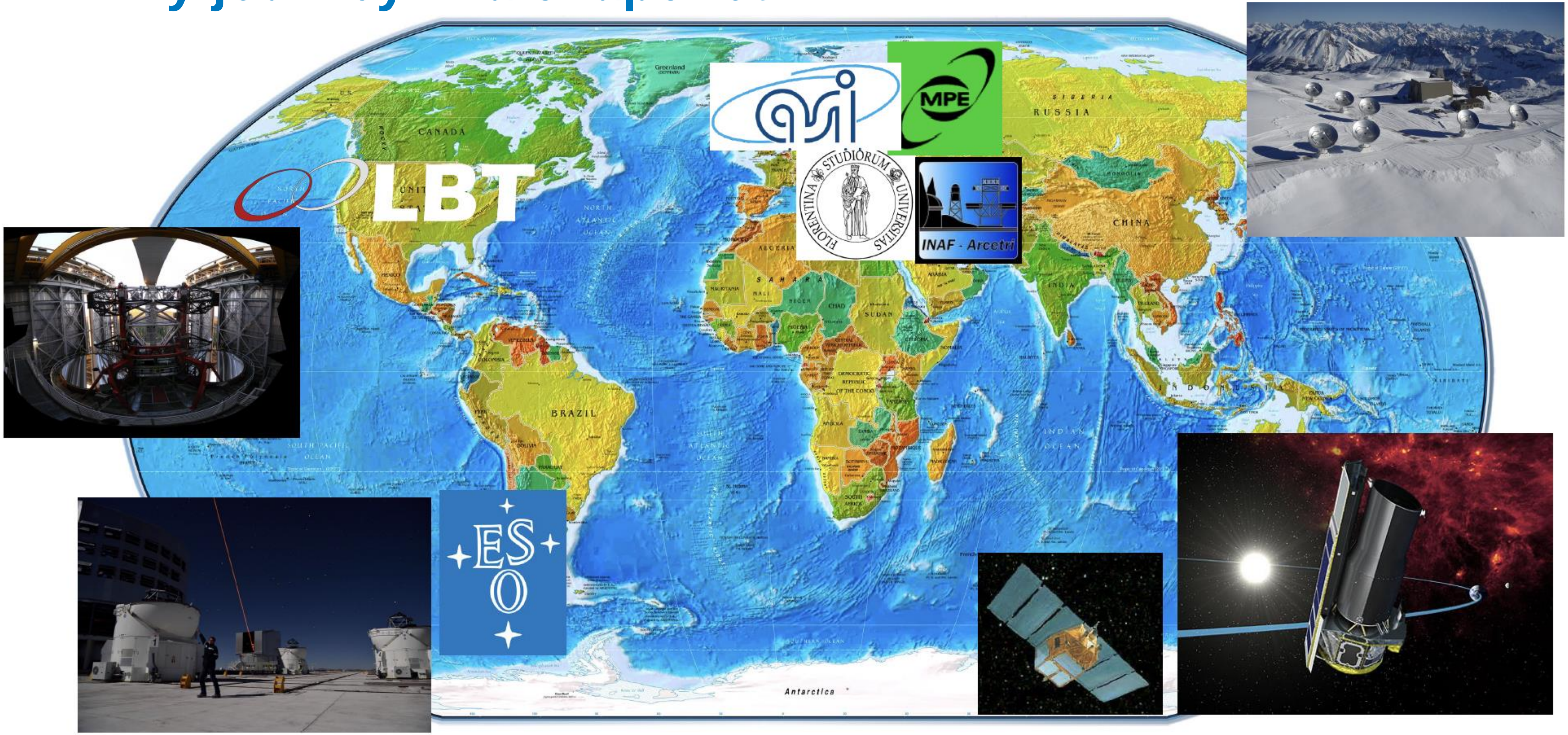
# Introduction to Telescopes and Types of Instruments

*A (almost) holistic view of Paranal Instrumentation*

*Eleonora Sani*

# Who I am and what I do

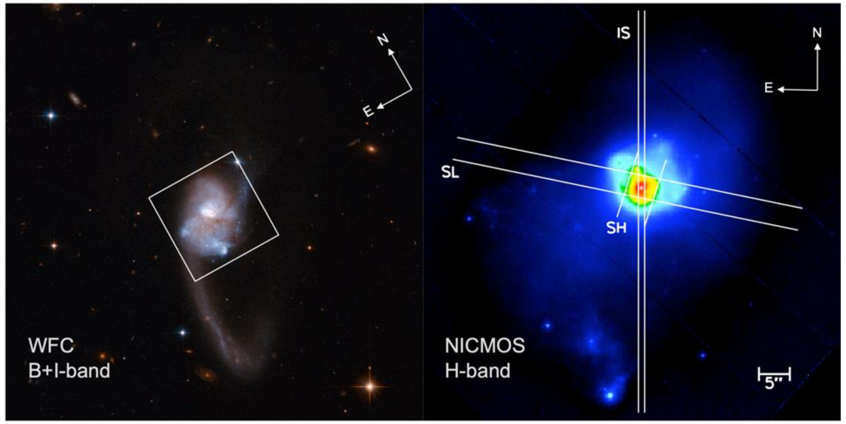
# My journey in a snapshot

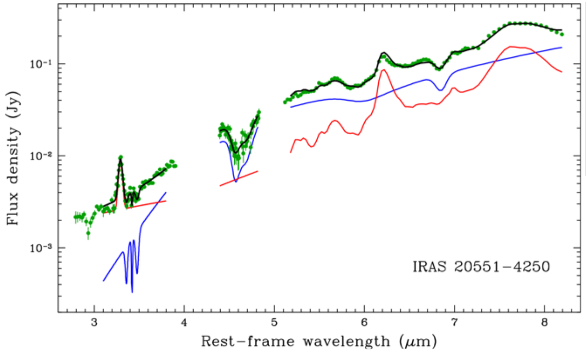


# Main Scientific Topics

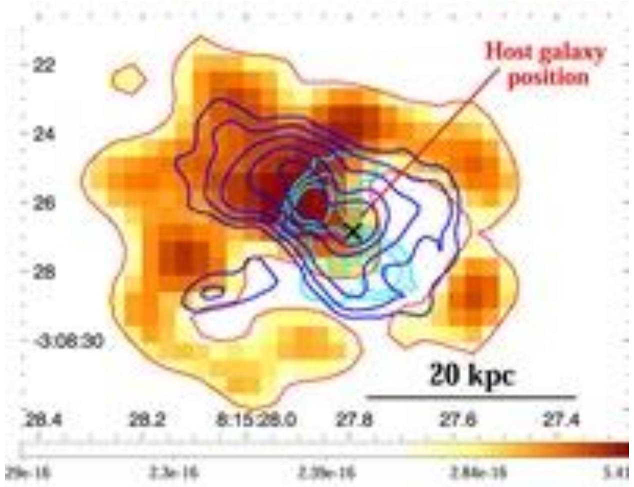
*Active Galactic Nuclei – Star Formation connection*

- Dominant process in composite sources
  - Risaliti, E.S. +06a,b; Sani+08; Sani+10; Sani+12b
- AGN structure and environment
  - Sani+12a; Rojas, E.S. +20; Jimenez-Gallardo, E.S. +22; Kakkad, E.S. +22; Hon, Berton, E.S. +23
- BH – bulge scaling relations
  - Sani+11; Ricci, E.S.+17b; Sani+18; Ricci F., E.S. +22, Vietri, E.S.+24



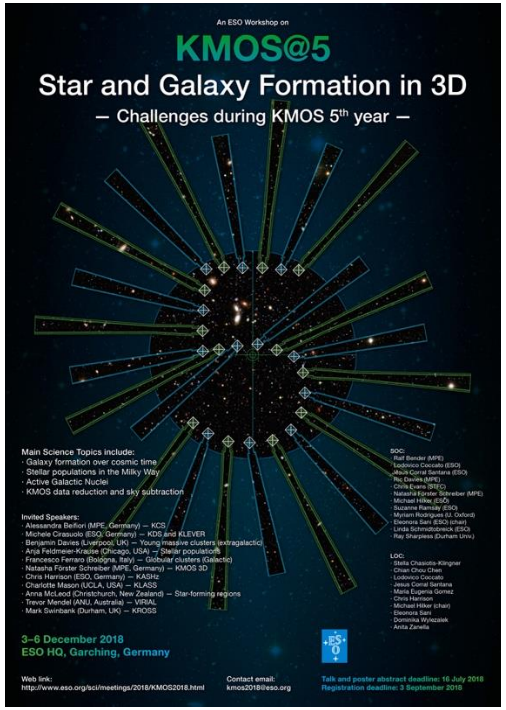




Emission of BH-accreting gas dominates over Star Formation in mid-IR




H$\alpha$ emission associated with an X-ray cavity

# Role and duties at ESO




*My first 6 yrs at ESO*

- Core duties
- Instrument scientist
- UT coordinator
- Training coordinator




*Deputy Head of Paranal Science Operations*

- Definition and implementation of department policies
- Line management
- Staffing plan and scheduling

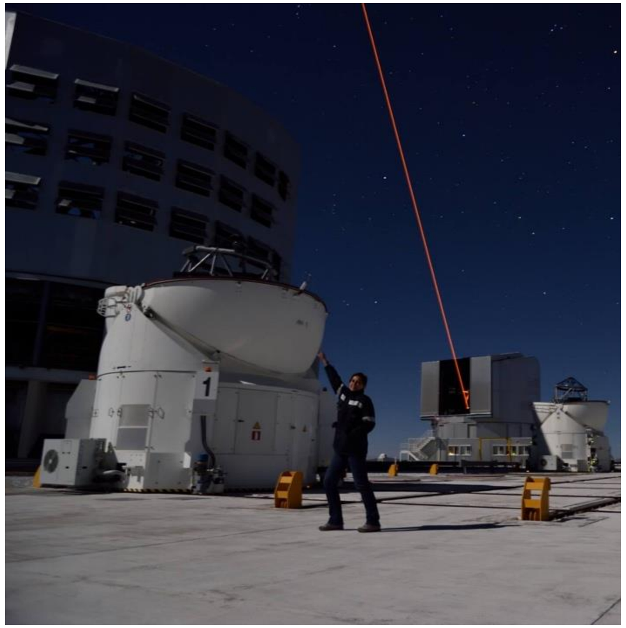
*Instrument Operations Team coordinator*

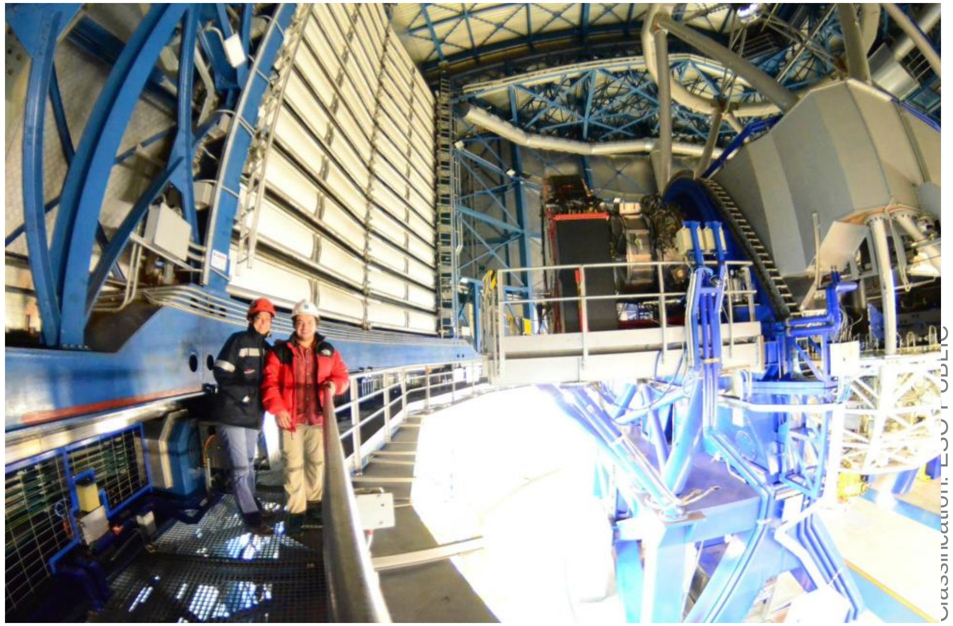
- Oversee Instruments status and performances
- Instrument Scientist support
- Cross-department board member

# What I really like

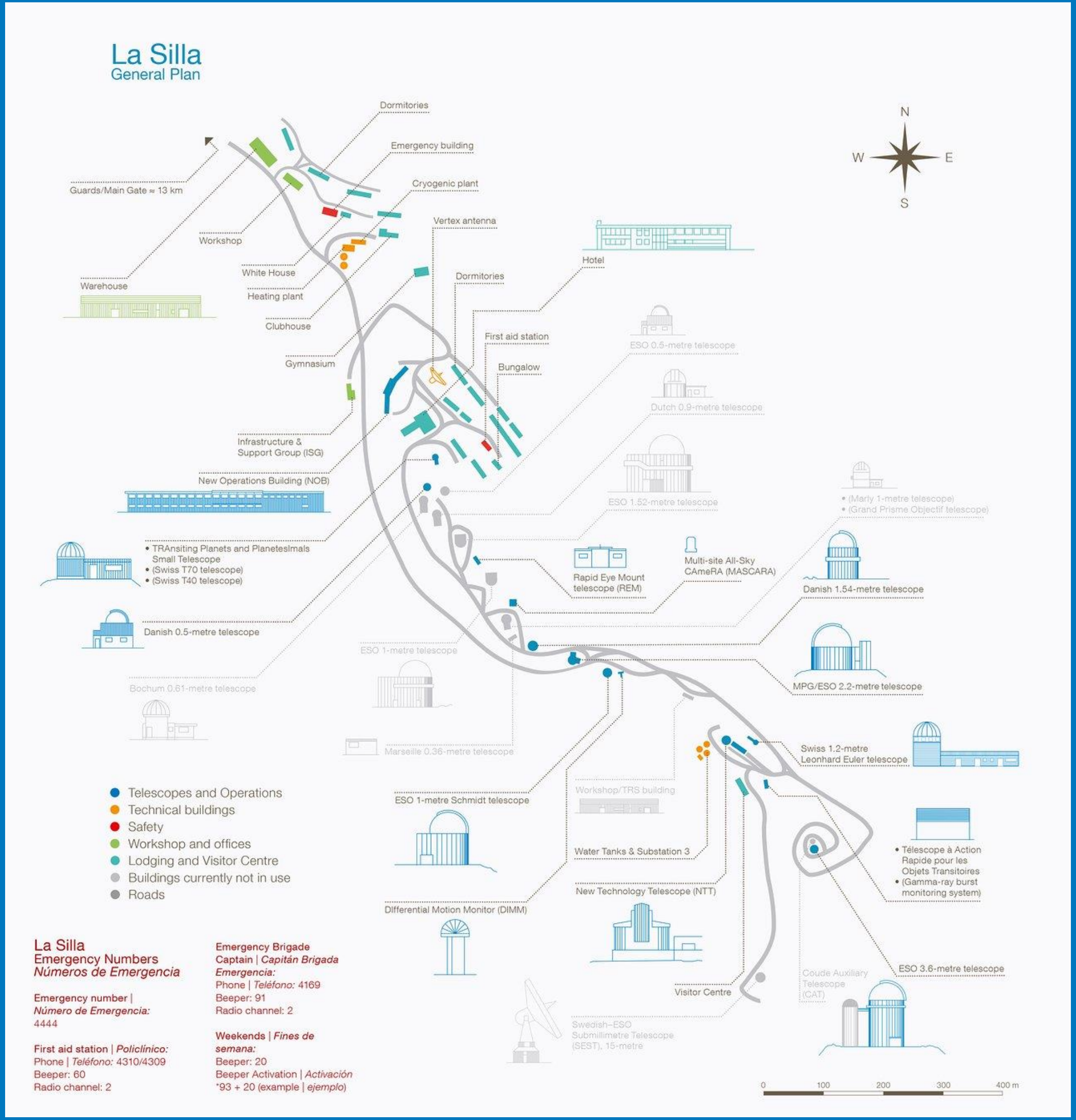
*Instruments are prototypes…*

- Be at the forefront of astronomical technology
- Understand and stretch instruments to their limits
- Improve instrument performances and operations
- Being the joining link between the scientific community and the technical side at the Observatory





