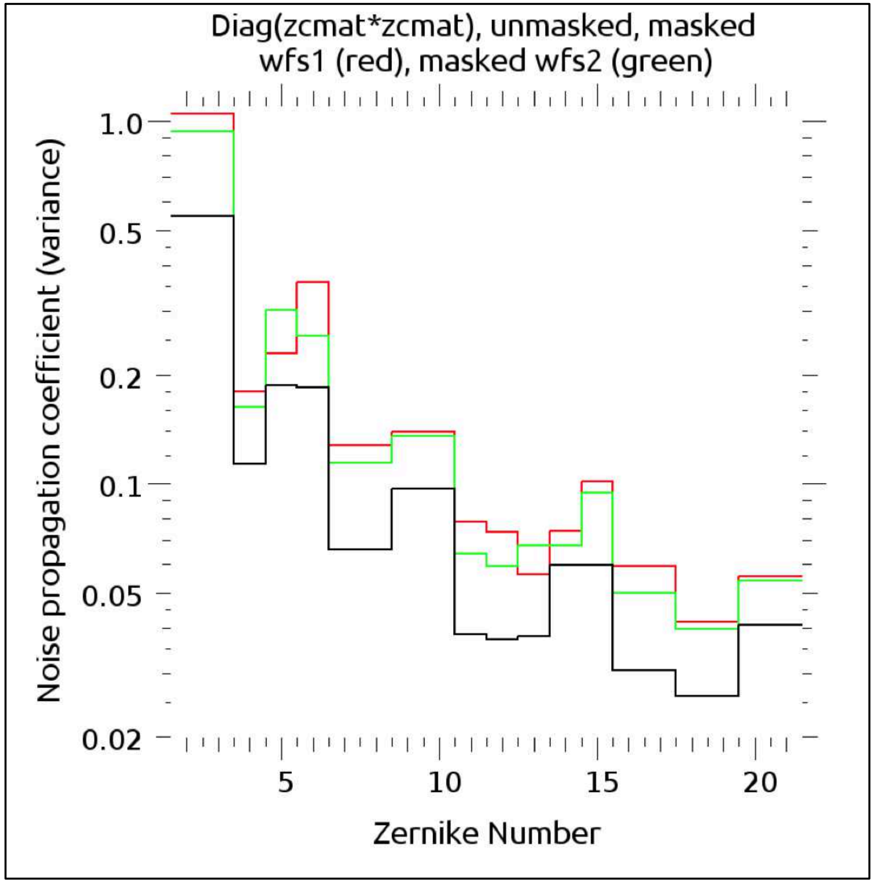
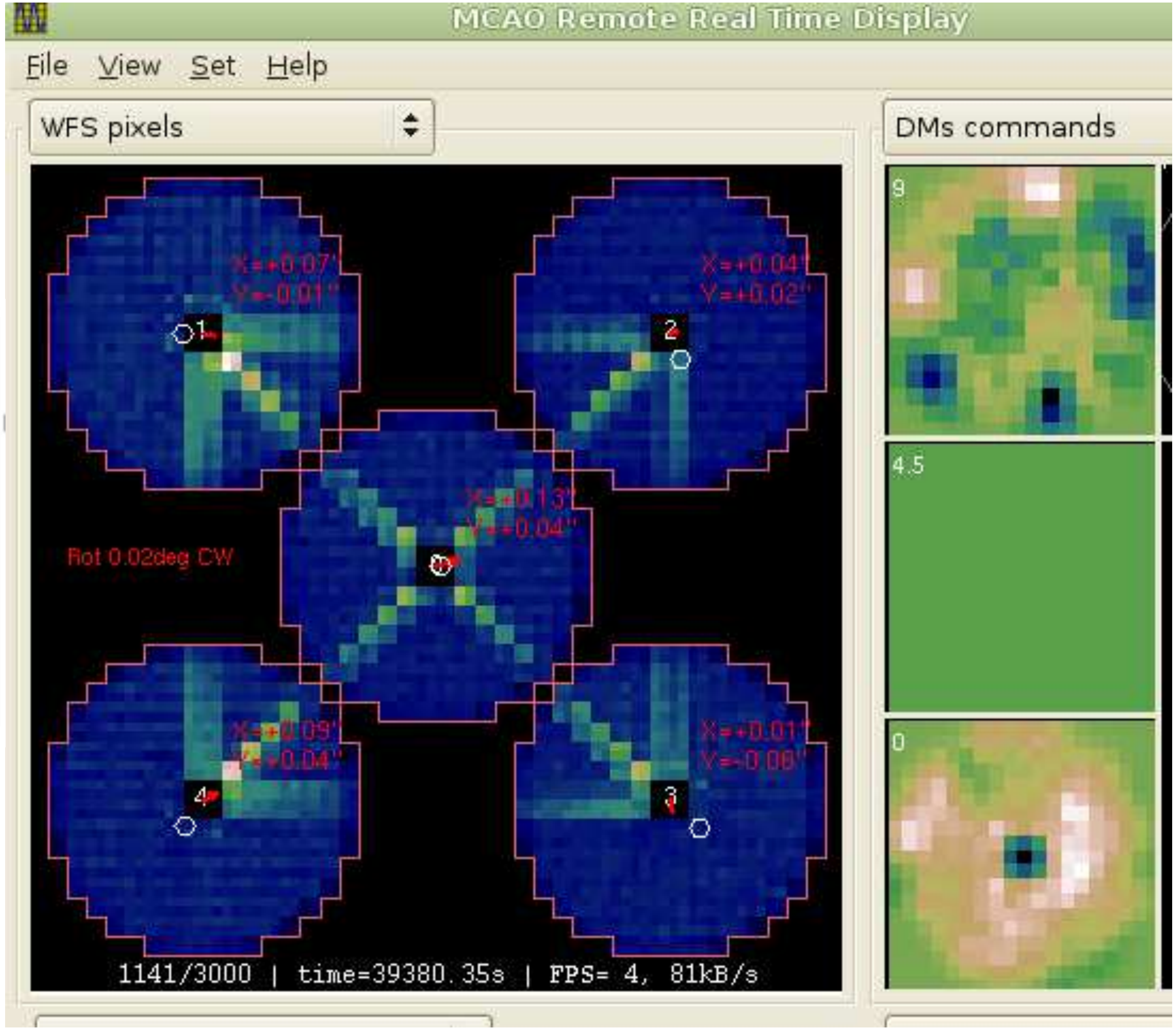




# Impact of “Fratricide Leaks”



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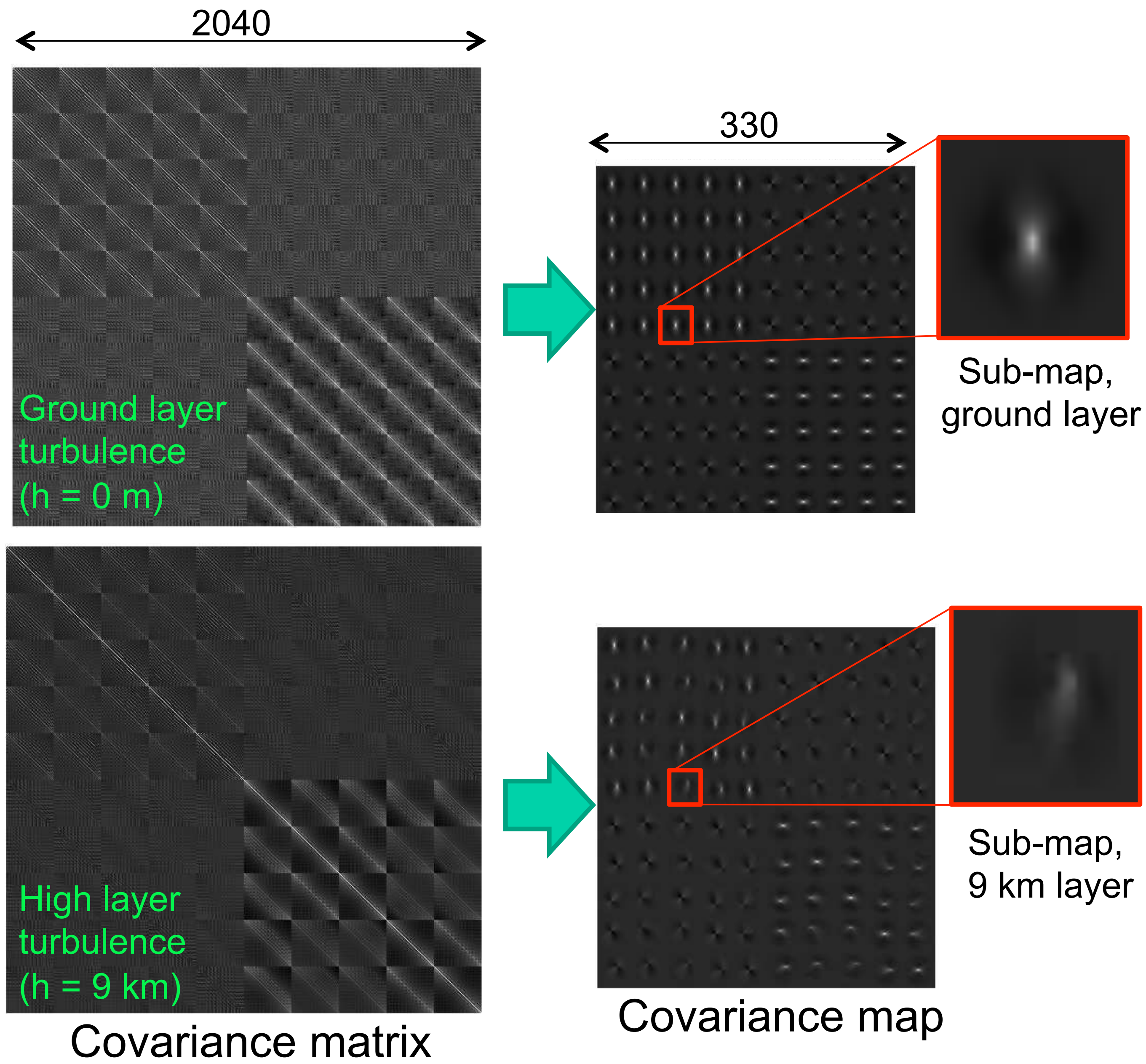
# GeMS' SLODAR



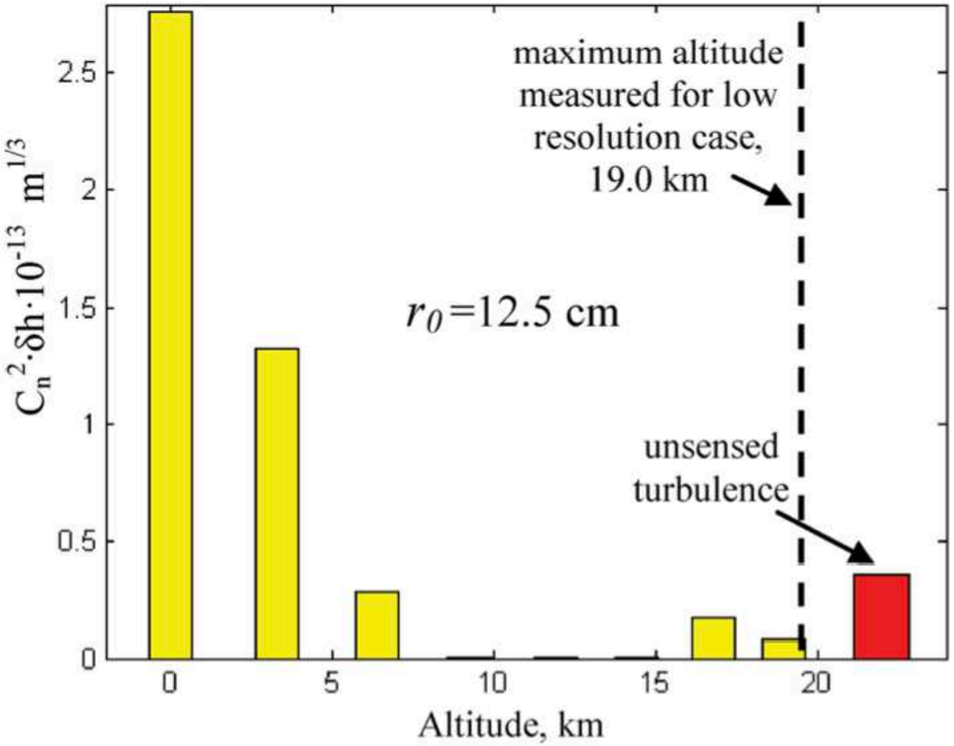

Theoretical covariance maps are built from realistic simulations (yorick/yao model of GeMS)

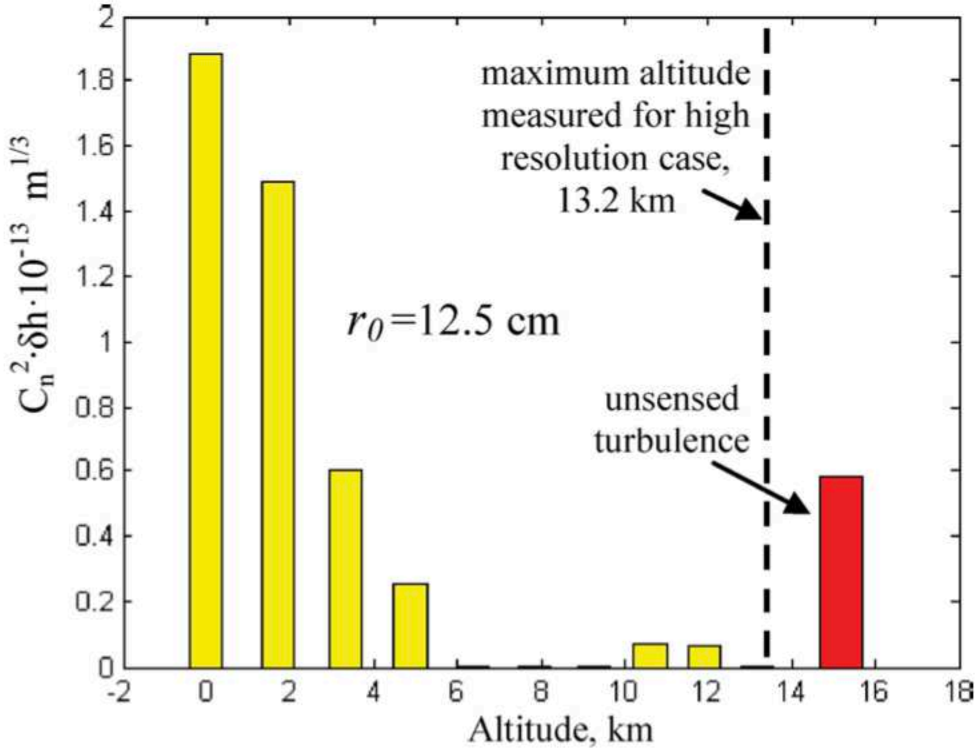
Profile is retrieved by fitting the data with the theoretical maps

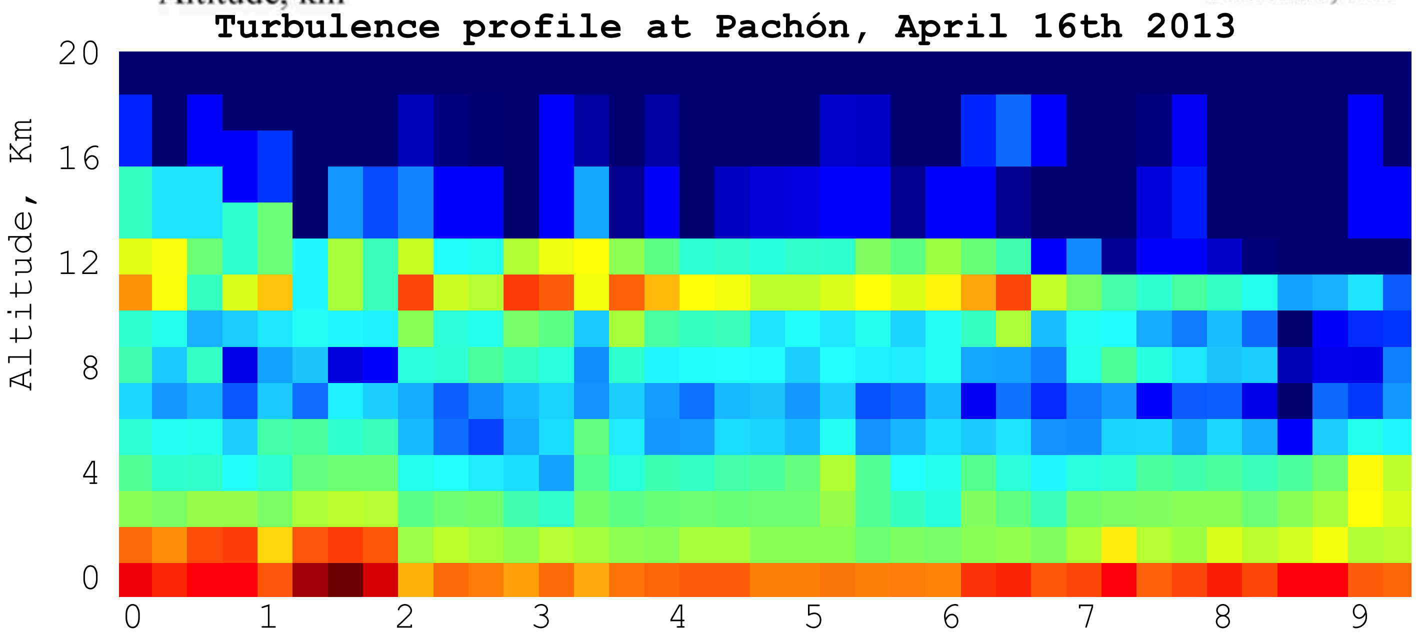
[Cortes et al. – MNRAS – 2012]

# GeMS' SLODAR

Some examples of on-sky data:



## Limitations of the method: presence of strong dome seeing

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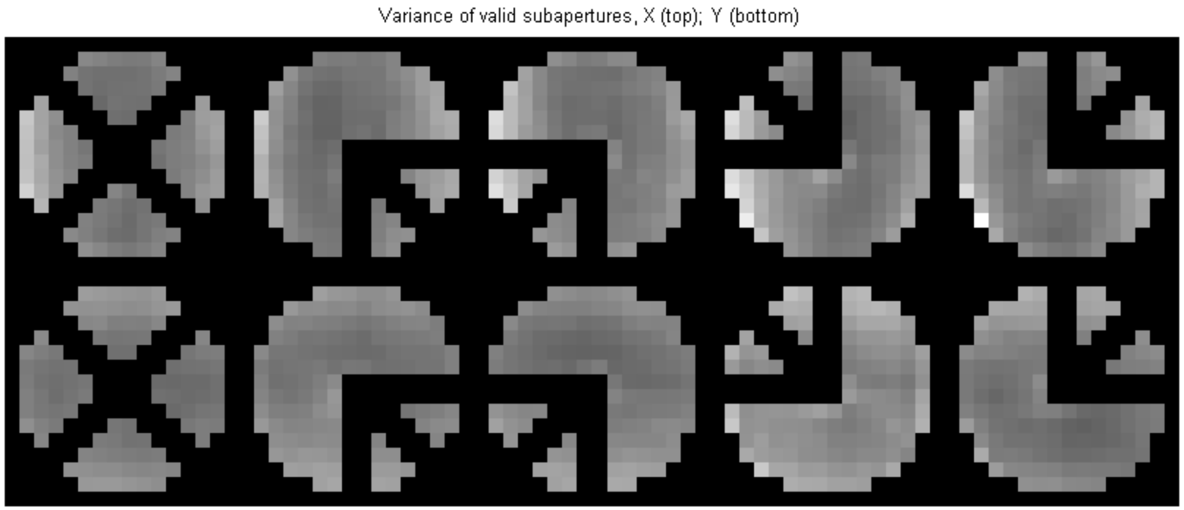


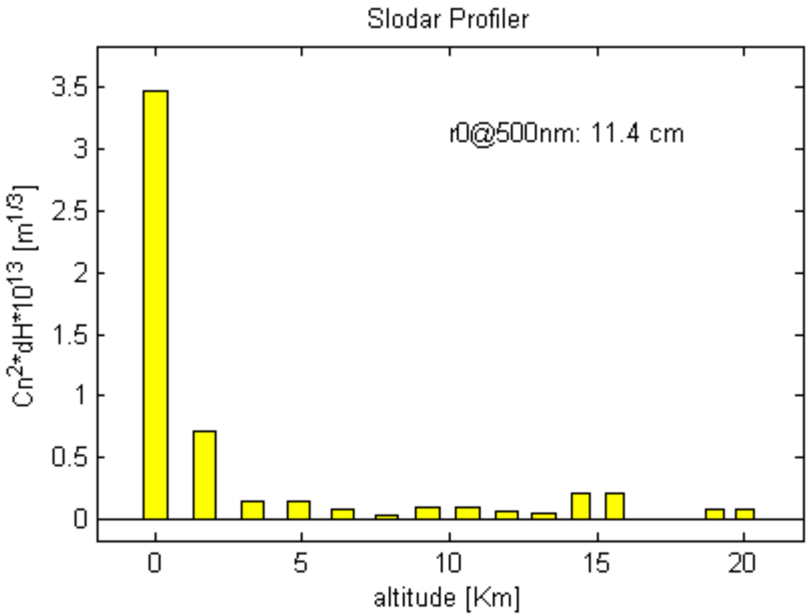


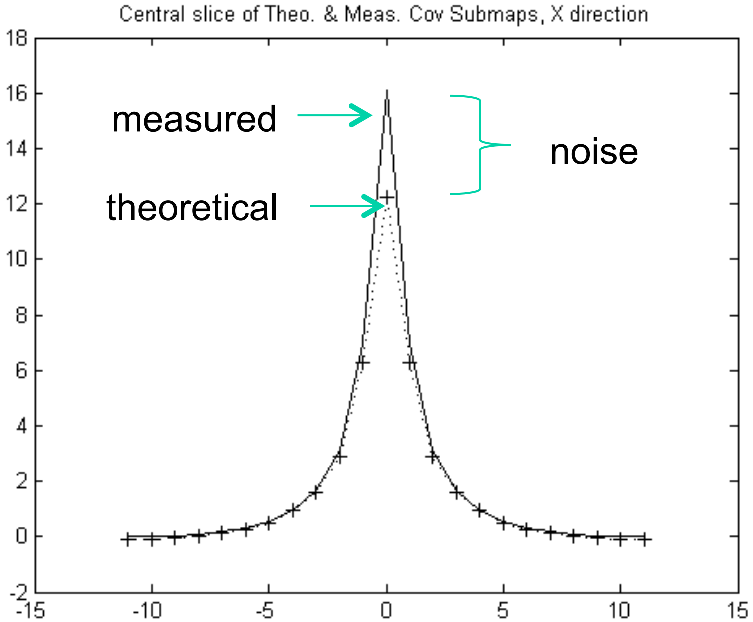


**[Guesalaga et al. AO4ELT3]**

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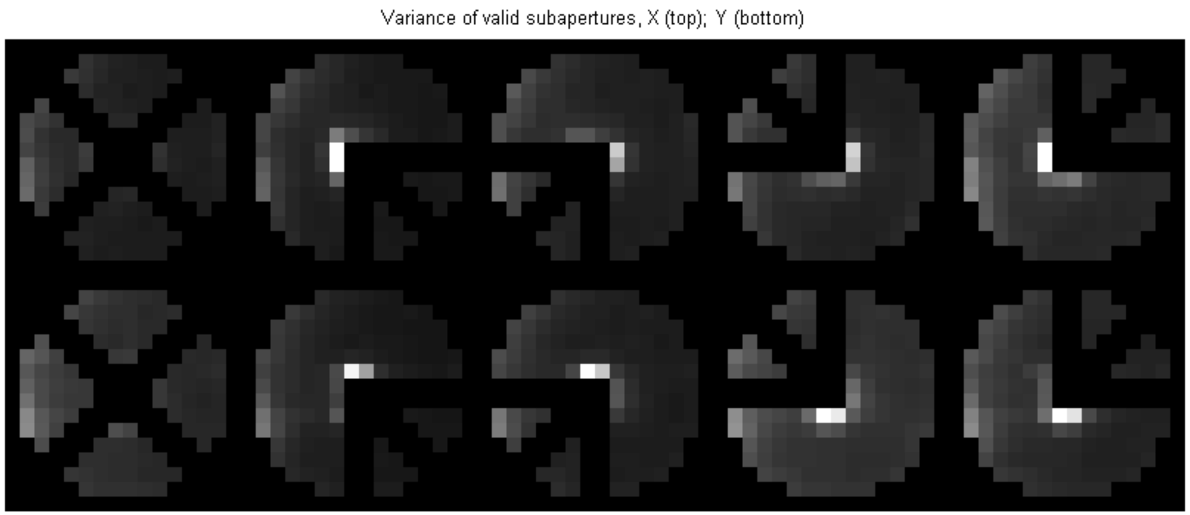


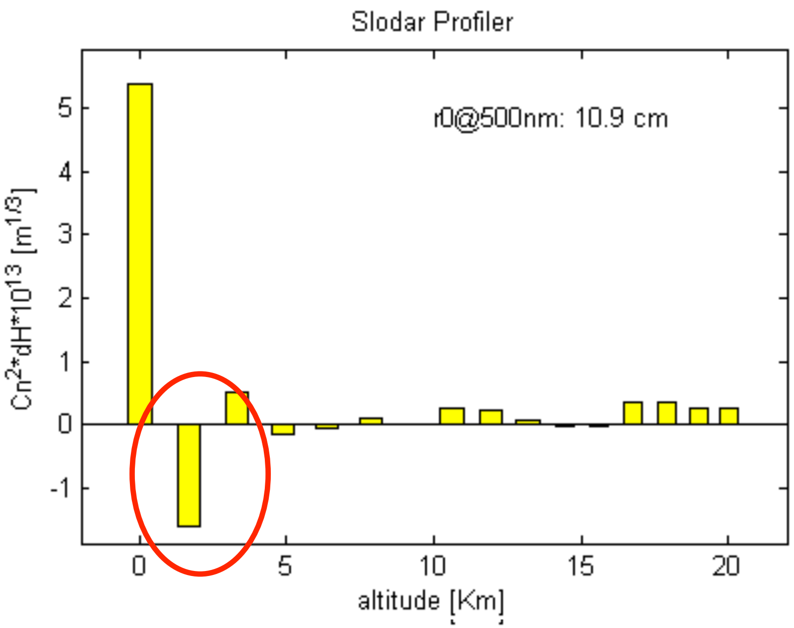


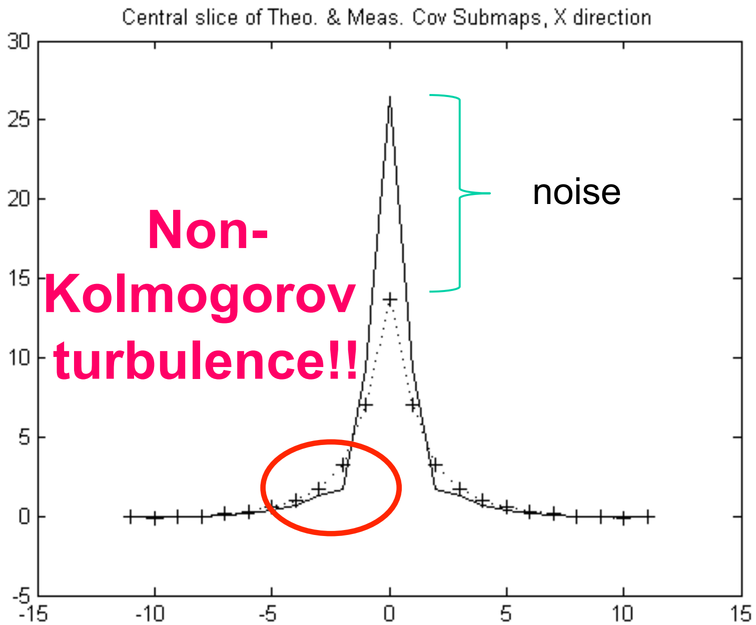


**[Guesalaga et al. AO4ELT3]**

Non-Kolmogorov (or non stationary) turbulence does exists !

