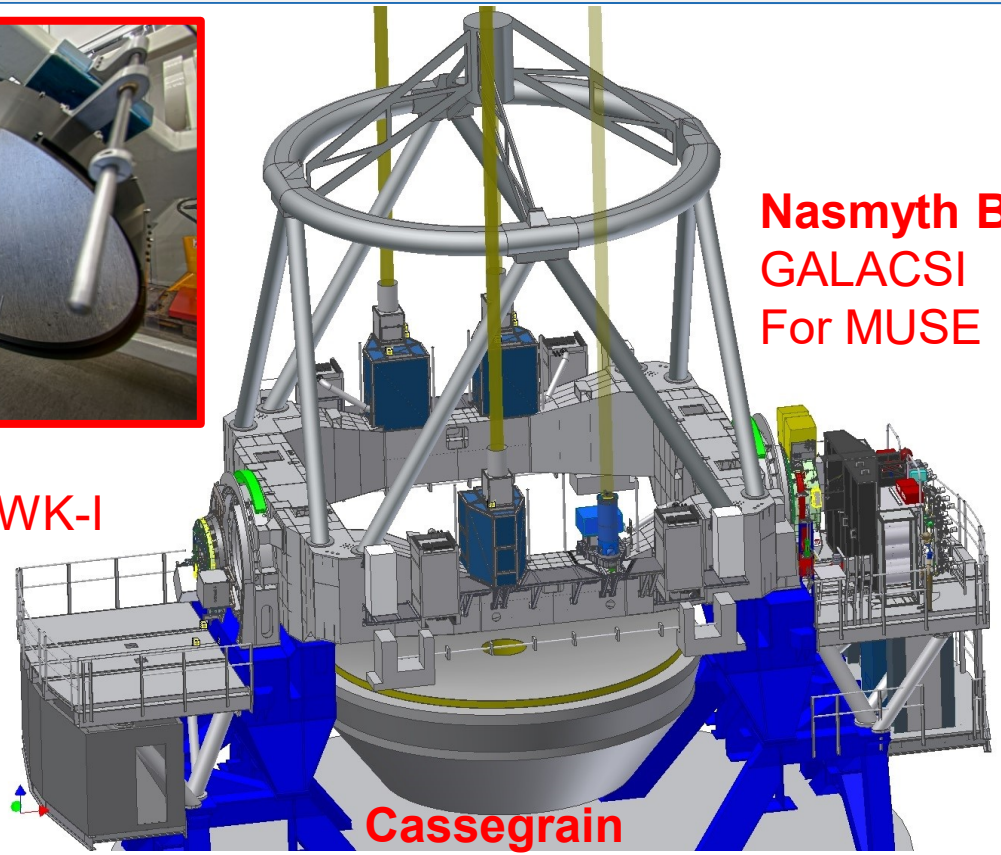
# MUSE/GALACSI NFM: VLT's LTAO mode and its upgrades

Sylvain Oberti
On behalf of the AOF / GALACSI / IRLOS+ team
LAM seminar - 04.11.21

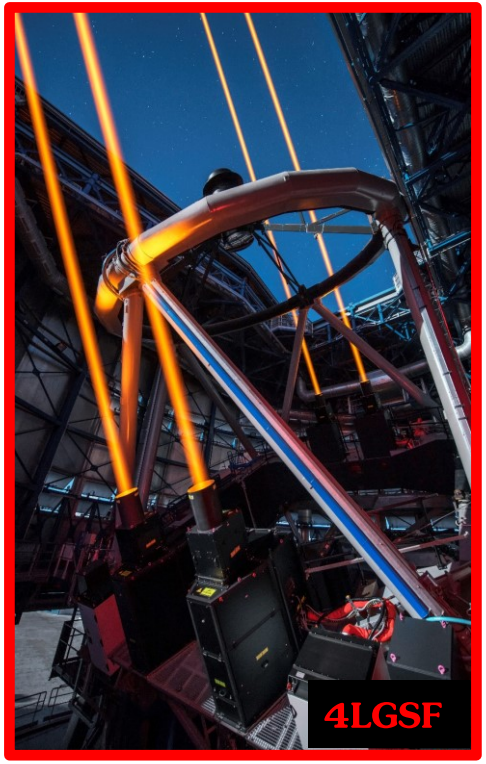
# The Adaptive Optics Facility @ VLT's UT4


**Nasmyth A**

- GRAAL for HAWK-I
- *Future: MAVIS*



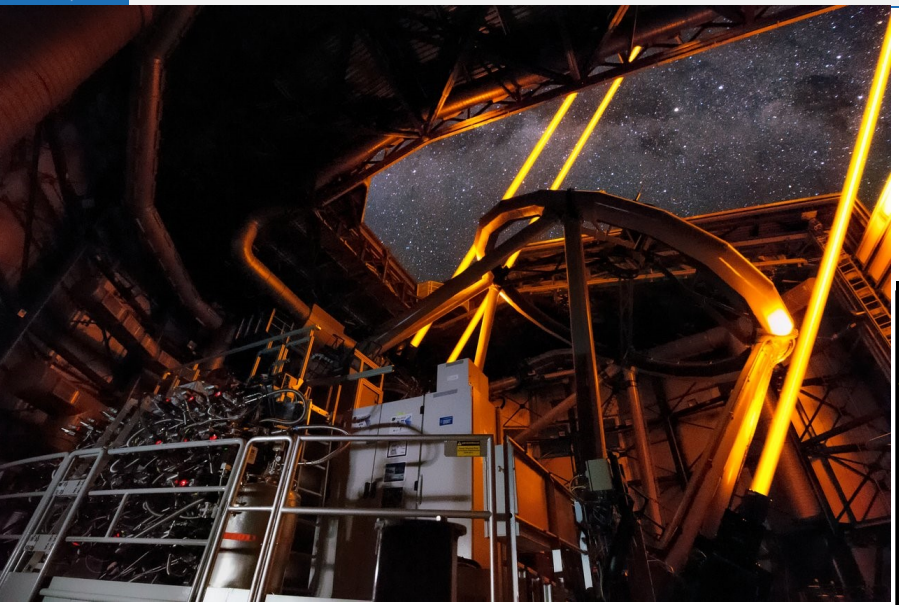
**Nasmyth B**
GALACSI
For MUSE




**Cassegrain**
Near future: ERIS

# AOF team: 2006-2021

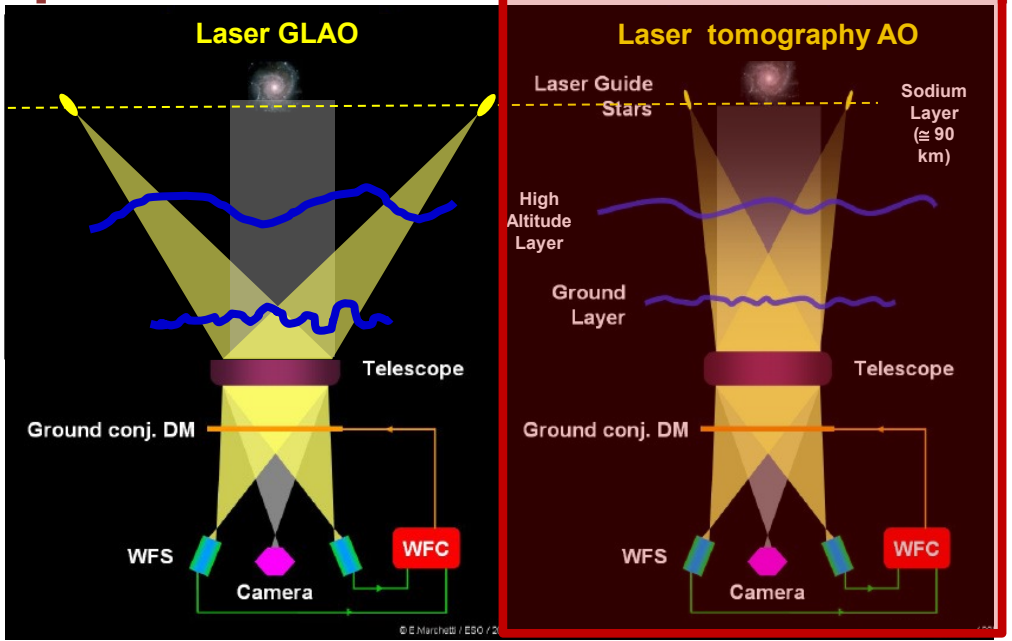
# MUSE: AO modes of GALACSI



## Performance requirements

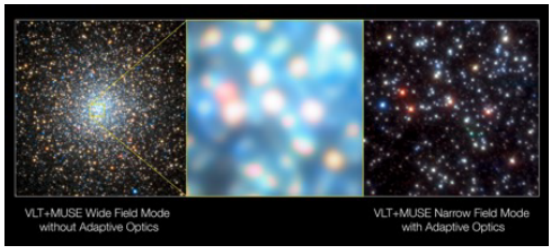
- WFM: improve EE x2 in 0.2” over 1’
- NFM: SR > 5% (goal 10%) @ 650 nm