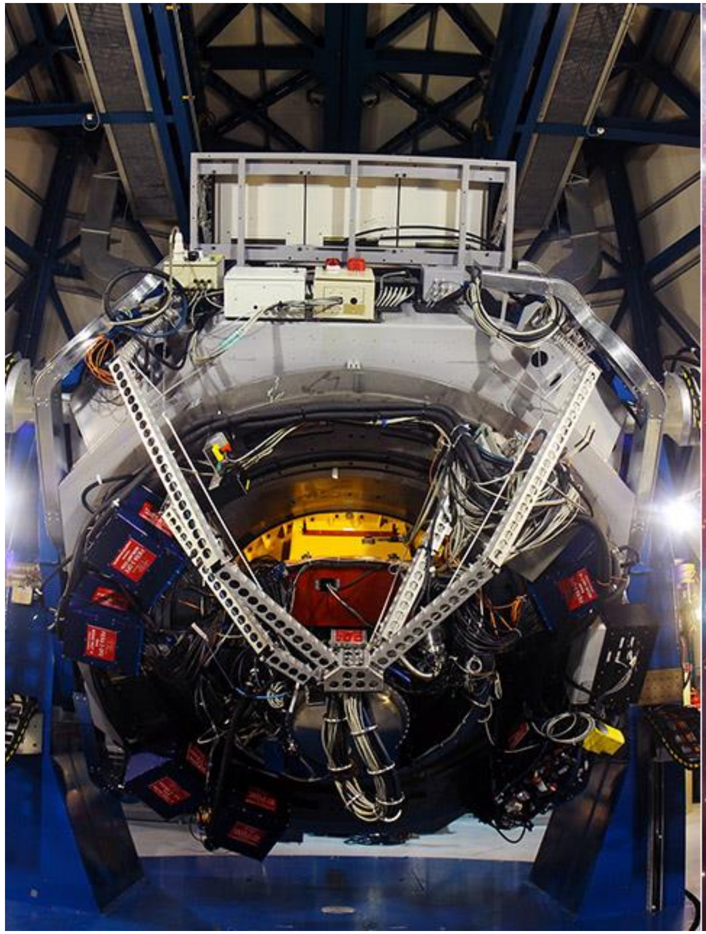
# What La Silla can provide astronomers with



# What Paranal can provide astronomers with

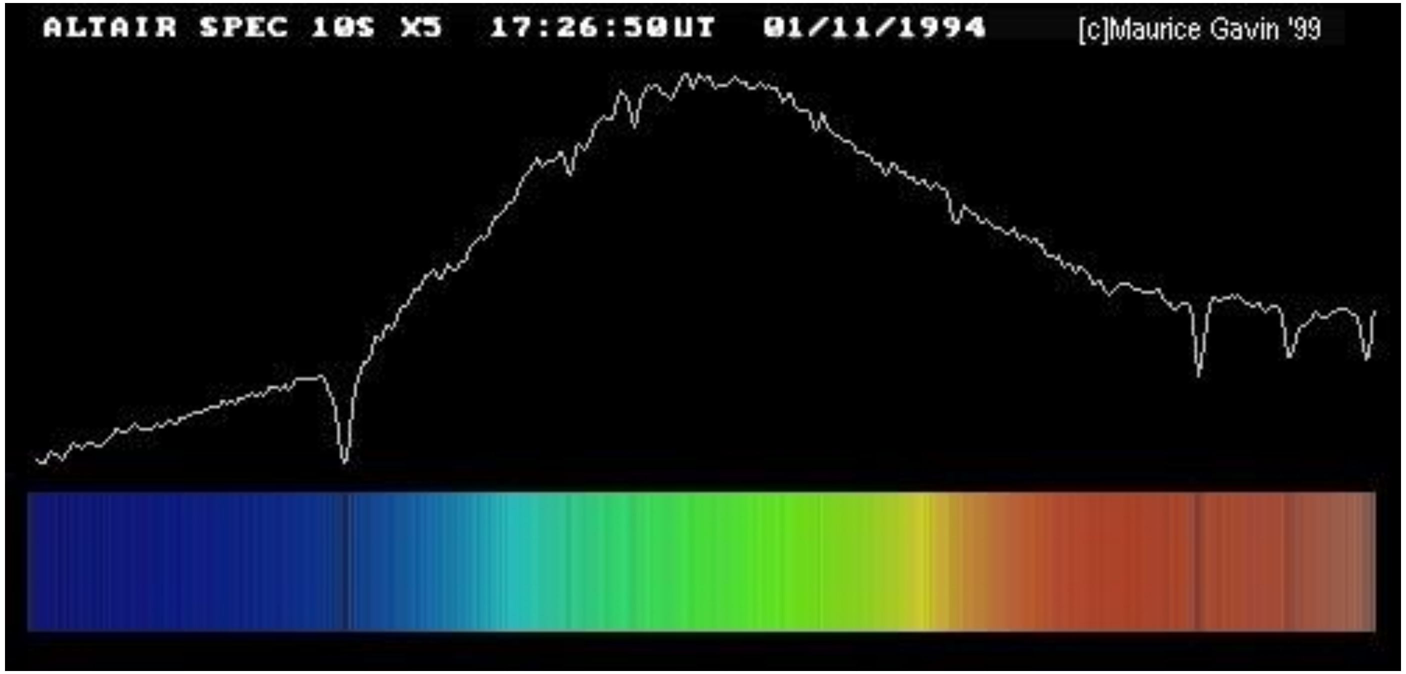
# Imagers

*Give the **mugshot** of an astronomical object*

# Spectrographs

*Give the **fingerprint** of an astronomical object*


Wavelength

*SPECTRAL RESOLUTION*

$$R = \frac{\lambda}{\Delta\lambda}$$

$\Delta\lambda$ = 0.1 nm
@ 600 nm
R = 6000

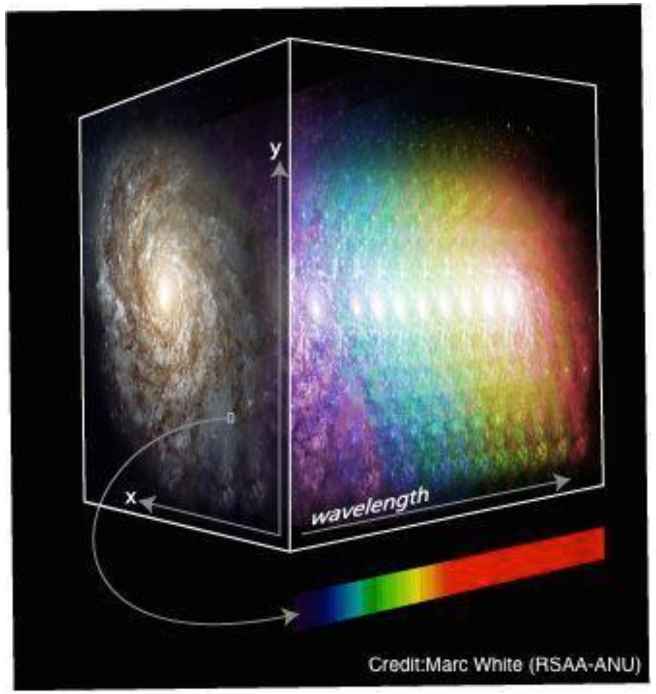
- See Luca Sbordone's talk on Spectroscopy

# Integral Field Units

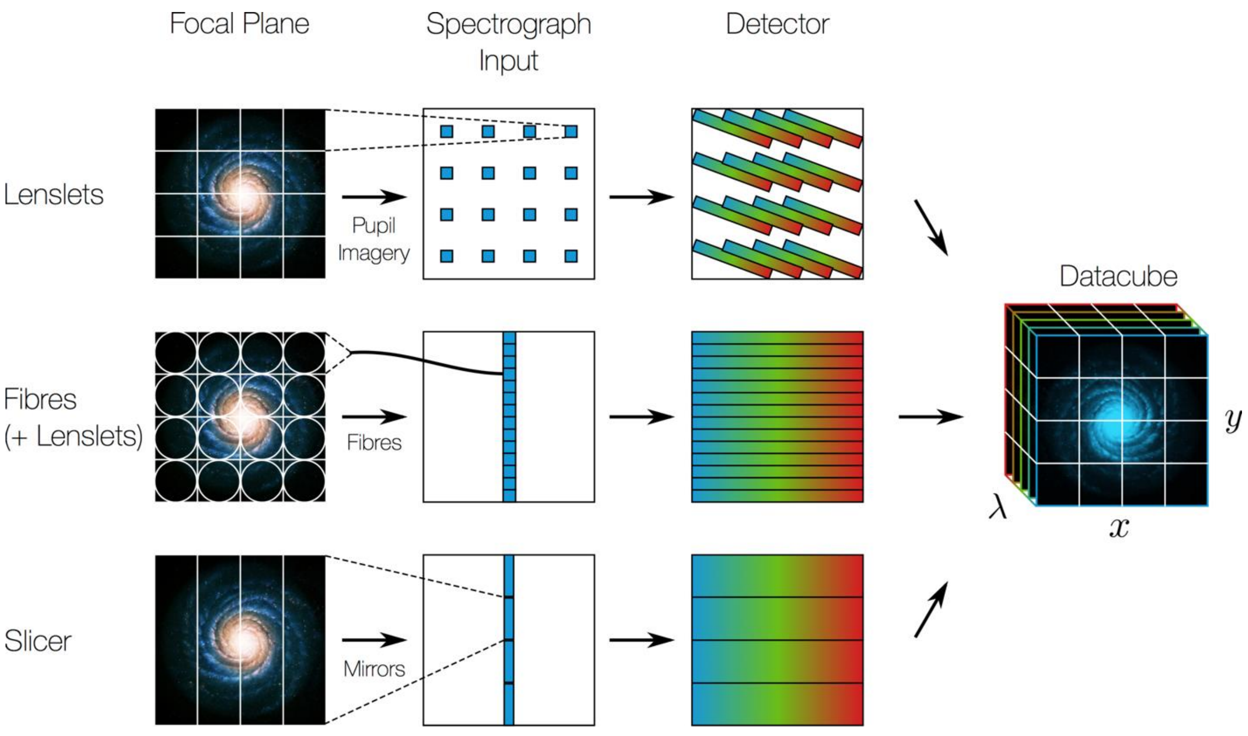
*Give both the **mugshot** & the **fingerprint** of an astronomical object*