What is the impact on tomographic performance ?

However:

- Wind speed and direction can be predicted and measured.
- Frozen Flow assumption holds for long enough for predictive reconstructors.

**[Guesalaga et al. – MNRAS – 2014]**

# GeMS's Tomography Calibrations & Limitations

Tomography is easy, calibrations are difficult…

**Differential aberrations between WFSs**

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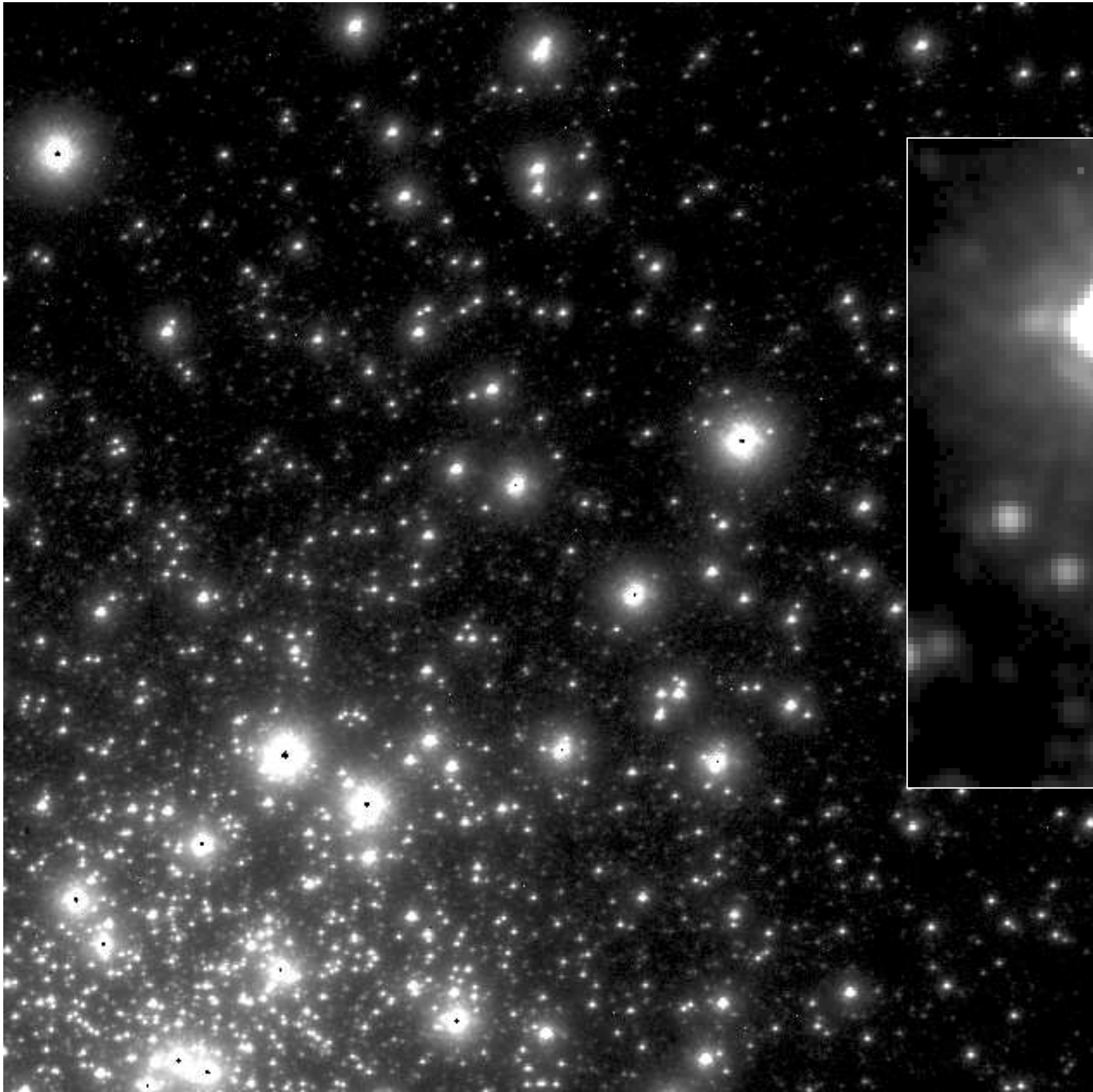
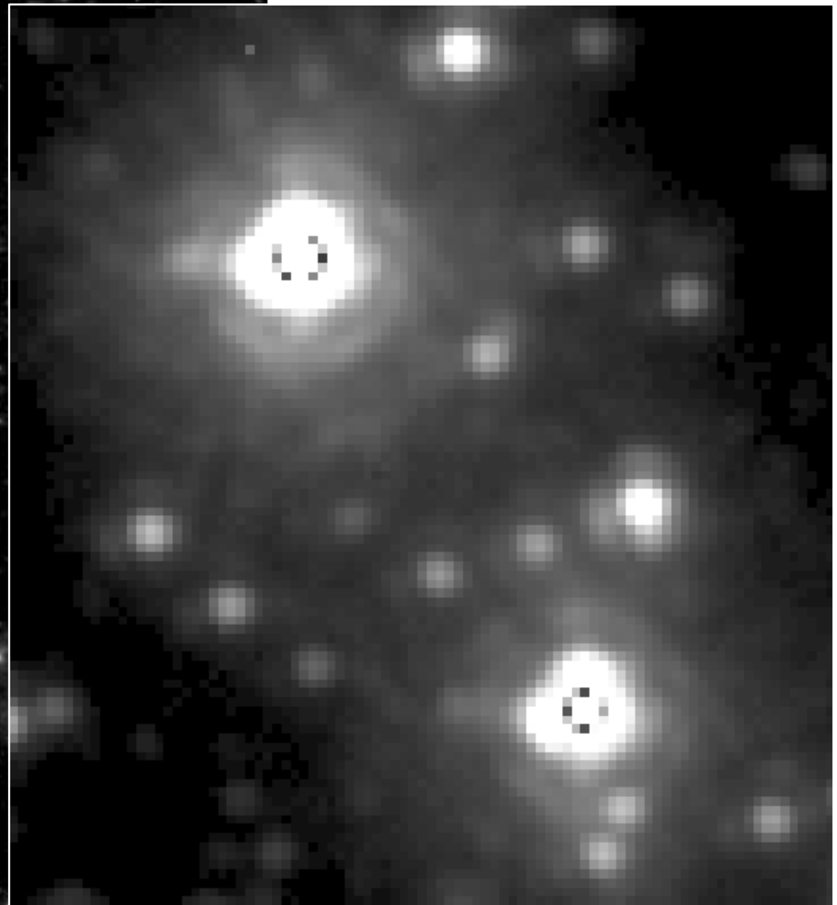
# Quasi-static aberrations





Cf. CANARY

# Science with MCAO

WFAO is opening new opportunities for a large range of science cases

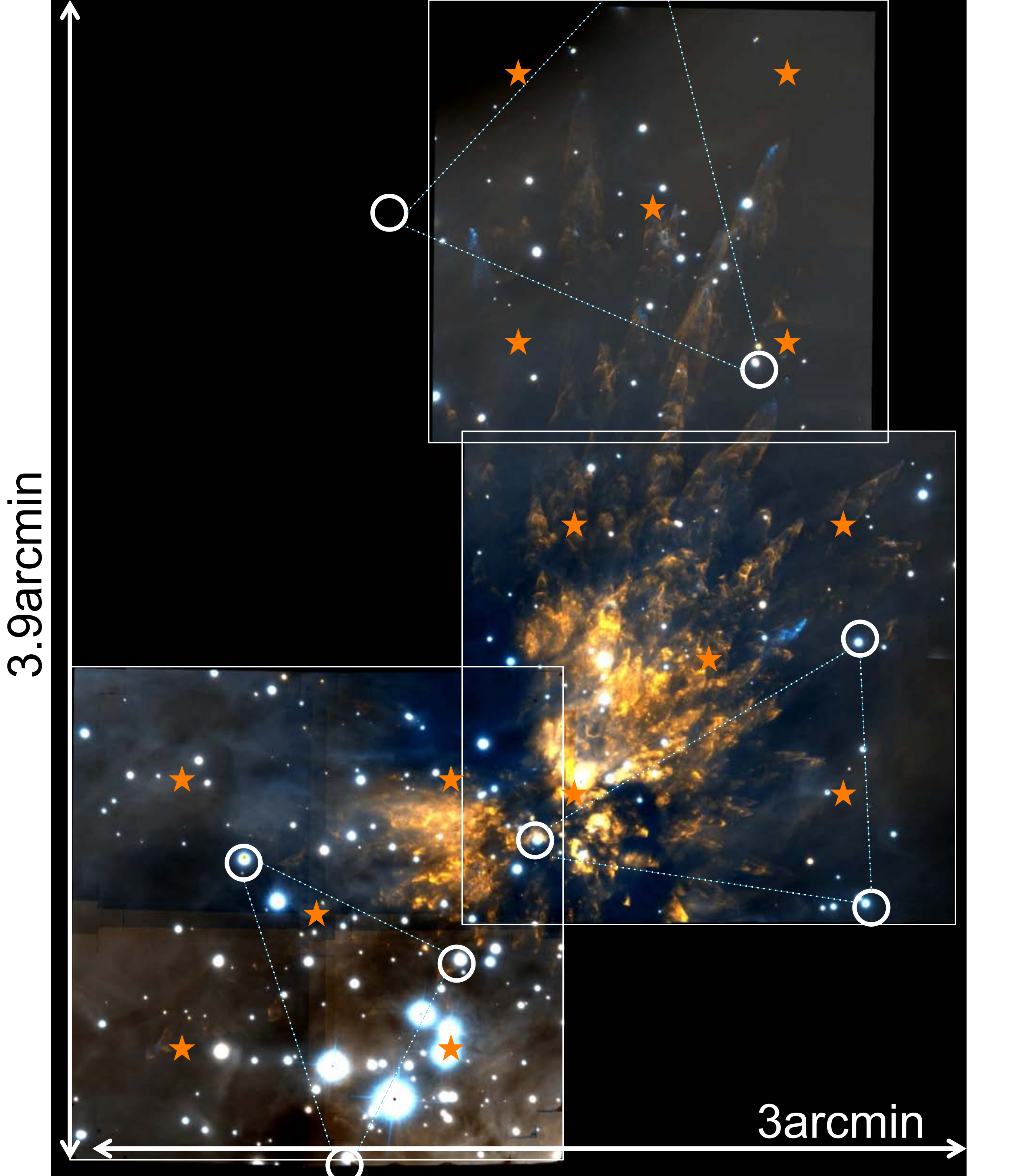
3 Fields:
OMC1 – North
OMC1 – Center
OMC1 – South-East

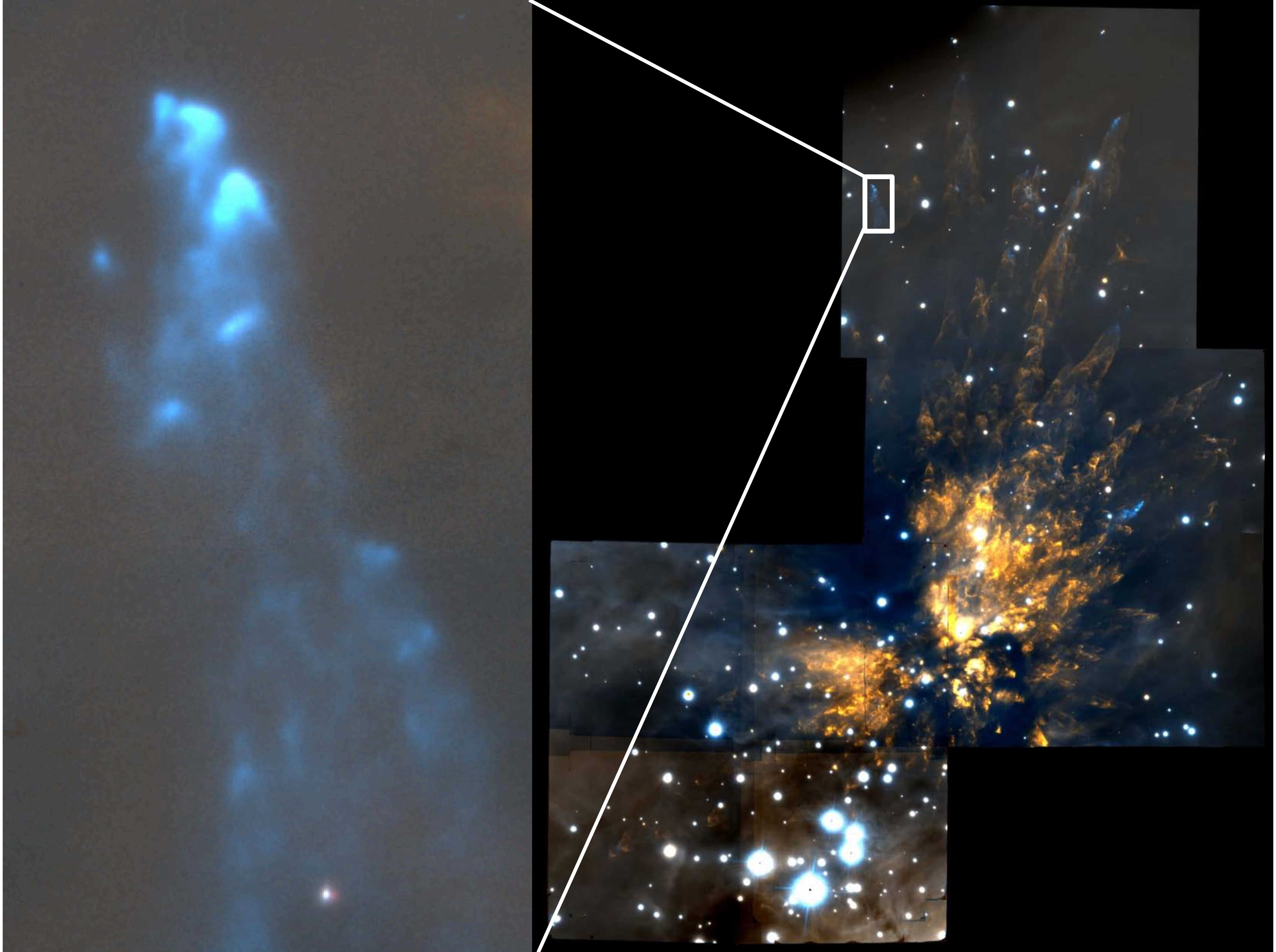
Filters:
Mol. Hydrogen (H2) - 2.122 µm (orange)
[Fe II] - 1.644 µm (blue)
Ks continuum - 2.093 µm (white)

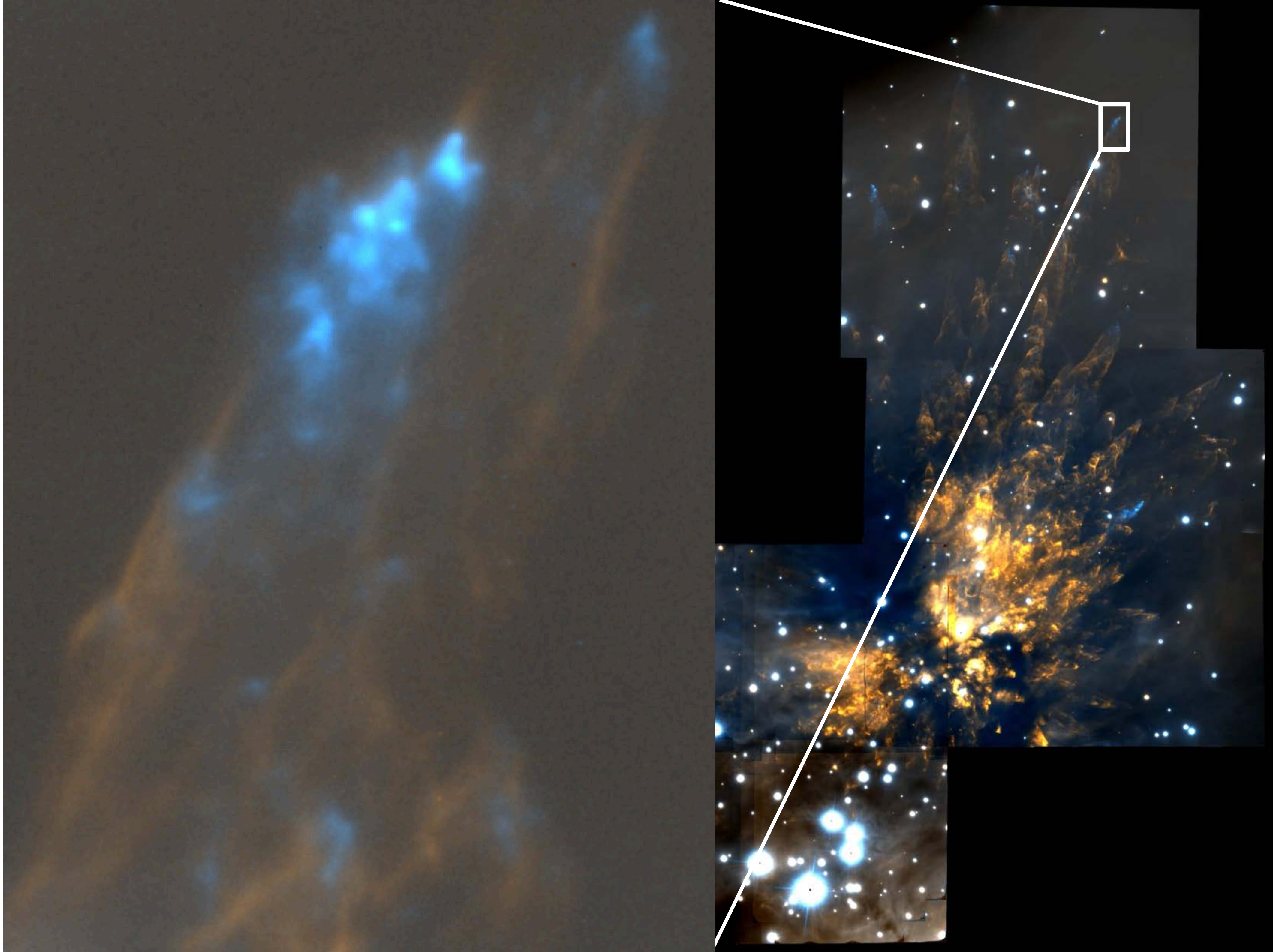
Exposure Time per field:
H2 = 12min
[Fe II] = 10min
Ks continuum = 10min

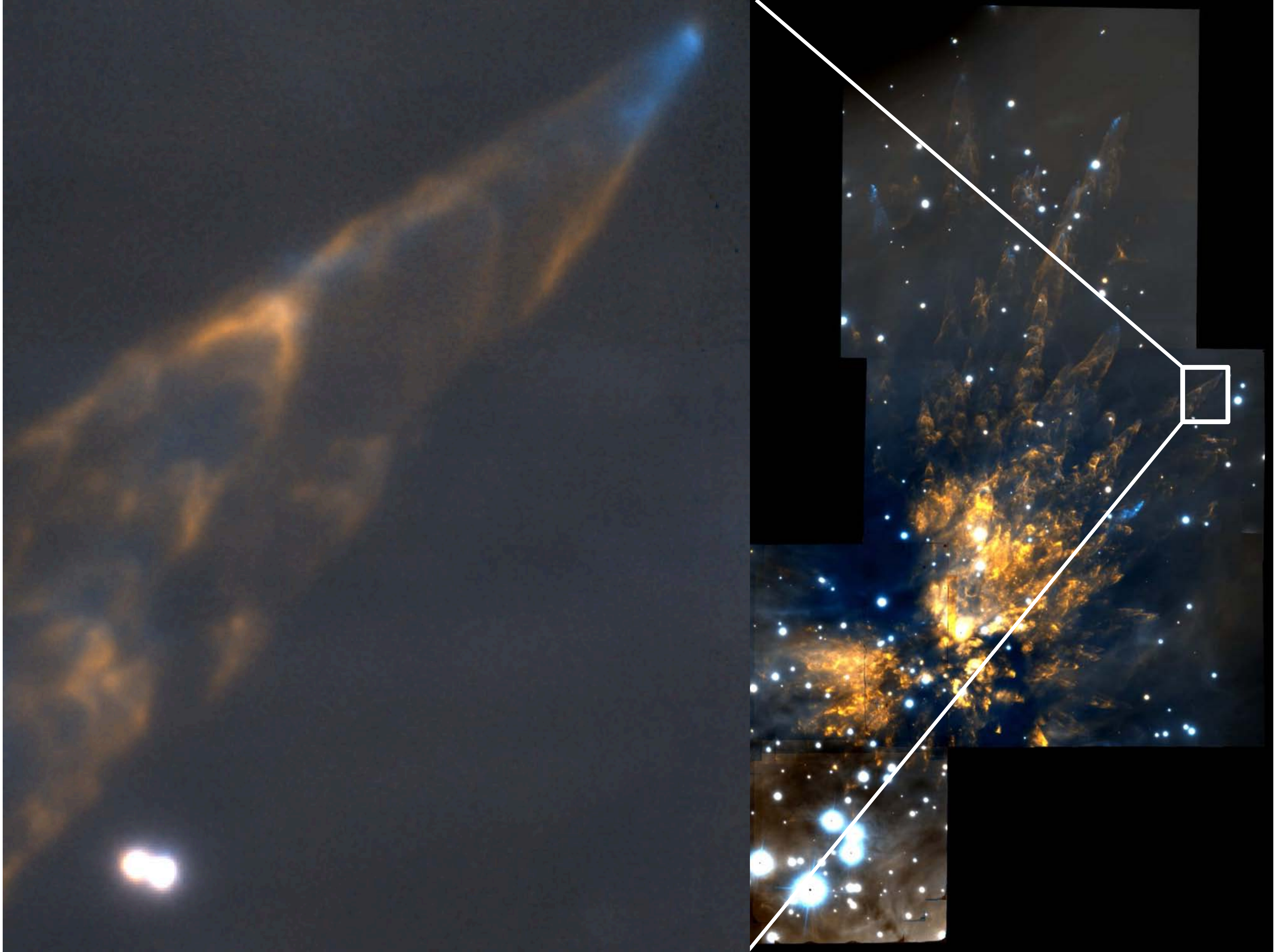
<FWHM> :
H2 = 90mas
[Fe II] = 100mas
Ks continuum = 90mas