## GALACSI NFM



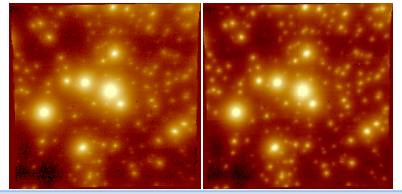
# GALACSI NFM Upgrades Timeline

**NFM commissioning Q1 2018**

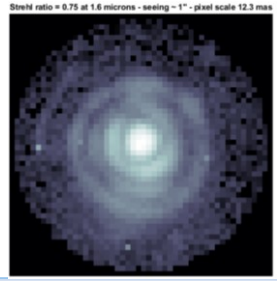



Credit: ESO/S. Kammann

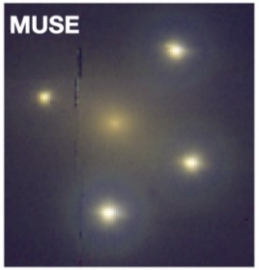
**IRLOS+ Start March 2019**



**Tomography optimization October 2019**

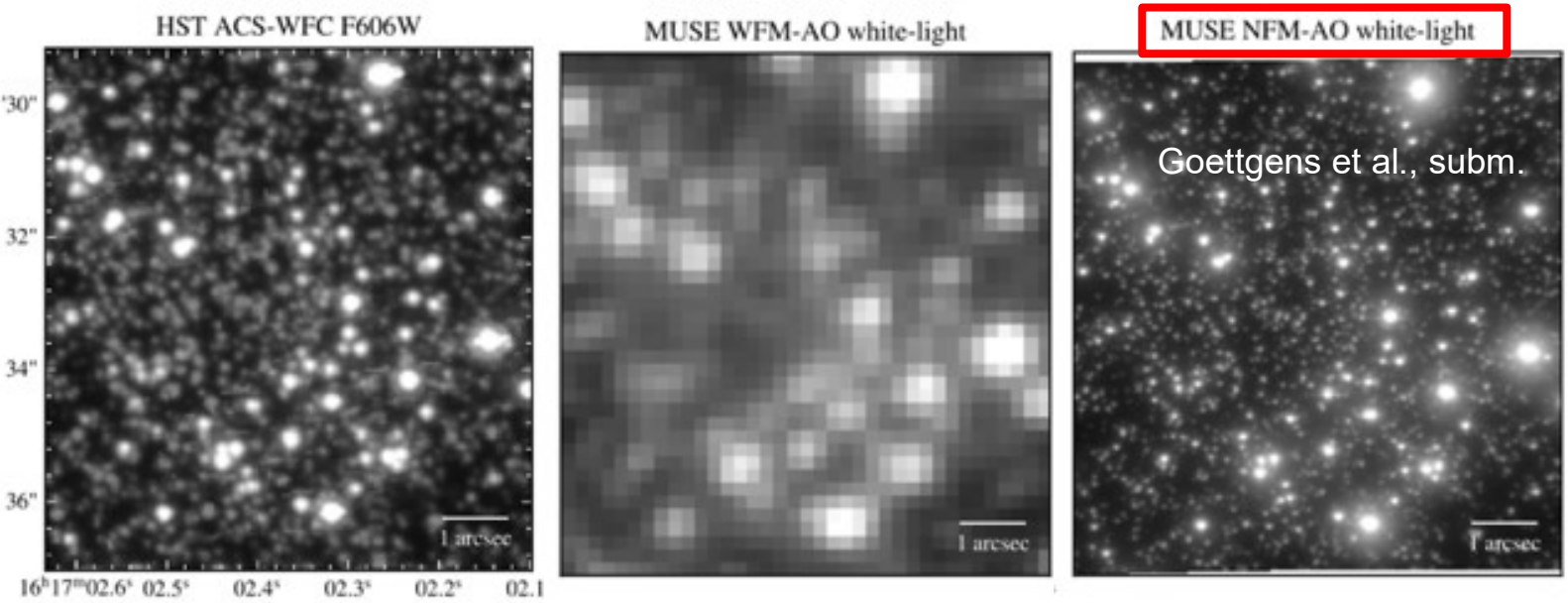



**IRLOS+ AIV & Comm 1 March 2021**




**IRLOS+ Comm 2 July 2021**

# GALASCI/MUSE Narrow Field Mode




- The LTAO mode of MUSE is providing high spatial resolution in the visible domain
- Performance limitation by suboptimal tomography
- TT residuals and limiting magnitude of Jmag=15

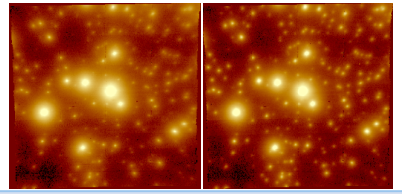
→ **Tomography optimization**

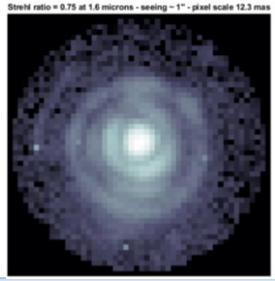
→ **IRLOS Upgrade**

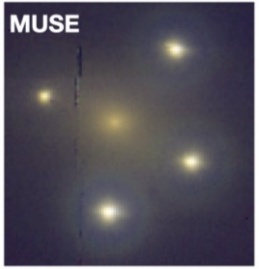
# GALACSI NFM Upgrades Timeline

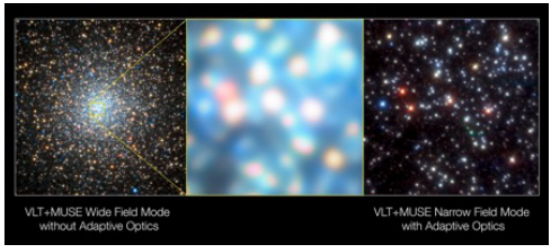
NFM commissioning Q1 2018

IRLOS+ Start March 2019





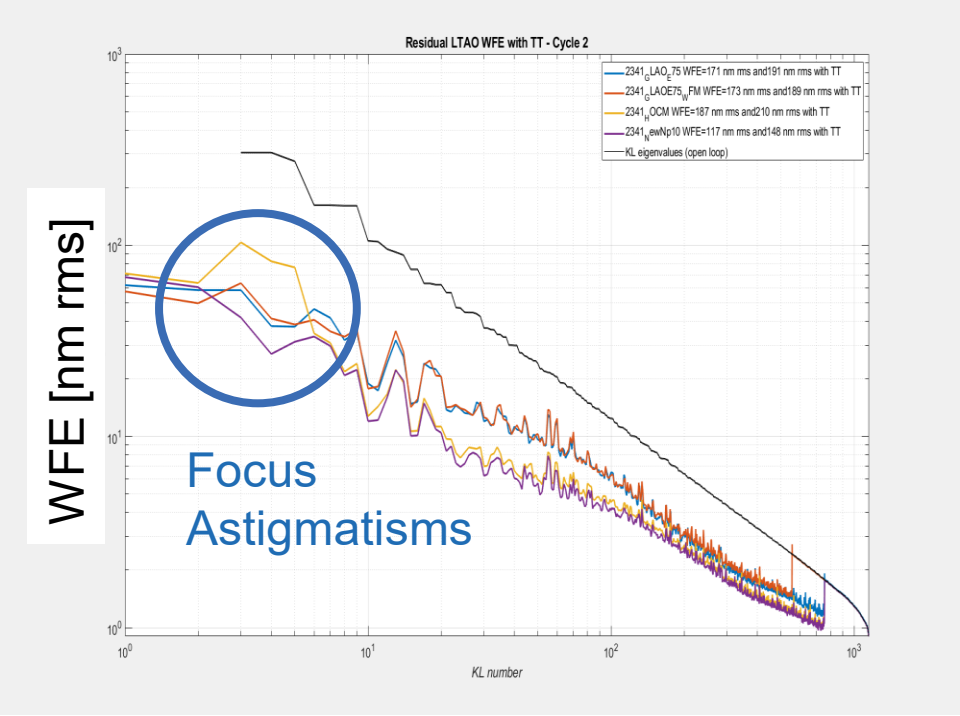

Credit: ESO/S. Kammann

**Tomography optimization October 2019**

IRLOS+ AIV & Comm 1 March 2021

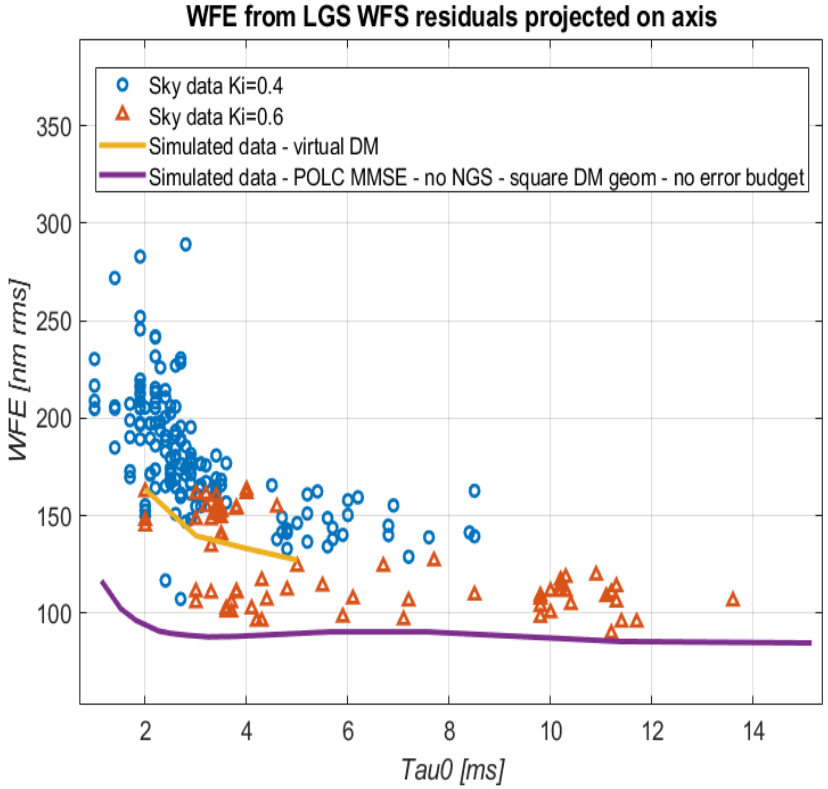
IRLOS+ Comm 2 July 2021

# Tomography Optimization in October 2019: I



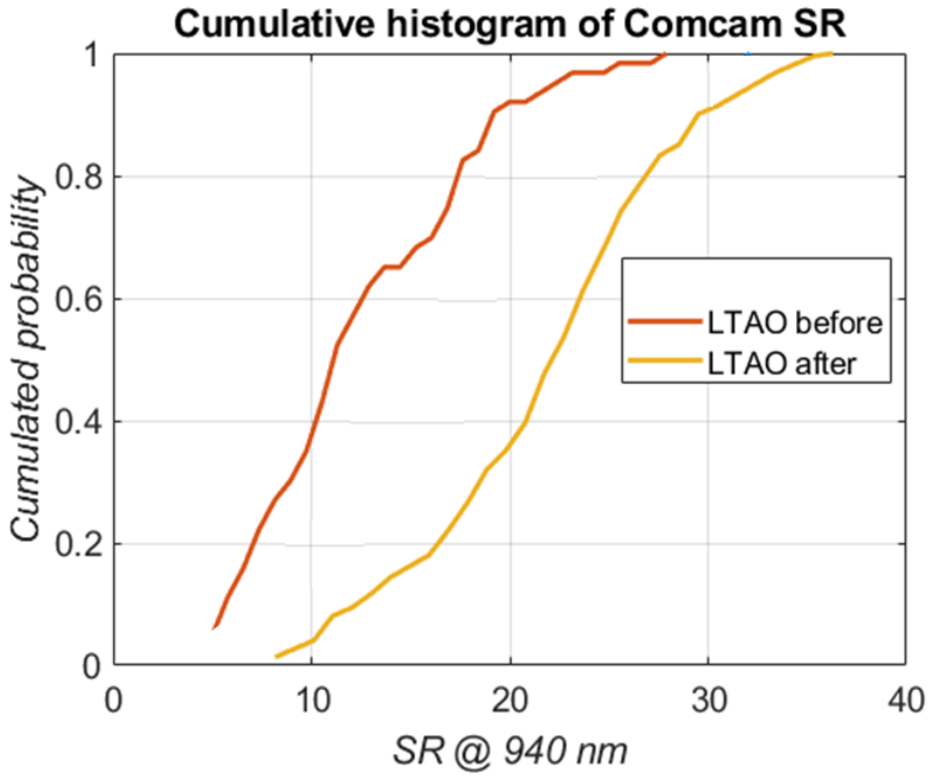

- Pseudo-synthetic reconstructor
- Tuned tomographic reconstruction of LO modes
- More aggressive tuning of LTAO reconstructor leading to controlling 850 modes
- Tuning of temporal controller in presence of new vibrations
- Operation under worse seeing conditions than initially expected