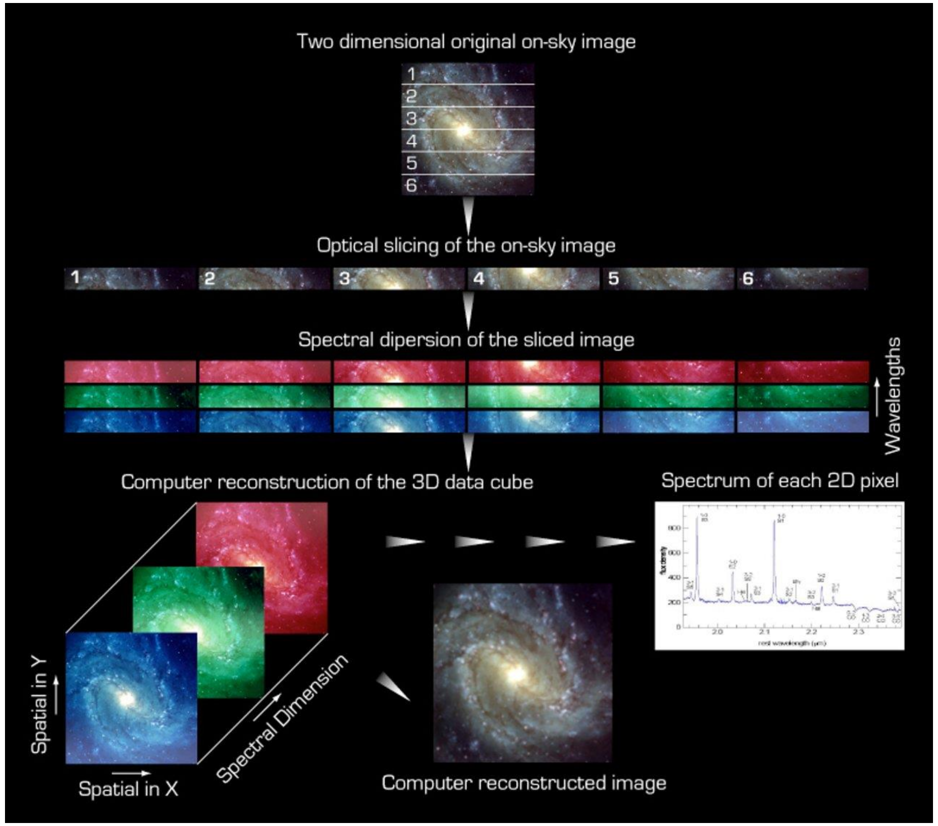

DATACUBE

- An image at each wavelength
- A spectrum for each pixel of the image



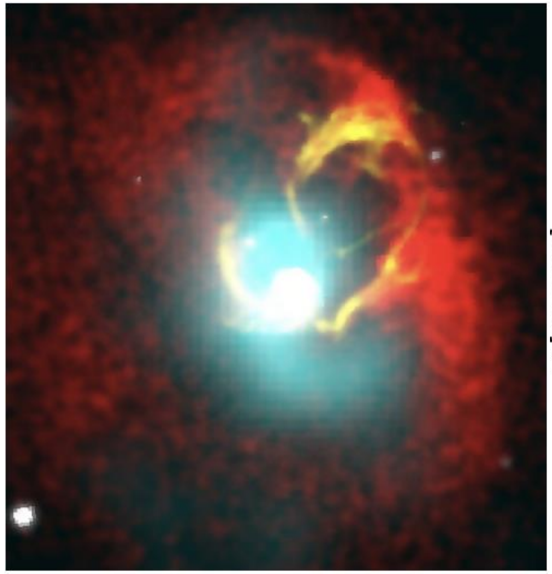
# Integral Field Units

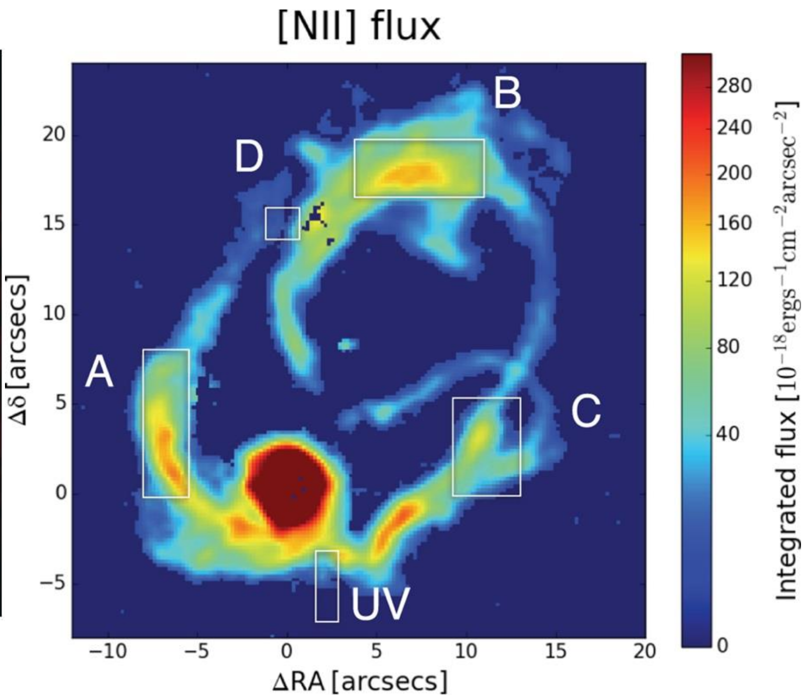


# Integral Field Units

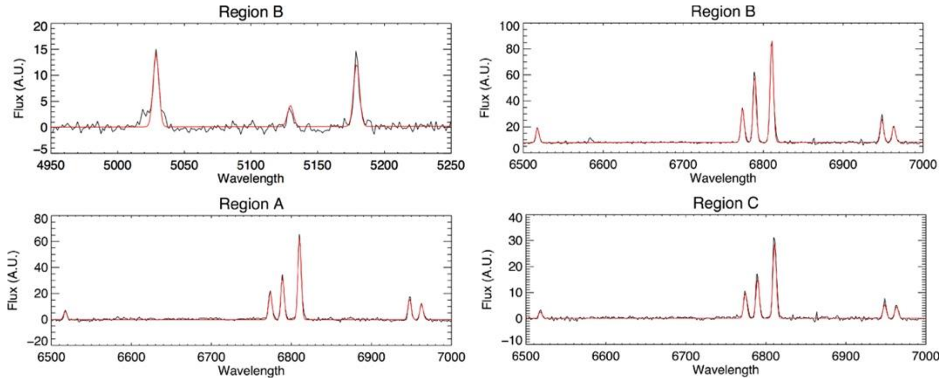
*Emission line maps and kinematic*

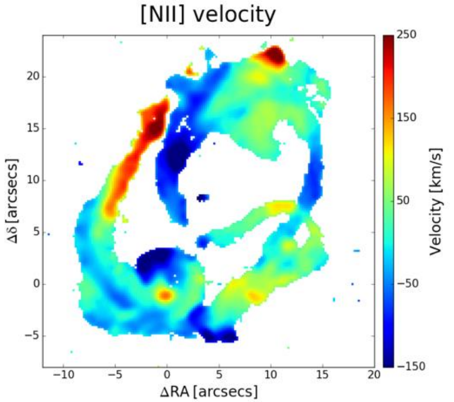


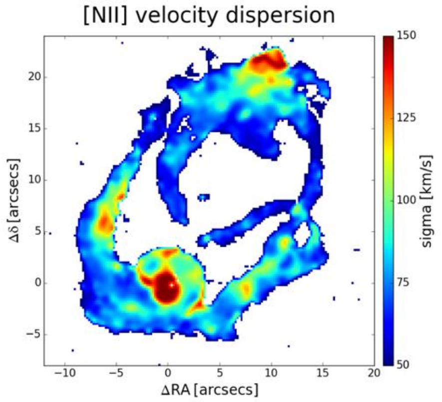



MURALES Survey

Ionized gas filaments *on* cavity rim
Balmaverde et al. 2018




Data Classification: ESO PUBLIC

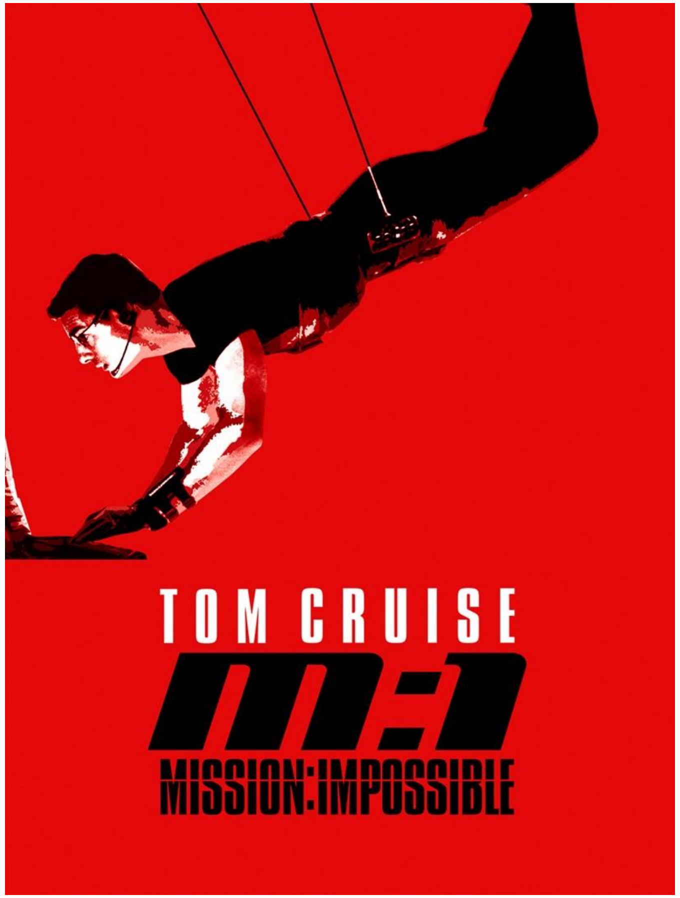
# What astronomers really want

Data Classification: ESO PUBLIC

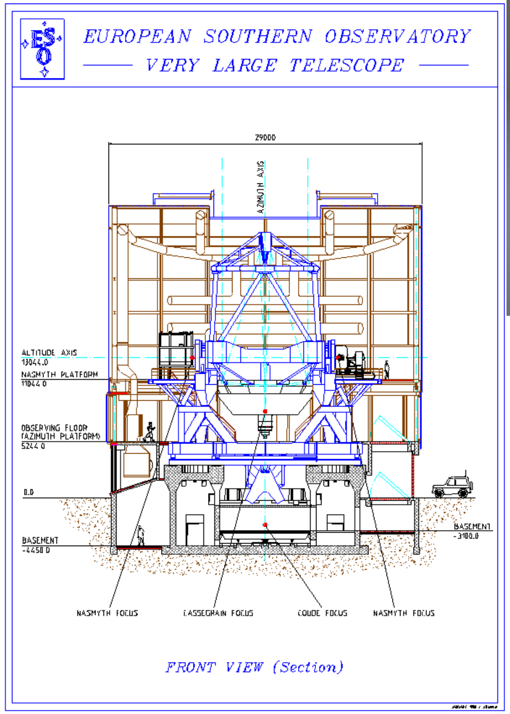
# What all astronomers really want…

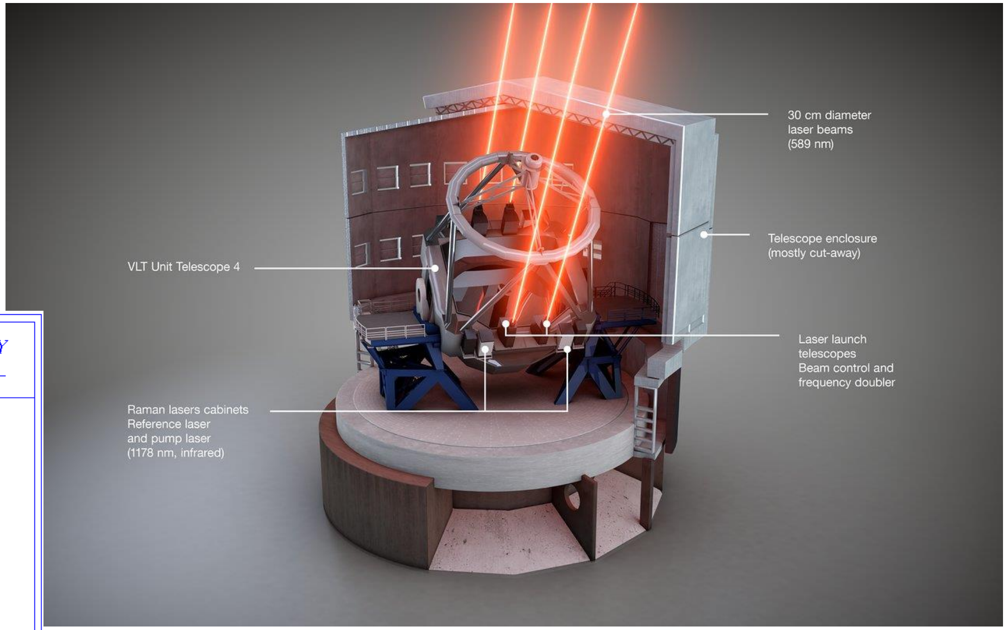
- **Sensitivity** to go deep/be efficient
- **Wide field of View** to capture information from extended objects/for many objects at the same time
- **High spatial resolution** to spot the smallest details ever seen
- **Large wavelength coverage** to collect information from many different line species/from wide continuum wavebands
- **High spectral resolution** to disentangle lines/to study line profiles/to spot extreme wings

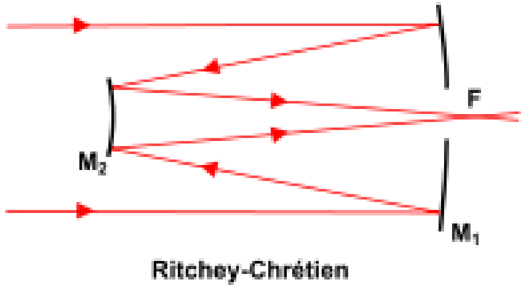
*All rolled into one!*



# Telescopes



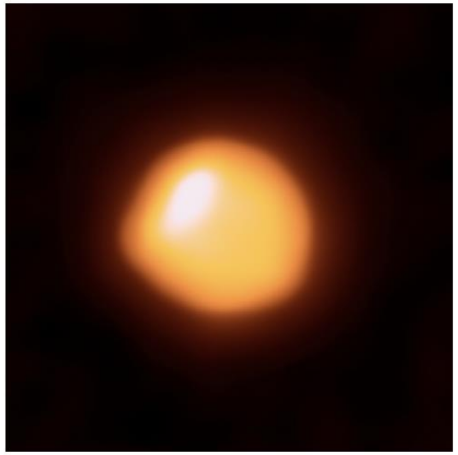

## Hyperbolic mirrors
to avoid coma aberrations

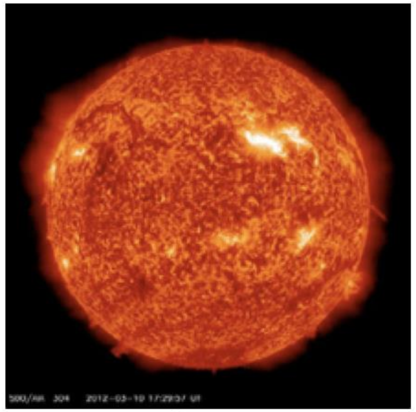
# The need for high angular resolution

# Range of angular sizes

Resolution of an UT in NIR: ~ 0.050"

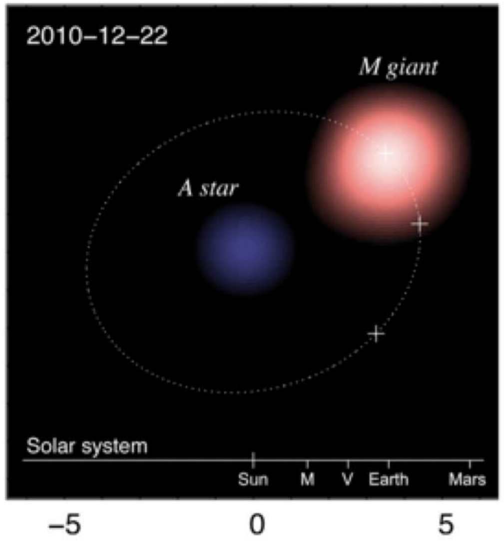
Betelgeuse
θ= 0.050"
d = 300 pc





Sun
θ=1800 " (0.5 deg)
d=5.10$^{-6}$ pc

Jupiter
θ= 50"
d=2.5 10$^{-5}$ pc




Binary SS Leporis
θ= 0.001 "
d=300 pc

# Range of angular sizes

SgrA* EH
θ= 0.00001 ‘’
d ~ 8 kpc

Quasar 3C173
θ= 0.000001 ‘’
d= 0.6 Gpc (z = 0.158)

Diffraction law: the resolving power of a telescope is limited by its diameter,

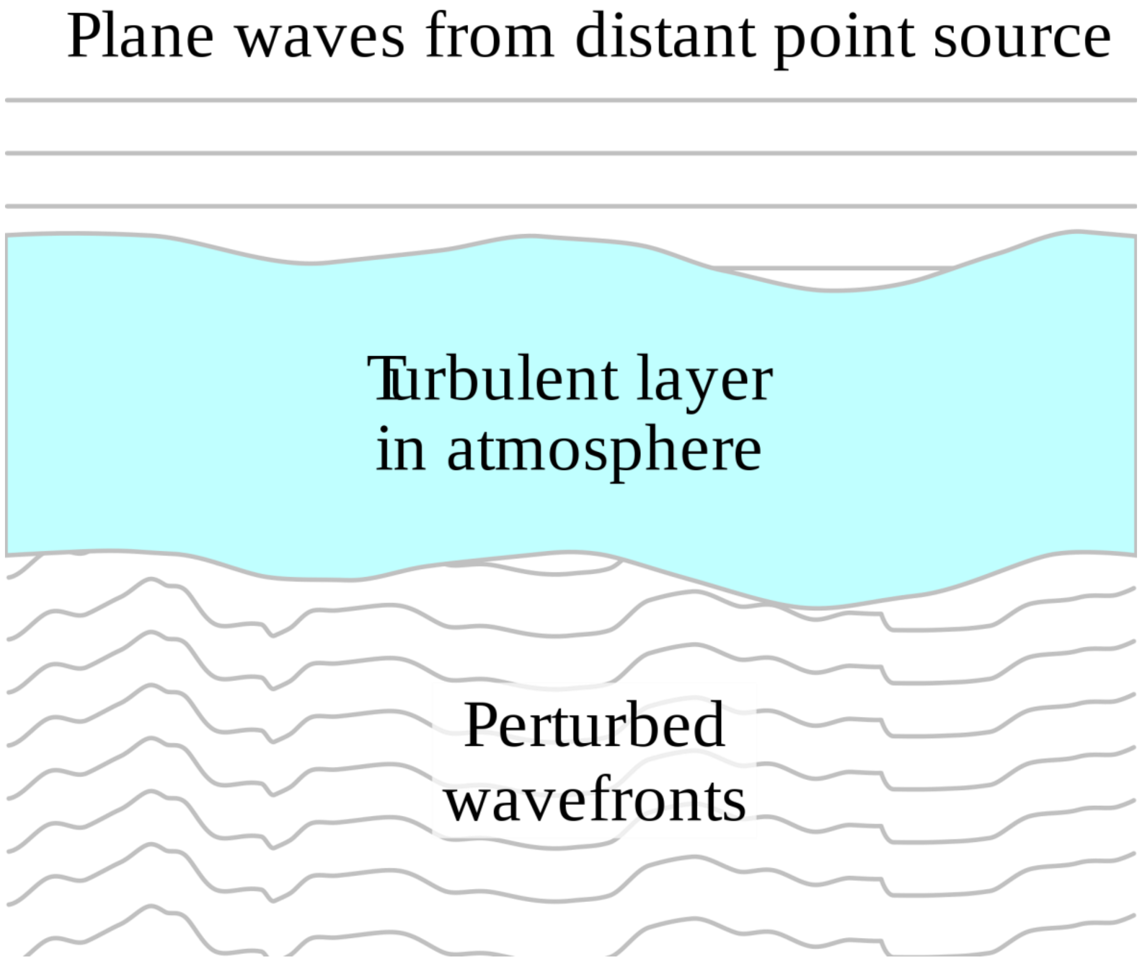
$\Delta\theta = \lambda/D$

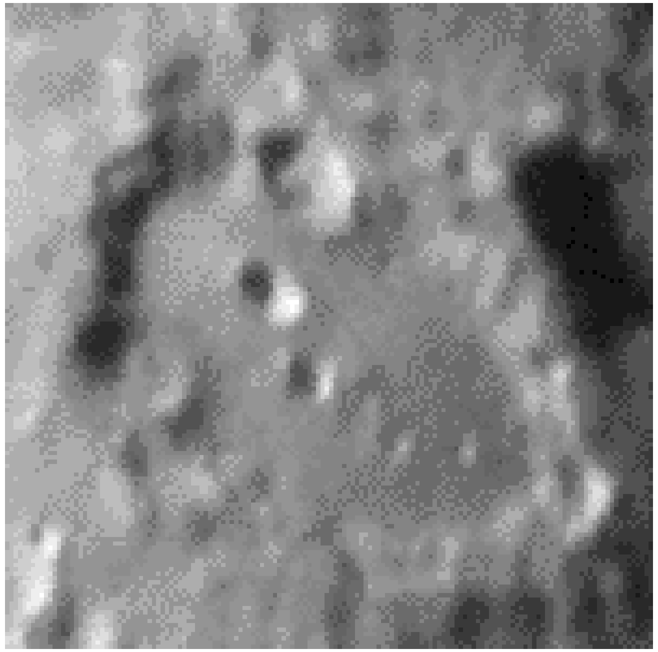
In near-IR (1.6 microns)
$1.6 \times 10^{-6}$ m / 8 m = 0.05” (50 mas)