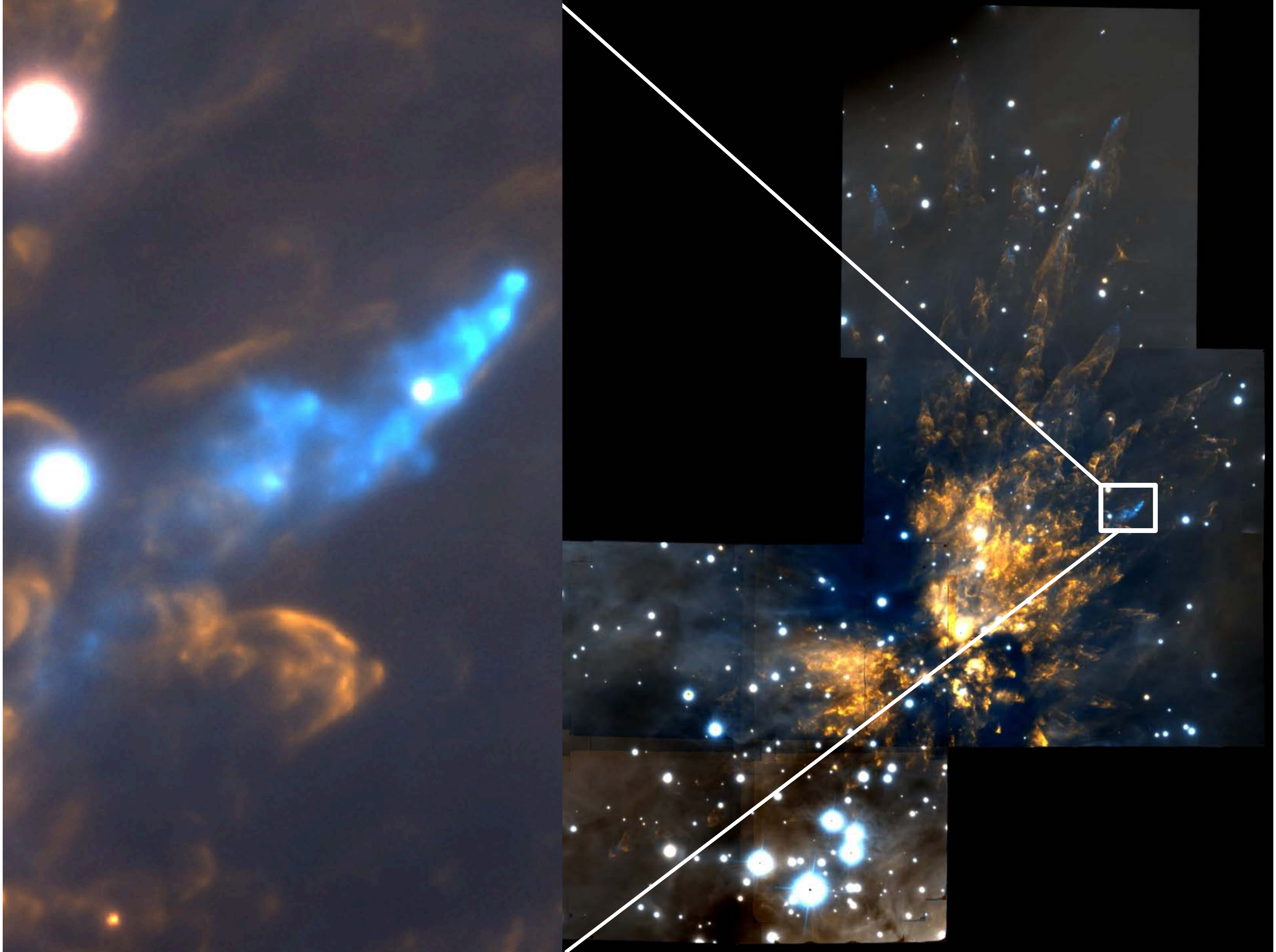
Natural seeing:
0.6” to 1.1” @ 550nm

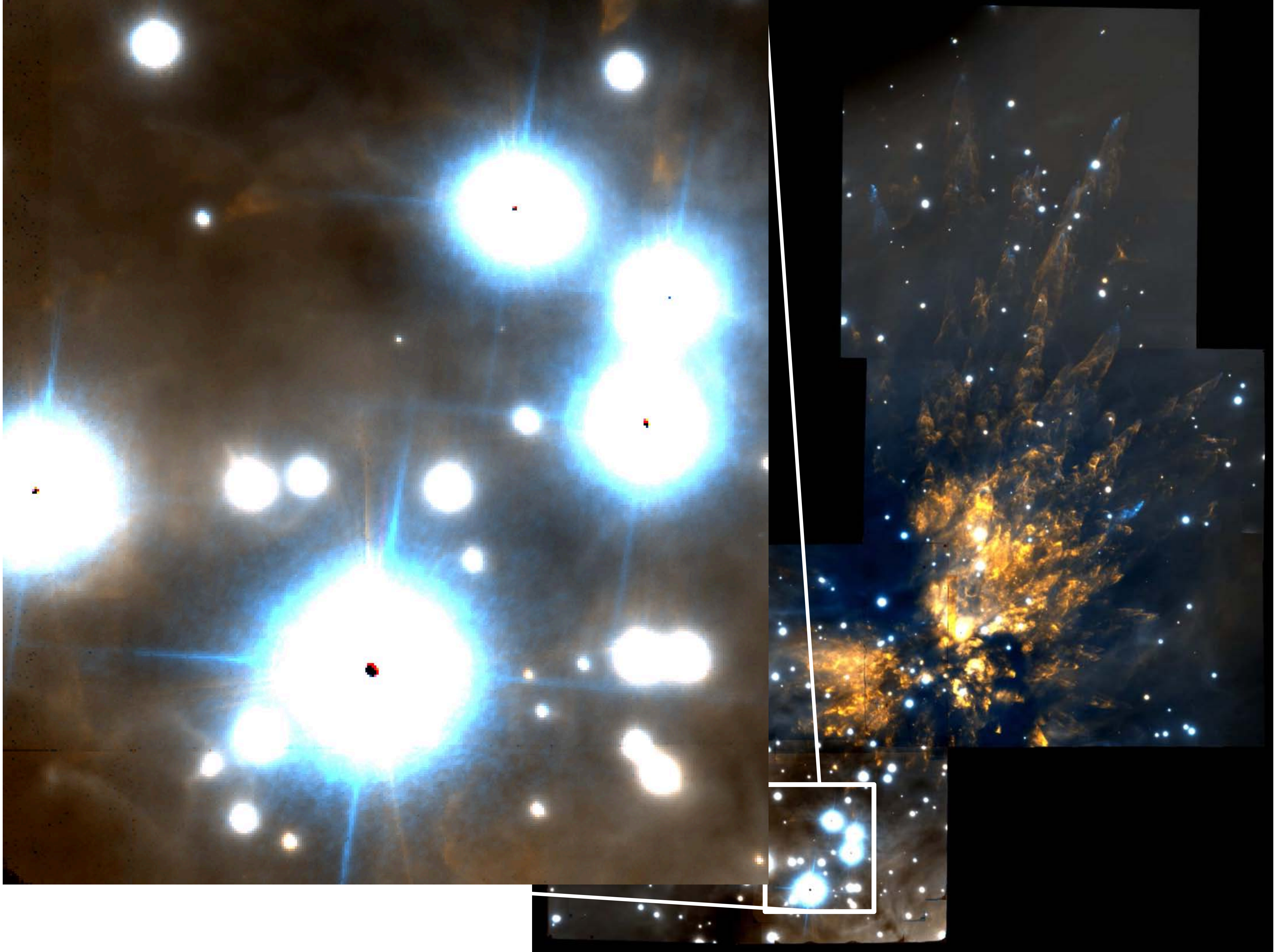


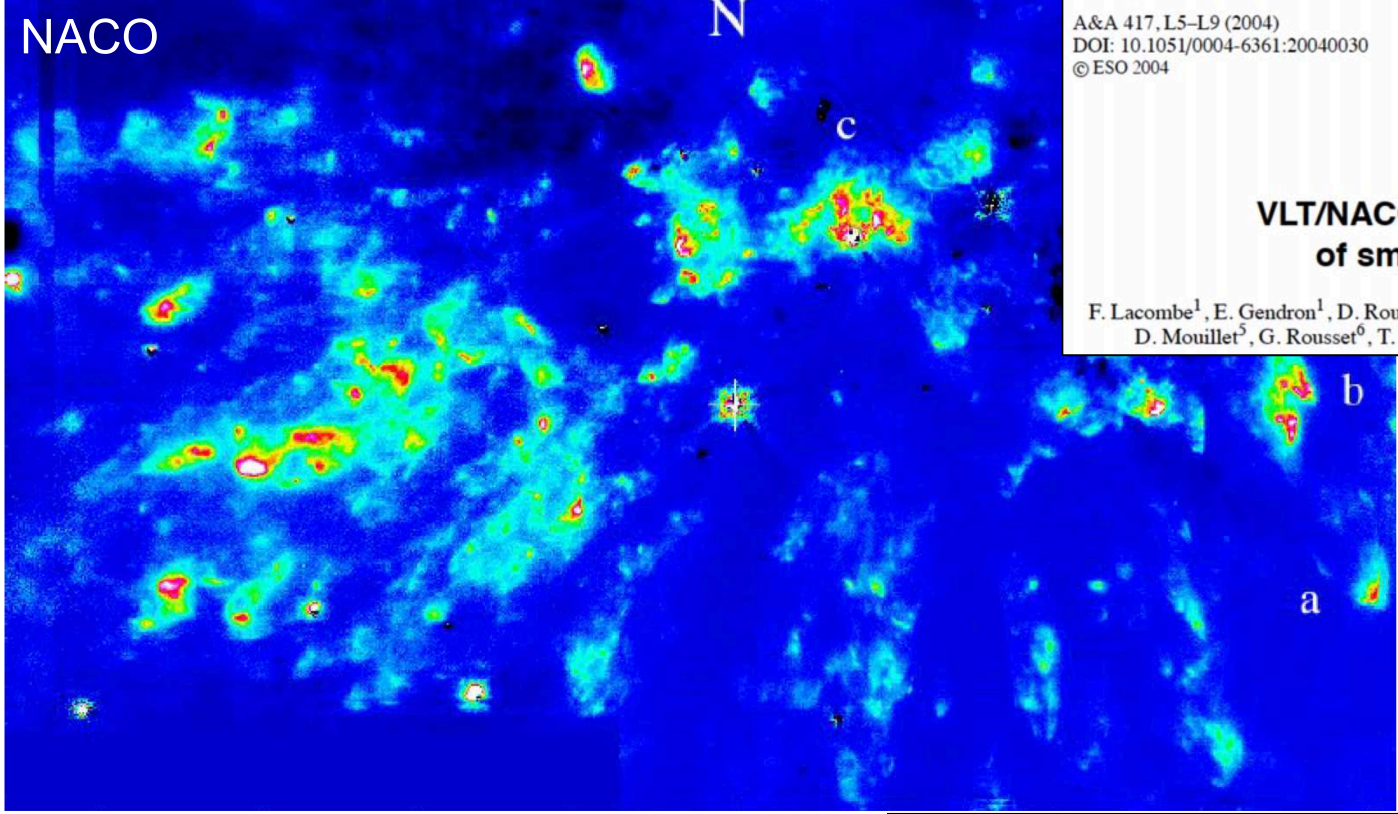










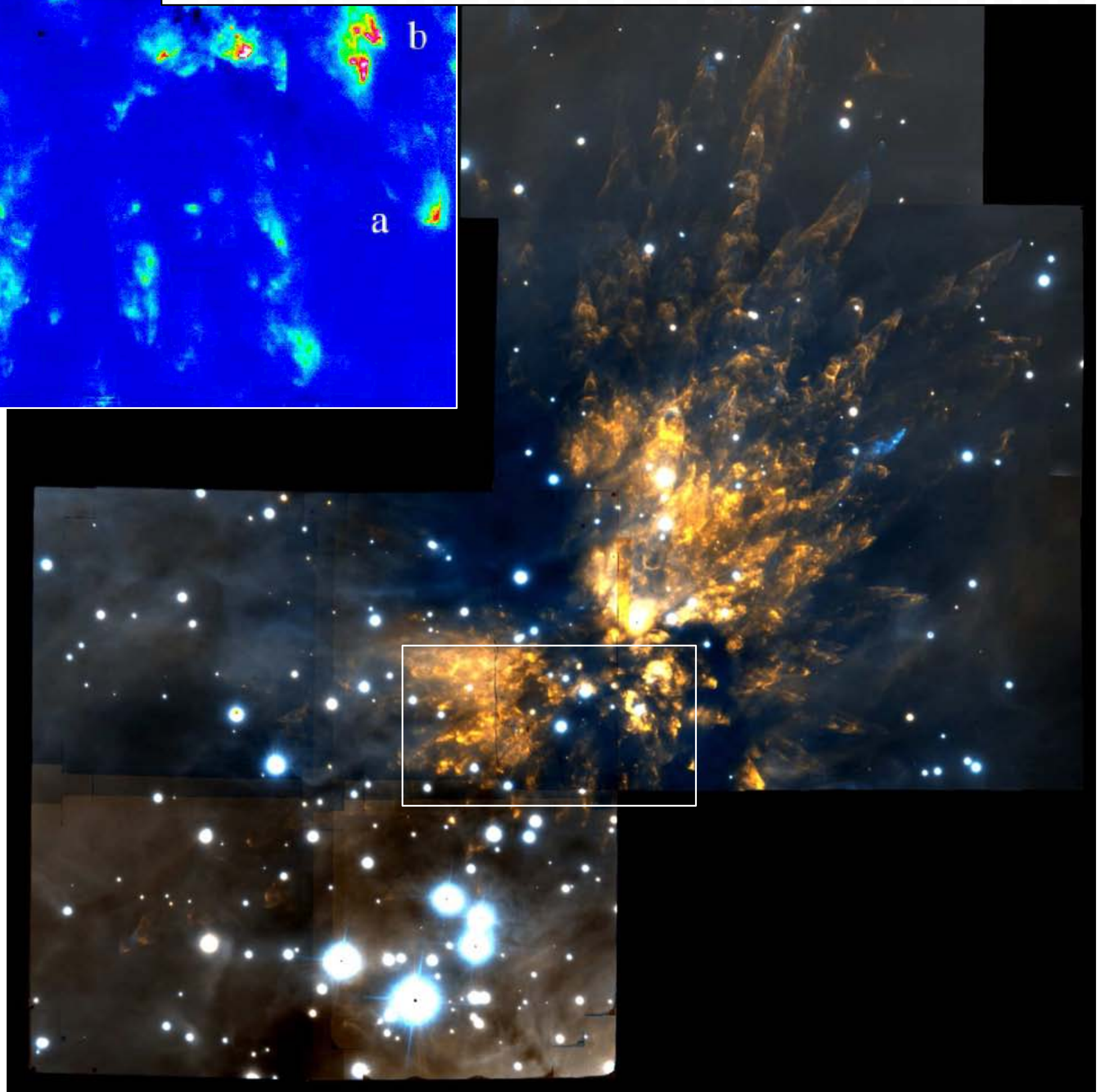


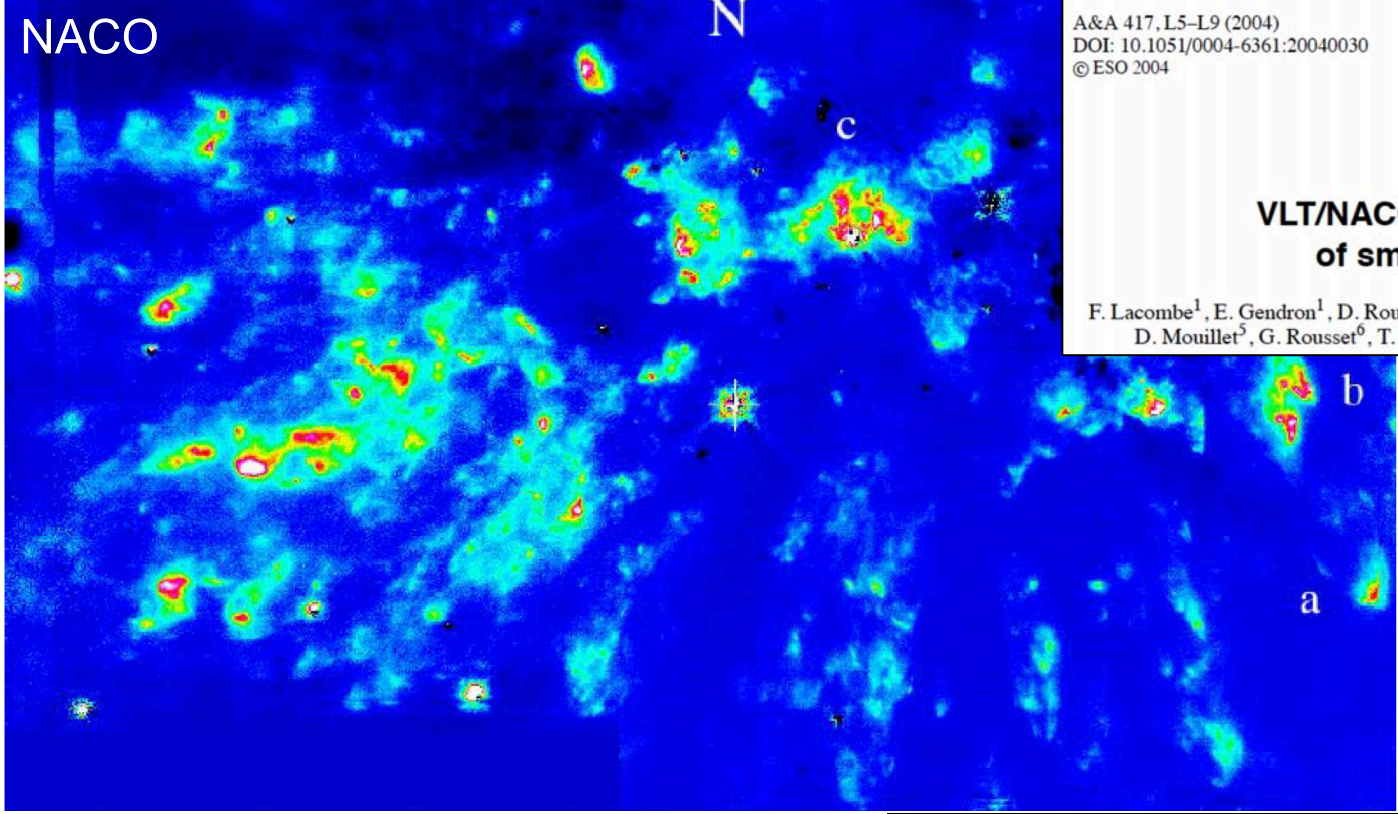

A&A 417, L5–L9 (2004)
DOI: 10.1051/0004-6361:20040030


Astronomy & Astrophysics

## VLT/NACO infrared adaptive optics images of small scale structures in OMC1*

F. Lacombe[1], E. Gendron[1], D. Rouan[1], Y. Clénet[1], D. Field[2], J. L. Lemaire[3,4], M. Gustafsson[2], A.-M. Lagrange[5], D. Mouillet[5], G. Rousset[6], T. Fusco[6], L. Rousset-Rouvière[6], B. Servan[7,†], C. Marlot[1], and P. Feautrier[5]



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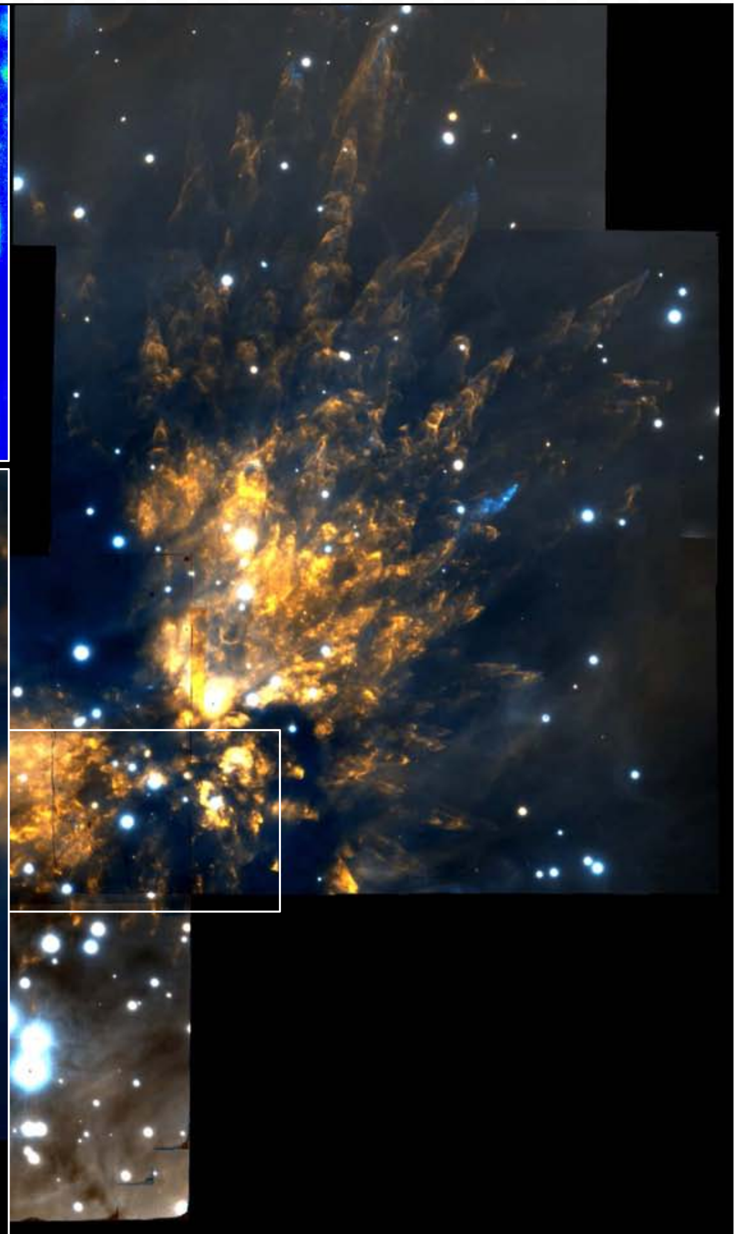