# Tomography Optimization in October 2019: I



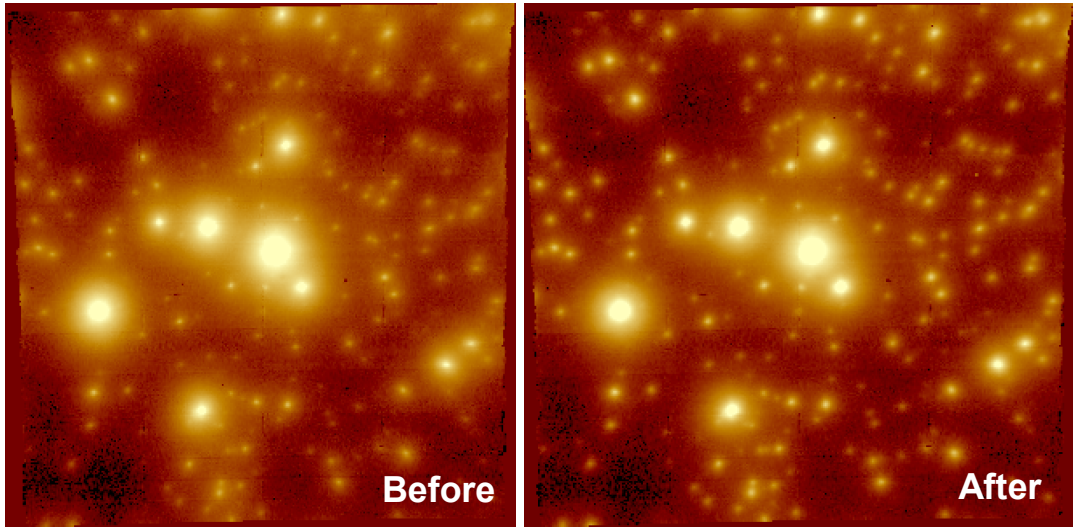

- Pseudo-synthetic reconstructor
- Tuned tomographic reconstruction of LO modes
- More aggressive tuning of LTAO reconstructor leading to controlling 850 modes
- Tuning of temporal controller in presence of new vibrations
- Operation under worse seeing conditions than initially expected

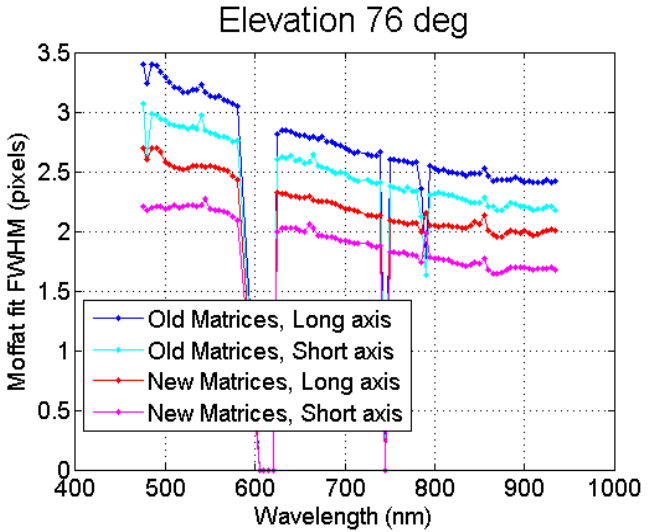
# Tomography Optimization in October 2019: I




- Pseudo-synthetic reconstructor
- Tuned tomographic reconstruction of LO modes
- More aggressive tuning of LTAO reconstructor leading to controlling 850 modes
- Tuning of temporal controller in presence of new vibrations
- Operation under worse seeing conditions than initially expected

# Tomography Optimization in October 2019: II

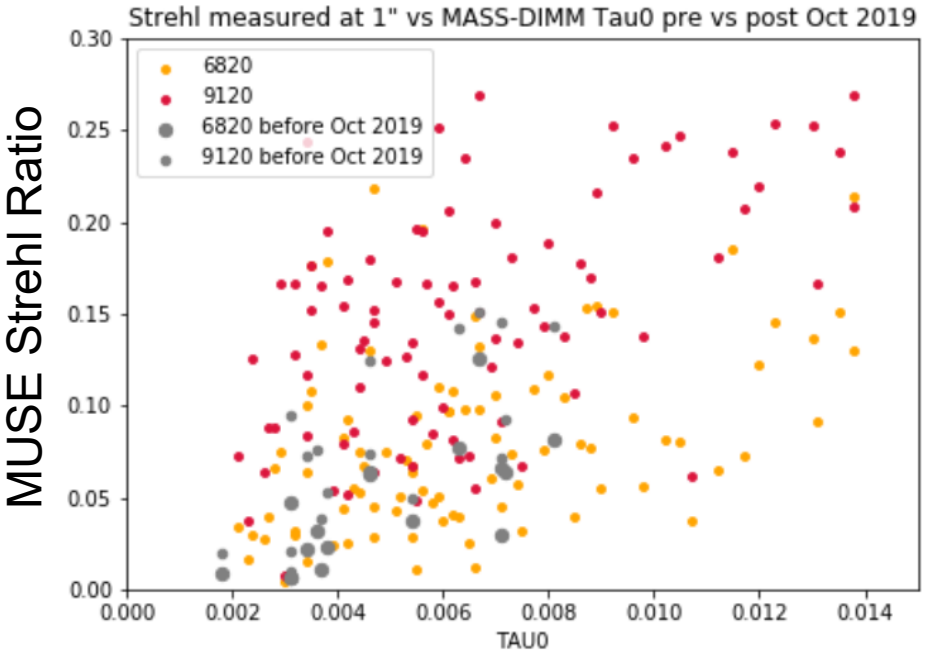


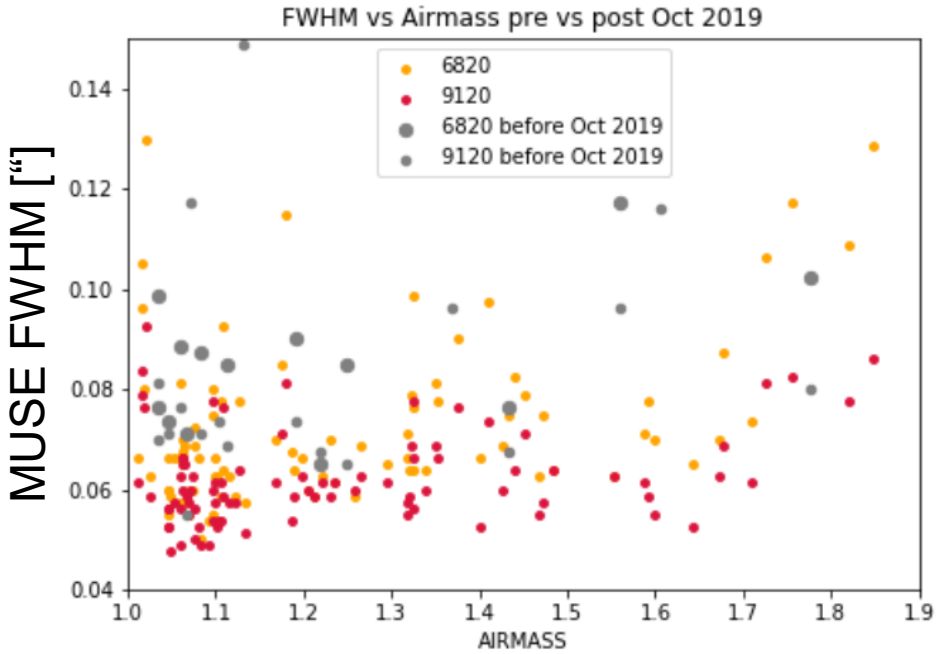




*Credit: Johanna Hartke and Claudia Reyes*

- Under good to median seeing conditions, PSF FWHM are as low as 35 mas (28 mas on the commissioning camera) at wavelengths ~ 900 nm.

# Tomography Optimization in October 2019: III



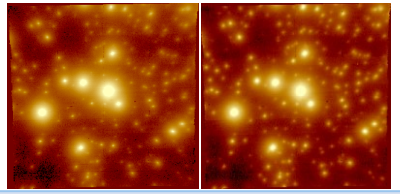



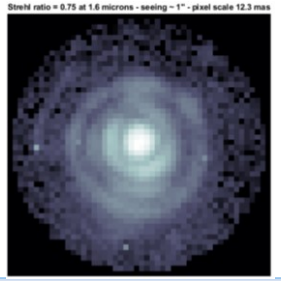

*Credit: Fernando Selman and Johanna Hartke*

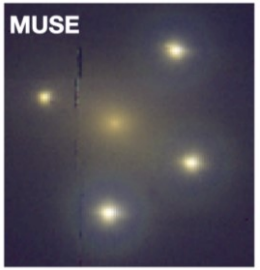
# GALACSI NFM Upgrades Timeline

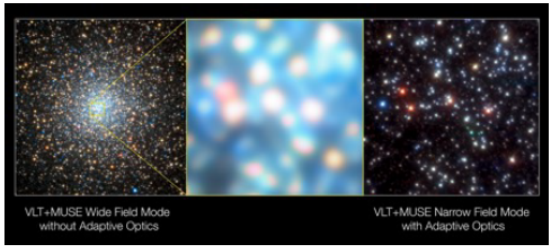
NFM commissioning Q1 2018

**IRLOS+ Start March 2019**






Credit: ESO/S. Kammann

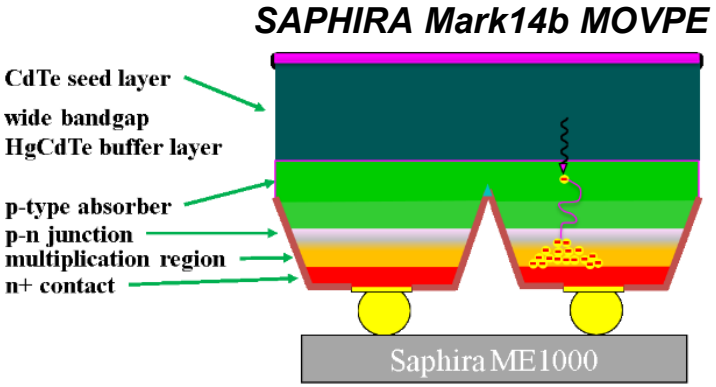
Tomography optimization October 2019

IRLOS+ AIV & Comm 1 March 2021

IRLOS+ Comm 2 July 2021

# IRLOS: The Low Order WFS for MUSE NFM

- IRLOS: InfraRed Low Order Sensor operating in J + H band
- IRLOS provides:
  - Fast Tip/Tilt control
  - Truth sensing for Defocus and Astigmatisms
  - Large scale for extended targets
- Old IRLOS Hawaii I with RON ~ 11 e- rms
- IRLOS Upgrade TLRs
  - Move to Saphira technology (baseline for **MAVIS, HARMONI** and **MAORY**)
  - Gain 2 magnitudes (goal)
  - Complete project within 2 years