Data Classification: ESO PUBLIC

# The effect of the atmosphere

# Seeing limited observations



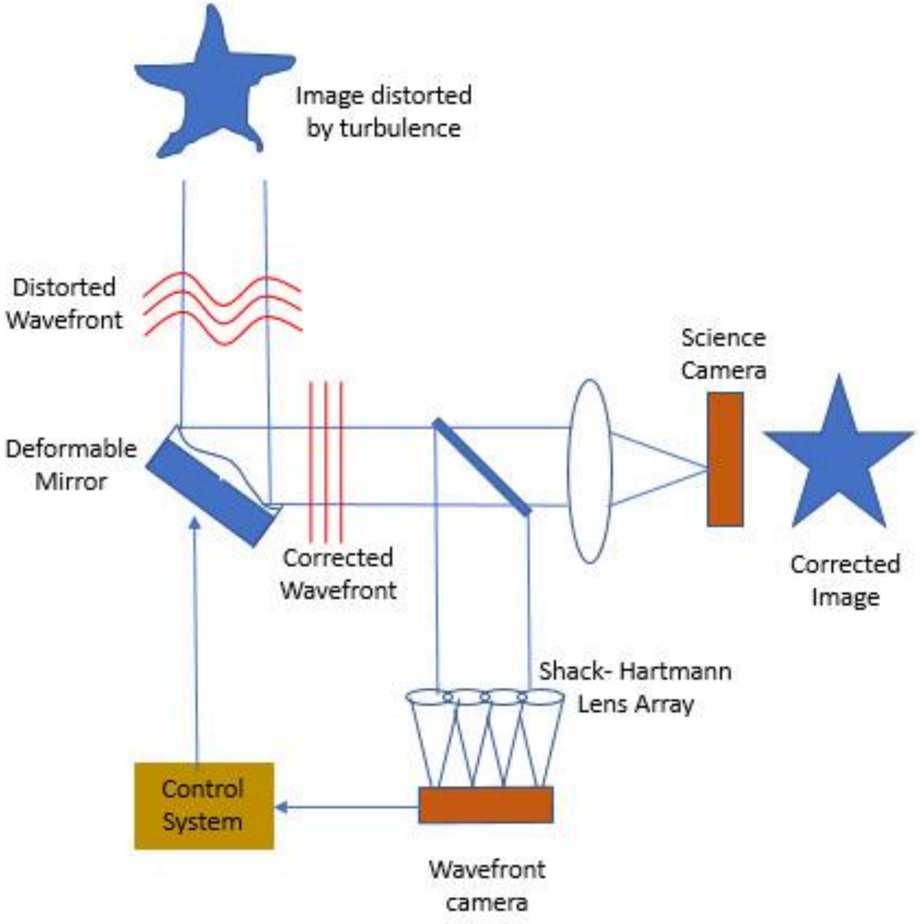



- 8m telescopes are limited to 0.3”-0.5” angular resolution → Can’t go too small
  - Limited details

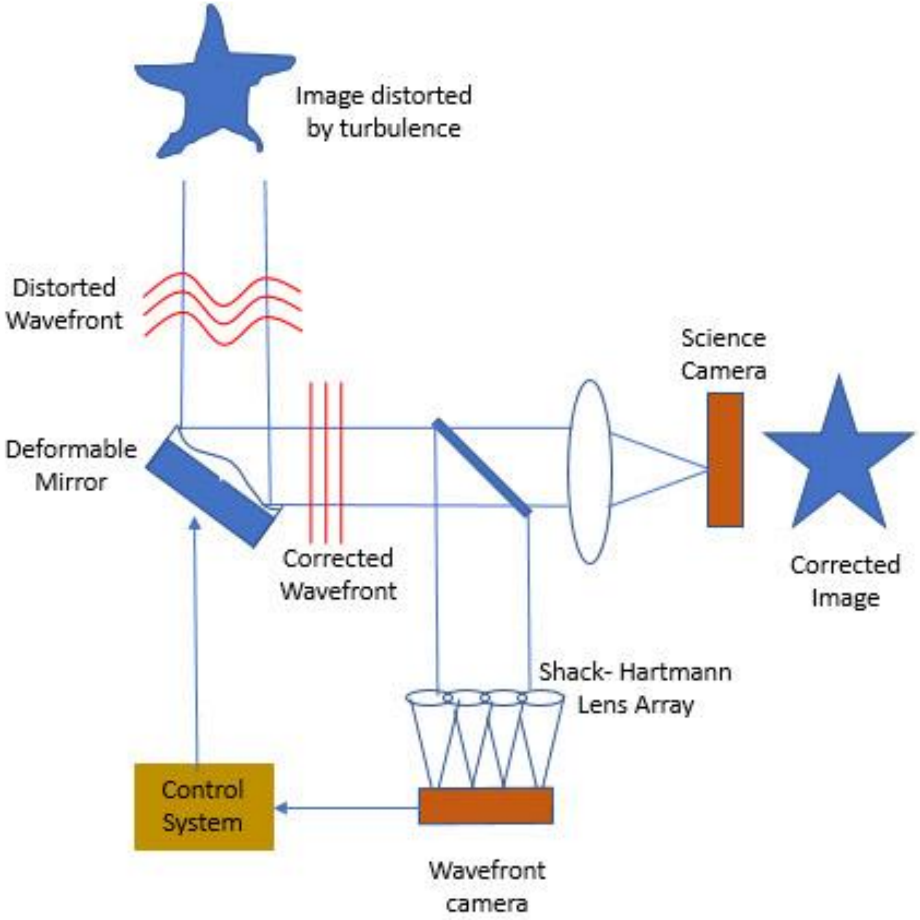
See Ana Jimene’s talk

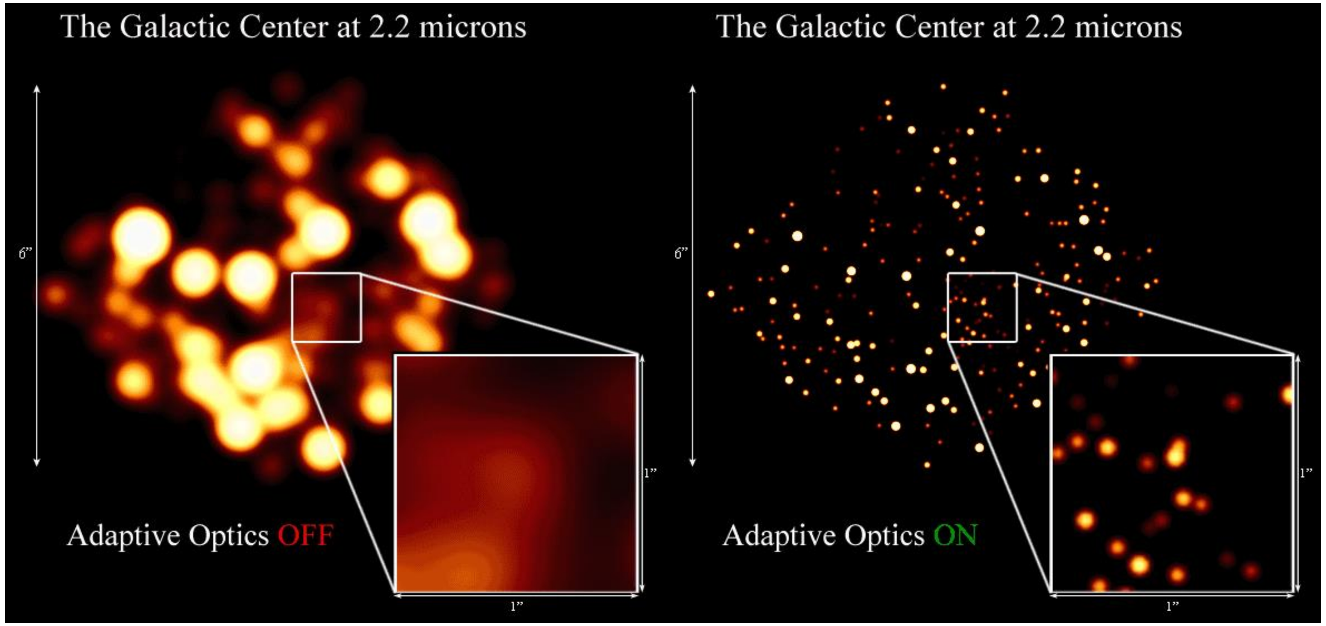
# Adaptive Optics assisted observations

# Overview of AO-assisted observations



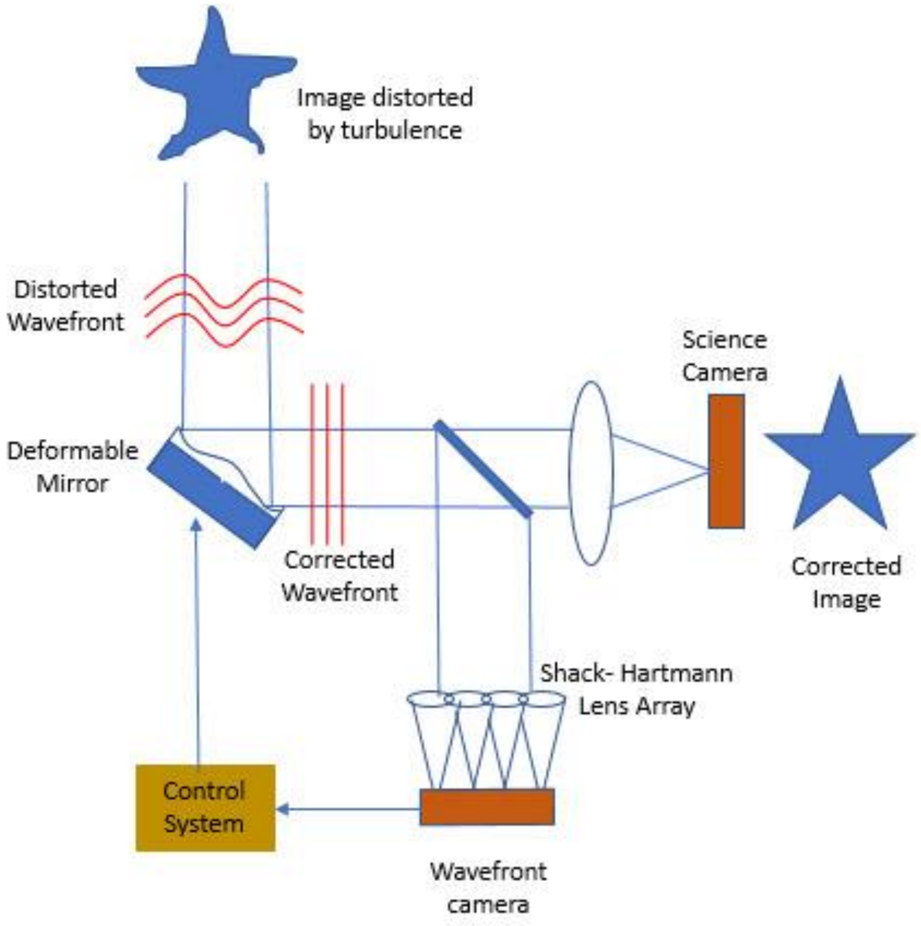
# Overview of AO-assisted observations

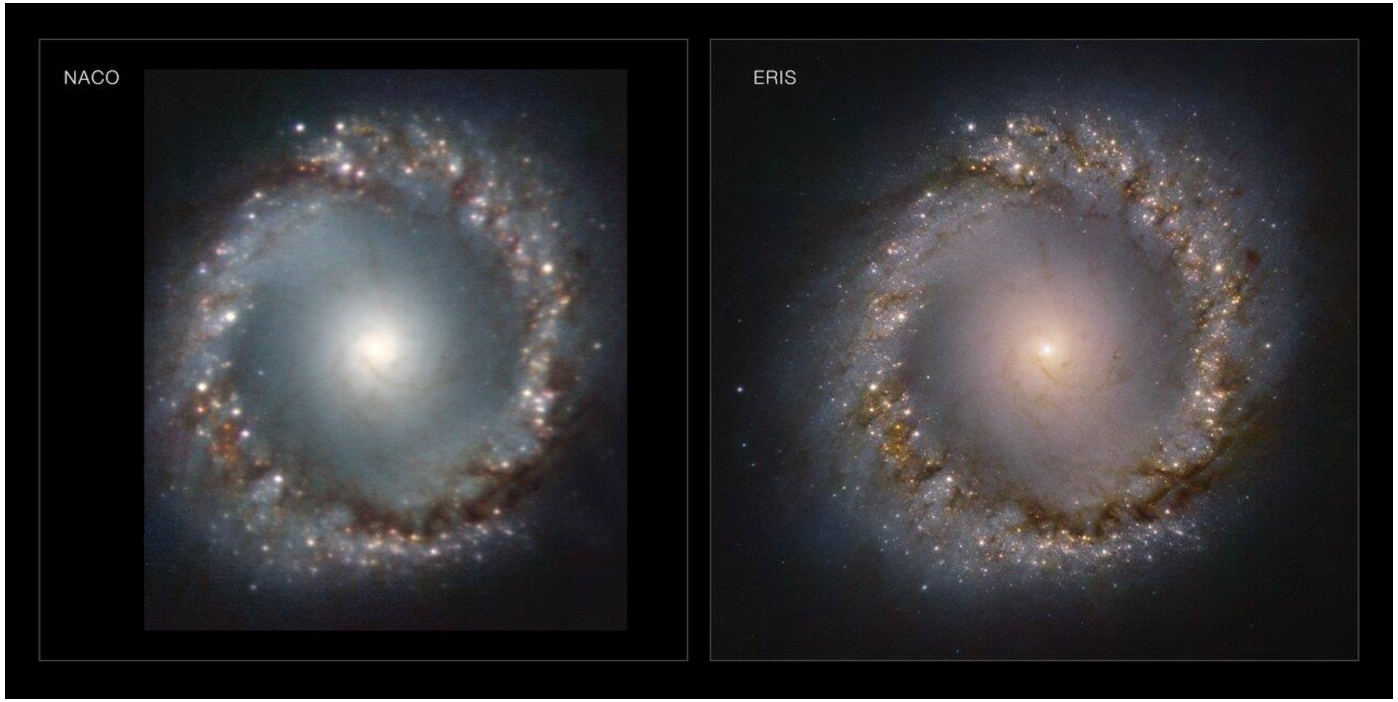



Data Classification: ESO PUBLIC

# Overview of AO-assisted observations




Data Classification: ESO PUBLIC

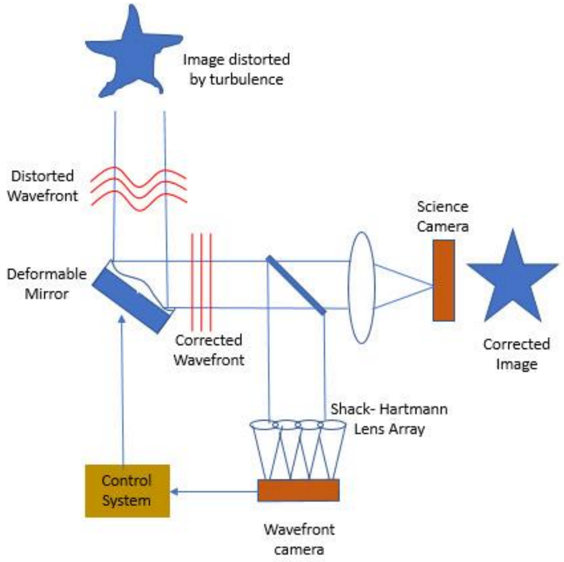
# Adaptive Optics assisted observations

## Extreme AO(SCAO), LTAO, GLAO, MCAO

# Overview of AO-assisted observations

- **SCAO (Single Conjugate Adaptive Optics)**
  - Single guide star (natural/artificial)
  - Small field of view correction (< 1 arcminute)
  - High spatial resolution (0.01 - 0.1 arcseconds)
- **LTAO (Laser Tomography Adaptive Optics)**
  - Multiple laser guide stars
  - Larger field of view than SCAO (a few arcminutes)
  - Comparable resolution to SCAO (slightly lower)
- **GLAO (Ground Layer Adaptive Optics)**
  - Multiple guide stars (natural/laser)
  - Wide field of view correction (10-20 arcminutes)
  - Reduced resolution (not diffraction-limited)
- **MCAO (Multi-Conjugate Adaptive Optics)***
  - Multiple guide stars at different altitudes
  - Wide field of view (similar to LTAO)
  - High resolution across a wider field (near diffraction-limited)