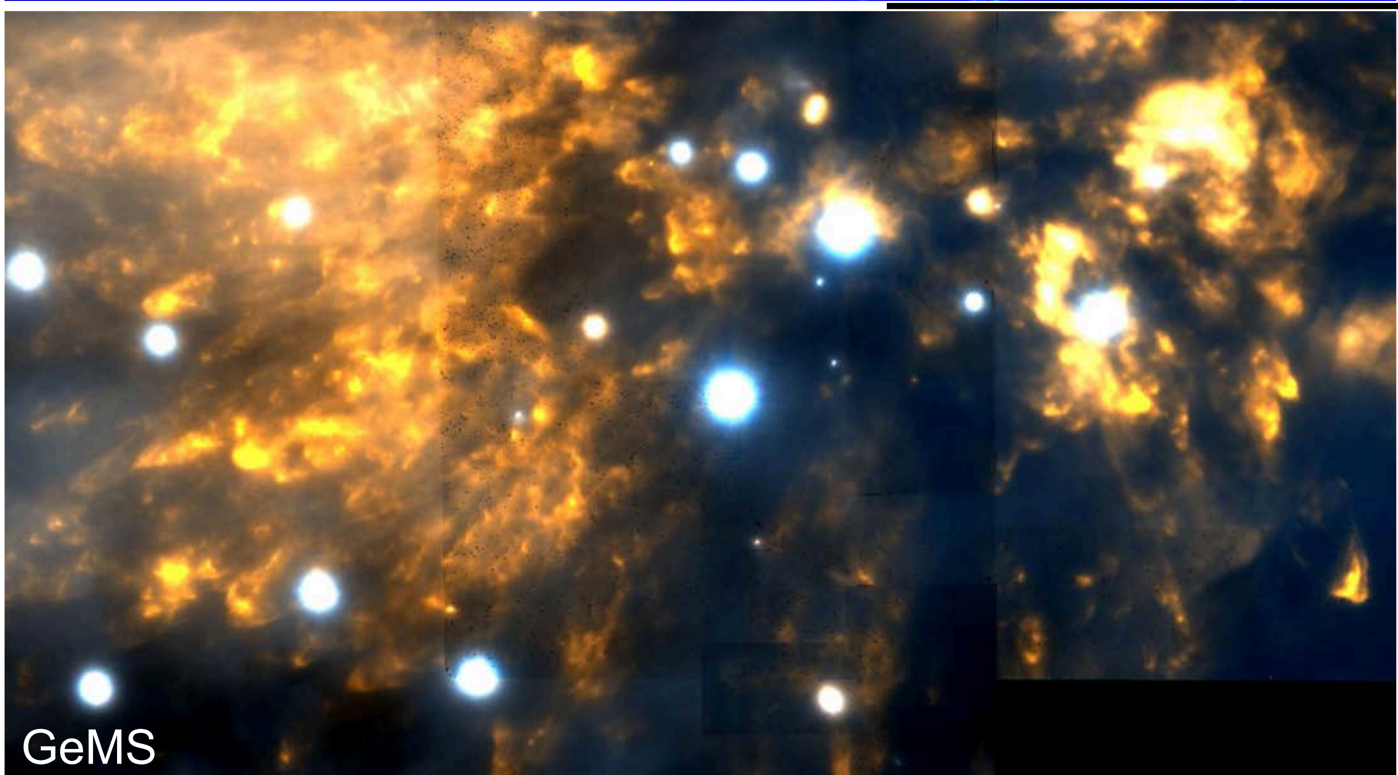

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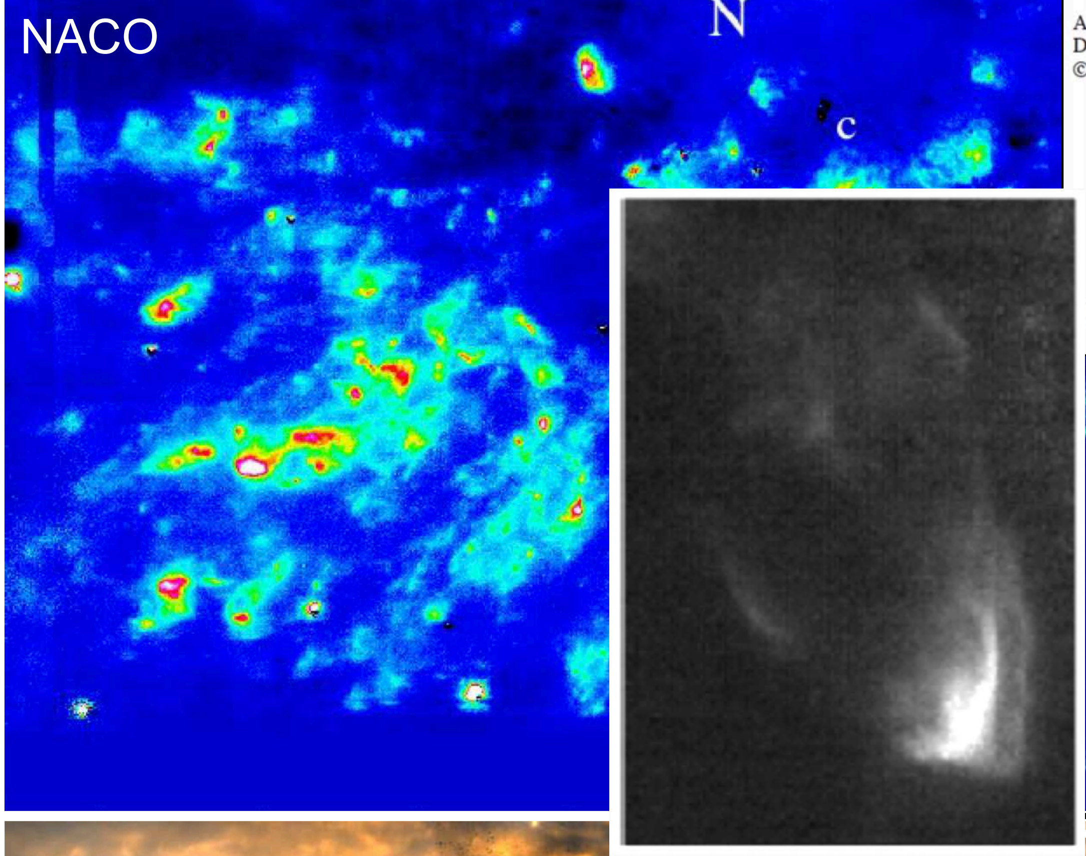
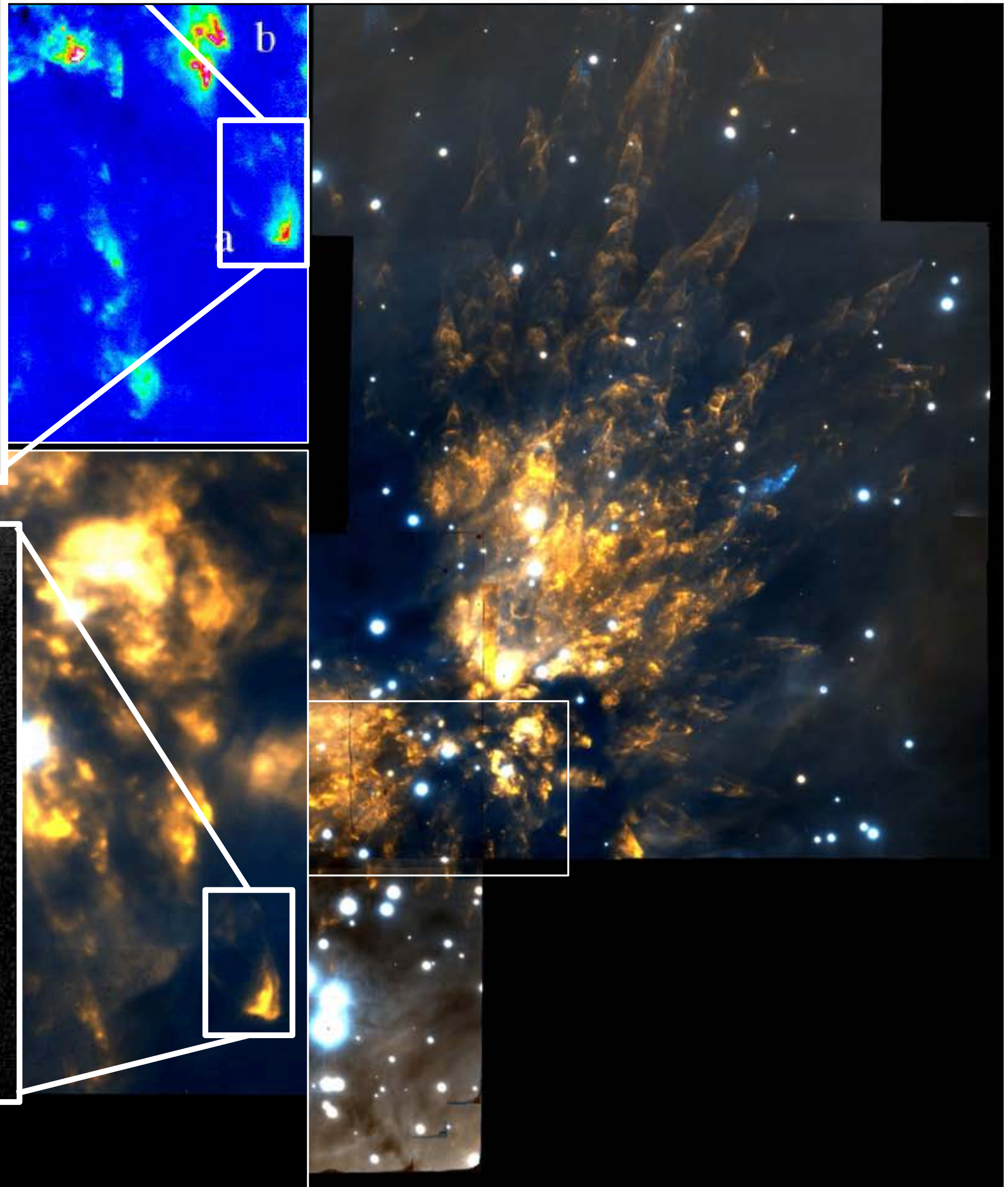
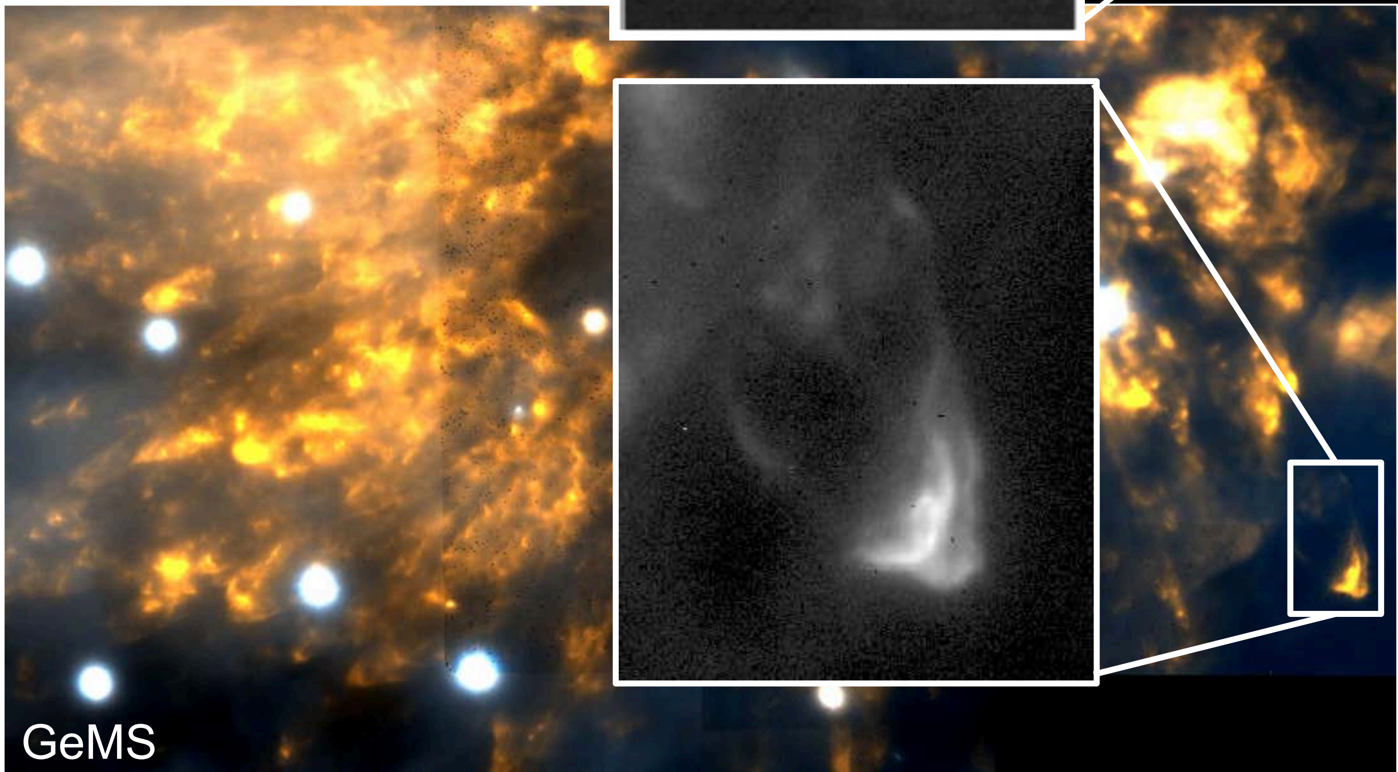
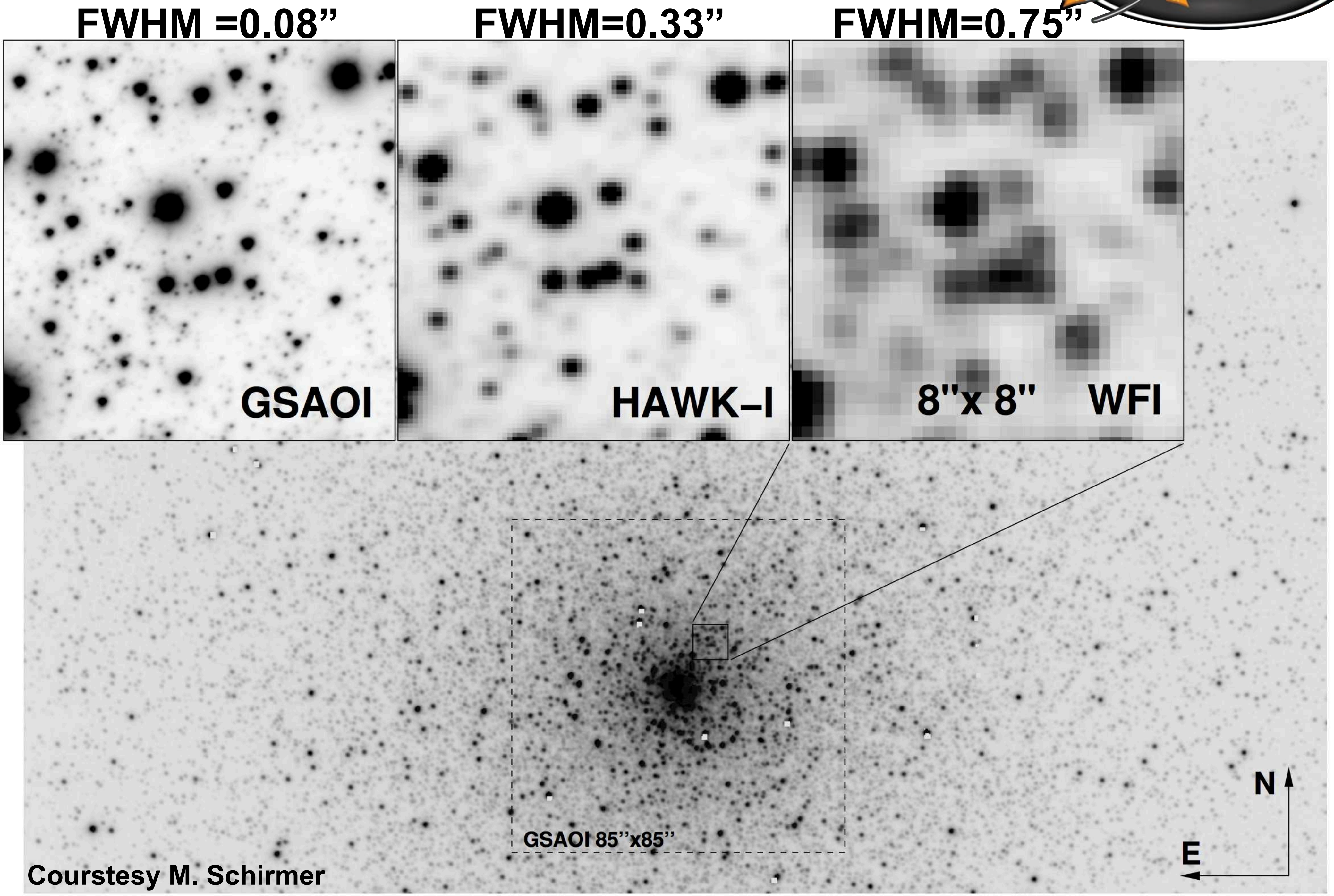
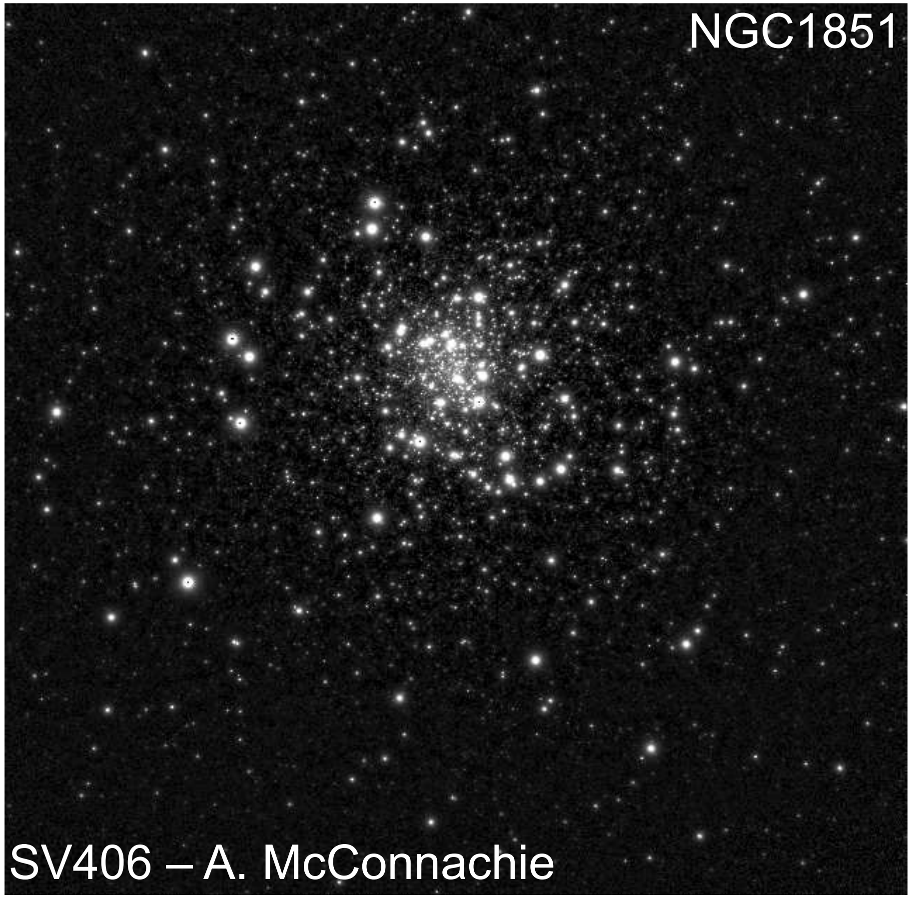


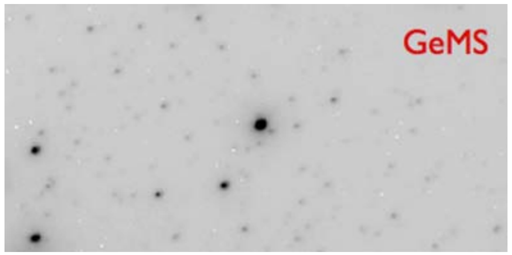




FWHM =0.08”
FWHM=0.33”
FWHM=0.75”
GSAOI
HAWK–I
8"x 8"
WFI
GSAOI 85’’x85’’
N
E
Courstesy M. Schirmer

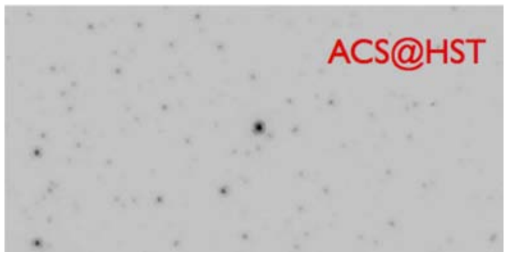
## Star Clusters



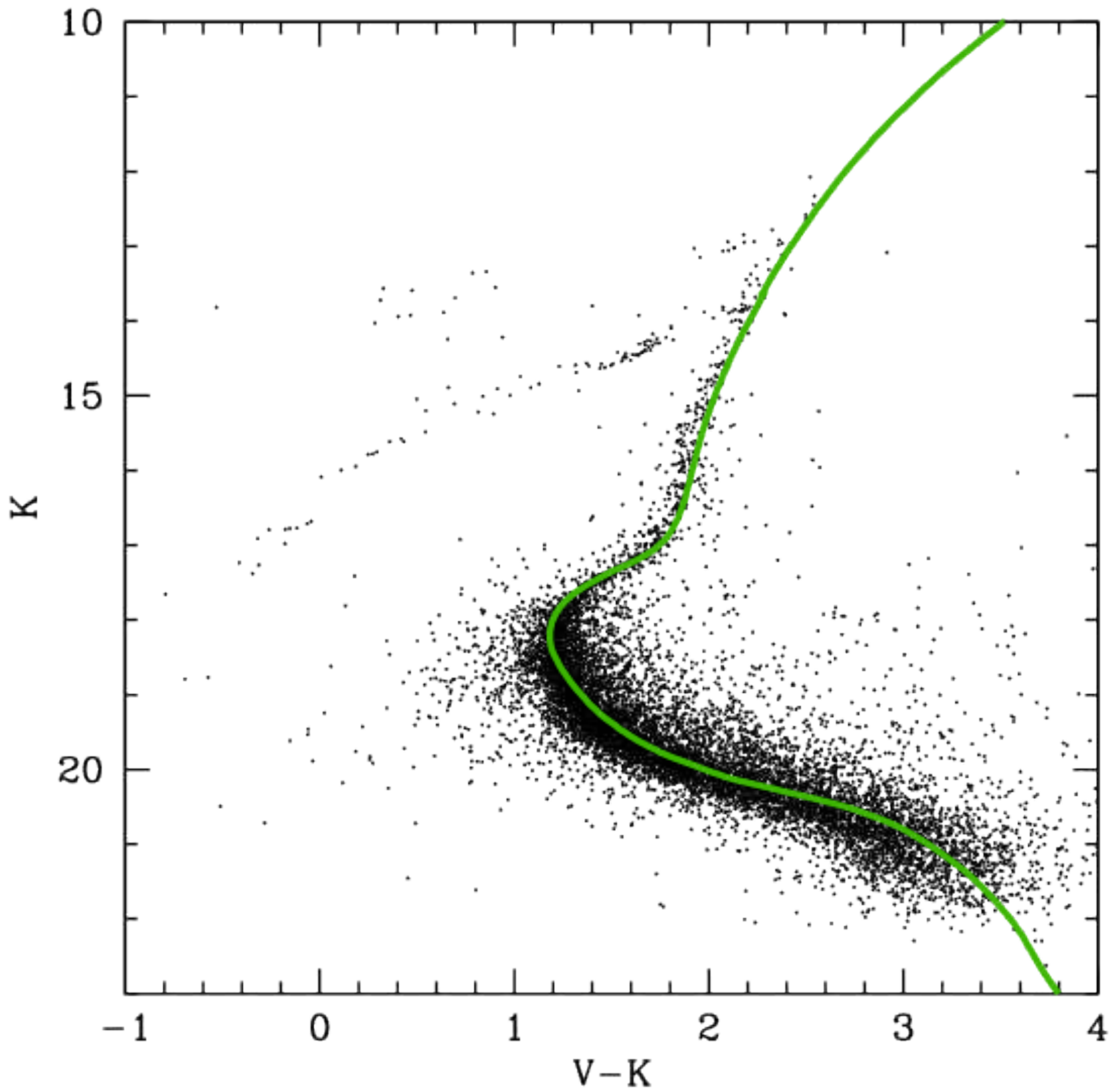

80mas




50mas

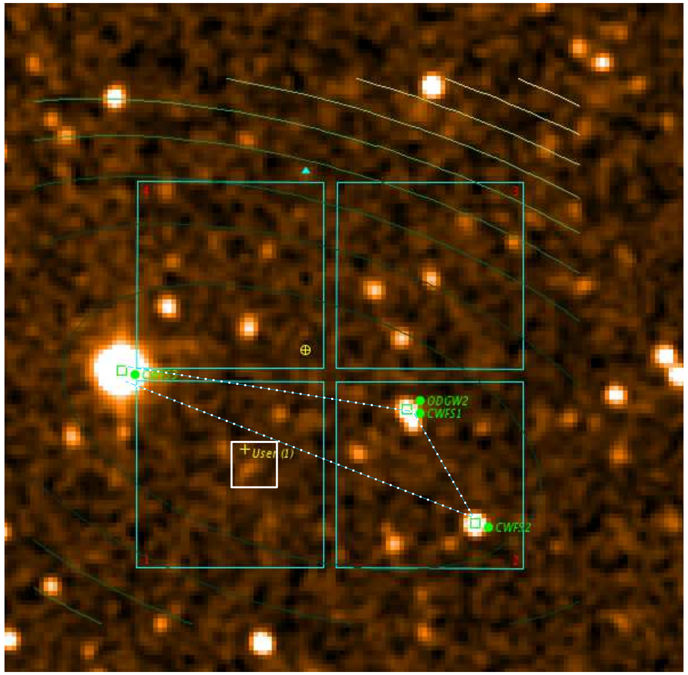



ISOCHRONES from Dotter et al. 2007 WEBsite
Z=0.001 age=10Gyrs



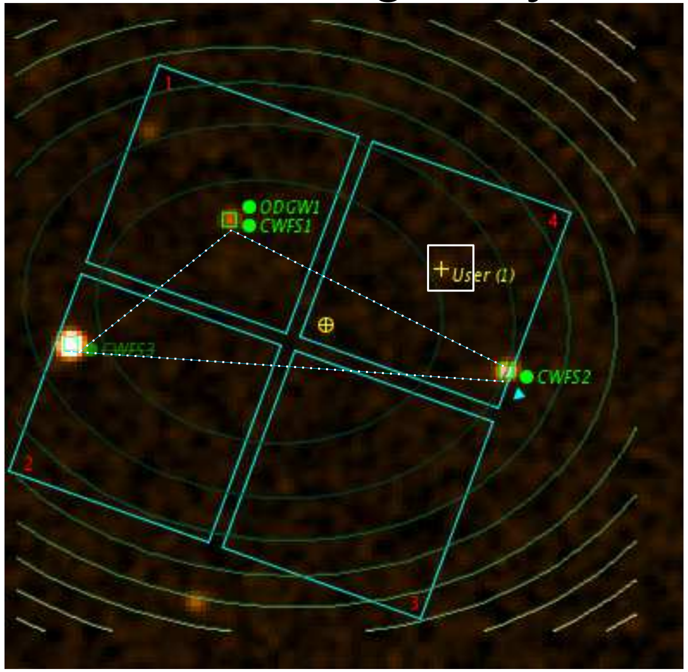

P. Turri – PhD thesis

Pulsar



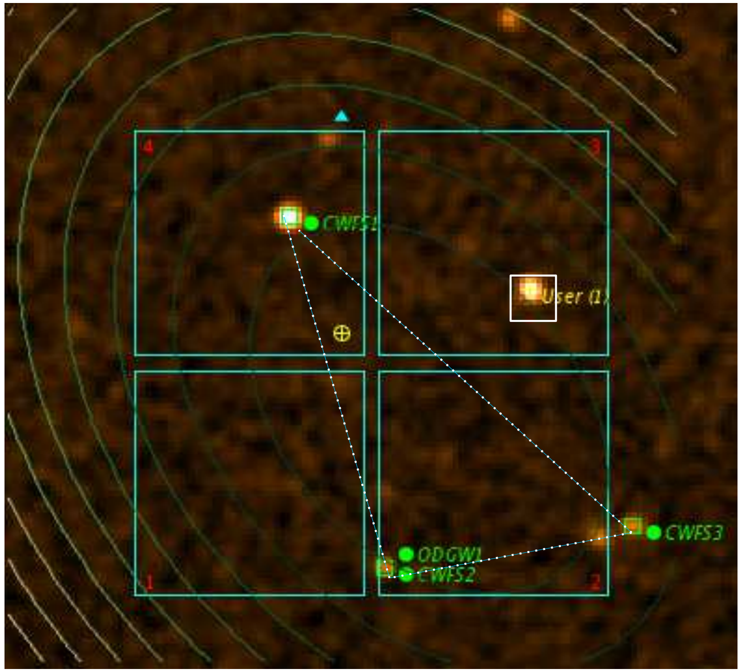

SV412 – R. Mennickent

Isolated galaxy




SV411 – P. McGregor

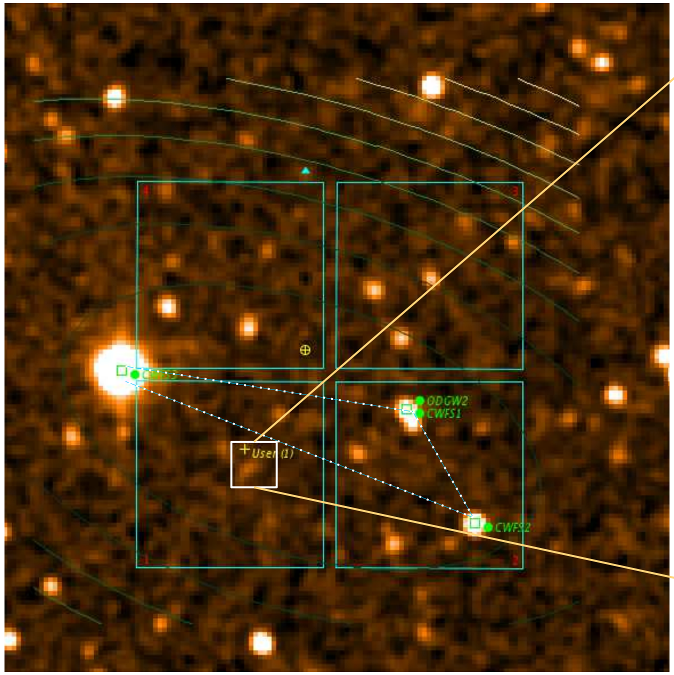
Quasar



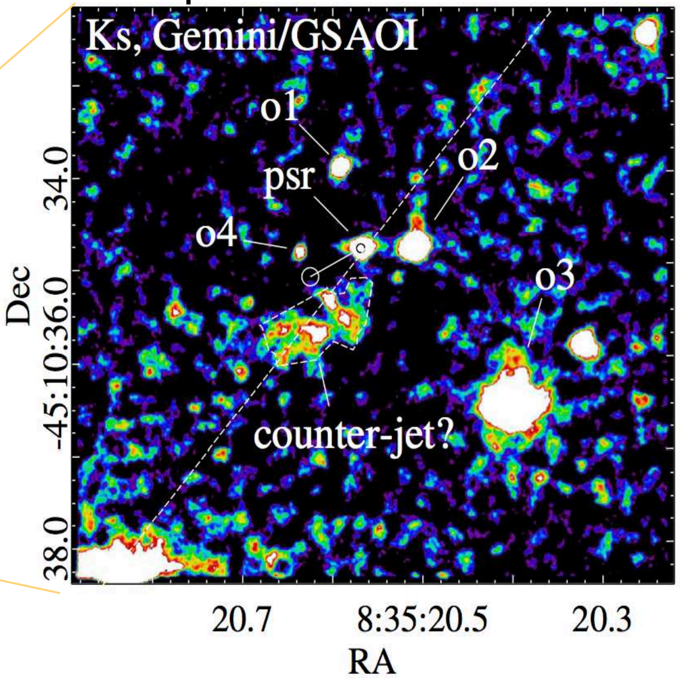

SV409 – D. Flyod

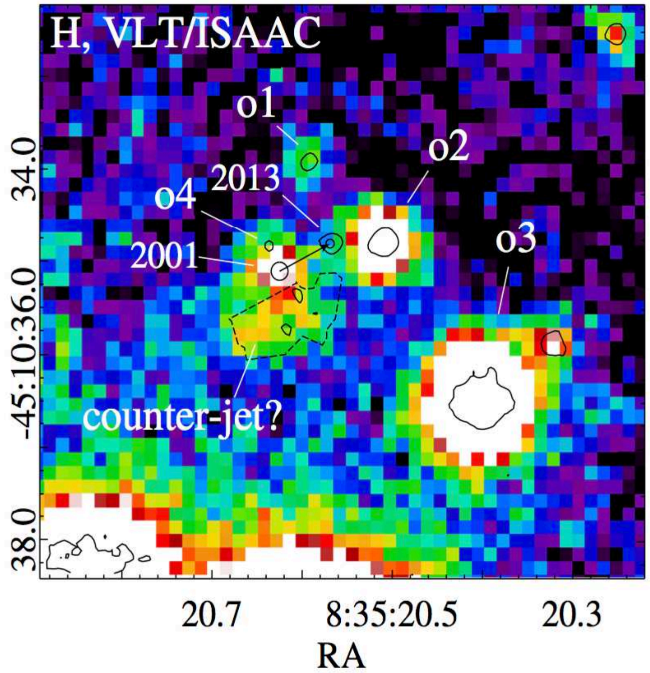
Filter = Ks
FWHM = 80mas
Exposure time = 1900s