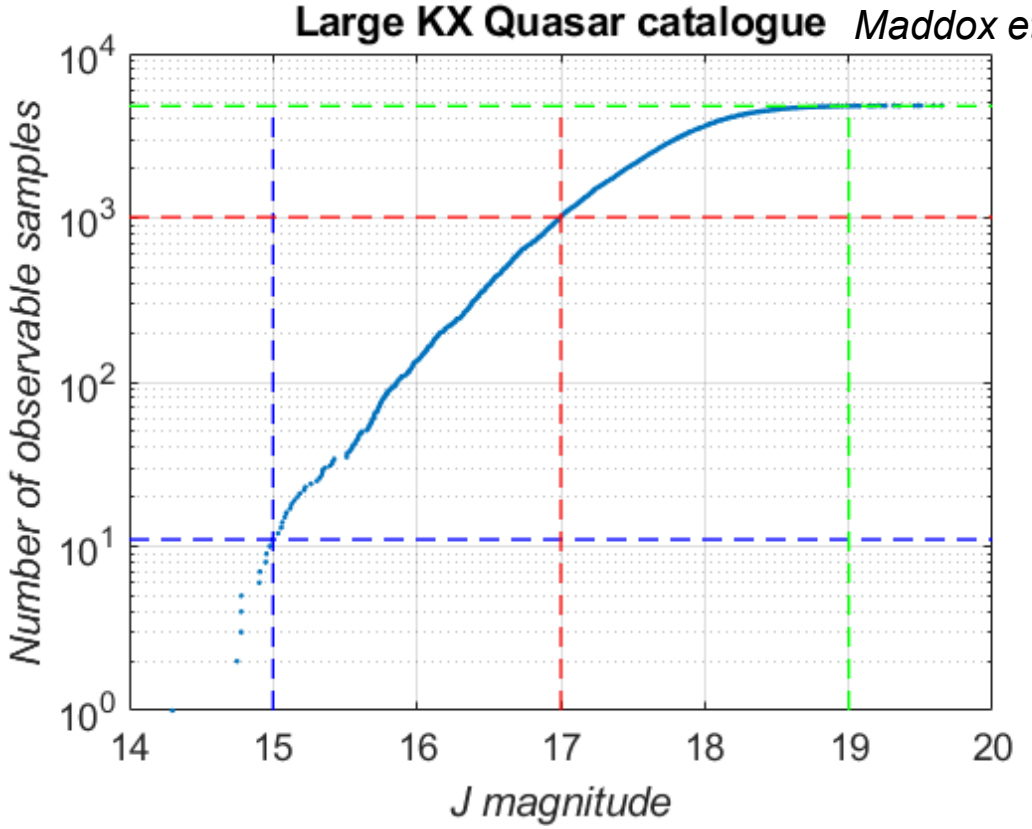


# Why upgrading IRLOS ?
# Design driver1: limiting magnitude

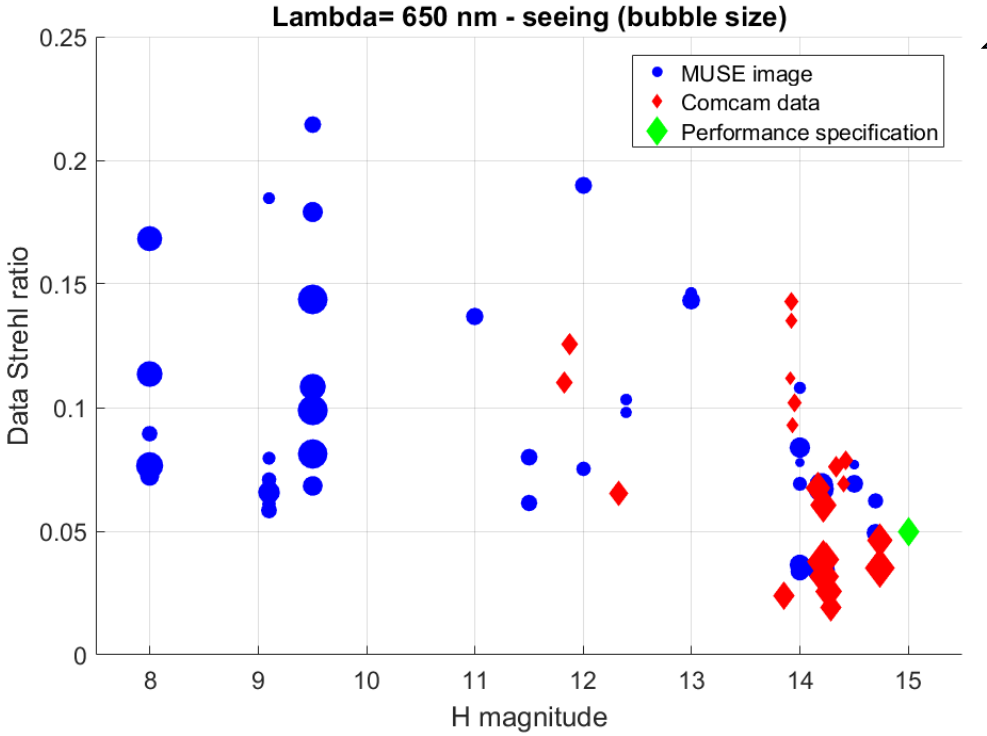
Tomorrow
Jmag=19

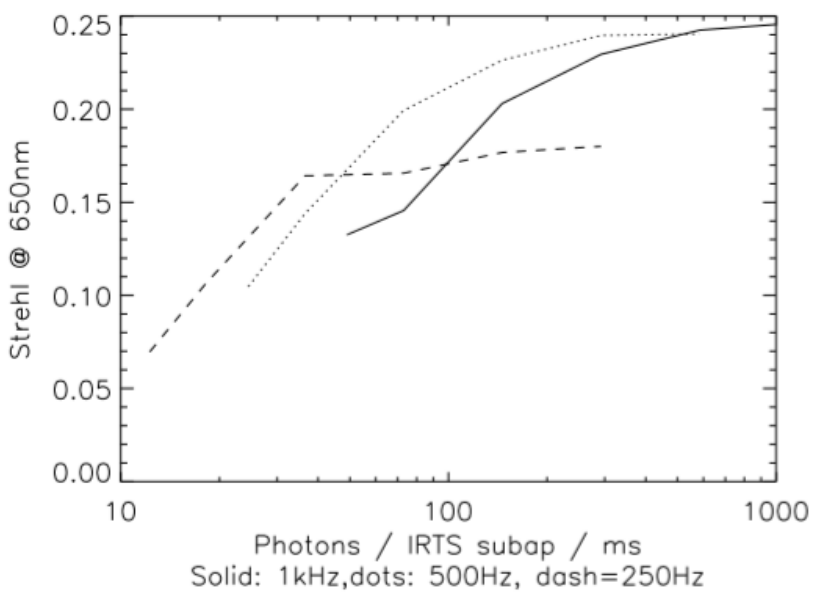
Today
Jmag=17

Yesterday
Jmag=15



# Design driver 2: improved performance



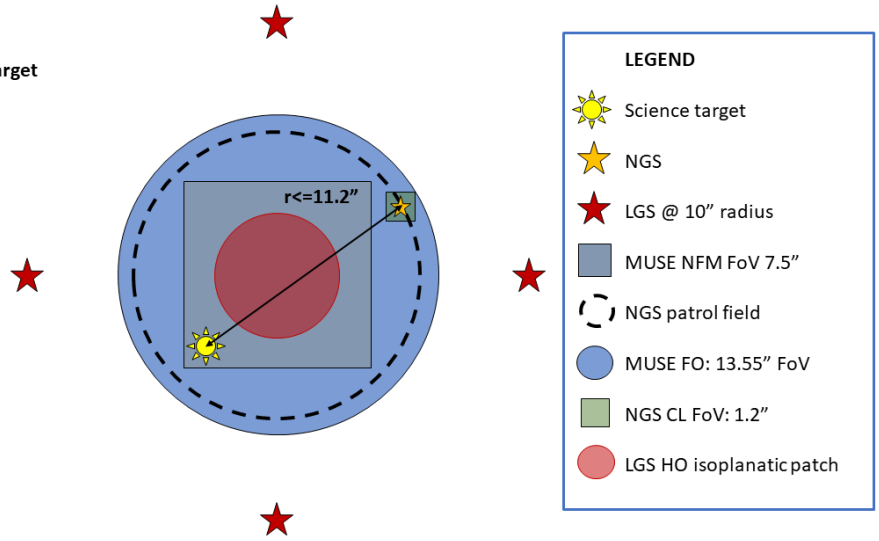



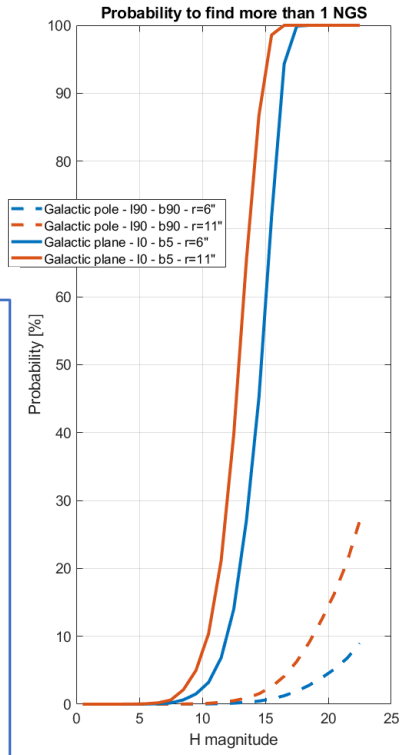

- **Yesterday, limited at 200 Hz because of the RON, now 500 Hz becomes nominal → SR/EE increase**

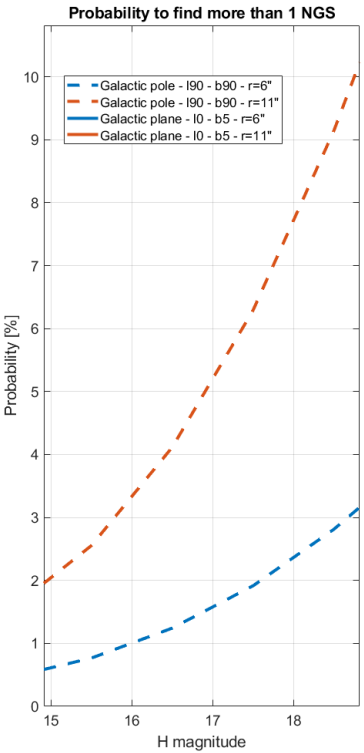
# Design driver 3: increased sky coverage

- Larger patrol field
- Larger sky coverage: Besançon model →
- Improved offsetting / dithering possibilities

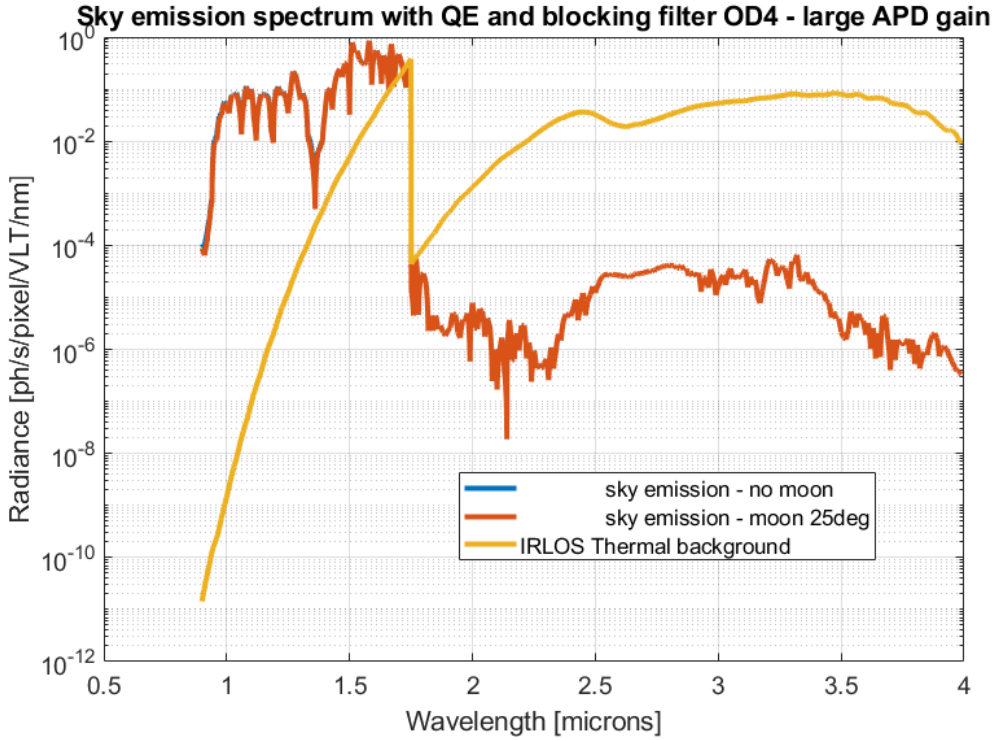
Guiding on unresolved target with small plate scale