*Not available yet

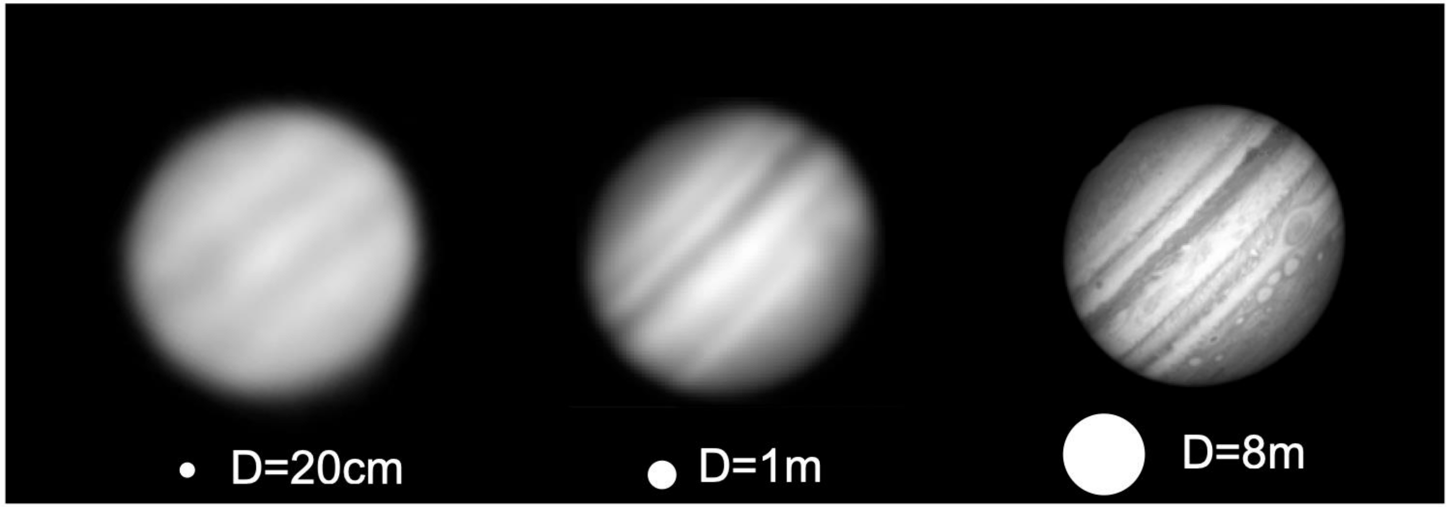



| AO System | Field of View | Pixel Scale (arcseconds) |
|---|---|---|
| SCAO | < 1 arcminute | 0.01 - 0.1 |
| LTAO | ~ arcminutes | ~0.1 |
| GLAO | 10 arcmin | > 0.1 |
| MCAO* | Few arcminutes | <~0.1 |

# Interferometry

Data Classification: ESO PUBLIC

# Overview of interferometric observations

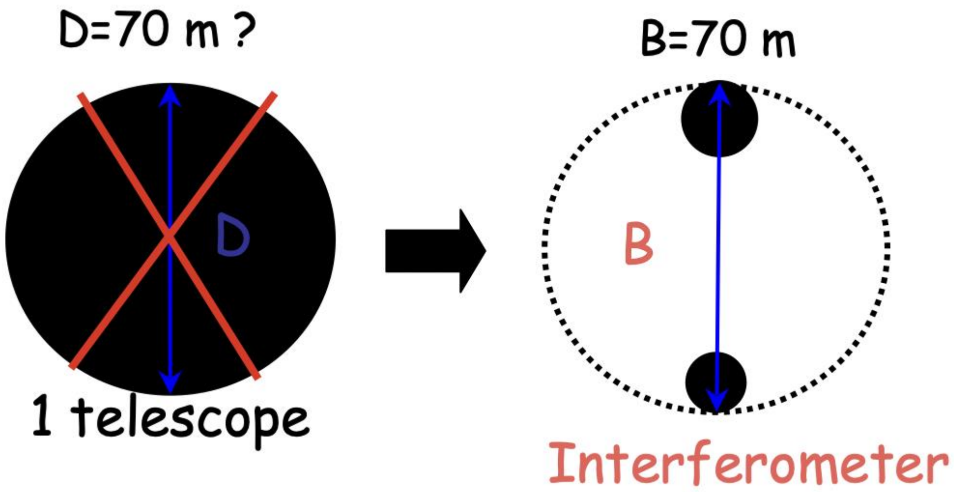



Diffraction law: the resolving power of a telescope is limited by its diameter,

$$\Delta\theta = \lambda/D$$

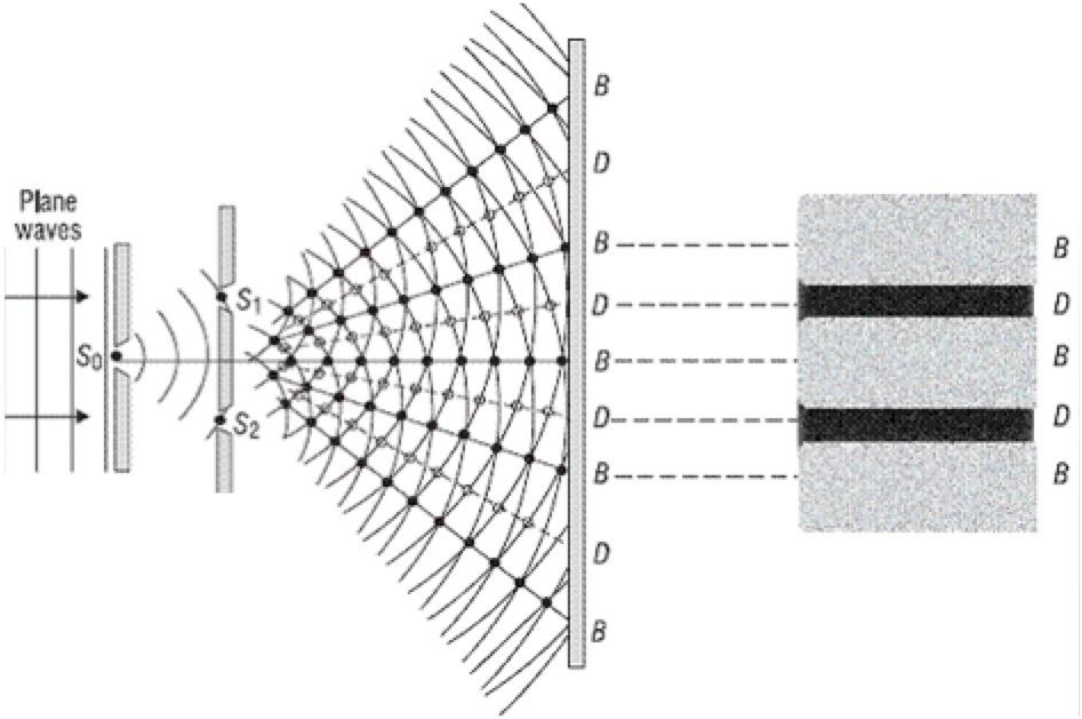
In near-IR (1.6 microns)
$1.6 \times 10^{-6}$ m / 8 m = 0.05” (50 mas)

- At 1,6 microns : $\Delta\theta < 5$ mas —> D > 70m




Use of the coherence of light
<u>between telescopes</u>

# Spatial coherence of light

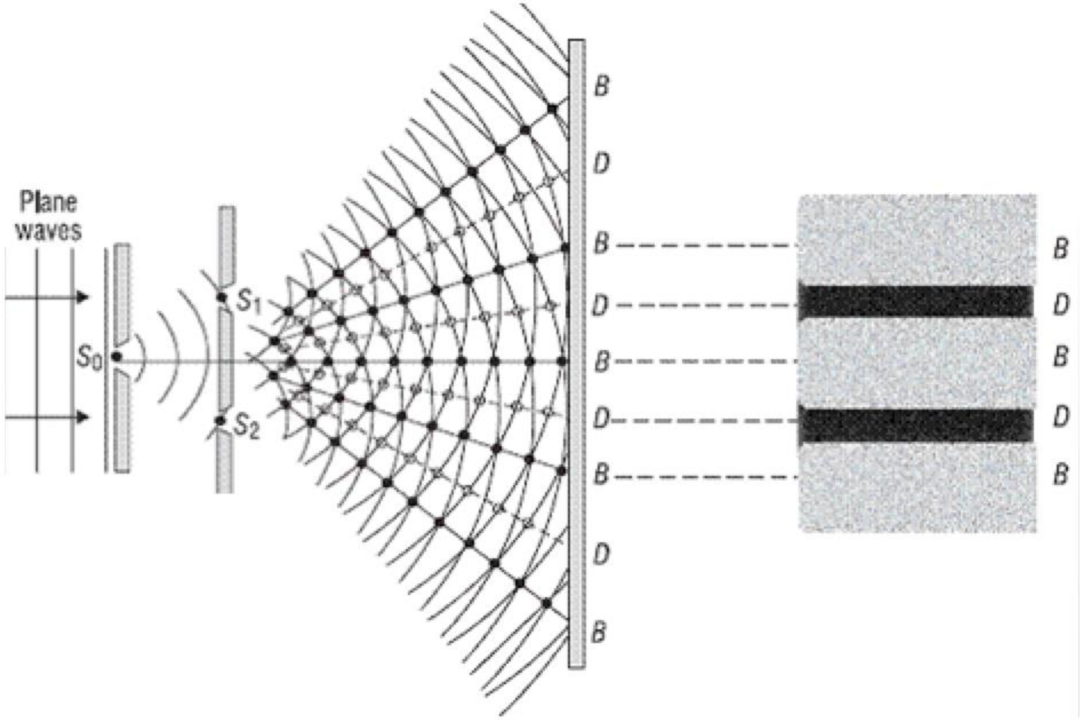



Young's Experiment

$$I = I_1 + I_2 + 2\sqrt{I_1 + I_2}\cos\Delta$$
$$\Delta = \varphi 2 - \varphi 1$$

In case the interfering waves have the same *frequency* and *wave number*

# Spatial coherence of light




Young's Experiment

$$I = I_1 + I_2 + 2\sqrt{I_1 + I_2}\cos\Delta$$
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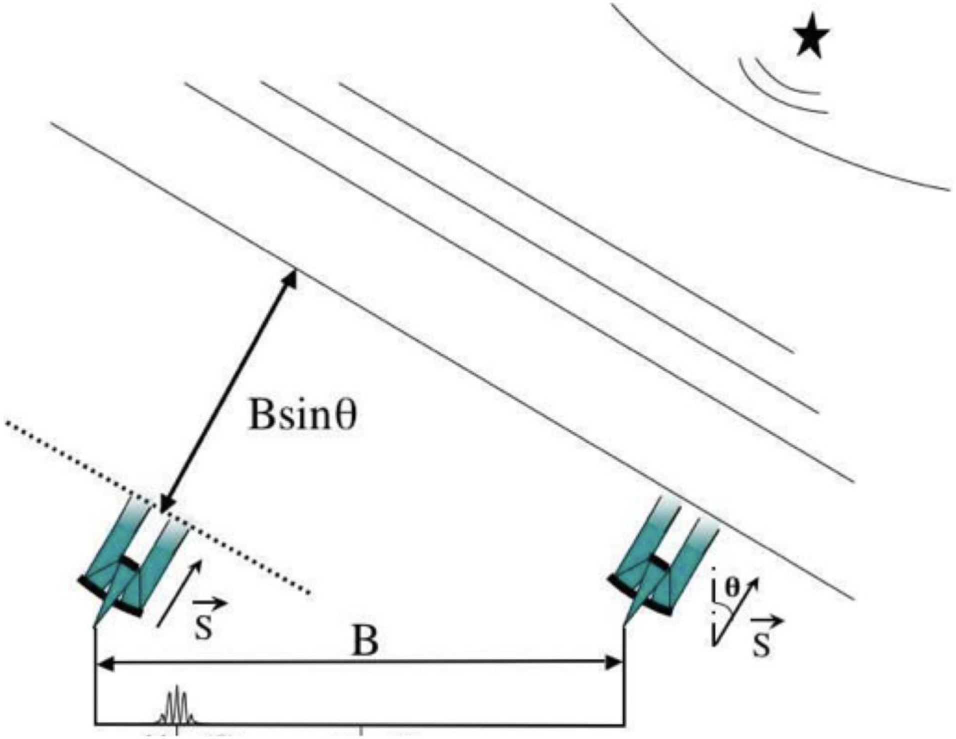
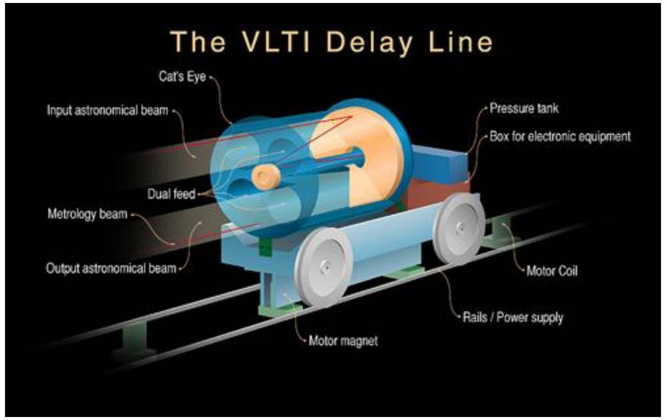
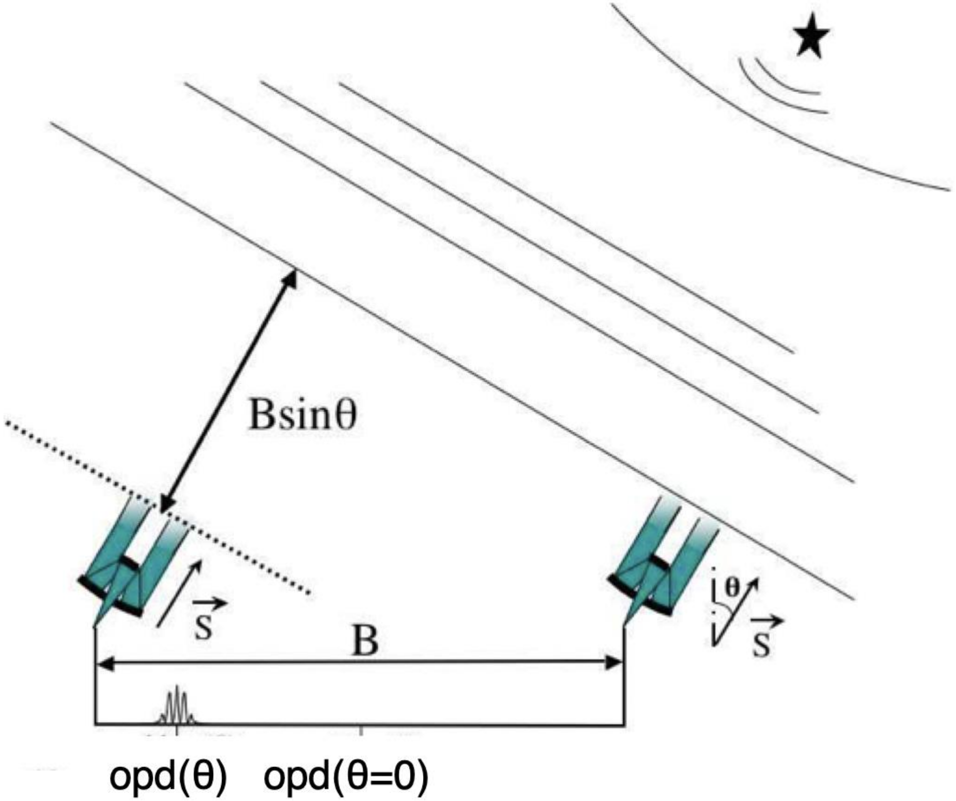



$$\Delta = \frac{2\pi}{\lambda}\,\mathrm{B}\sin\theta$$

# Delay Lines




Metrology system with position precision of 20 nm over 120 m (i.e. ~0.2 parts/billion)

$$\Delta = \frac{2\pi}{\lambda} \mathrm{B} \sin\theta$$

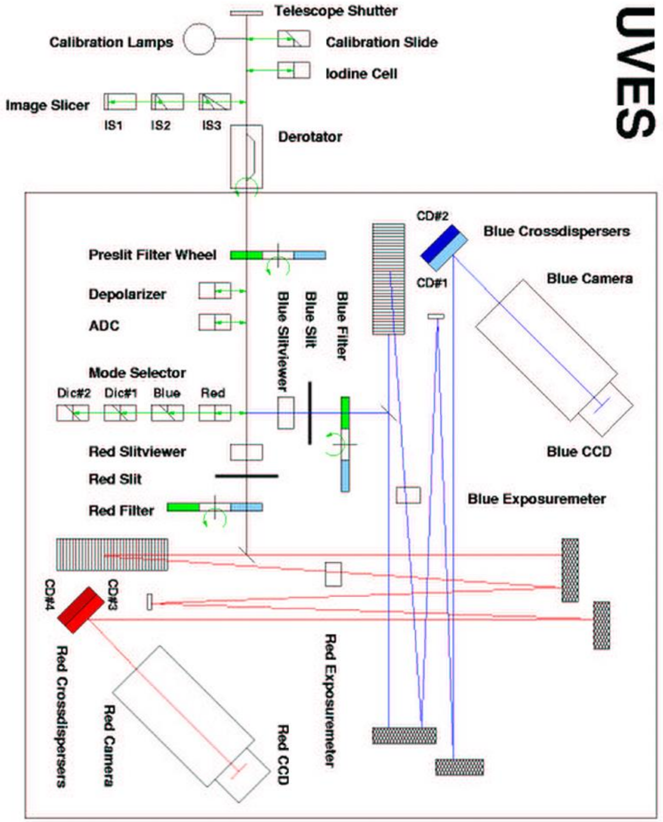
Data Classification: ESO PUBLIC

# “Workhorse” instruments

Data Classification: ESO PUBLIC

# UVES

*Ultraviolet and Visual Echelle Spectrograph (330 -1100 nm); resolving power 110000*