## Pulsar



SV412 – R. Mennickent

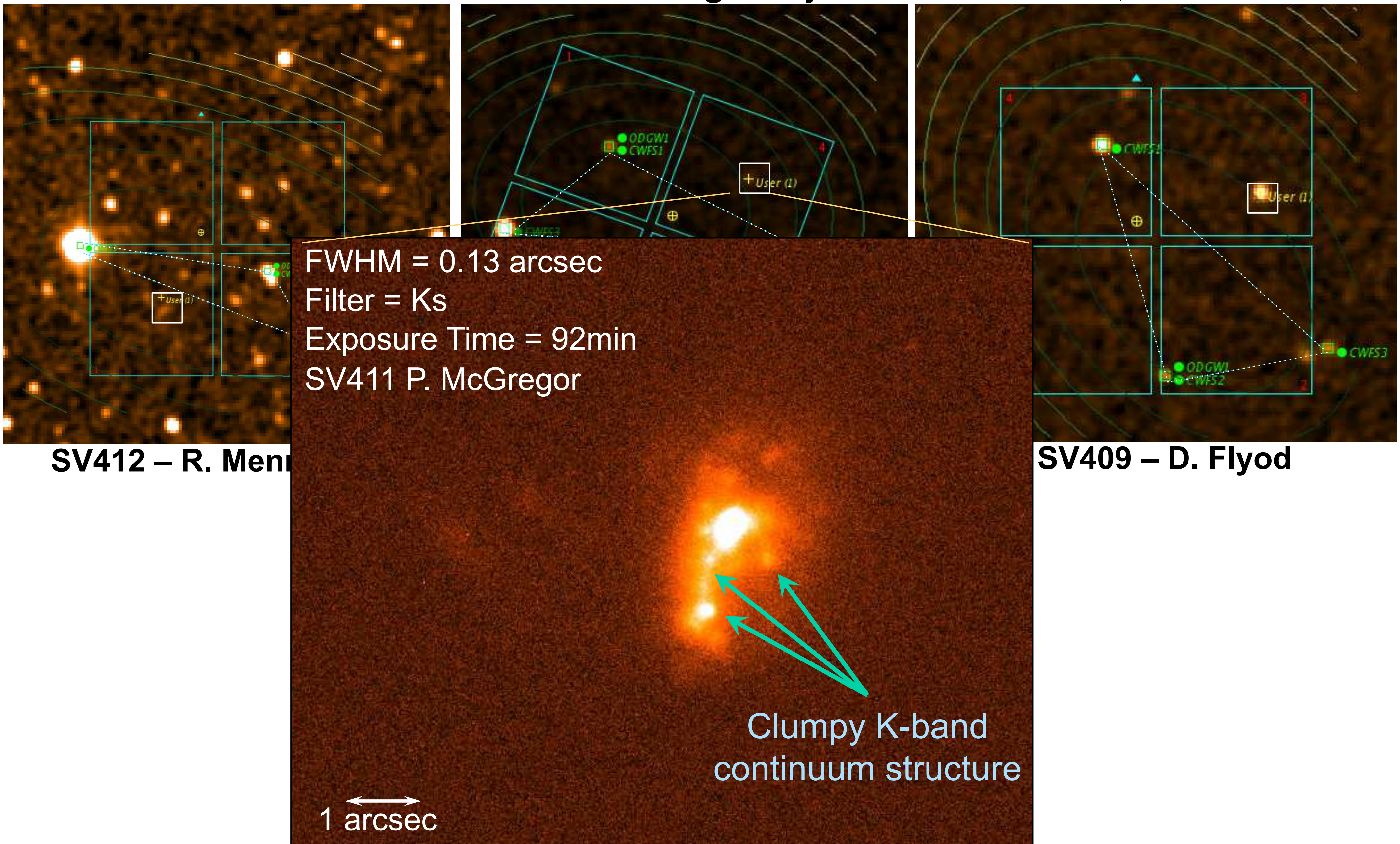



# The Vela pulsar and its likely counter-jet in the $K_s$ band *

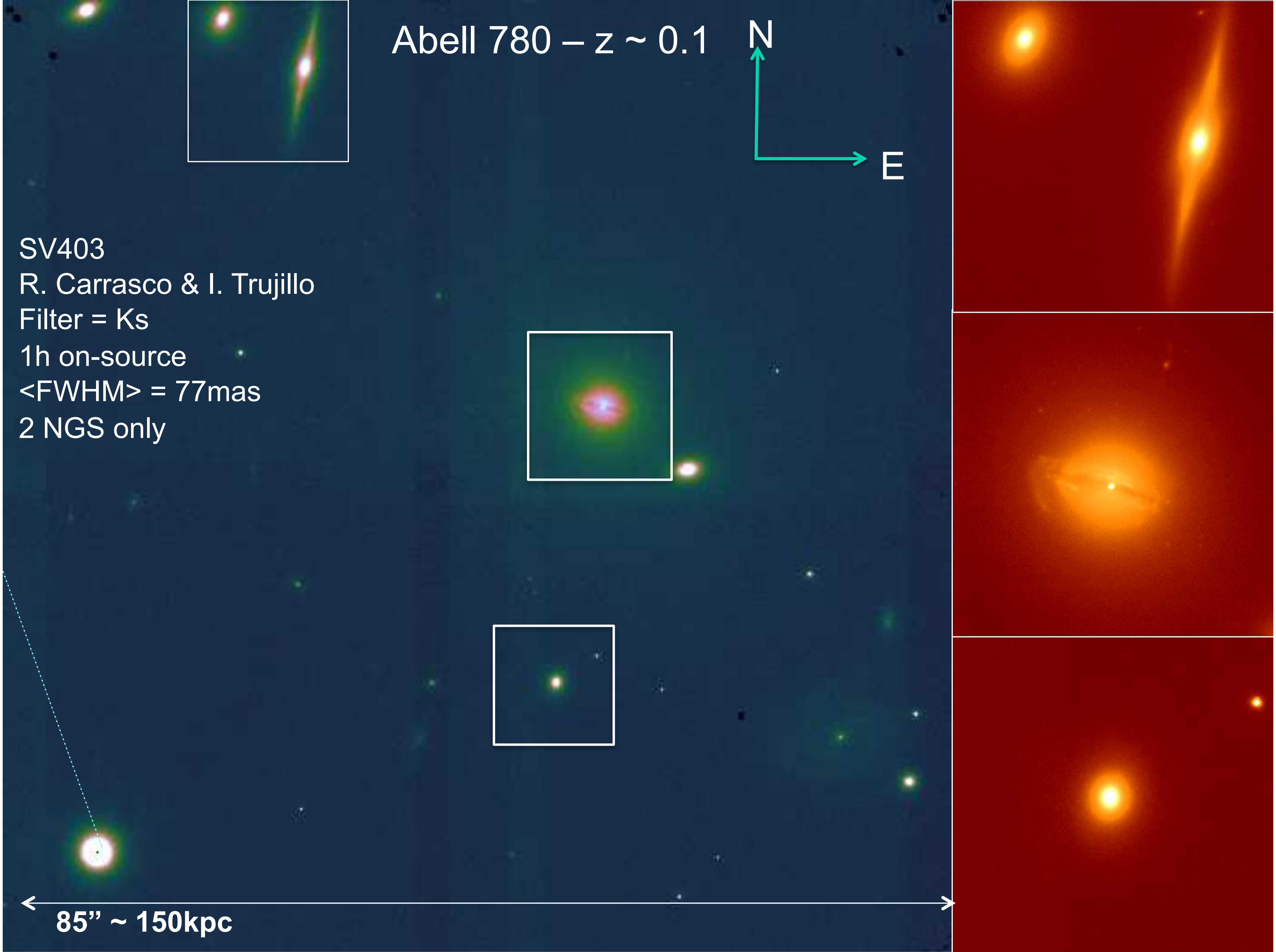
D. Zyuzin,[1]† Yu. Shibanov,[1,2] R. E. Mennickent,[3] A. Danilenko[1] and S. Zharikov[4]
[1] *Ioffe Physical Technical Institute, Politekhnicheskaya 26, St. Petersburg, 194021, Russia*
[2] *St. Petersburg State Polytechnical Univ., Politekhnicheskaya 29, St. Petersburg, 195251, Russia*
[4] *Department of Astronomy, Universidad de Concepcion, Casilla 160-C, Concepcion, Chile*
[4] *Observatorio Astronómico Nacional SPM, Instituto de Astronomía, UNAM, Ensenada, BC, Mexico*

Pulsar | Isolated galaxy | Quasar




**SV412 – R. Menn**

**SV409 – D. Flyod**


Abell 780 – z ~ 0.1
N
E
SV403
R. Carrasco & I. Trujillo
Filter = Ks
1h on-source
<FWHM> = 77mas
2 NGS only
85" ~ 150kpc

# New challenges for WFAO

Current WFAO science instruments:

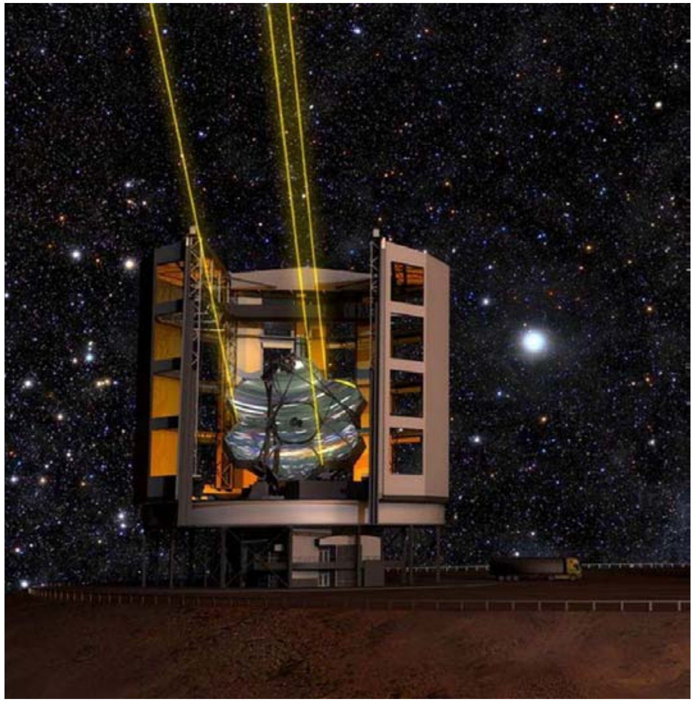
**SOAR Adaptive Module**

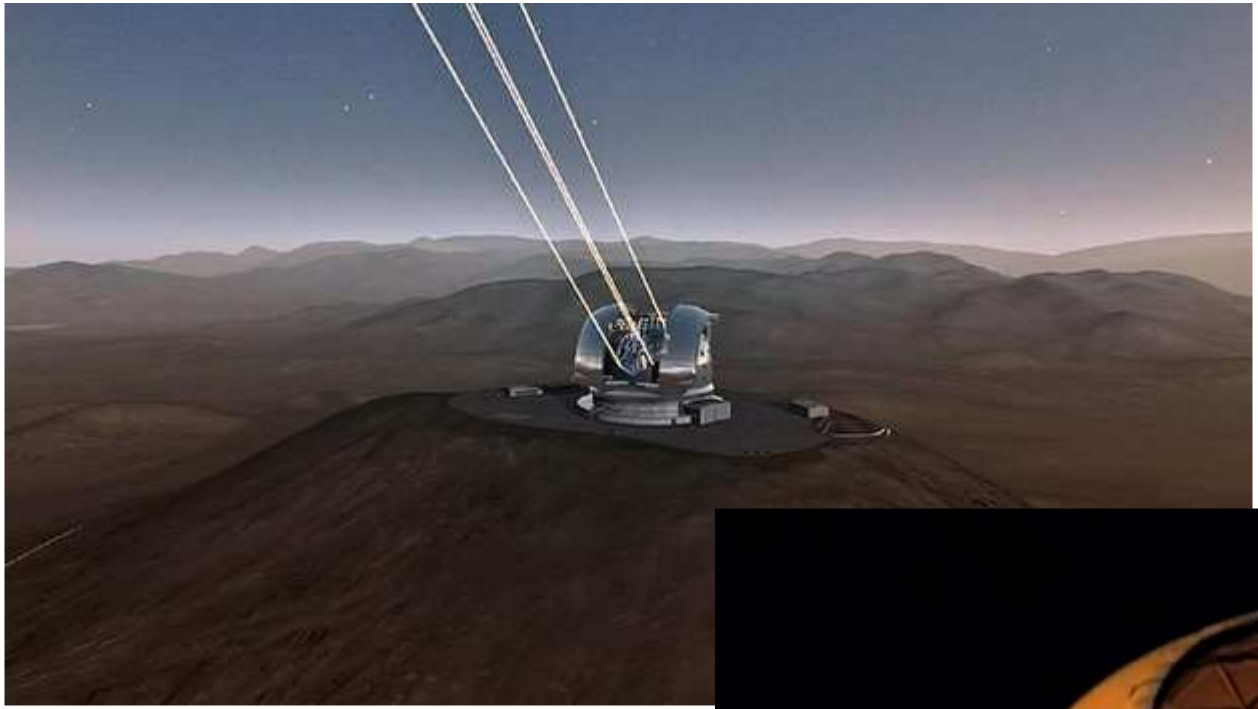
Current WFAO demonstrators:

Near future WFAO science instruments:

AO Facility
2015

All the ELTs are based on multi-LGS WFAO systems





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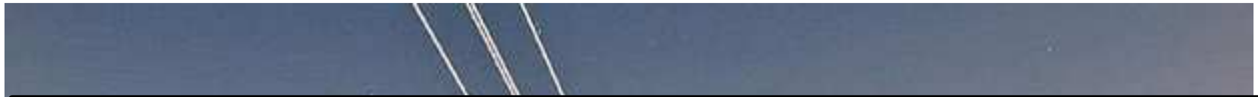


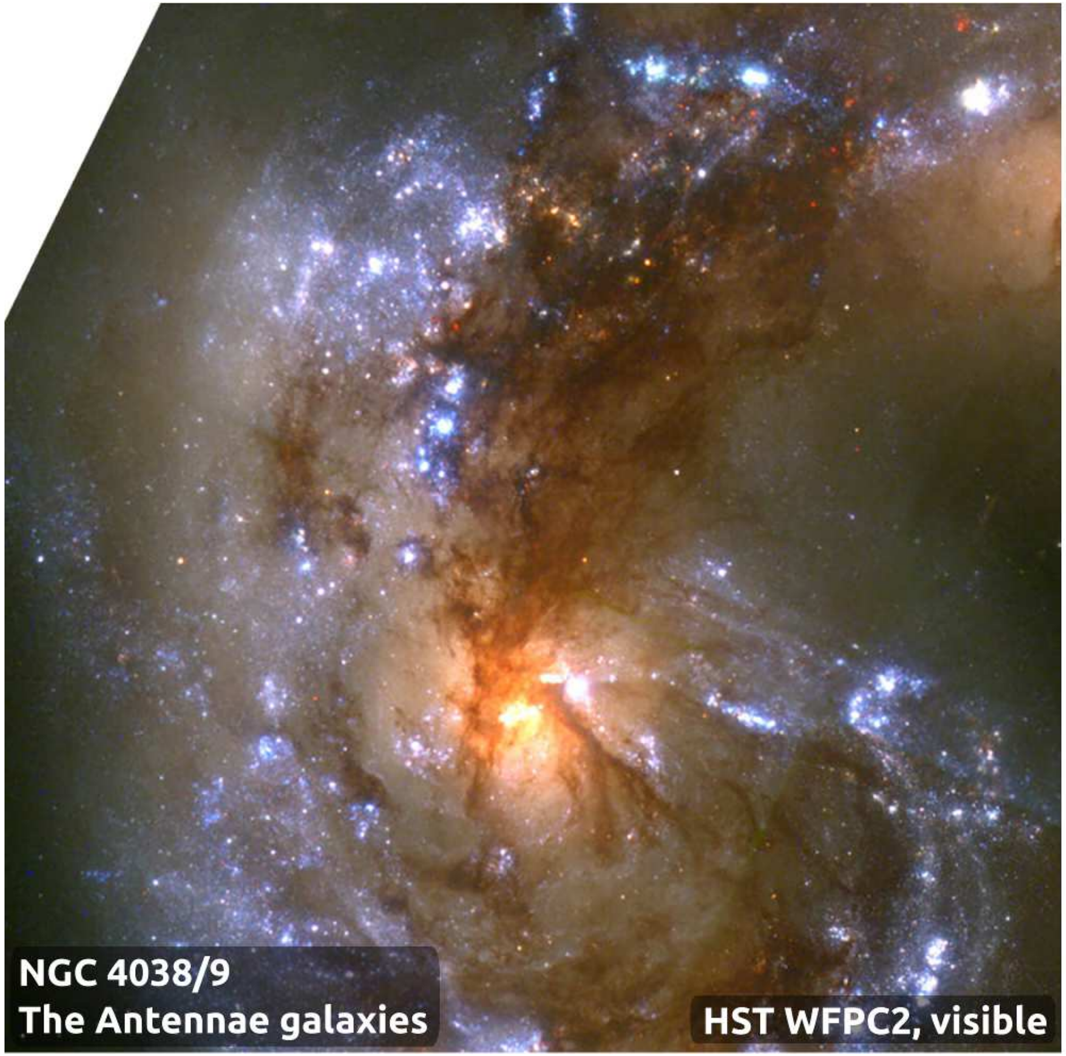
Slide from Norbert Hubin (head of ESO AO group), conference AO4ELT 2013

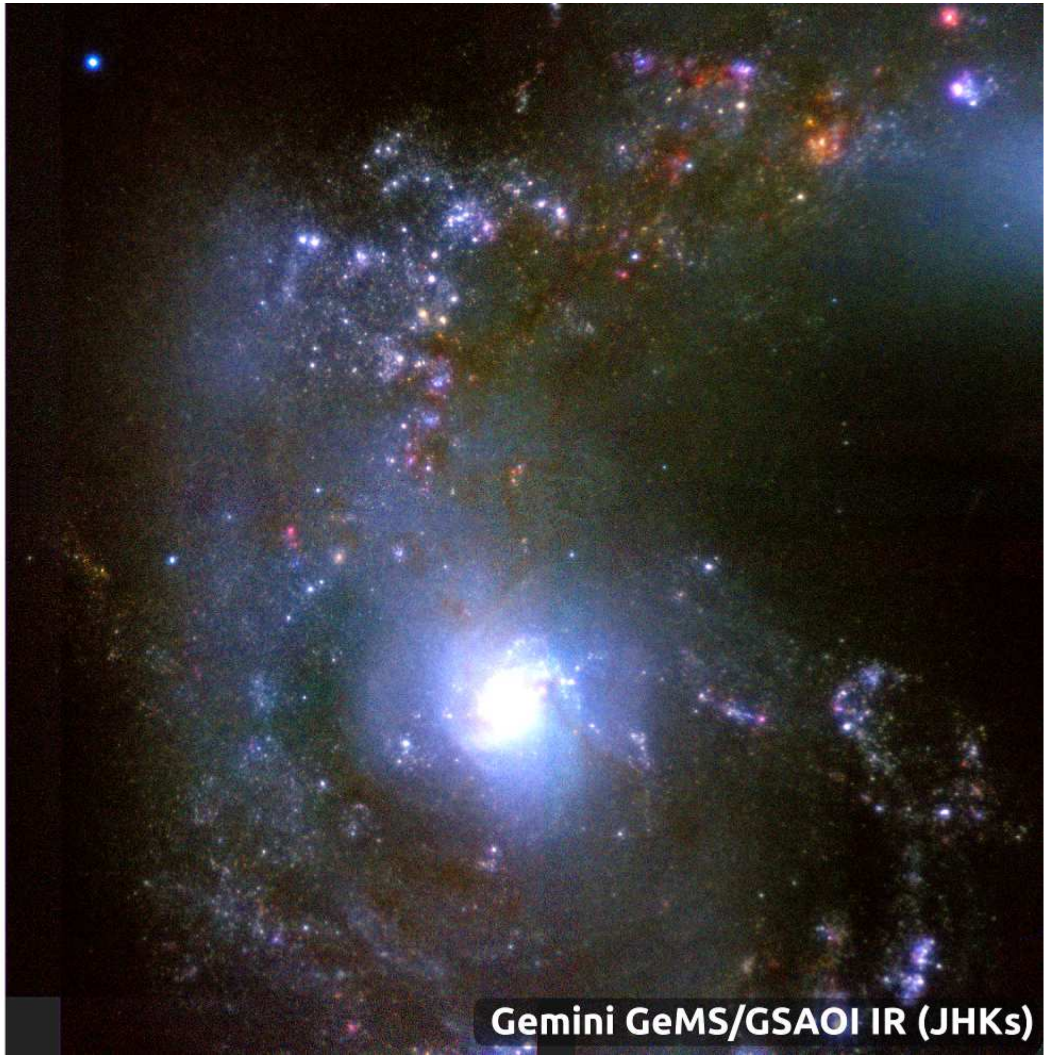
## Global vision & walking before running

- All AO systems for E-ELT are challenging & costly:
  - Many new concepts are still in demonstration phase or have not been fully operated on smaller telescopes for science ➔ **Pathfinders**
  - Technologies required are often one step behind ➔ **Dev. needed**
  - Operation, Control & calibration strategies are still being figured out ➔ crucial effective operation of AO system for science ➔ **Pathfinders**

# Conclusions

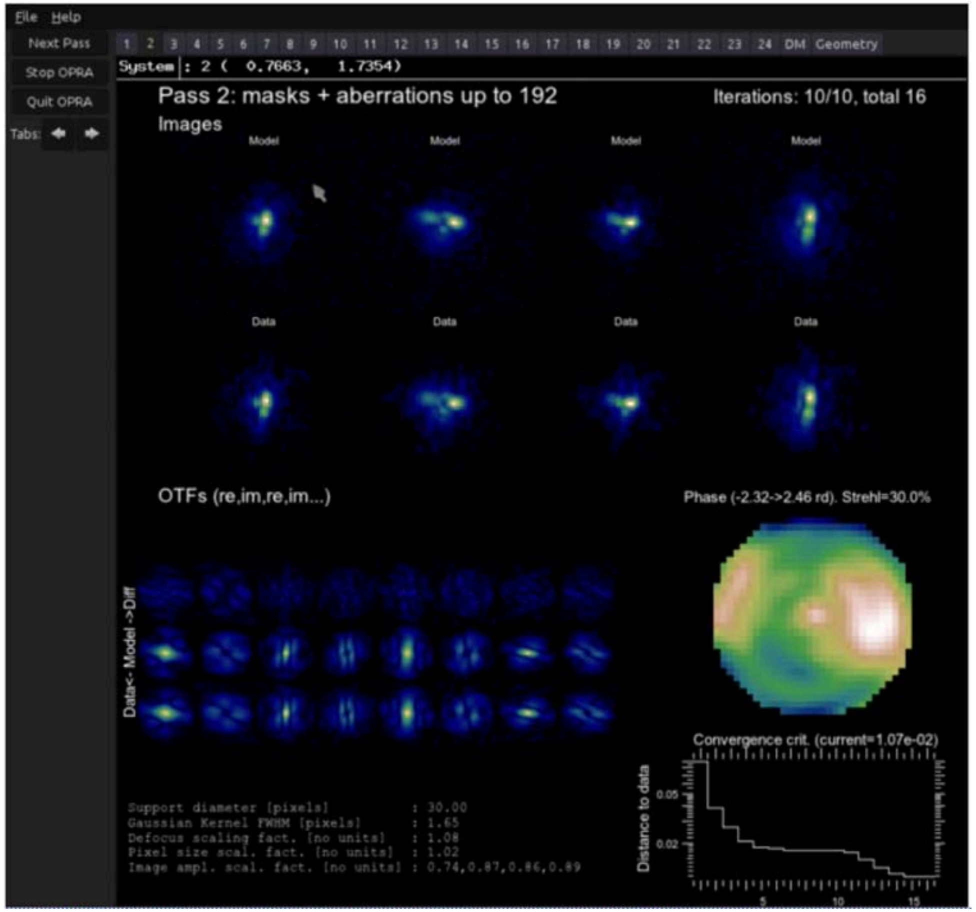
WFAO is opening new opportunities for a large range of science cases