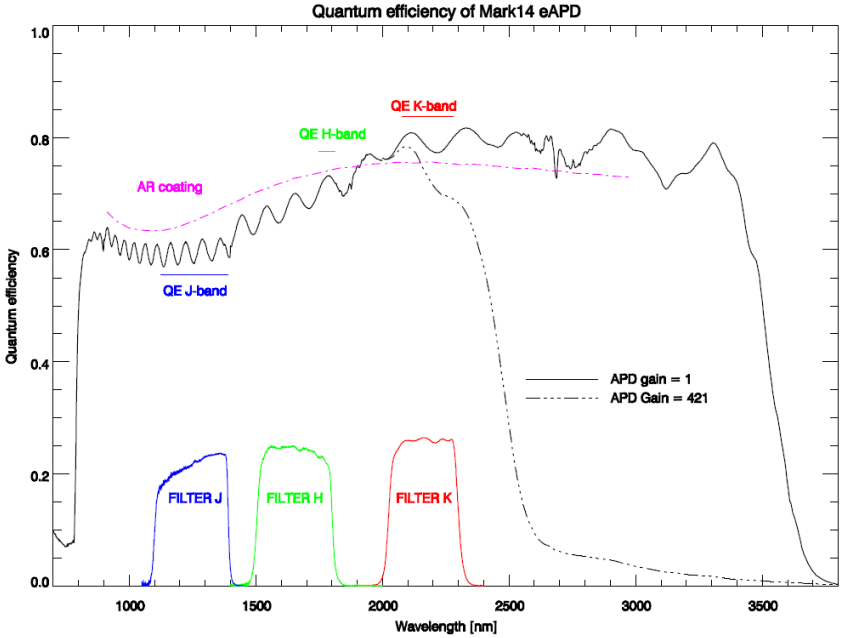



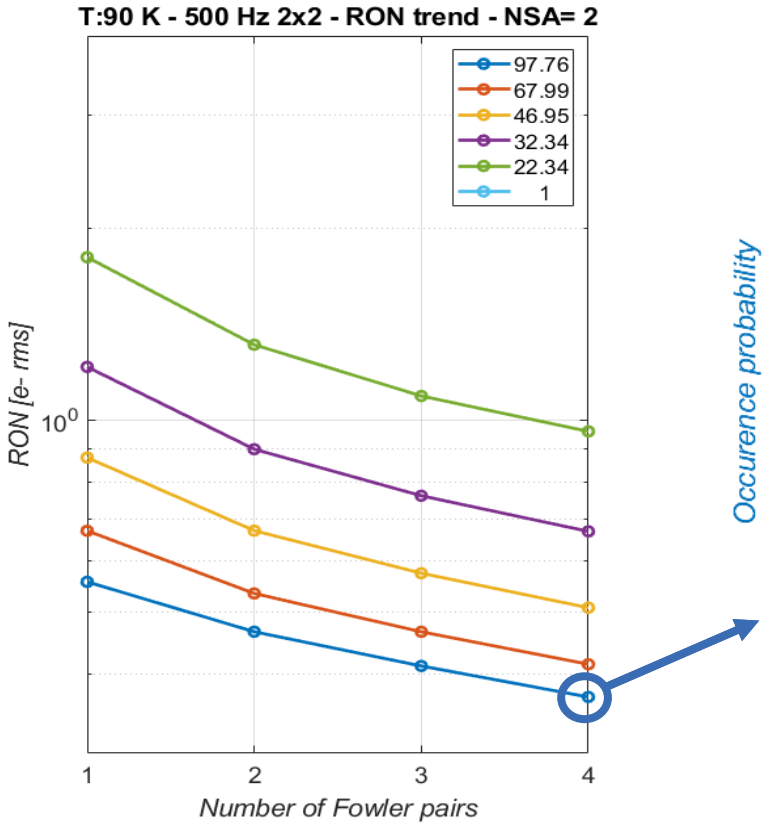
# IR WFSing: Sky + thermal background noise

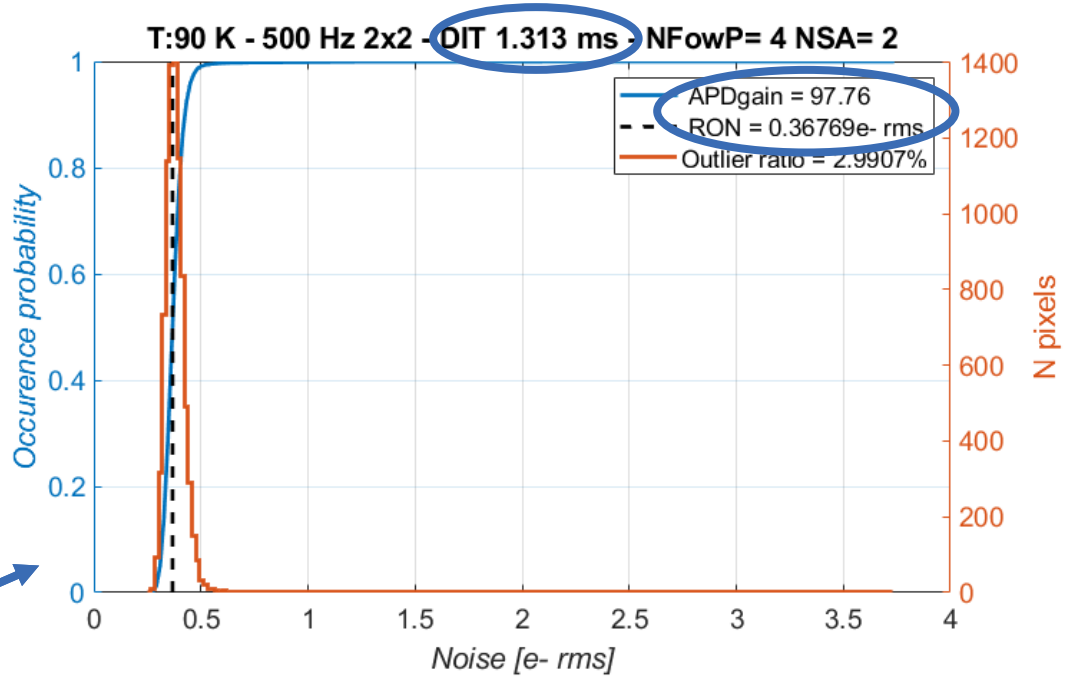



- Balanced budget for unresolved targets
  - Dark < 50 e-/s/pix
  - Thermal background < 70 e-/s/pix
  - 14e-/s/pix <Sky<140 e-/s/pix vs. plate scale



# Read-out optimization: low RON !



# Read-out optimization: SNR matters !

**FOWLER SAMPLING**

SIGNAL:

$$S = F \cdot T_{eff} = F \cdot \left(T_{int} - N_p \cdot dt\right)$$

NOISE

RON LIMITED

$$\sigma_S^2 = \frac{2 \cdot \sigma_{ron}^2}{N_p}$$

POISSON LIMITED

$$\sigma_S^2 = F \cdot T_{int} + F \cdot dt \left(\frac{1}{3N_p} - \frac{4N_p}{3}\right)$$

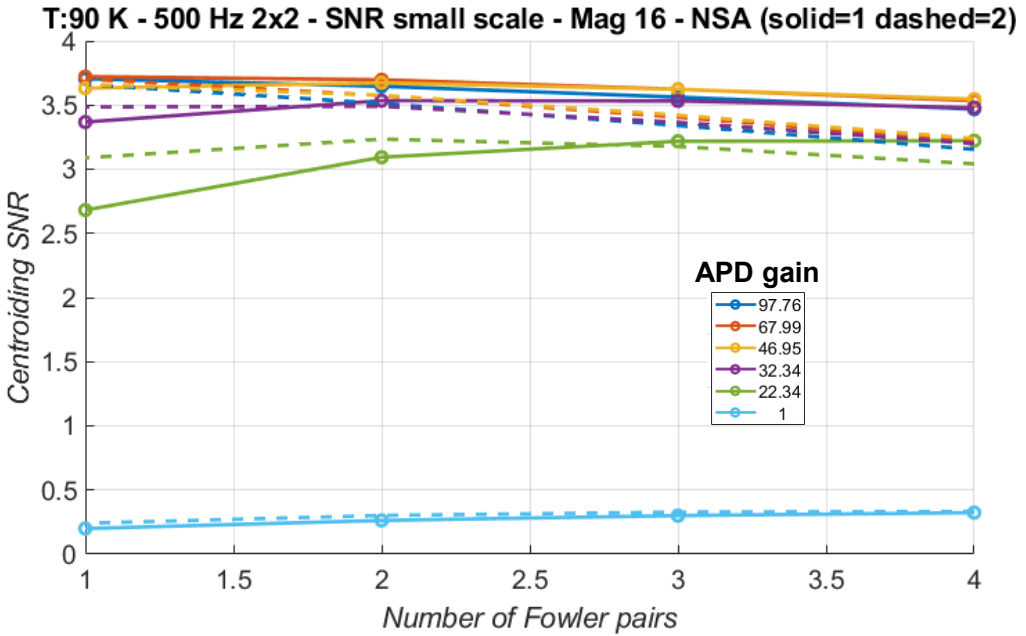
**SIGNAL TO NOISE RATIO**

$$SNR_{Fowler,RO} = SNR_{DCS}\sqrt{N_p}\left(1 - N_p \frac{dt}{T_{int}}\right)$$

$$SNR_{Fowler,Pois.} = SNR_{dcs,Pois.} \frac{1 - N_p \frac{dt}{T_{int}}}{\sqrt{1 + \frac{dt}{3T_{int}}\left(\frac{1}{N_p} - 4N_p\right)}}$$

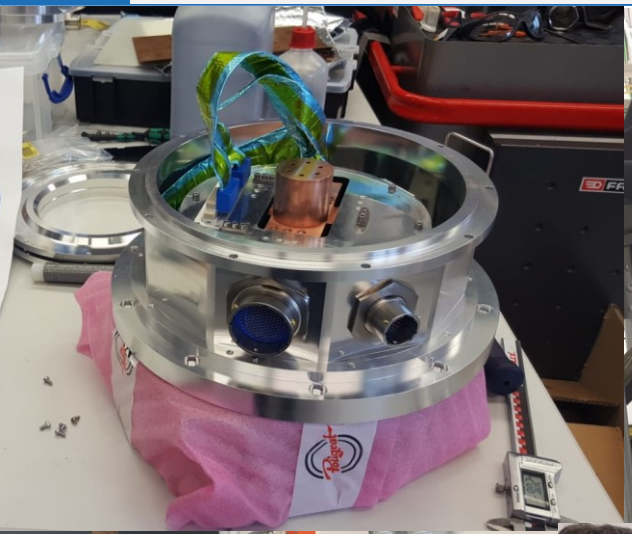
**TOTAL SIGNAL TO NOISE RATIO**

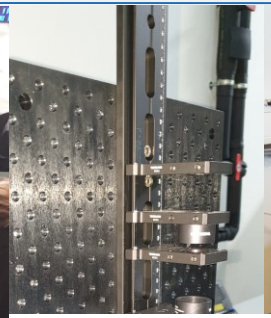
$$SNR_{Fowler} = \frac{F \cdot \left(T_{int} - n_p dt\right)}{\left[\frac{2 \cdot \sigma_{ron}^2}{n_p} + F \cdot T_{int} + F \cdot dt \left(\frac{1}{3n_p} - \frac{4n_p}{3}\right)\right]^{1/2}}$$