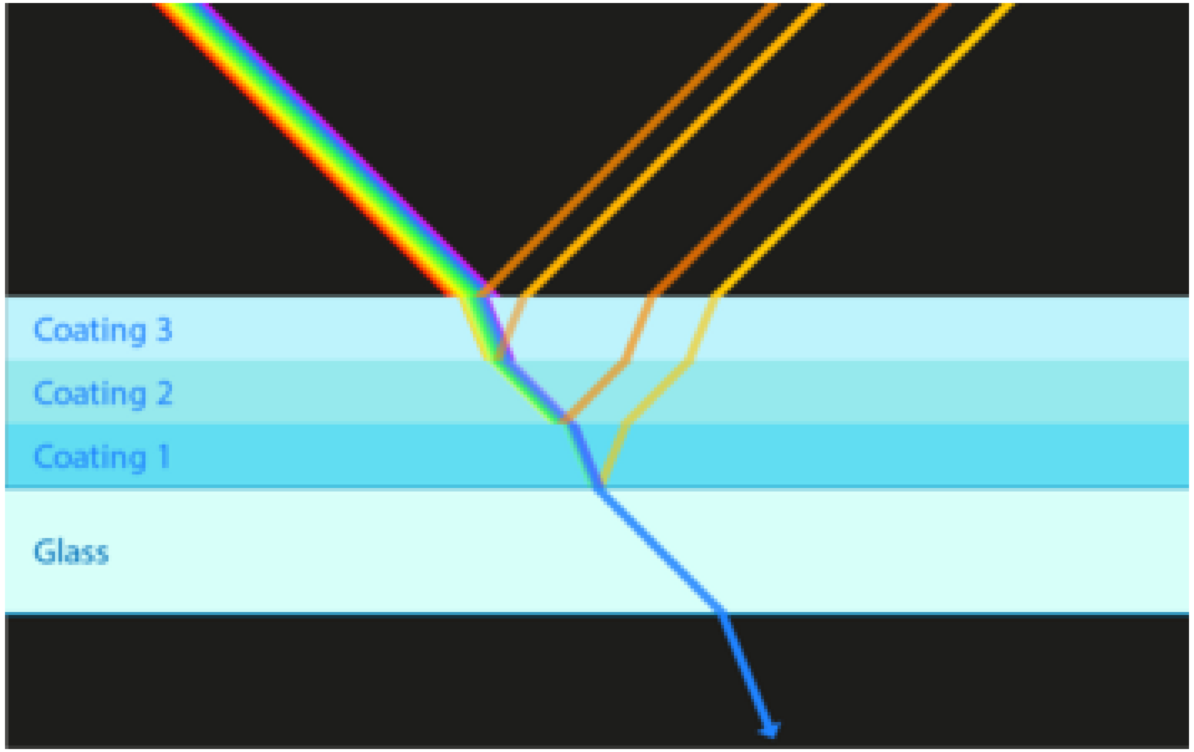


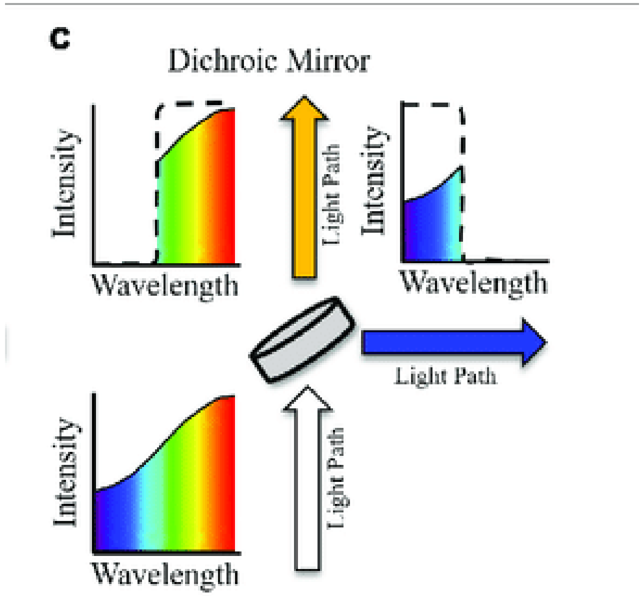

**Spectroscopic Modes**

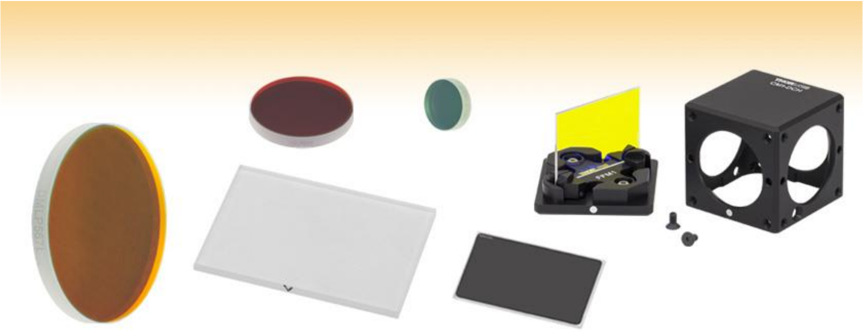
| Instrument mode | Accessible λ range (nm) | Maximum resolution (λ/Δλ) | Covered λ range (nm) | Magnitude limits |
|---|---|---|---|---|
| Blue arm | 300-500 | 80,000 | 80 | 17-18 |
| Red arm | 420-1100 | 110,000 | 200-400 | 18-19 |
| Dichroic #1 | 300-400 | 80,000 | 80 | 17-18 |
| | 500-1100 | 110,000 | 200 | 18-19 |
| Dichroic #2 | 300-500 | 80,000 | 80 | 17-18 |
| | 600-1100 | 110,000 | 400 | 18-19 |
| Iodine cell | 500-600 | 110,000 | 200 | 17 |

# Digression: dichroic mirrors

*Use refraction to select certain wavebands*



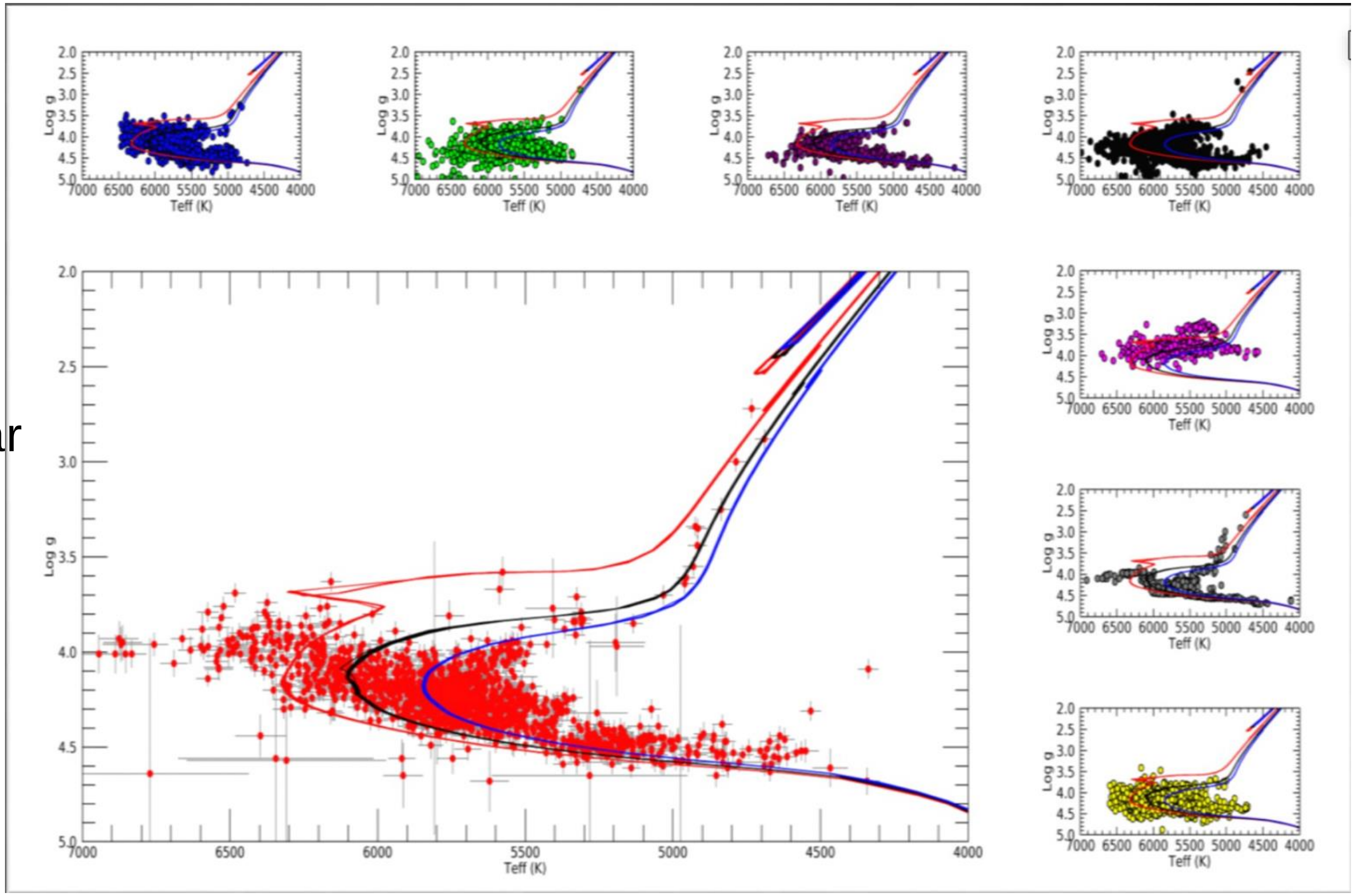



# UVES view of Milky Way disk

*UVES contribution (among many) to the ESO GAIA Survey*

- 10.000 stars
- More than 40 UVES-based papers
- From the characterization of the field population to the detailed chemistry of open and globular clusters; to constrains on stellar physics and characterization of variable sources
- Exploring the limits and the systematics of high-resolution spectral analysis with multi-analysis approach