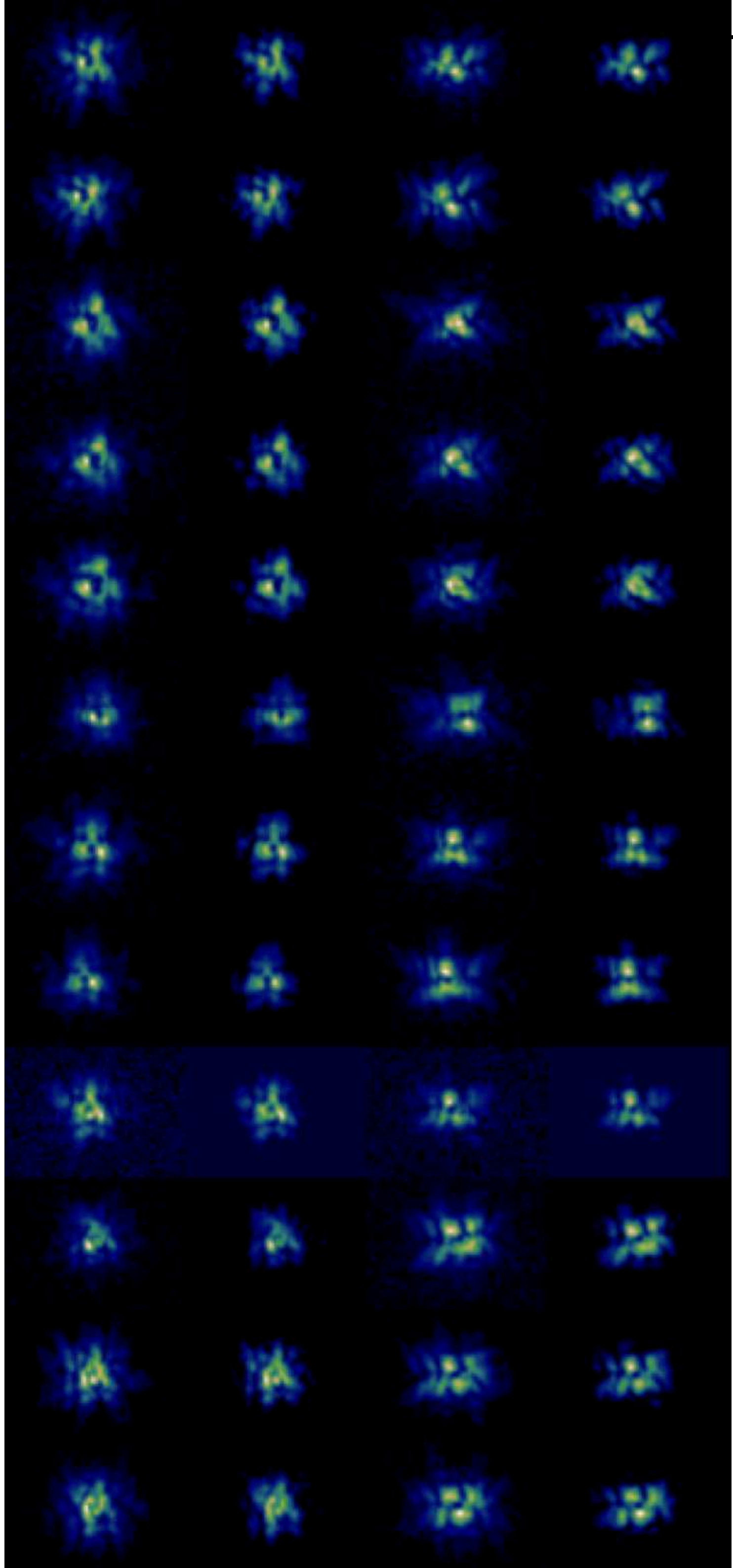


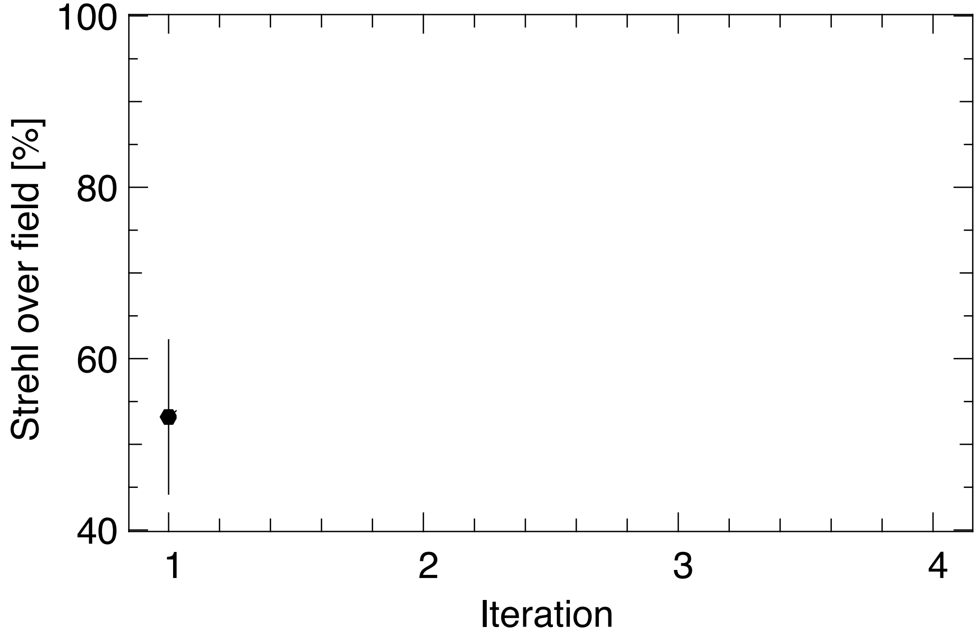



## Tomographic phase diversity:

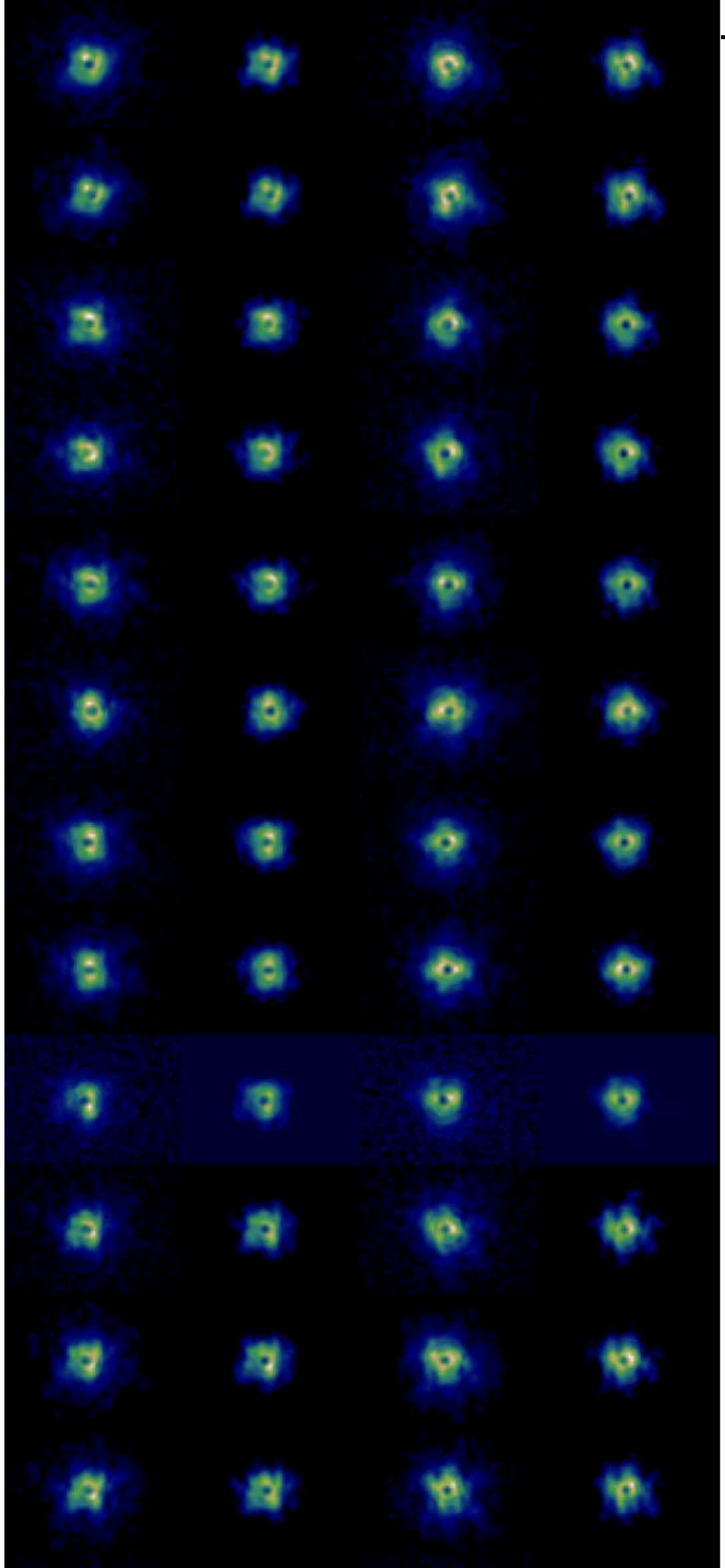
- The classical PD approach can be extended to process data over an extended field of view.
- Instead of solving for a 2D phase, solve for a 3D phase (discrete or continuous). E.g 2-3 phase planes + a tomographic projector
- Naturally more overconstrained/robust than PD in individual direction + tomographic reconstruction (assuming # of field positions/images is larger than the # of phase planes).

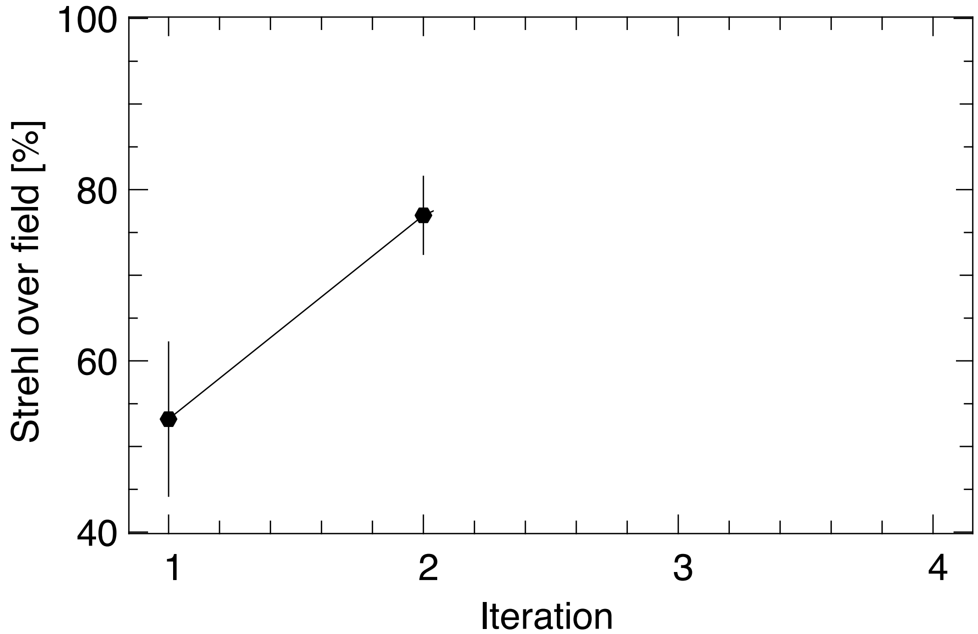






100
80
60
40
Strehl over field [%]
1
2
3
4
Iteration





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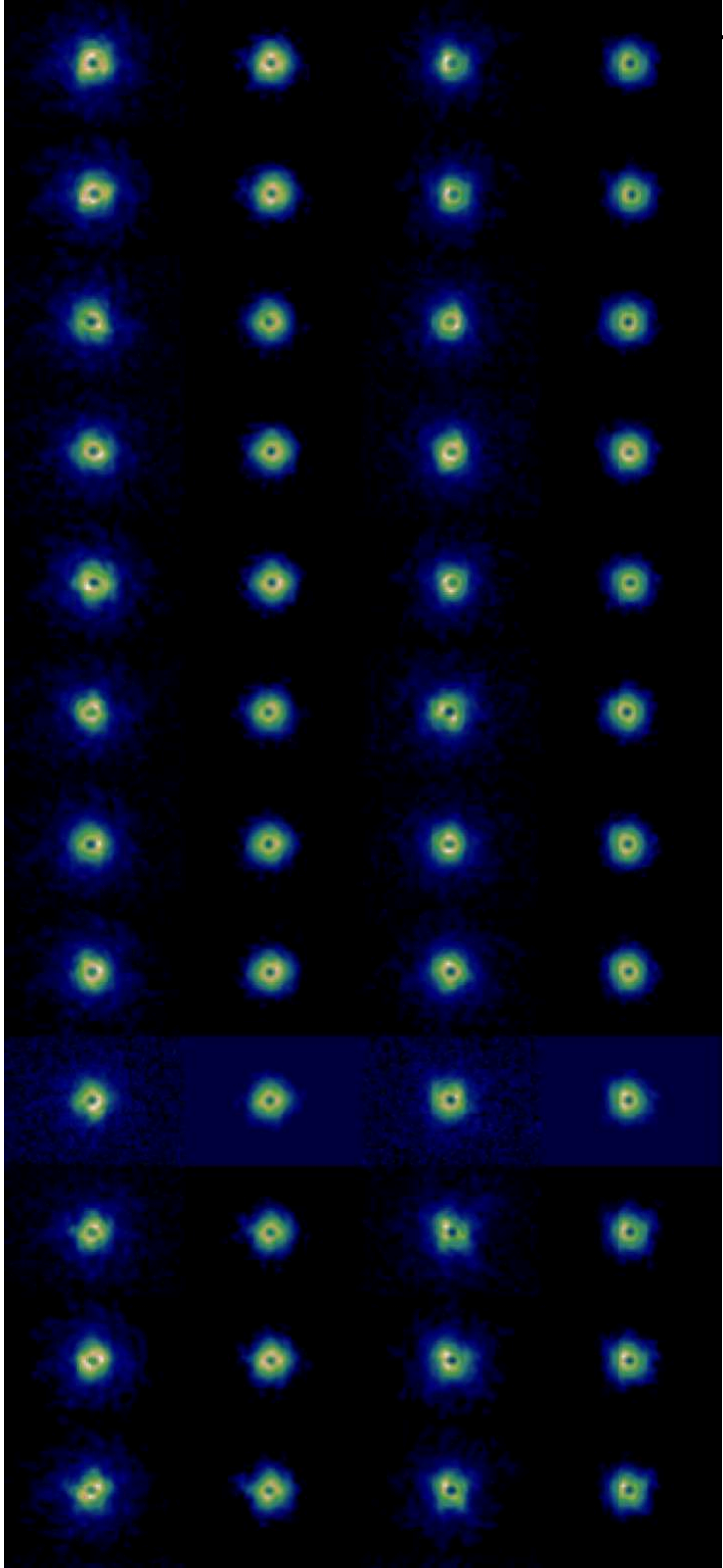
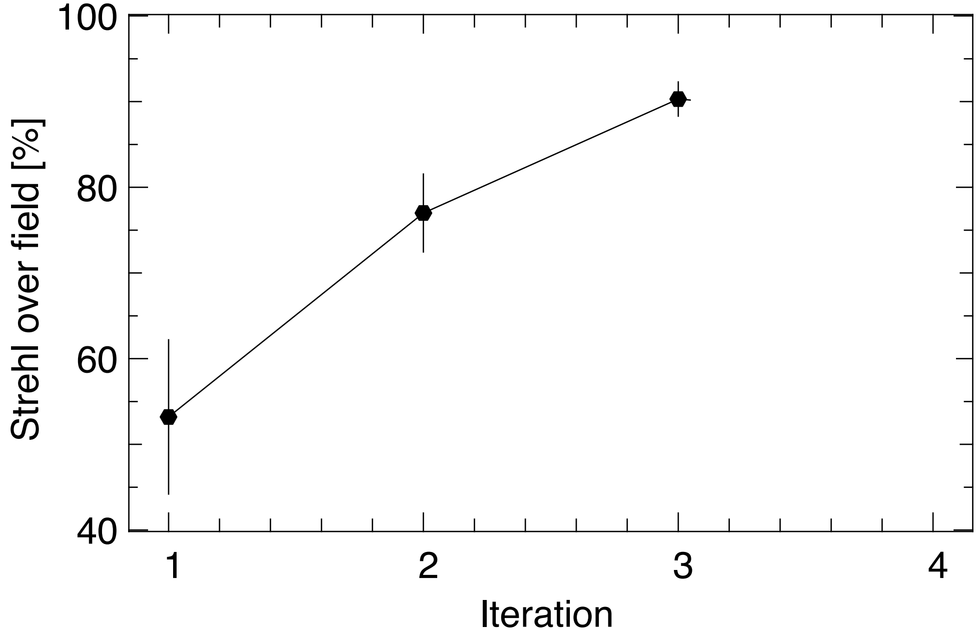
Strehl over field [%]
Iteration





100
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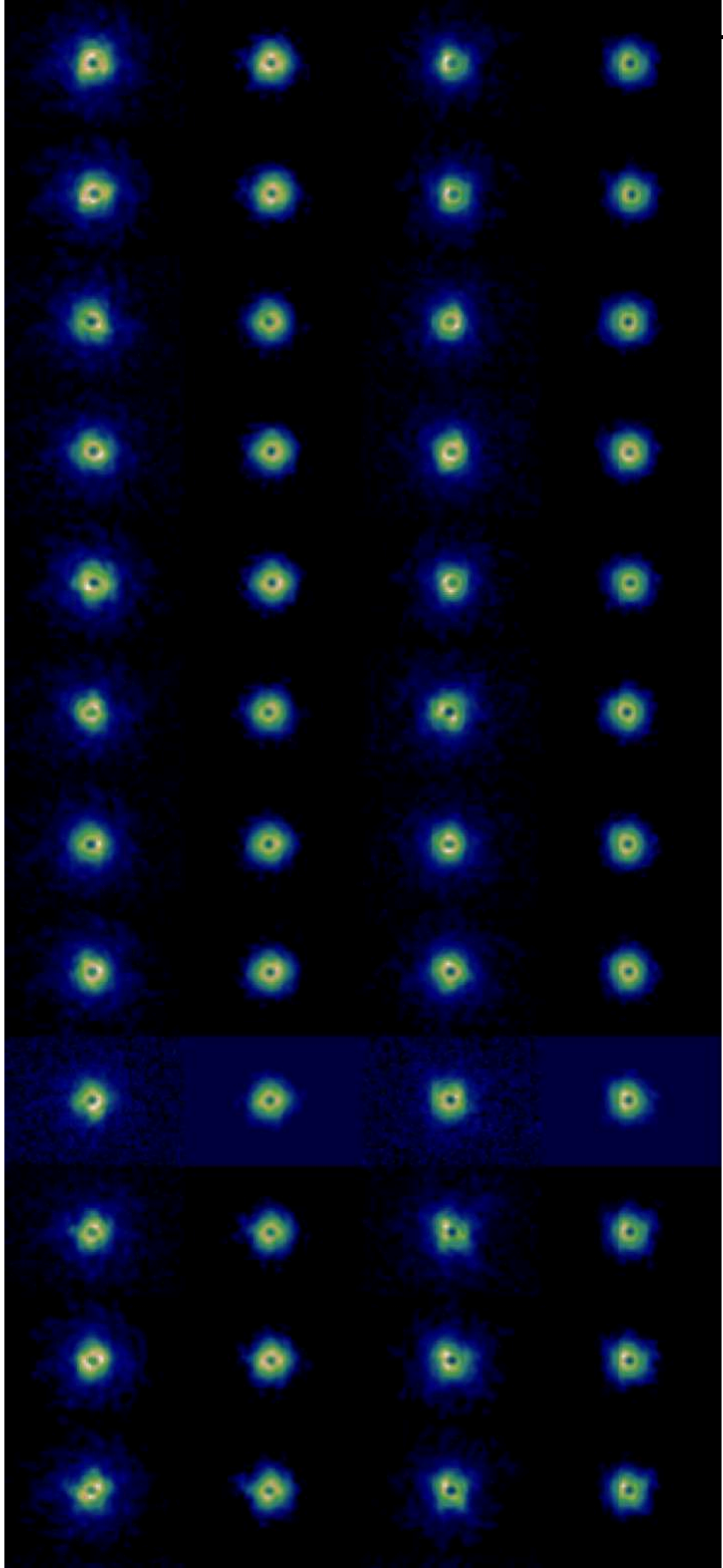

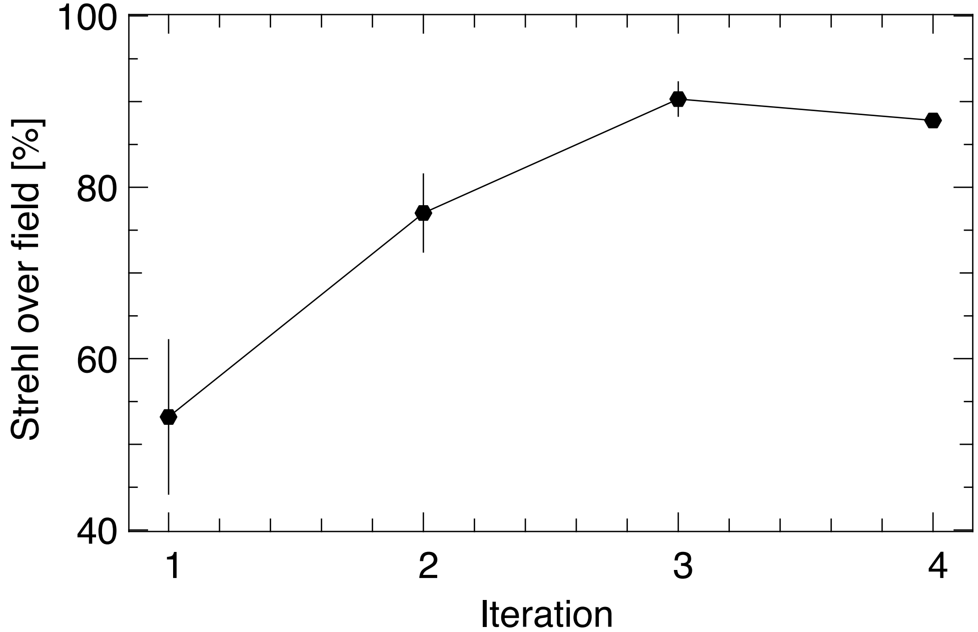

100
80
60
40
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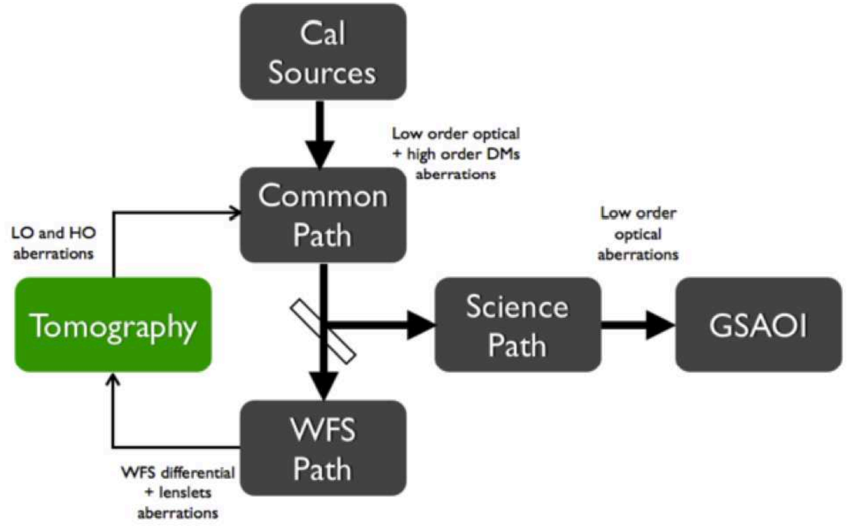
3
4
Iteration




(NCPA optimizes the wave-front in the science beam, but may degrade it severely in the NGSWFS path ! )

( NCPA issues for wide-field AO systems: Impossibility to compensate for anything that's not close to a DM conjugation altitude ! )

## Wind profiler method (Wang et al. 2008)

Time-delayed cross correlation between two wave front sensors, $WFS_A$ and $WFS_B$, is :

$$T^{AB}(\Delta u, \Delta v, \Delta t) = \frac{\left\langle \sum_{u,v} S^A_{u,v}(t) \cdot S^B_{u+\Delta u, v+\Delta v}(t+\Delta t) \right\rangle}{O(\Delta u, \Delta v)}$$

$S^{WFS}_{u,v}(t)$ : X and Y slopes of the WFS in subaperture (*u,v*) at time *t*

$O(\Delta u, \Delta v)$ : overlapping illuminated subapertures for offset

$\Delta t$ : is a multiple of the acquisition time

Signal is retrieved by deconvolution $\mathrm{FT}^{-1}[\mathrm{FT}\,[T^{AB}]/\mathrm{FT}[A]]$

$$A(\Delta u, \Delta v) = \frac{1}{2} \frac{\left\langle \sum_{u,v} S^A_{u,v}(t) \cdot S^A_{u+\Delta u, v+\Delta v}(t) \right\rangle}{O(\Delta u, \Delta v)} + \frac{1}{2} \frac{\left\langle \sum_{u,v} S^B_{u,v}(t) \cdot S^B_{u+\Delta u, v+\Delta v}(t) \right\rangle}{O(\Delta u, \Delta v)}$$