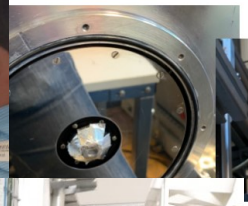
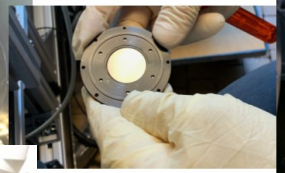
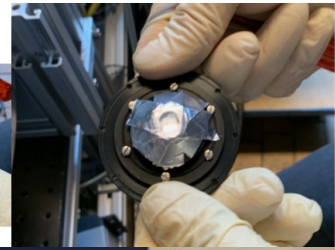


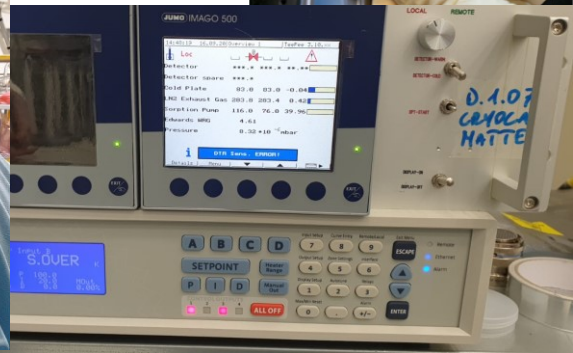

**SNR including background noise and excess noise factor**

# Design phase in 2019 / MAIT in 2020

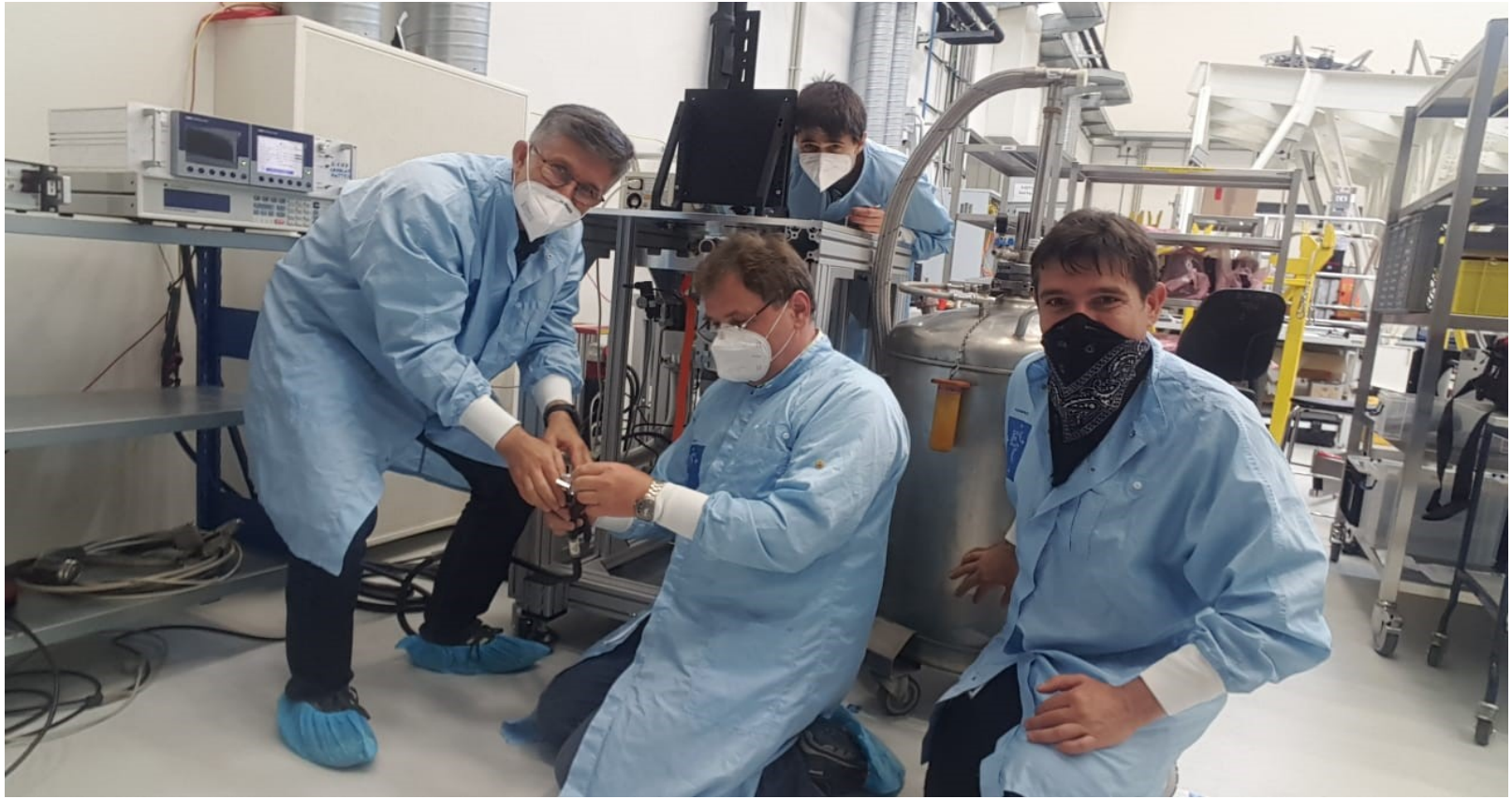




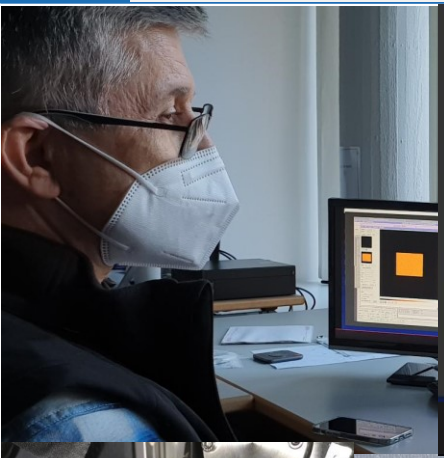




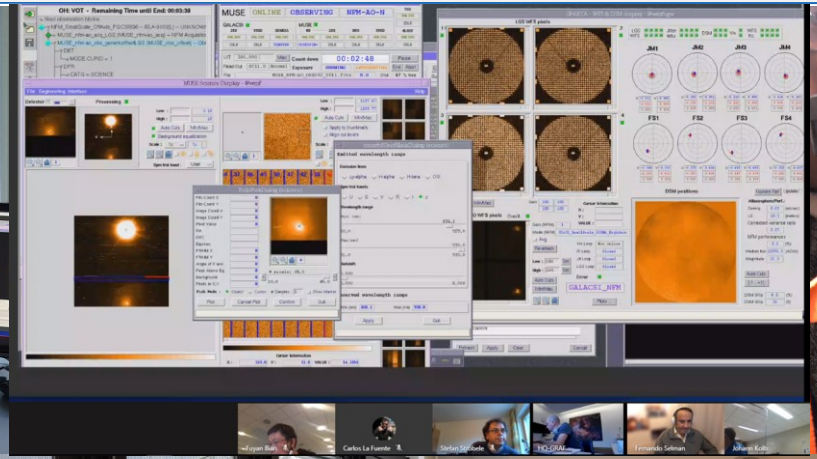



# Despite COVID, successful PAE in October 2020



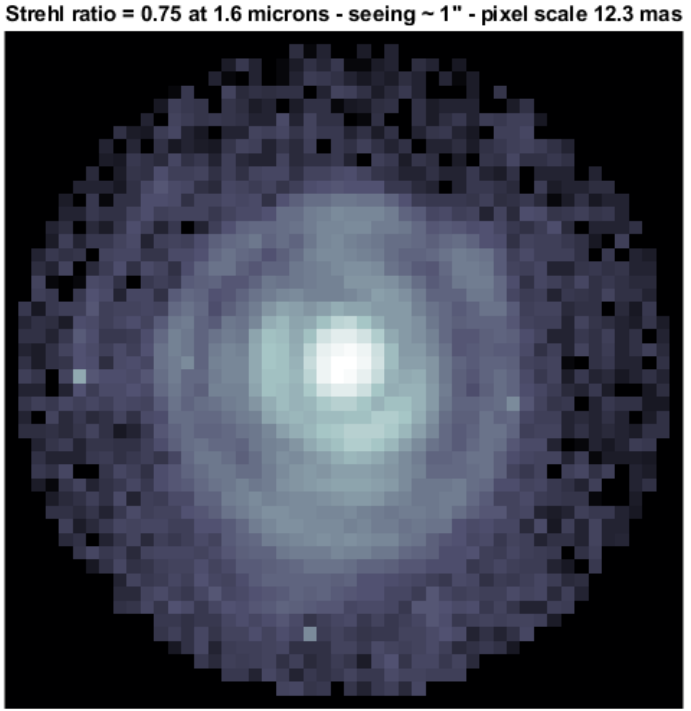
# Remote AIV & commissioning 1: March 2021






# 1st commissioning achievements

- Robust operation at **J magnitude > 17 @ 500 Hz**
- The **project TLRs are fulfilled** in terms of limiting magnitude, time to completion and budget
- **MUSE NFM** is **back in routine operation** with upgraded performance
- **LTAO** performance
  - SR ~0.75 in H band with a seeing of 1” incl. static aberrations with TT loop @ 200 Hz
  - Equivalent to 0.18 @ 650 nm
    - ~4 times > specified performance
    - ~twice > goal performance

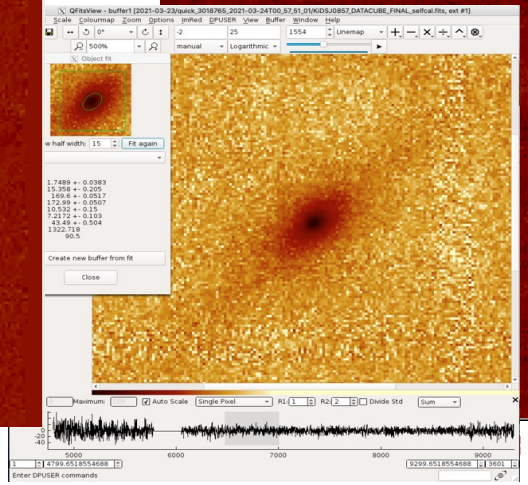


# MUSE NFM verification: commissioning OBs

**PGC 33606**
SmallScale - 500Hz
J = 10.69
Band: Cousins I
FWHM ~ 68 mas
Airmass: 1.235
Tau0: 4.8 ms

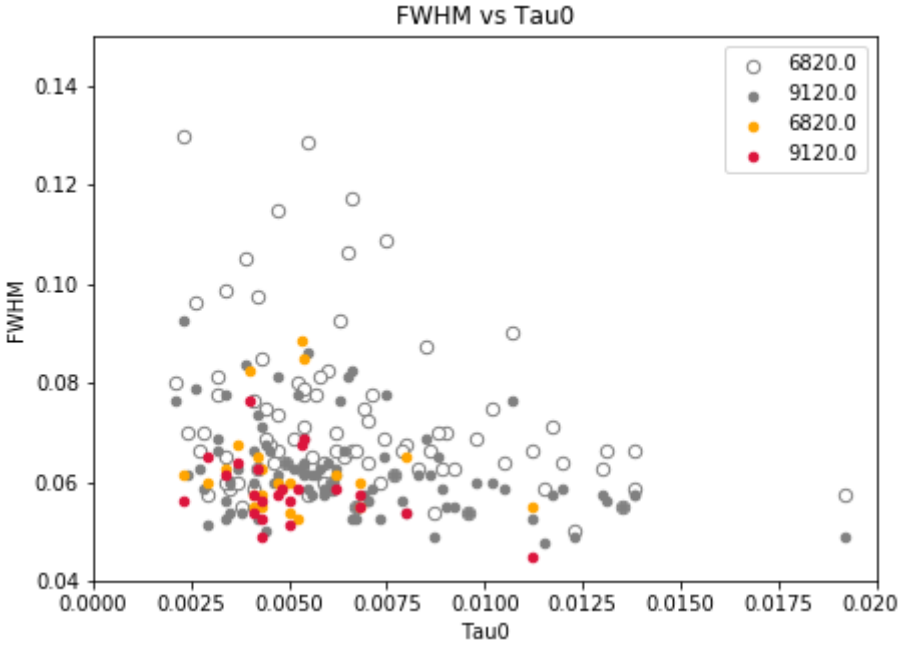
*Credit: Fernando Selman and Johanna Hartke*