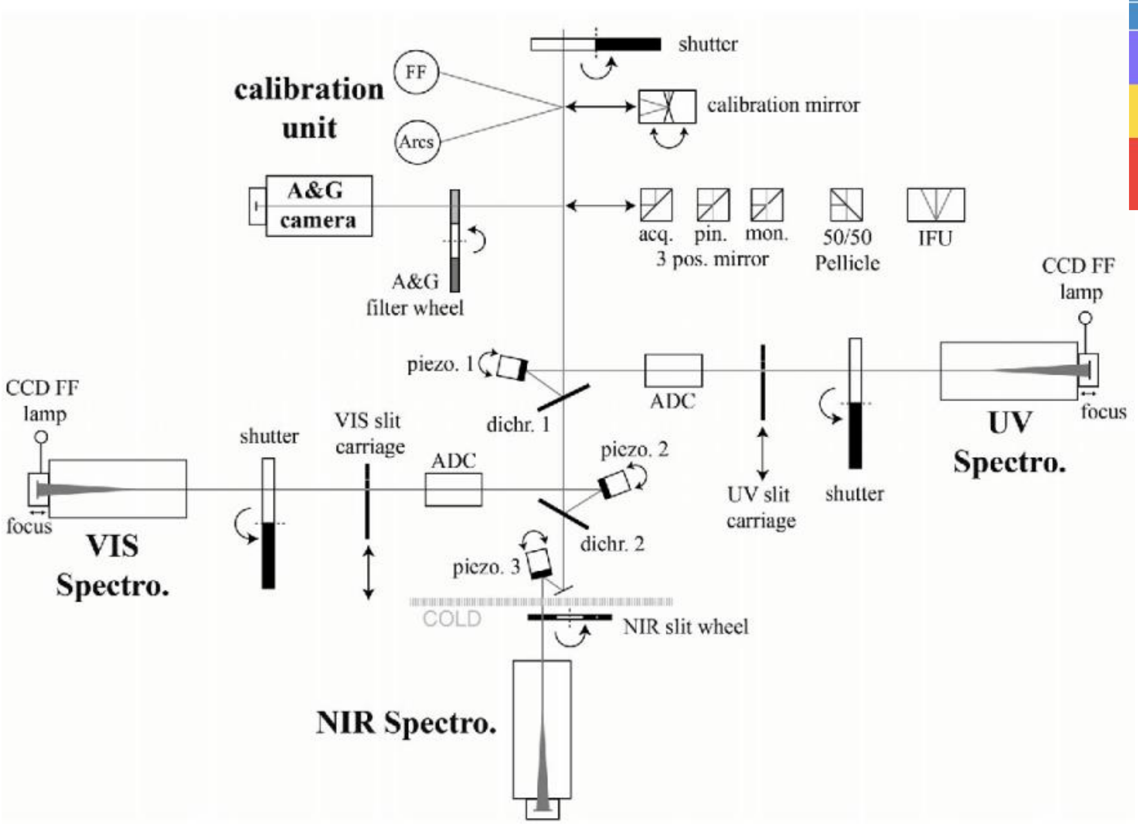



Randich et al. 2022

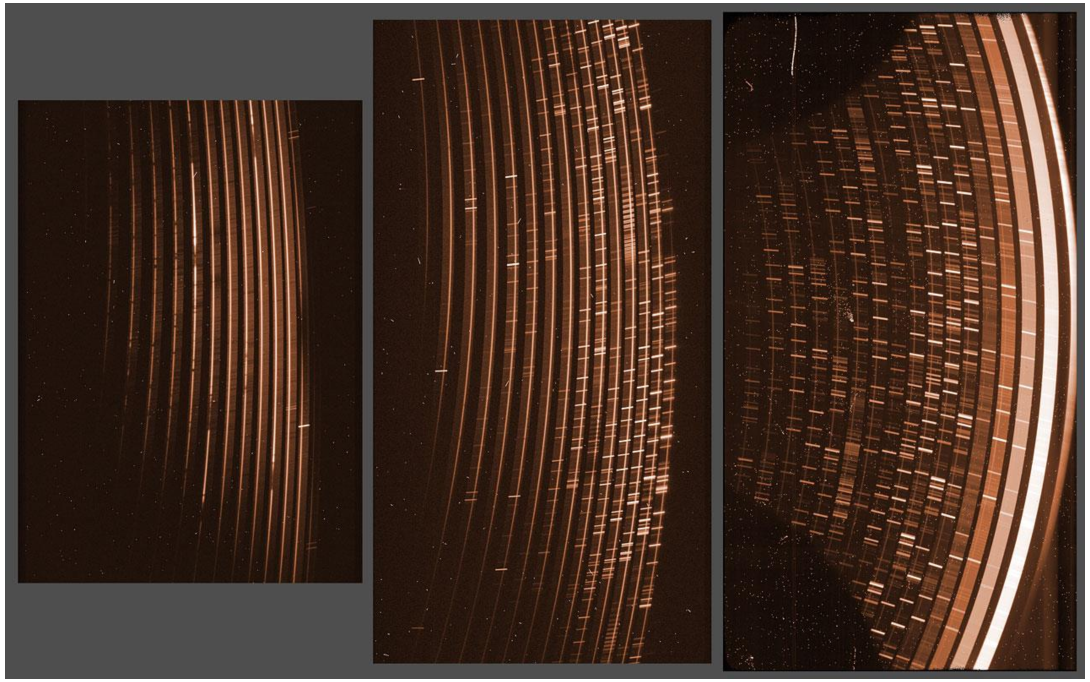
Data Classification: ESO PUBLIC

# XShooter

*Broadband Echelle Spectrogrph; 3 Channels; R~3000-18000*



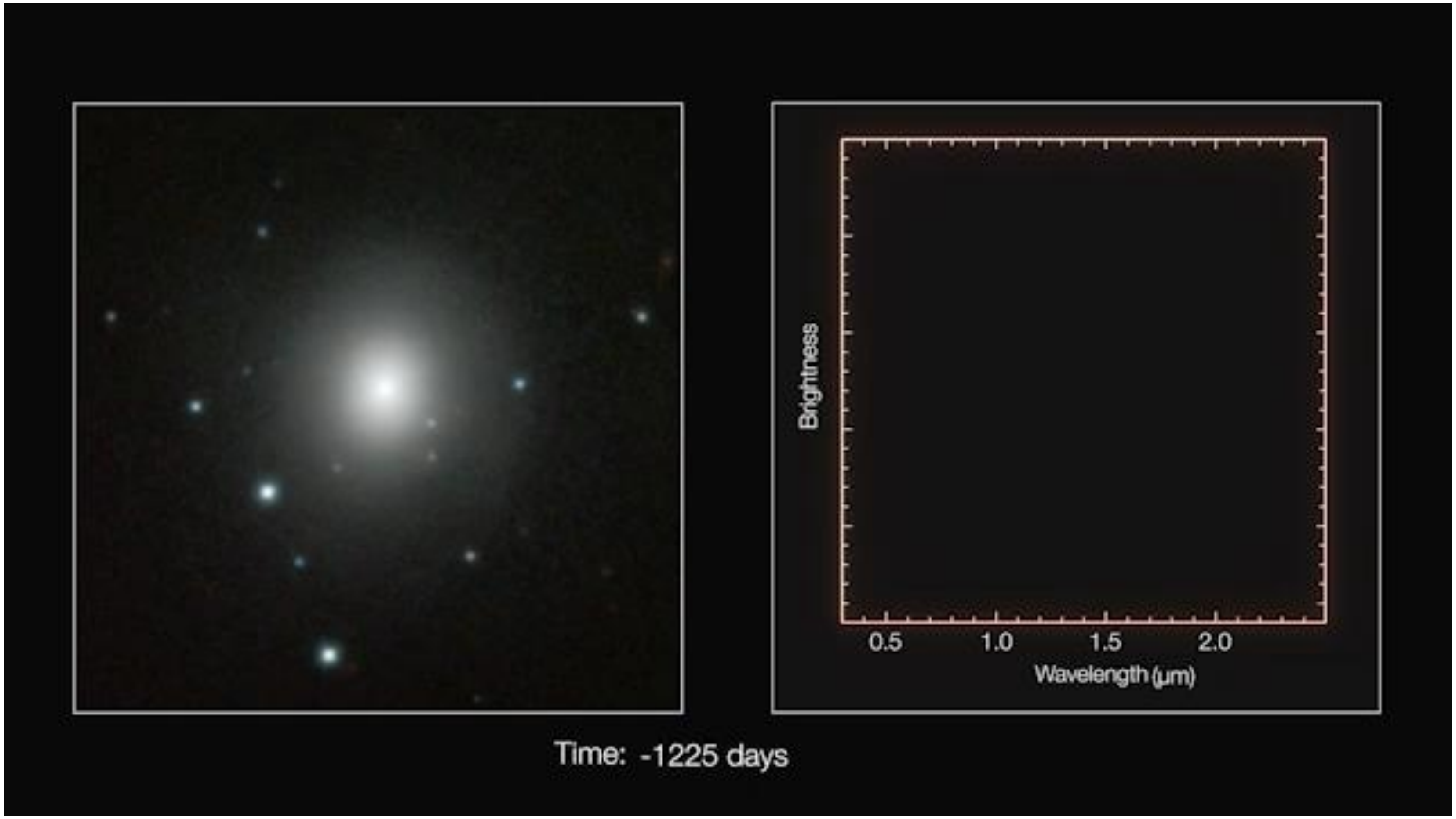

| Arm | λ-range | N. of orders | scale | AB limit |
|---|---|---|---|---|
| | (nm) | | ("/pix) | (mag) |
| UVB | 300-560 | 12 | 0.161 | 21.2 (at 356.1 nm, ord N.21)<br>21.7 (at 438.8 nm, ord N.17) |
| VIS | 550-1020 | 15 | 0.158 | 20.9 (at 653.8 nm, ord N.35)<br>20.8 (at 777.6 nm, ord N.21) |
| NIR | 1020-2480 | 16 | 0.248 | 21.0 (at 1245.2 nm, ord N.21)<br>20.6 (at 1634.4 nm, ord N.16)<br>18.7 (at 2179.2 nm, ord N.12) |



Data Classification: ESO PUBLIC

# XShooter observations of first Kilonova

*Broadband Echelle Spectrogrph; 3 Channels R~3000-18000*




- Gravitational Wave and GRB triggers
- Identification of candidates to be the ever-observed optical counterpart of a GW
- Spectroscopic follow up for 1 month
- Heavy elements produced by r-processes in binary Neutron Star merger

Abbott et al. 2017

# Integral Field Spectrographs

## MUSE, ERIS, KMOS

# Integral Field Units

| Instrument | Spectral Coverage | Observing Mode | Spectral Resolution | Multiplex | Note |
|---|---|---|---|---|---|
| MUSE | optical<br><br>465 - 930 nm | integral field spectroscopy | 1770 @ 480nm<br><br>3590 @ 930nm | no | IFU size on sky 60"x60" with spaxel size 0.2" (WFM) or 7.5"x7.5" with spaxel size 0.025" (NFM); GLAO, LTAO, no AO; RRM. |
| KMOS | near-IR<br>0.8 - 2.5 µm | multi-object integral field spectroscopy (24 arms) | 1800 - 4000 | yes | 24-arms Integral Field Spectroscopy; 2.8x2.8", 0.2" sampling IFU over a 7.2' field; |
| ERIS | near-IR 1-5 µm | imaging, coronagraphy: apodizing phase plate (K/L-band only) and focal plane coronagraphy (L/M-band only), sparse aperture mmask interferometry, integral field spectroscopy (JHK), long-slit spectroscopy (L-band only) | 5000-11200 (IFS), 900 (NIX long-slit spectroscopy) | no | AO modes: NGS, LGS, LGS-SE, noAO |

# MUSE

*Multi Unit Spectroscopic Explorer*

Wide Field Mode (Currently offered)

| | |
|---|---|
| Field of view | 59.9"x 60.0" |
| Spatial Sampling | 0.2" /pixel |
| Spatial resolution (FWHM) | 0.4" @ 700nm |
| Resolving power | 1770 (480 nm) -- 3590 (930 nm) |
| Limiting magnitude<br>(1 hr, airmass=1.0, seeing 0.8"@V) | $V_{AB}$ = 22.64 mag (550 nm)<br>$R_{AB}$ = 22.70 mag (650 nm)<br>$I_{AB}$= 22.28 mag (784.9 nm) |

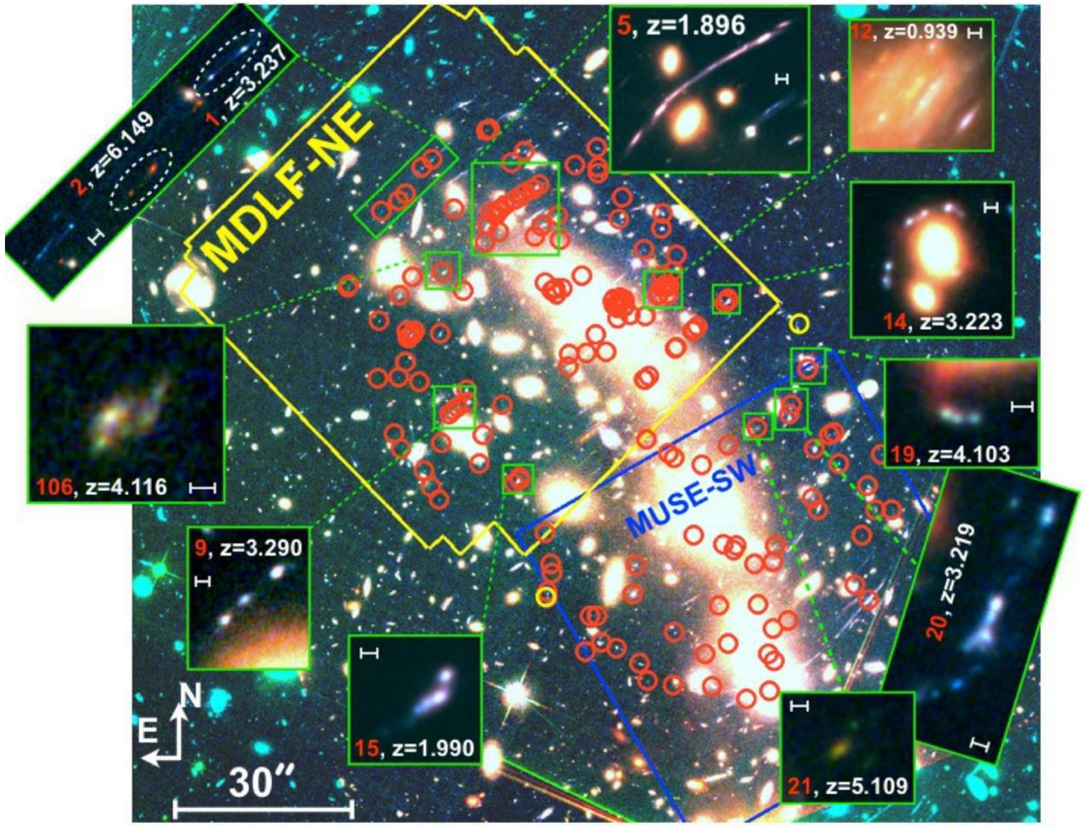
Wide Field Mode with AO (Currently offered)

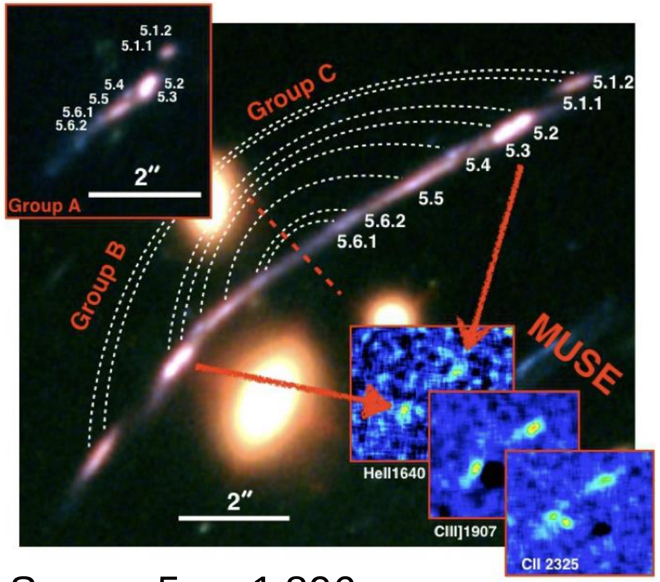
| | |
|---|---|
| Gain in ensquared energy within one pixel with respect to seeing | 2 |
| Condition of operation with AO | 70th percentile |
| Sky coverage with AO | 70% at Galactic Pole |

Narrow Field Mode (Currently offered)

| | |
|---|---|
| Field of view | 7.42" x 7.43" |
| Spatial Sampling | 0.025" / pixel |
| Spatial resolution(FWHM) | 55 mas - 80 mas |
| Resolving power | 1740 (480 nm) -- 3450 (930 nm) |
| Ensquared Energy (25 mas) | 10% - 1% |
| Predicted limiting flux in 1 hr | $2.3 \times 10^{-18}$ erg $s^{-1}$ $cm^{-2}$ |
| Predicted limiting magnitude in 1 hr | $R_{AB}$ = 22.3 mag |
| Predicted limiting surface brightness in 1 hr | $R_{AB}$ = 17.3 mag $arcsec^{-2}$ |

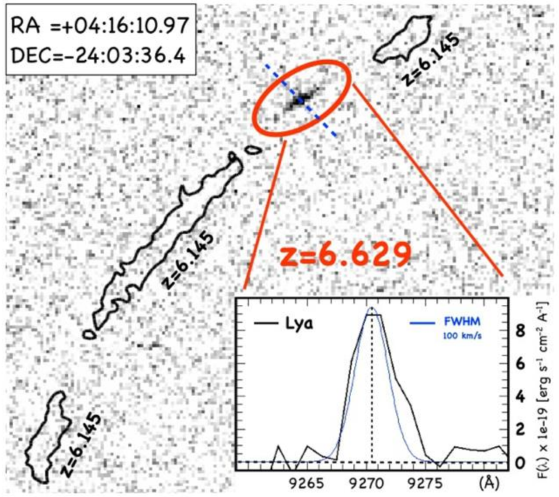
# MUSE Deep Lensed Field on Hubble Frontier Field MACS J0416




Source 5, z=1.896

Source 2




Vanzella et al. 2020

Candidate POPIII stellar complex at z=6.29

17.1 GALACSI/MUSE (GLAO) 30 hours on MACS J0416

Spectroscopic redshift of 48 galaxies (136 multiple images) with 0.9 < z < 6.2

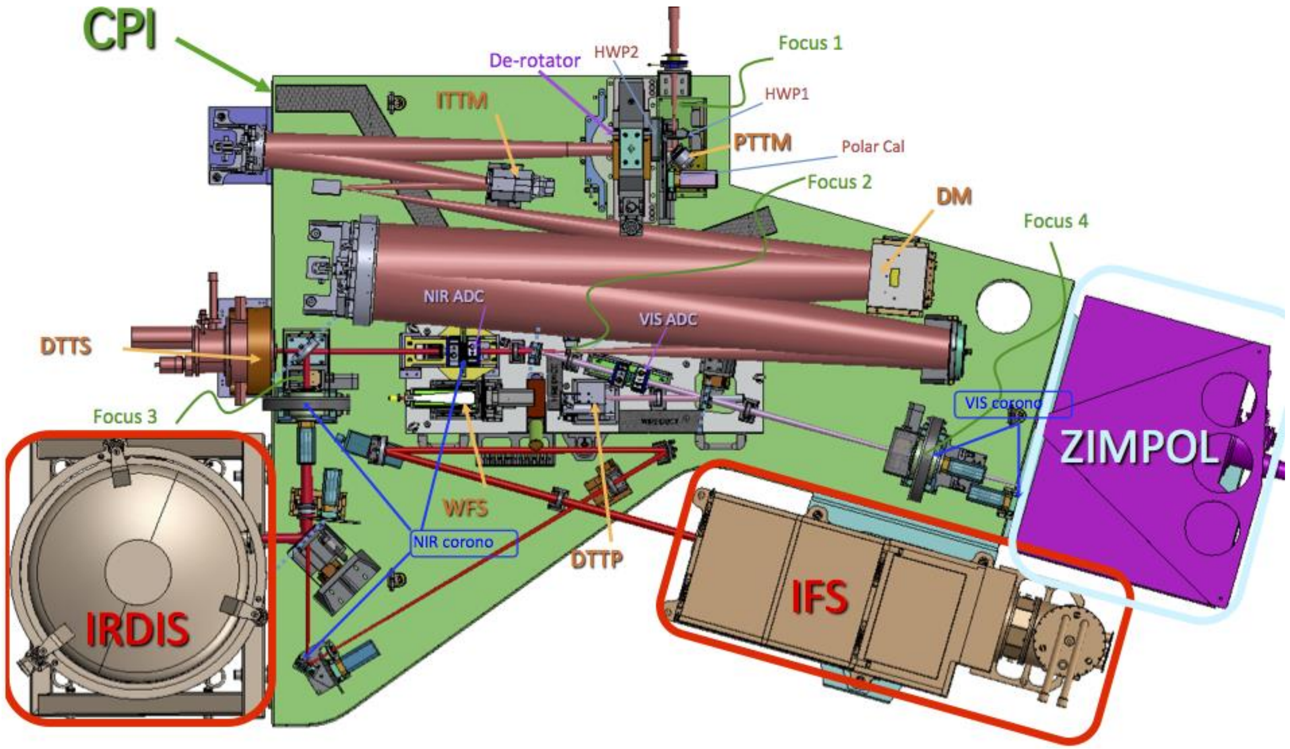
Vanzella, E.S., et al. 2021

# Specialized Instruments

## Extreme-AO assisted imaging

# SPHERE

*SPectro-polarimetric High contrast Exoplanet REsearch*




| AO performance | H-band Strehl Ratio | R-band Strehl Ratio |
|---|---|---|
| Good | > 75% | > 20% |
| Median | 50 - 75% | 5 - 20% |
| Poor | < 50% | < 5% |