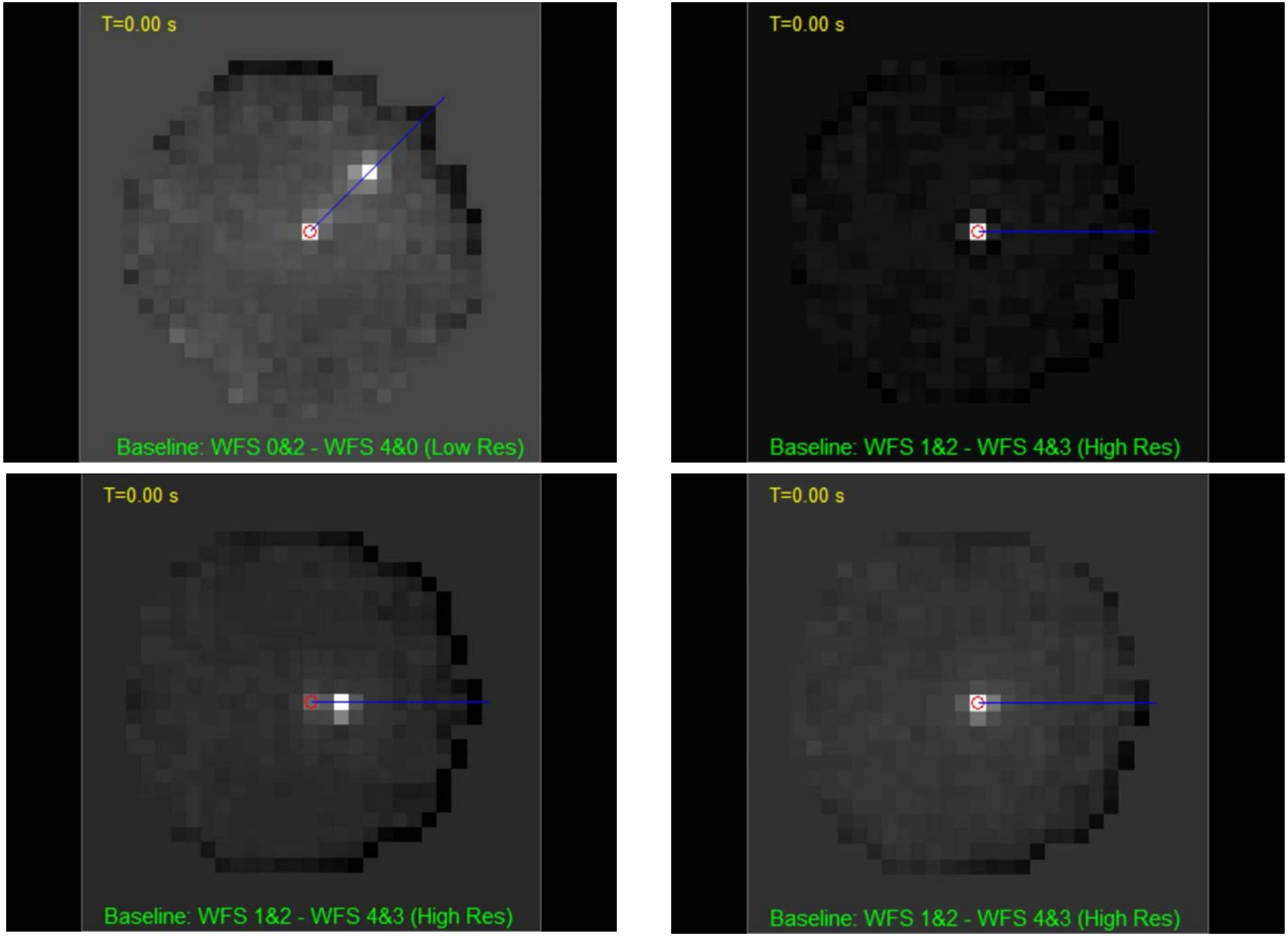
$A$ is the average of the autocorrelations of $WFS_A$ and $WFS_B$

[Cortes et al. – MNRAS – 2012]

# GeMS' wind profiler

For T = 0 s, the turbulence profile in altitude is extracted from the baseline

For T > 0, the layers present can be detected and their velocity estimated

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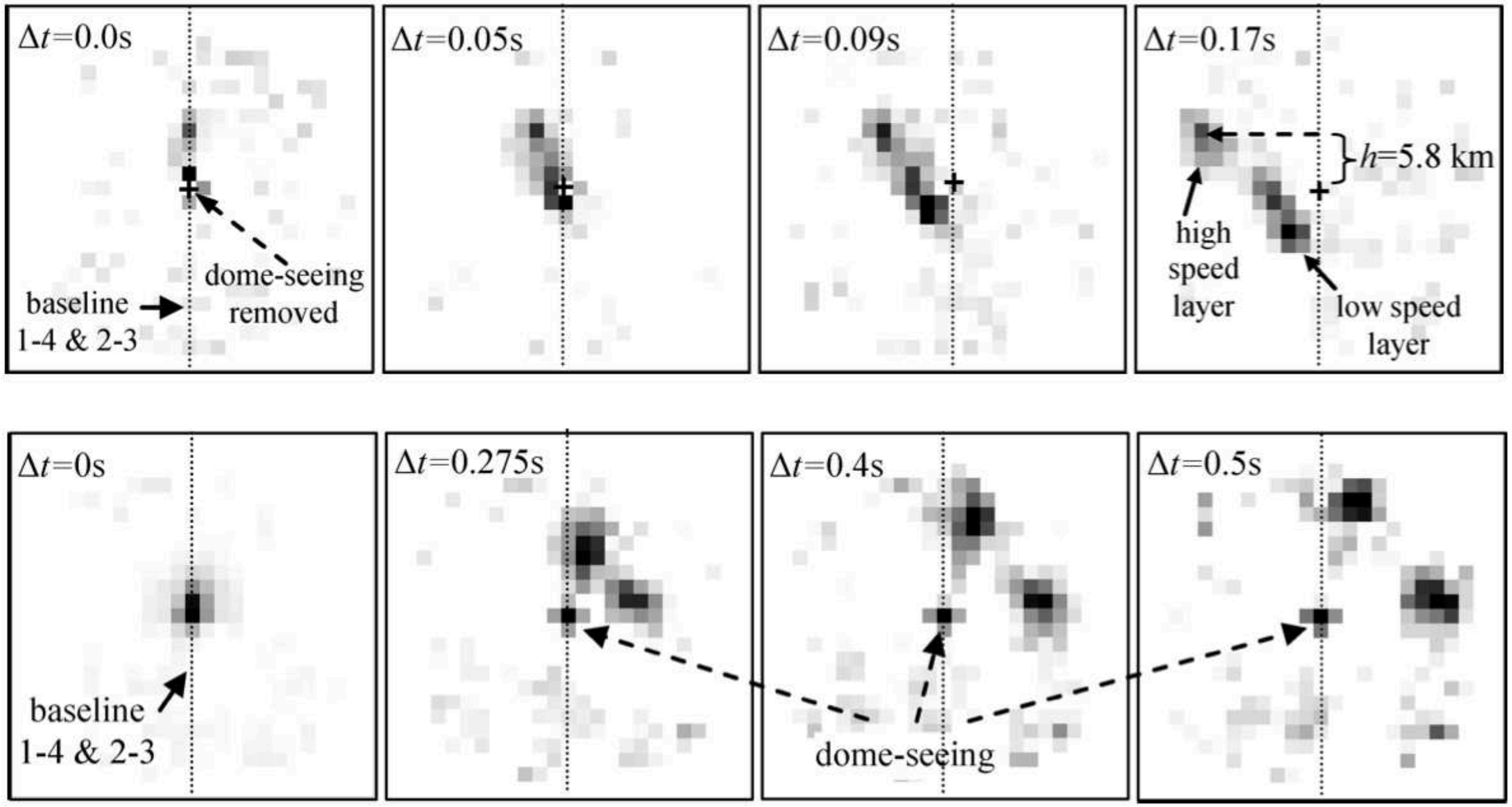
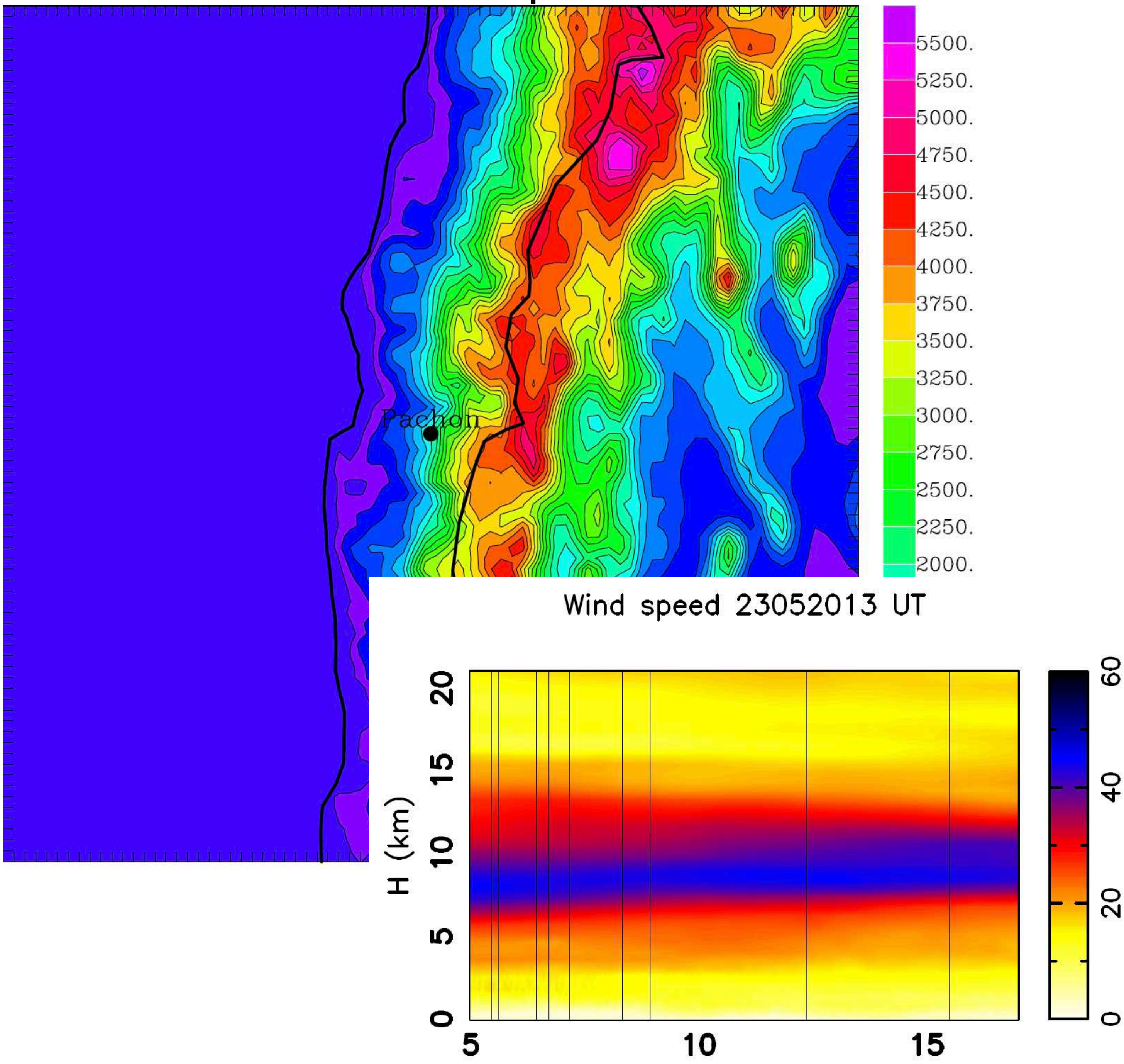
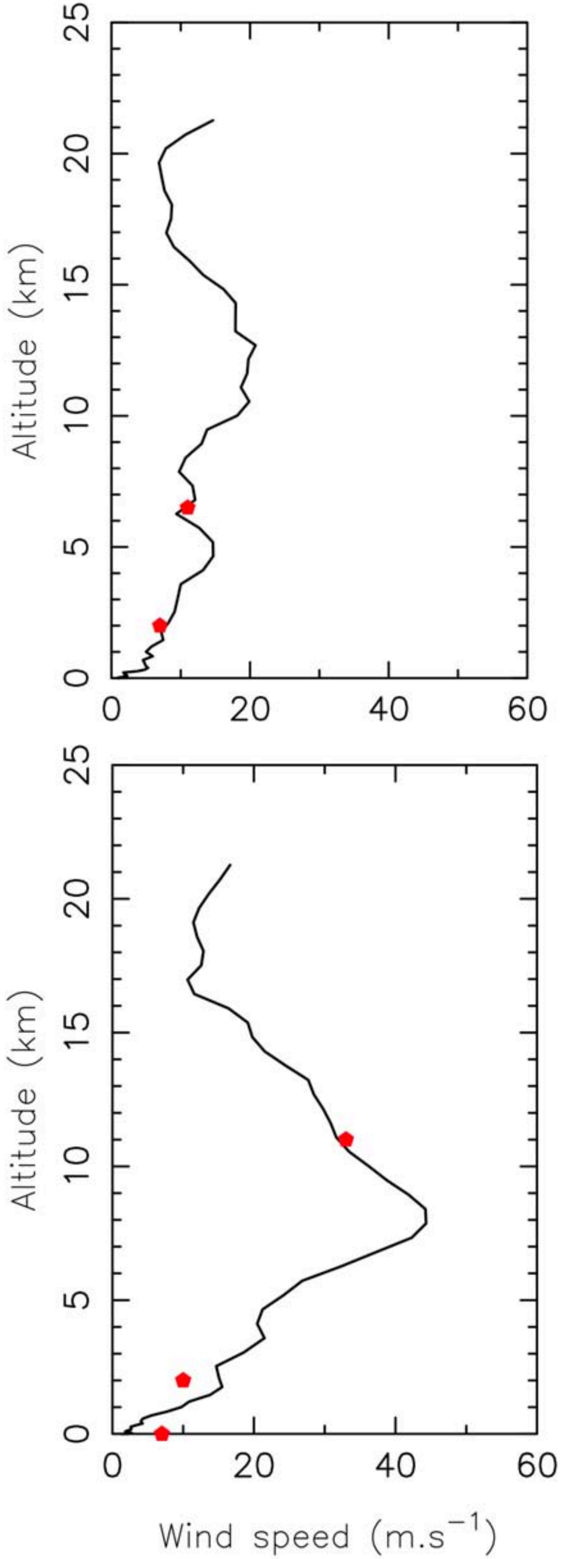



[Cortes et al. – MNRAS – 2012]

# GeMS' wind profiler

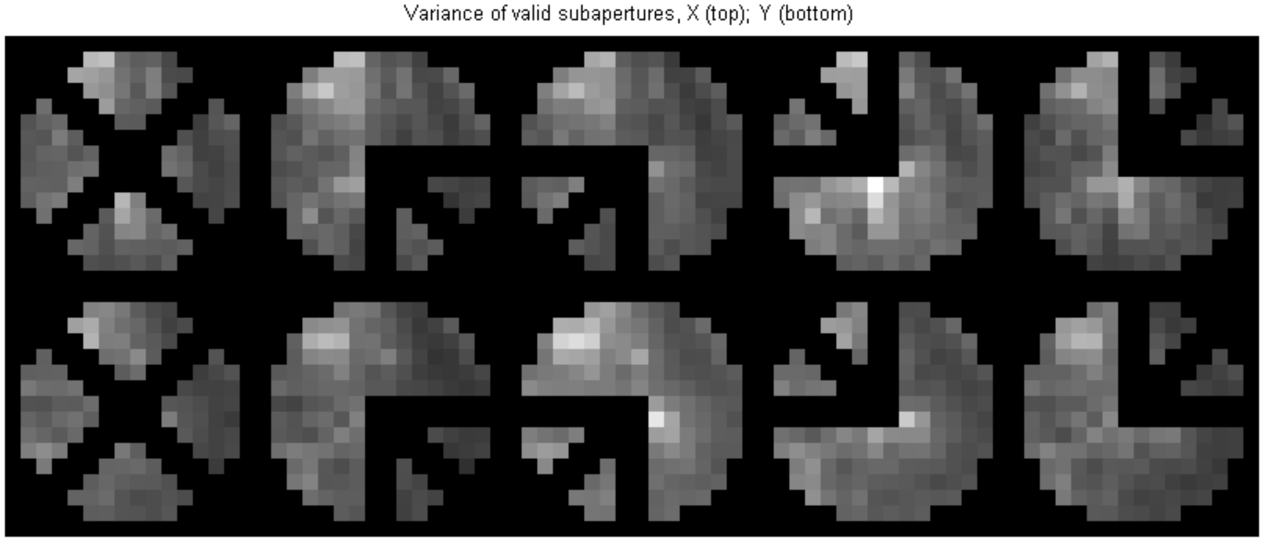
## Cross-Check with wind predictions

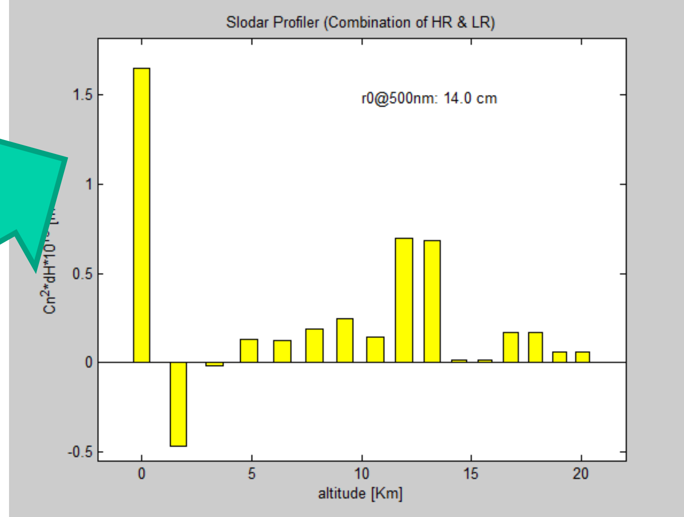


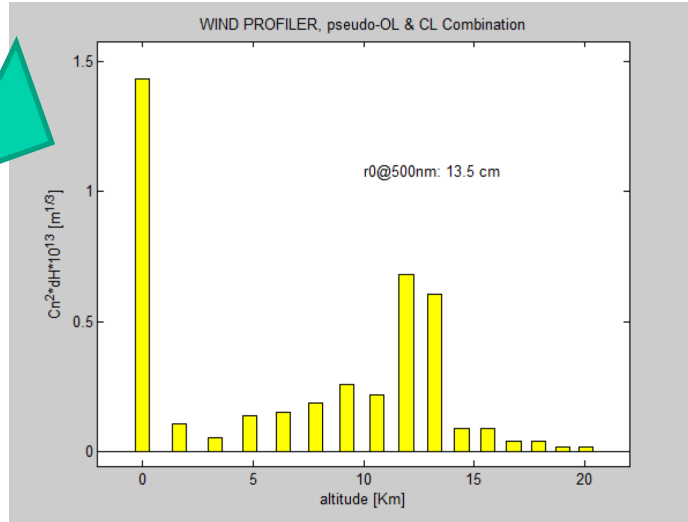



# GeMS' wind profiler

Wind profiler solves the "negative Cn2" issue



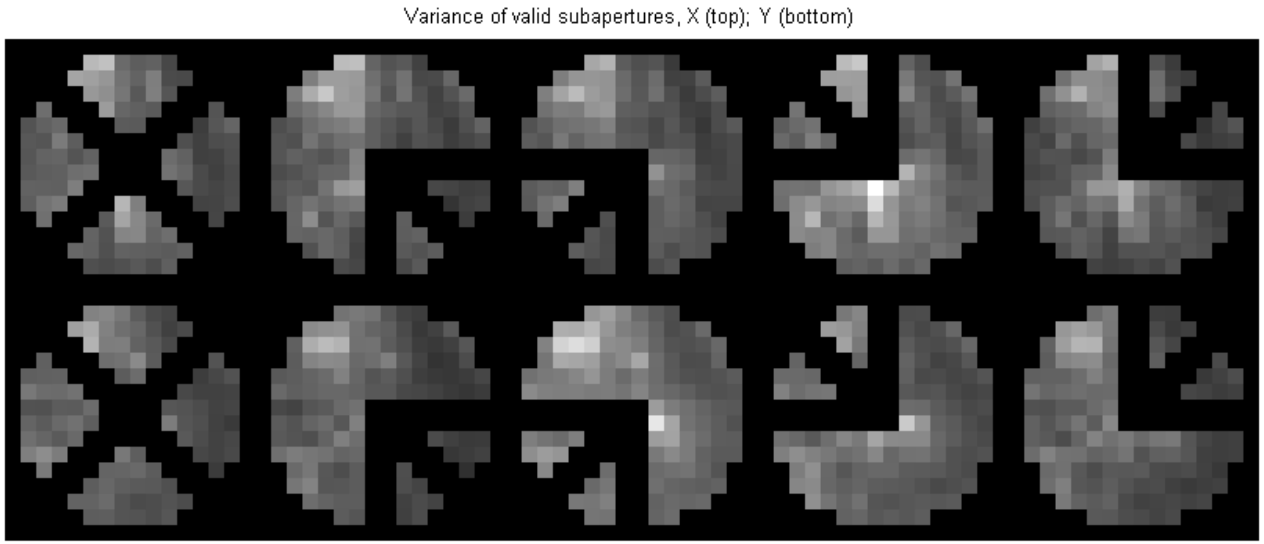



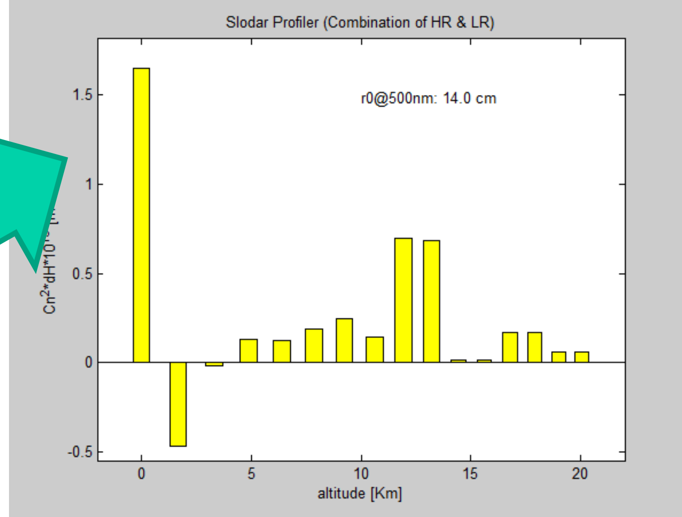



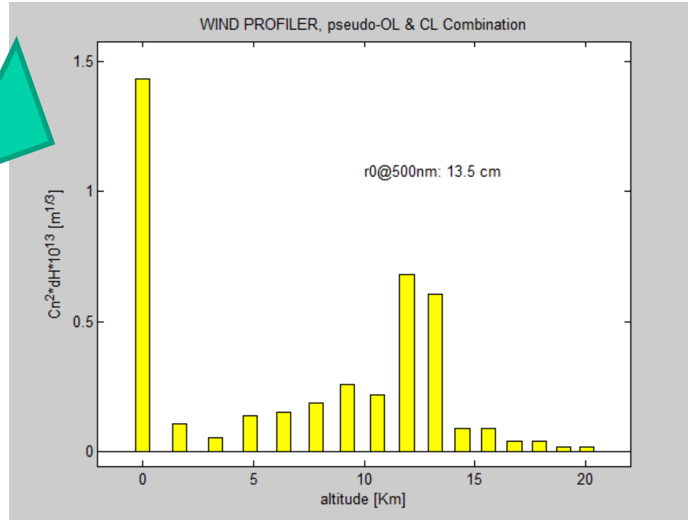

[Guesalaga et al. – MNRAS – 2014]

# GeMS' wind profiler

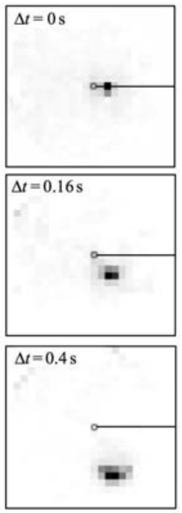
## Wind profiler solves the "negative Cn2" issue