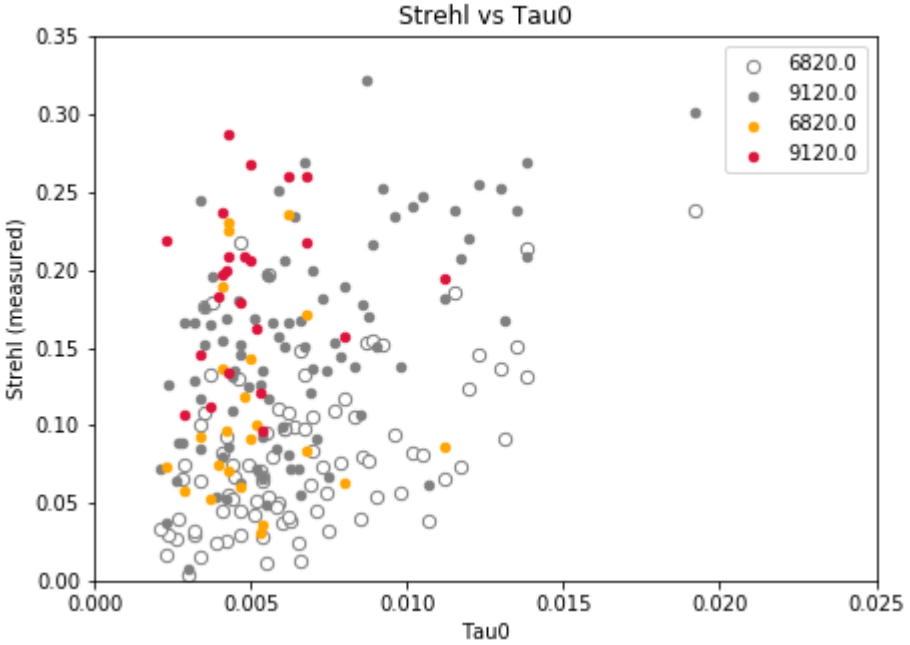
***"A pathfinder to observe high redshift galaxies with MUSE"***



SmallScale - 500Hz
**J = 16.4** Re = 0.45" *z* = 0.1764
Band Cousins I
FWHM ~ 175 mas
Airmass: 1.11 Tau0: 9.2 ms
ExpoTime: 300 s

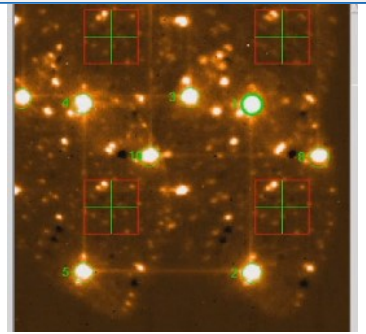
# Performance on MUSE vs. Tau0

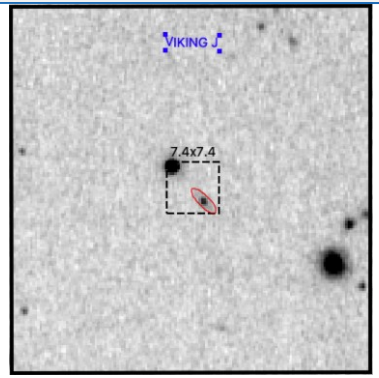


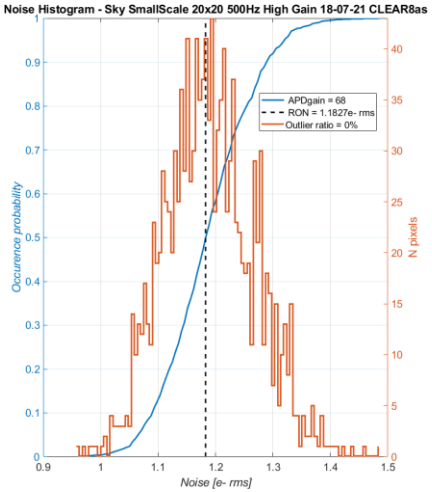

- MUSE NFM regular  Quality Control on standard targets. On going accumulation of performance points as a function of observing conditions
- As expected, the performance is less impacted by low Tau0 cases (colored vs. gray points)

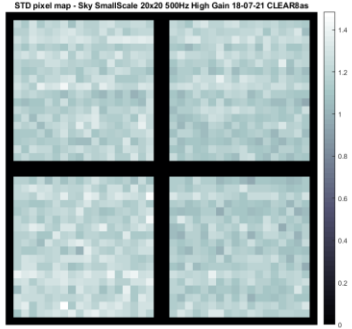
# Commissioning 2: Faint end mode deployment

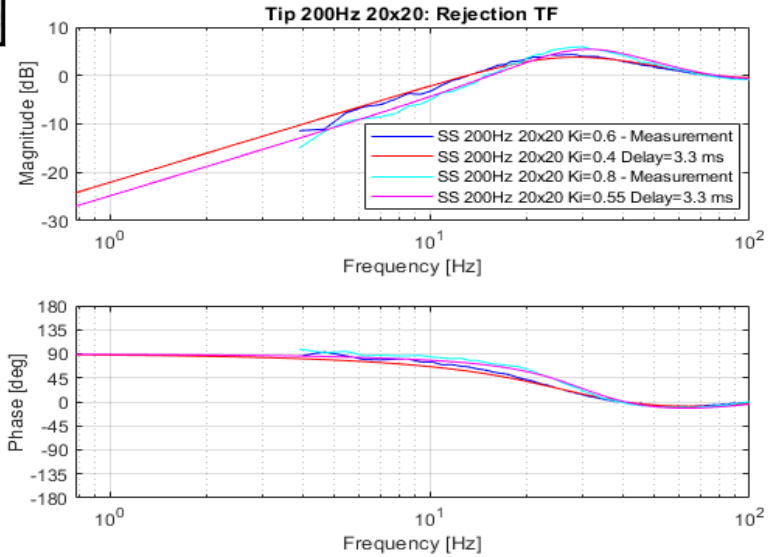




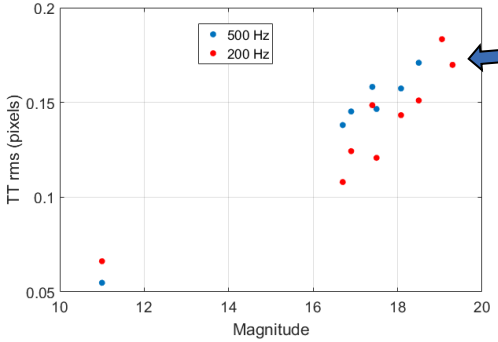

- Wrap-up of bright modes
- Total noise characterization
- Centroiding optimization for faint end
- Rejection transfer function optimization