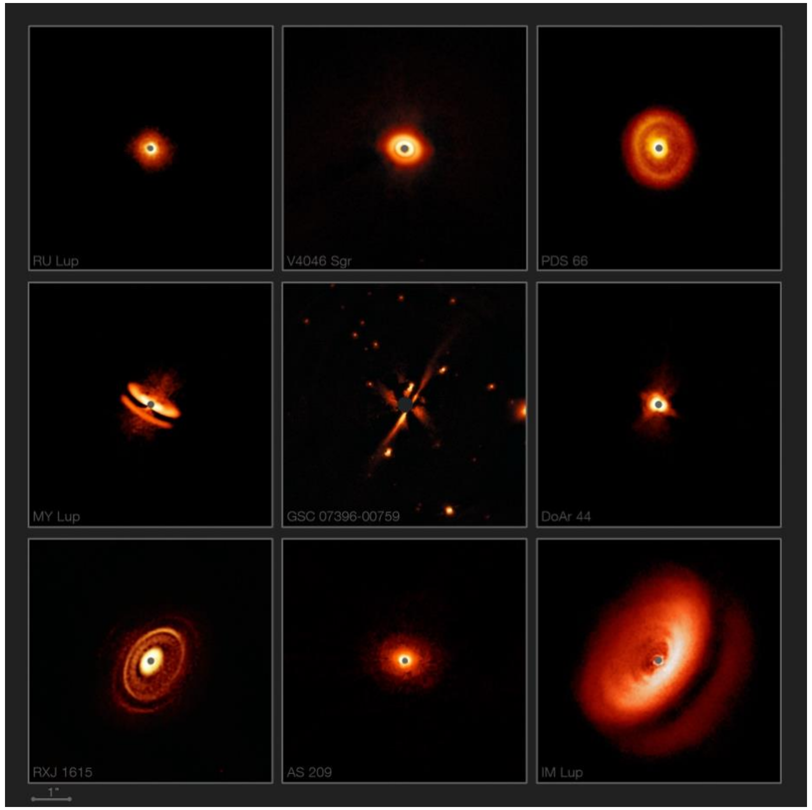
Strehl Ratio: ratio between the expected and the observed amplitude of the signal

Modes

- Dual imaging
- Long slit spectroscopy
- Dual-polarization imaging mode
- Sparse Aperture Masking
- Choronagraphy
- Integral Field Spectroscopy

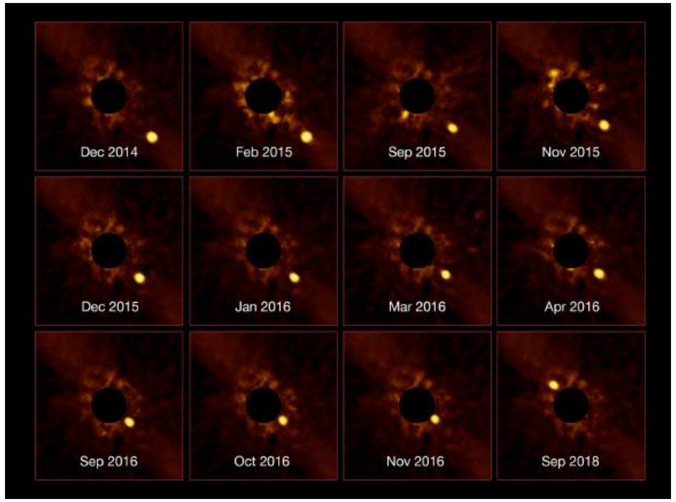
# SPHERE exoplanets ans protoplanetary disks

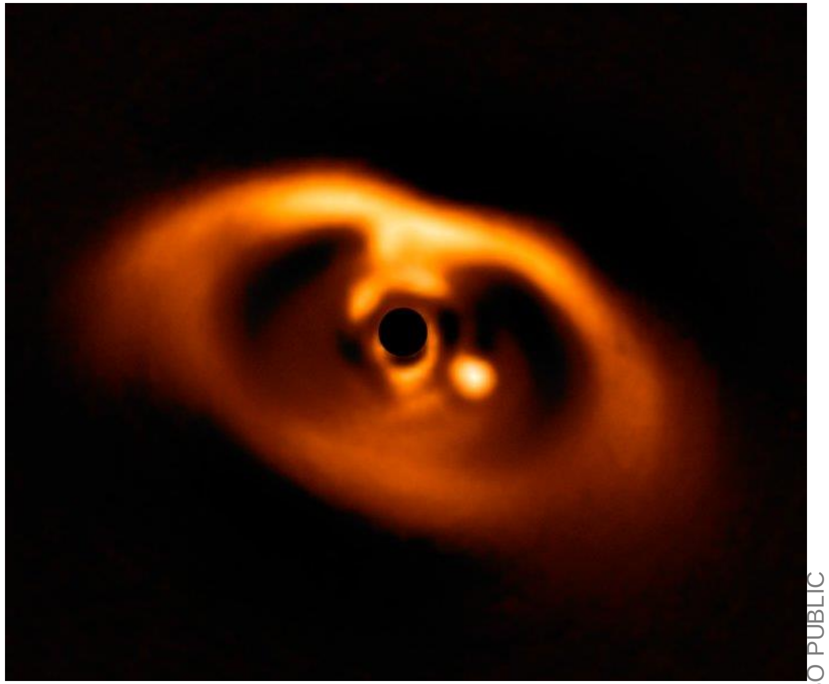
*SPectro-polarimetric High contrast Exoplanet REsearch*




Avenhaus et al. 2018
Sissa et al. 2018

Direct imaging of B Pictoris b



Newborn planet swapping the protoplanetary disk

Keppler et al. 2018
Müller et al. 2018

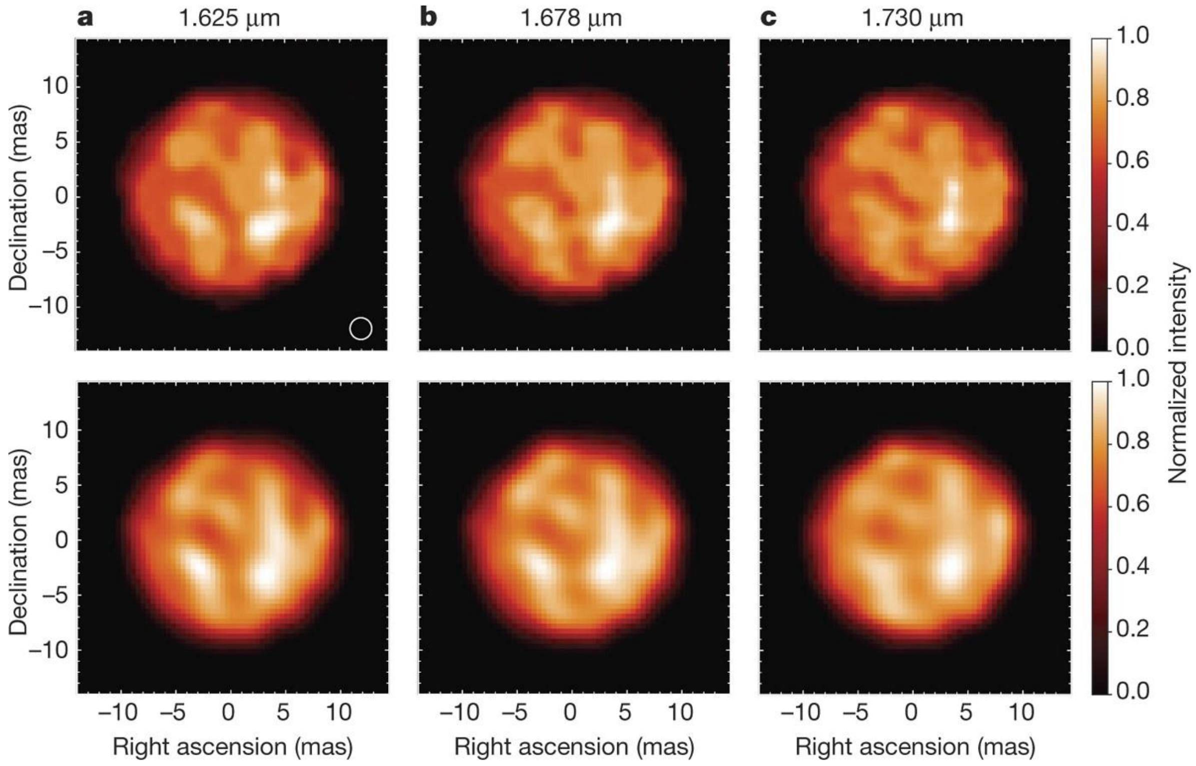
# VLT Interferometer

## PIONIER, GRAVITY, MATISSE

# Integral Field Units

| Instrument | Spectral Coverage | Observing Mode | Spectral Resolution | Multiplex | Note |
|---|---|---|---|---|---|
| GRAVITY | near-IR<br>2.05 - 2.45 µm | spectro-interferometry | R ~ 20, 500, & 4000 | no | 4 beam combiner - delivers spectrally dispersed visibilities, differential and closure phases |
| MATISSE | mid-IR<br>2.8 - 4.1 µm<br>4.5 - 5 µm<br>8 - 13 µm | spectro-interferometry | R ~ 30 (covers L&M-band)<br>R ~ 506, 959, 3666 (L or M band)<br>R ~ 30, 218 (N band) | no | 4 beam combiner - delivers spectrally dispersed visibilities, differential and closure phases |
| PIONIER | near-IR<br>1.65 µm | spectro - interferometry | R ~ 5 or 40 | no | 4 beam combiner - delivers spectrally dispersed visibilities and closure phases |

# VLTI-PIONIER Images of a star



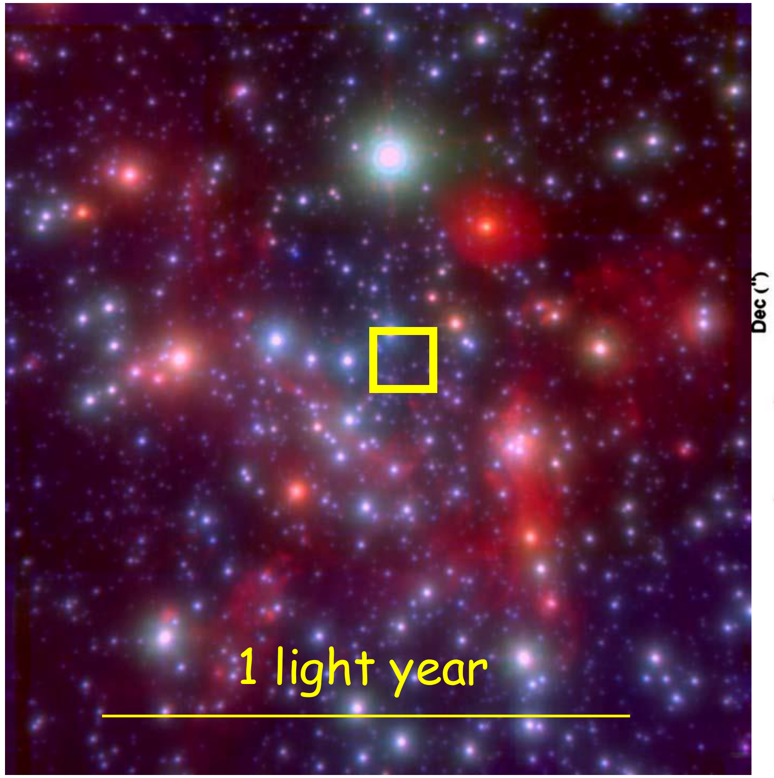

Large granulation cells detected on the surface of a giant star

Paladini et al. 2017

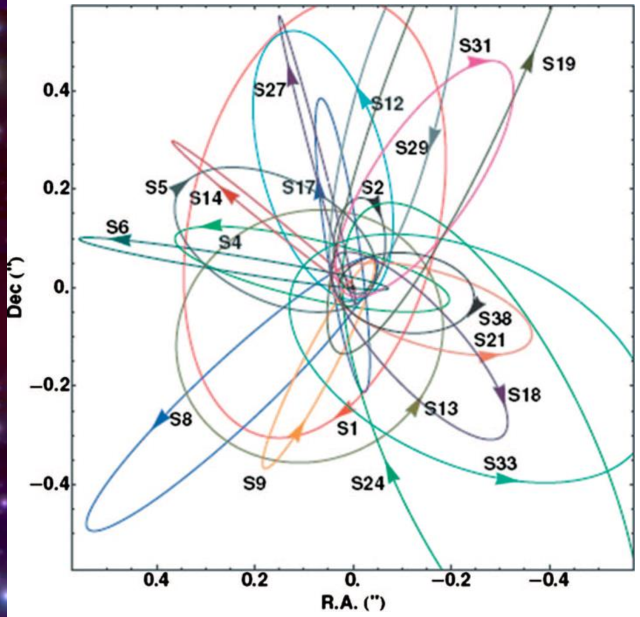
Data Classification: ESO PUBLIC

# GRAVITY ‘weights’ the Supermassive Black Hole in the Milky way

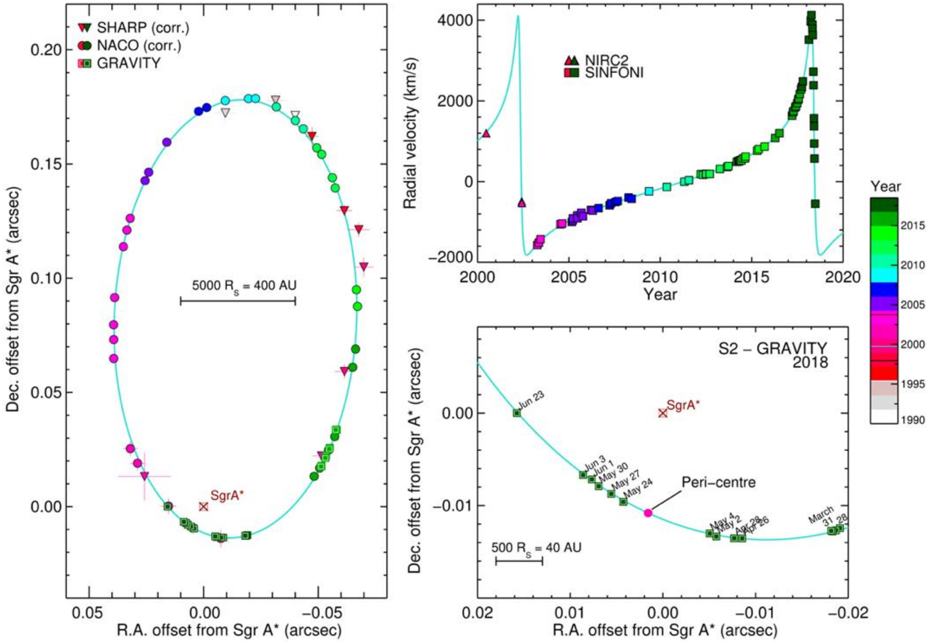
# GRAVITY ‘weights’ the Supermassive Black Hole in the Milky way




NACO – AO imaging




Gillessen et al. 2009




Gravity collaboration 2018

$M_{BH} \sim 1.6 \times 10^{6}$ MSun