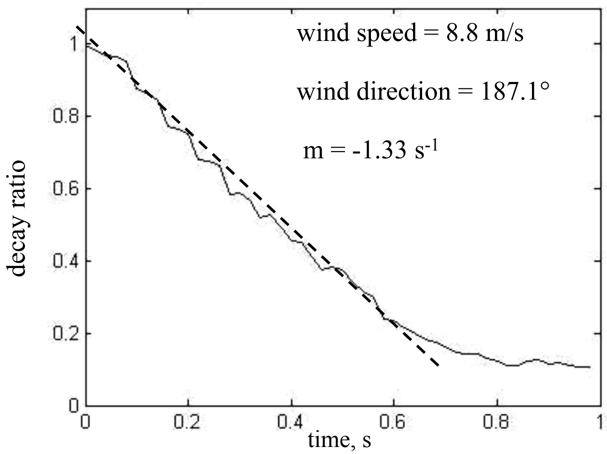


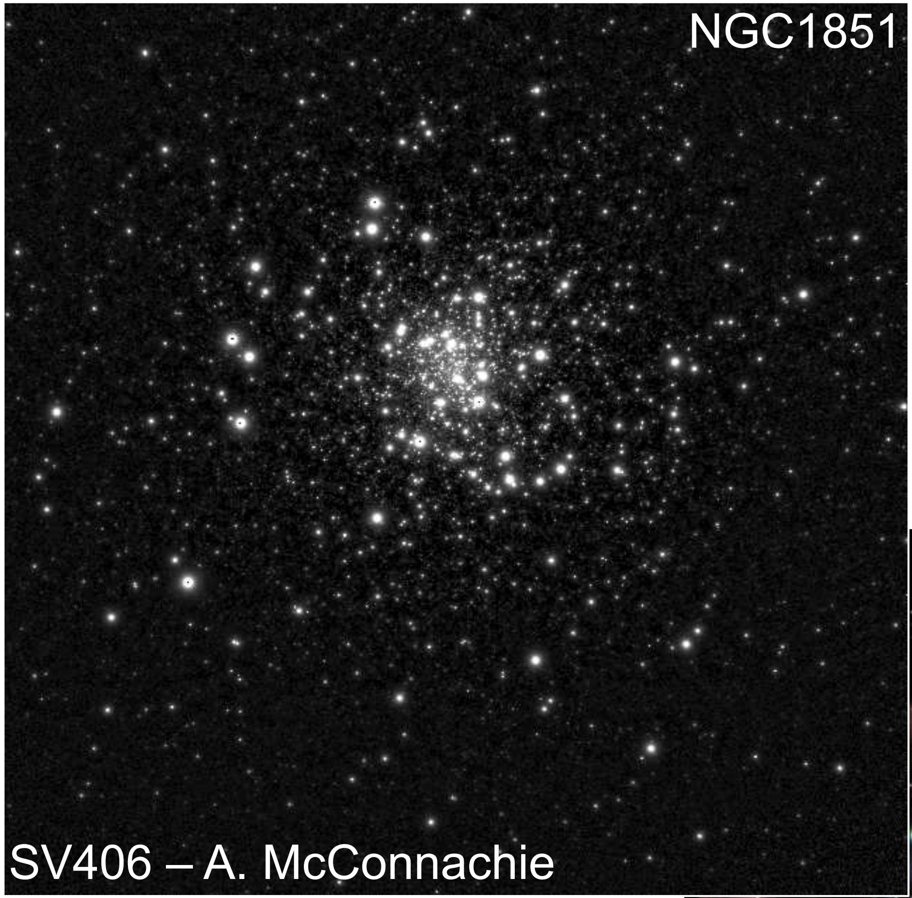

## Also allows to study the Frozen Flow hypothesis

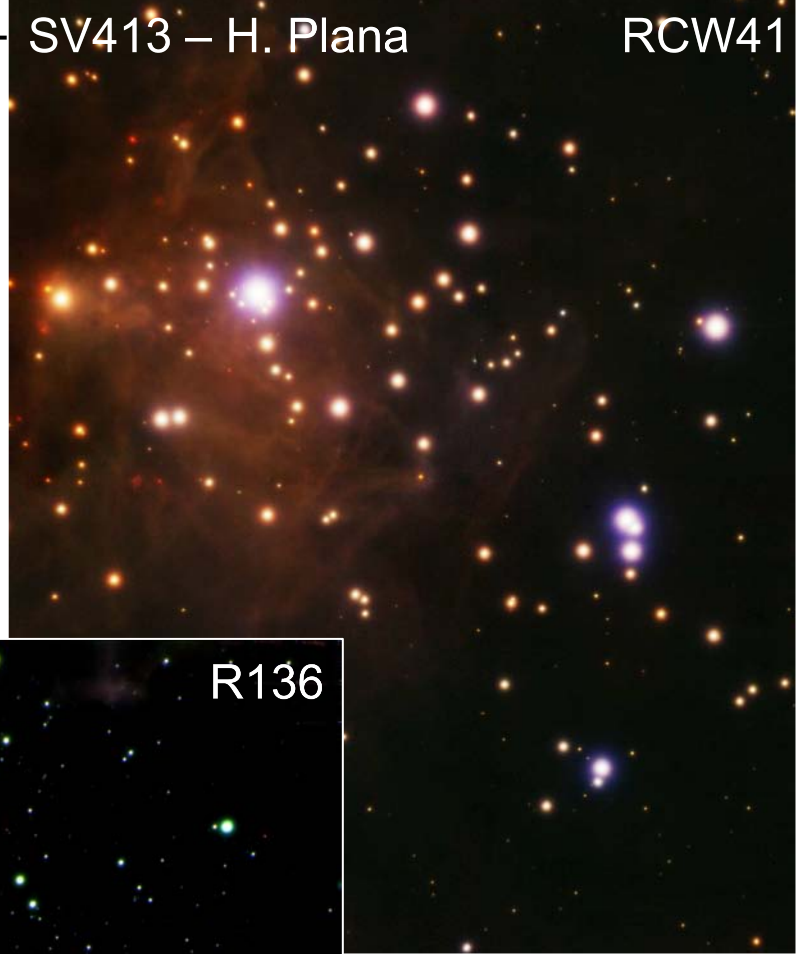


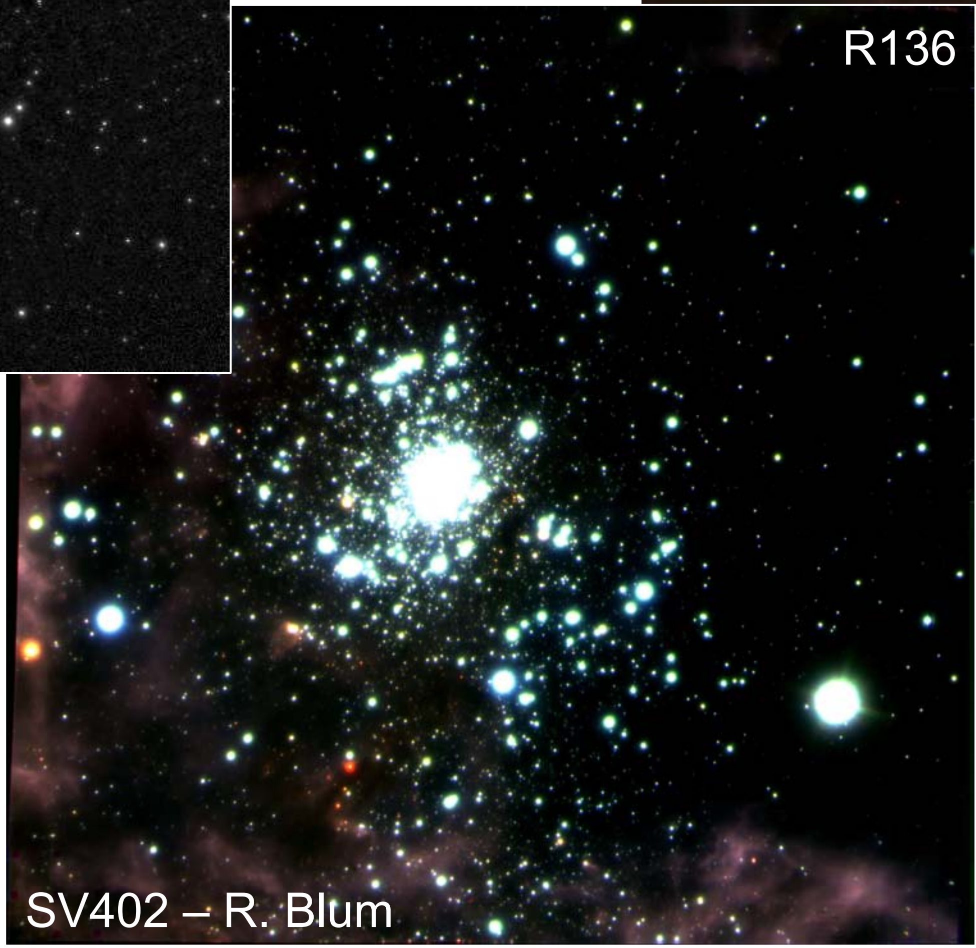




**[Guesalaga et al. – MNRAS – 2014]**

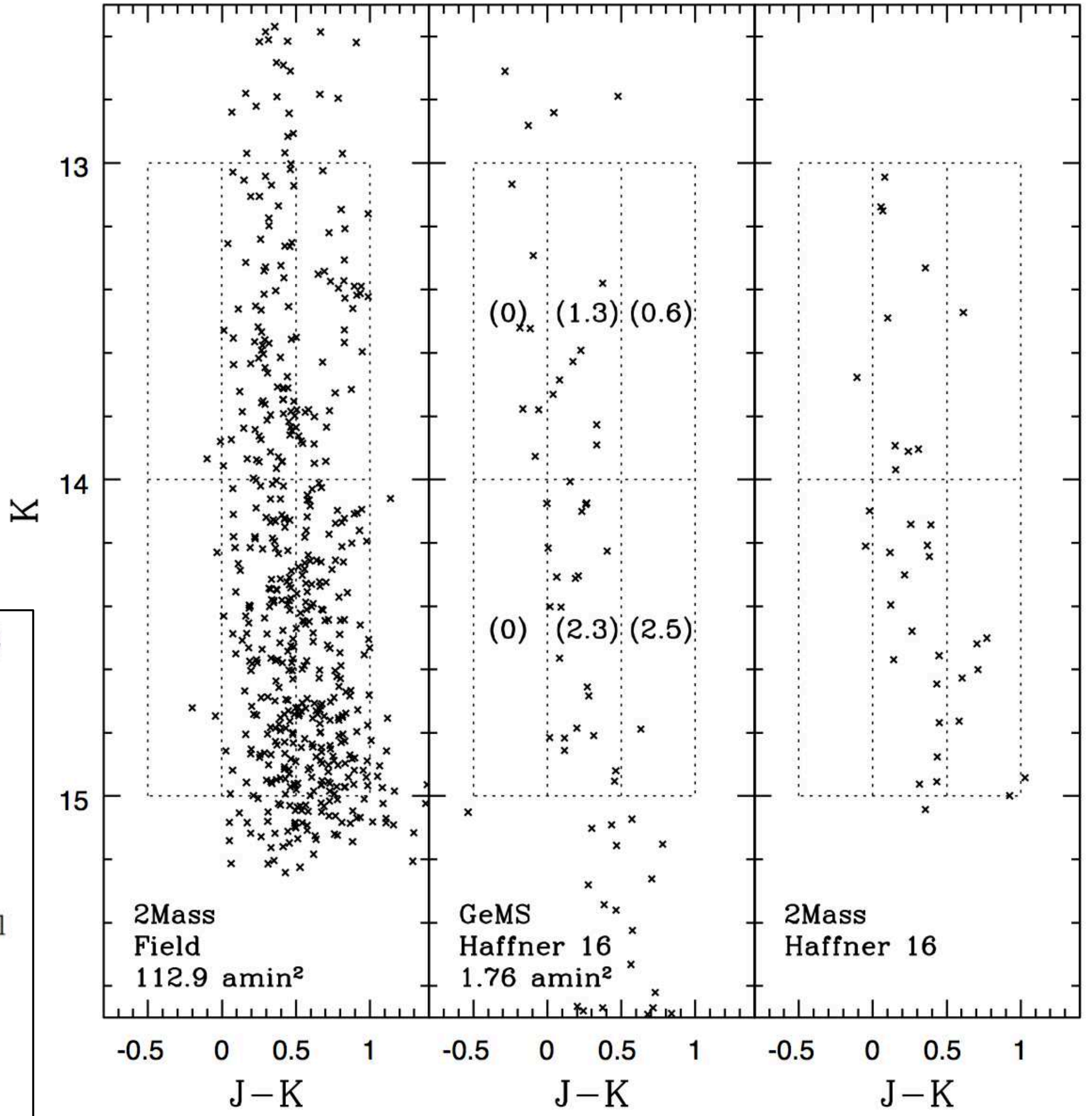
# Star Clusters



Low mass cluster
Age estimation based on PMS
~ 10Myr cluster




**HAFFNER 16: A YOUNG MOVING GROUP IN THE MAKING; Version 5.0; May 8, 2013**

T. J. Davidge

*Dominion Astrophysical Observatory, National Research Council of Canada, 5071 West Saanich Road, Victoria, BC Canada V9E 2E7*

Rodrigo Carrasco, Claudia Winge, Peter Pessev, Benoit Neichel, Fabrice Vidal

*Gemini Observatory, La Serena, Chile*

Francois Rigaut

*Australian National University*

## Why MCAO is good for astrometry ?

- Active control of plate scales
- Large FoV => more reference stars
- PSFs are uniform over the field

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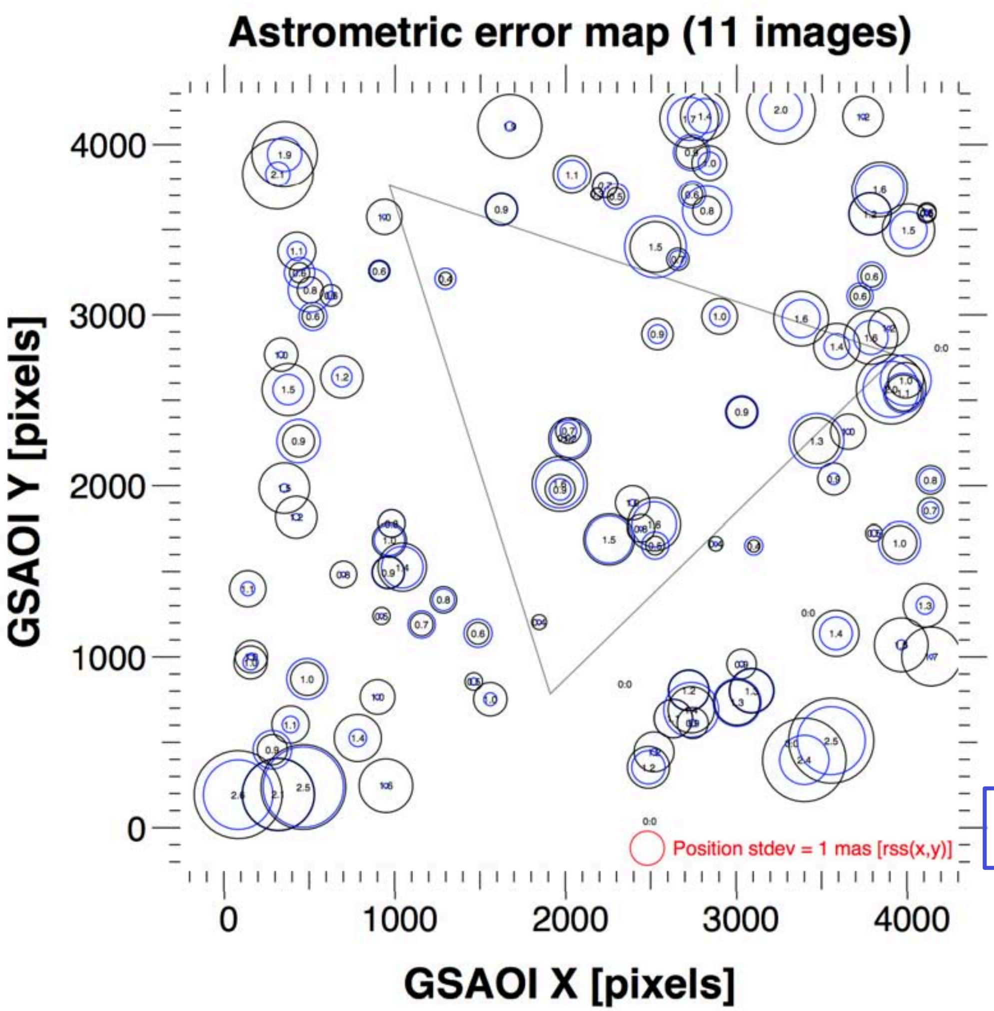
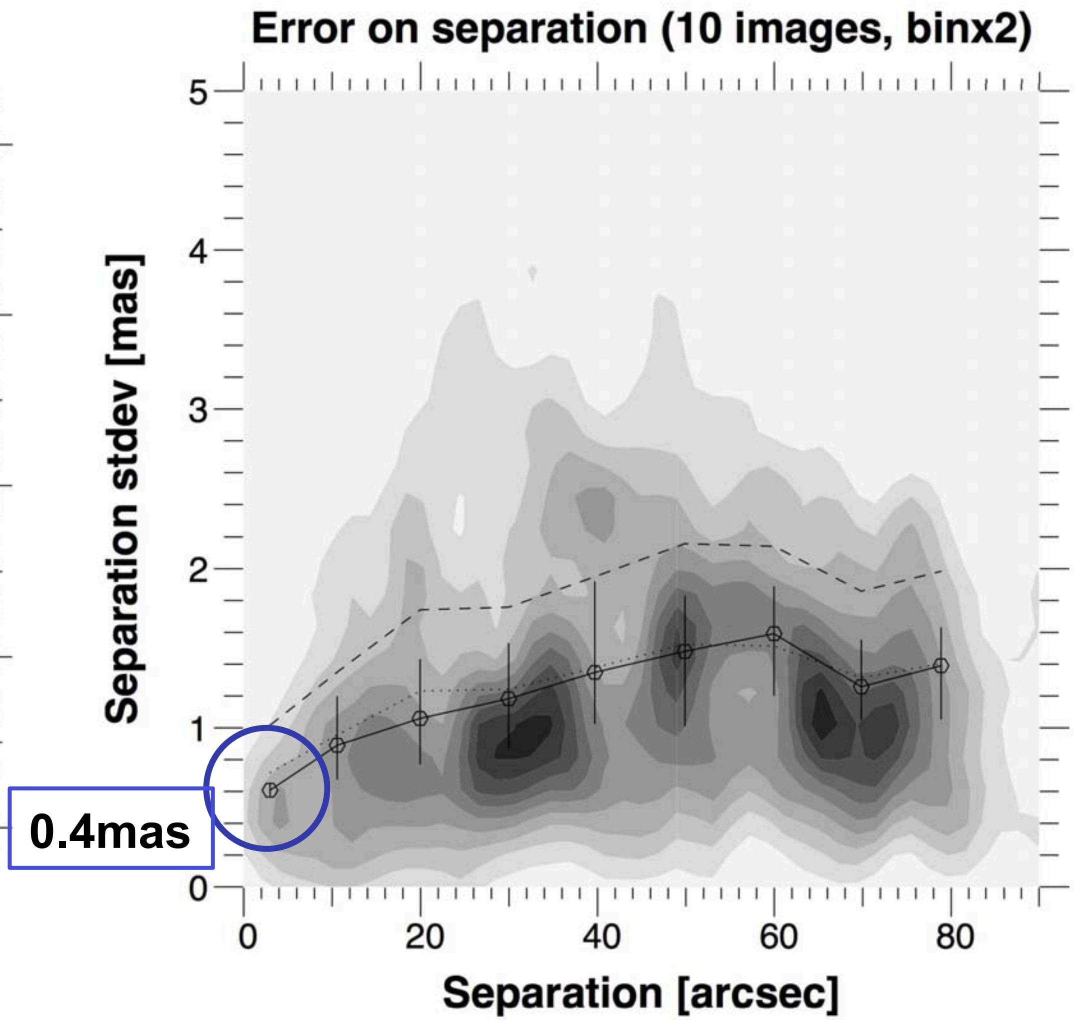
Rigaut, Neichel et al. 2012



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- Active control of plate scales
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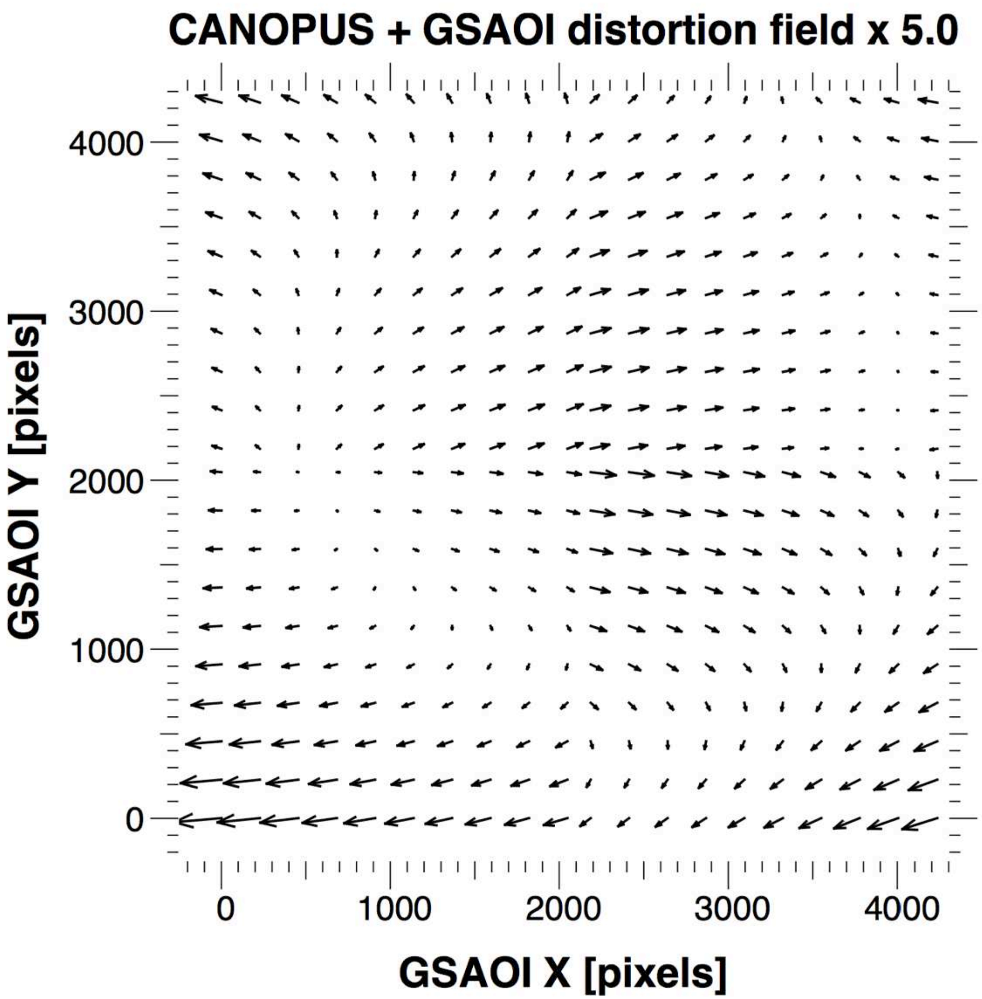
## But astrometry is challenging:

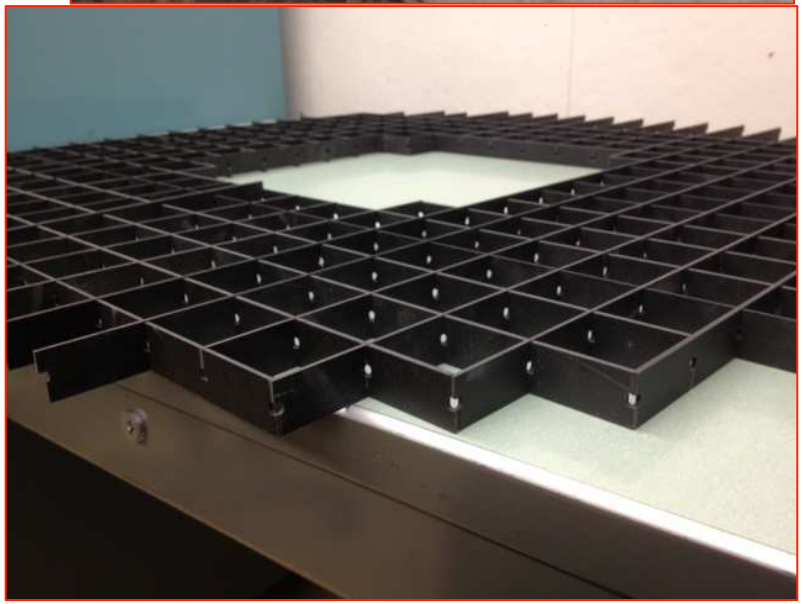


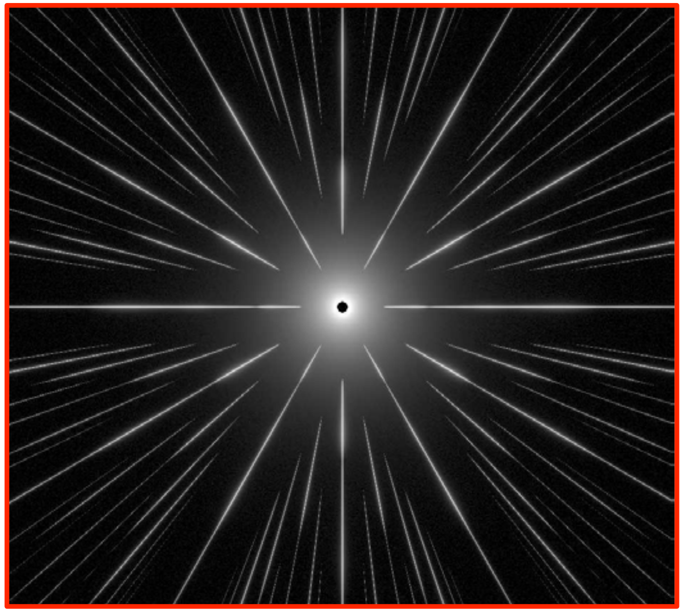

Distortions in Science plane are difficult to calibrate.

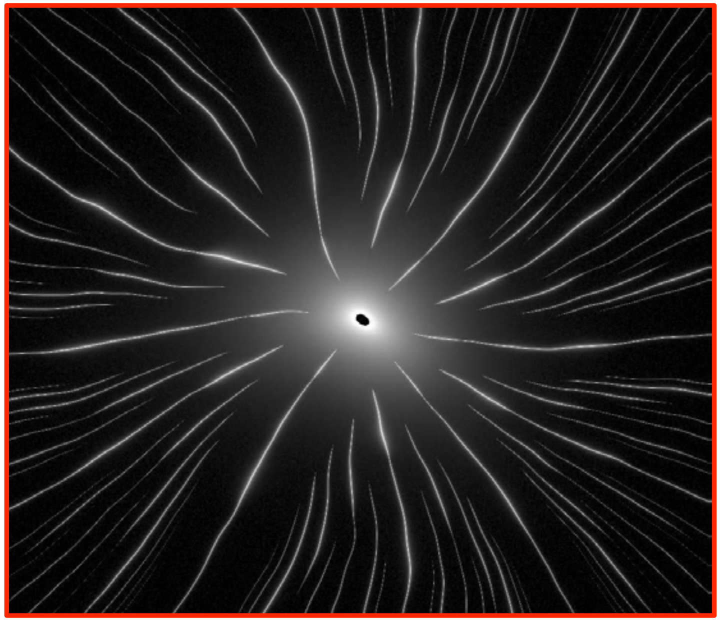
Multi-epoch astrometric performance is ~ 1 mas

For crowded fields, it can be calibrated
For sparse fields, looking for hardware solutions

# Diffraction grid for high-precision astrometry programs







*Guyon+12*
*Bendek+12*
*Ammons+12.*