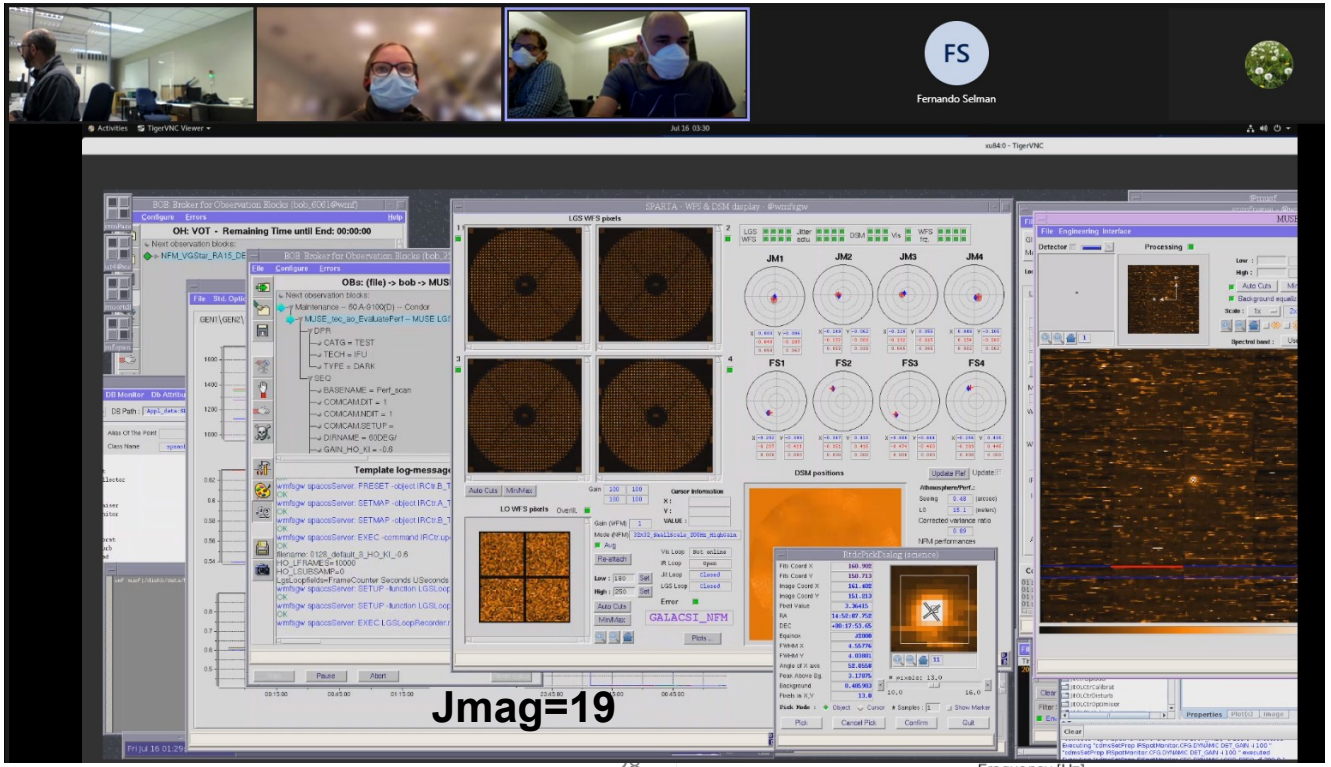



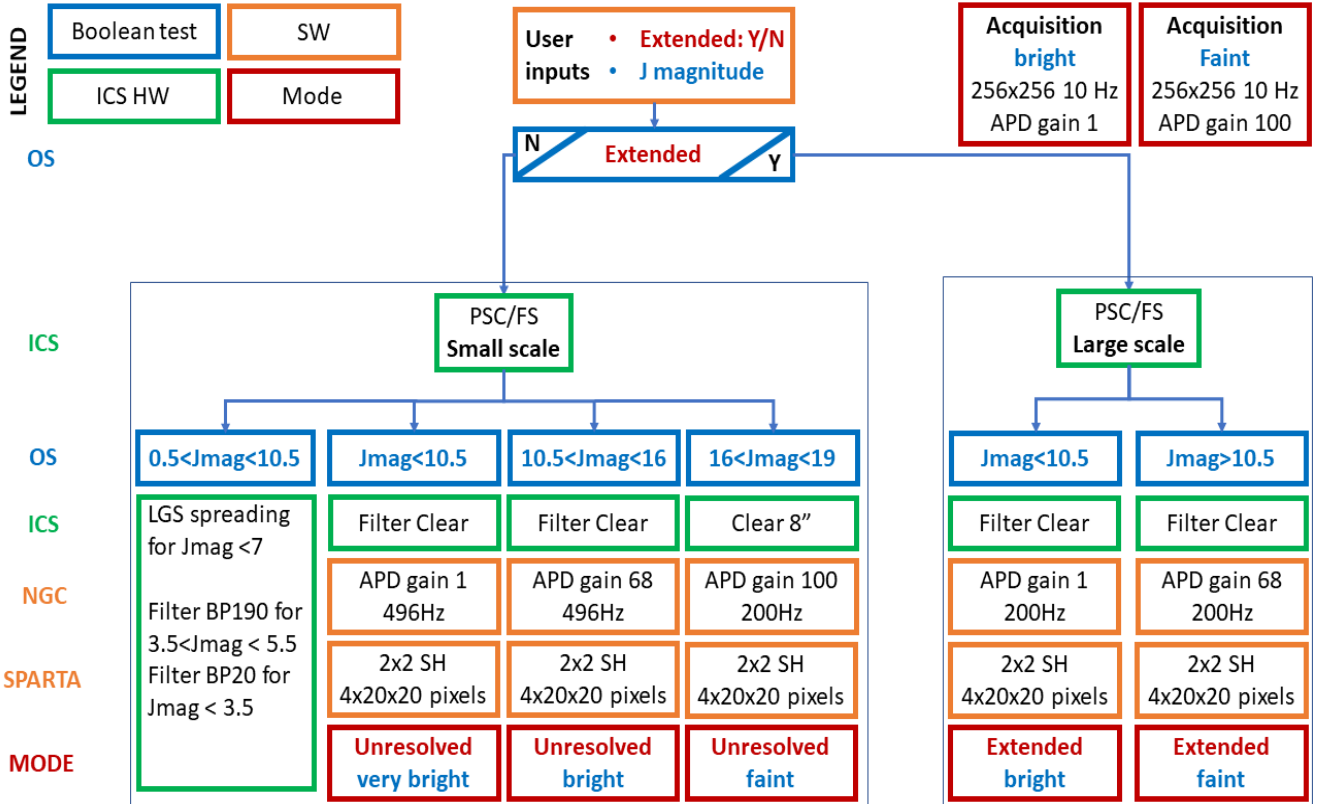
# Commissioning 2: Faint end mode deployment



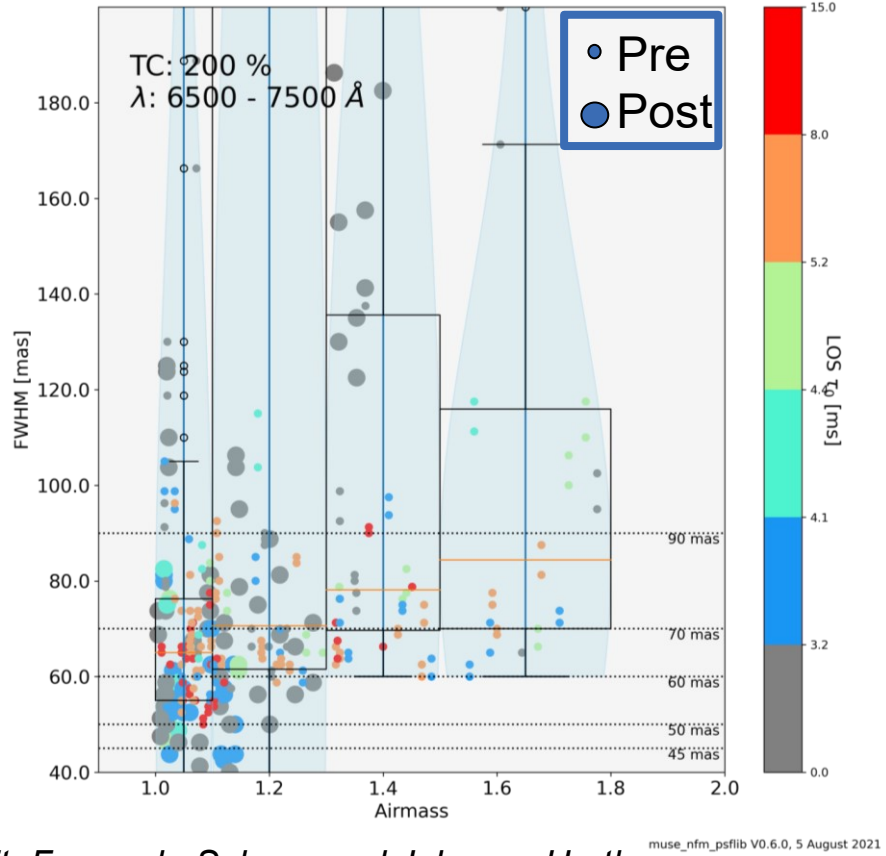

**Jmag= 19.3 → 2.11 photons / frame / subaperture → SNR =1**

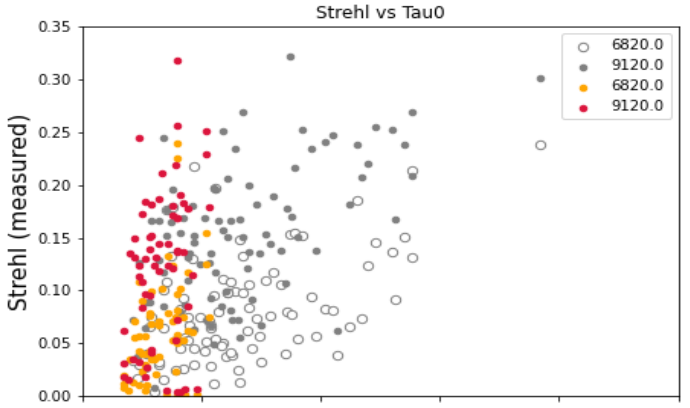


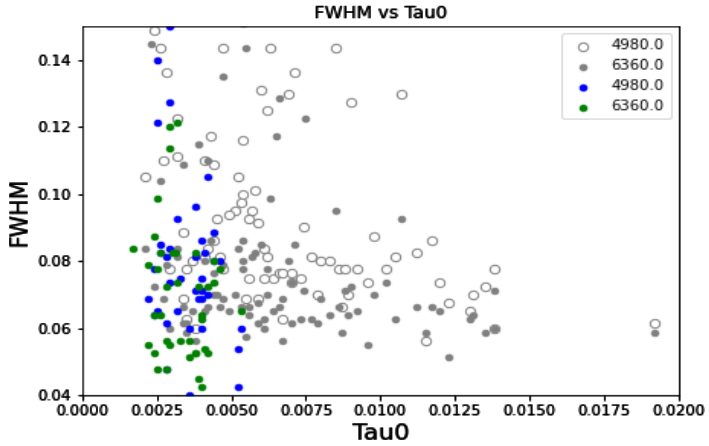
# Commissioning 2: deployed Modes



# Commissioning 2: MUSE performance



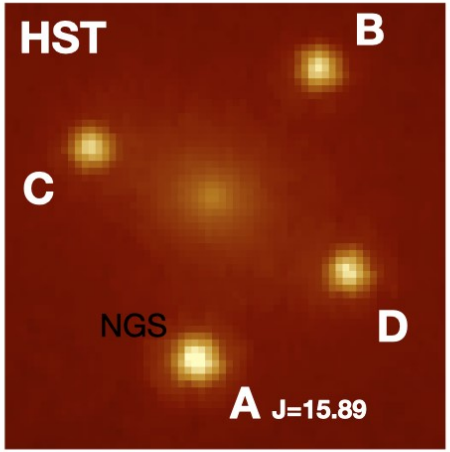




*Credit: Fernando Selman and Johanna Hartke*

# Show case: Einstein cross

https://www.eso.org/sci/publications/announcements/sciann17429.html

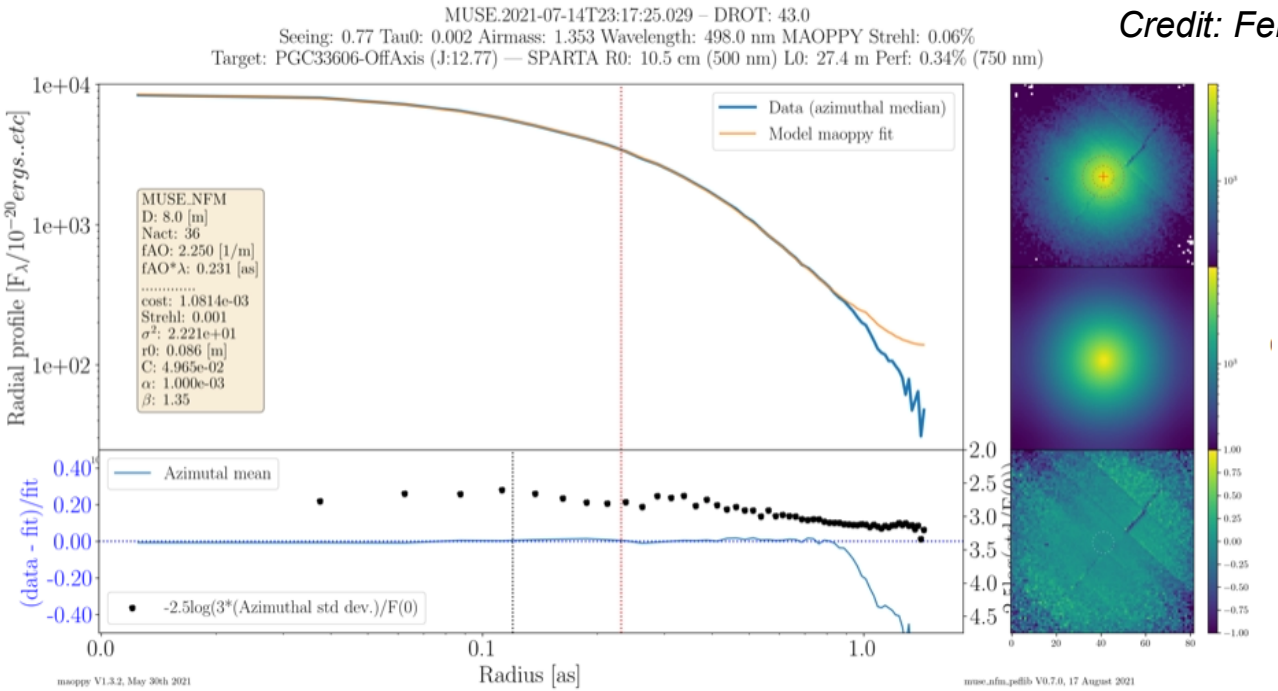
*DIMM seeing = 1.03*
*Airmass=1.14*
*Tau0=3.6 ms*
*600s total integration time*
*Cloudy sky (thin)*


| | 500 nm | 600 nm | 700 nm | 800 nm | 900 nm |
|---|---|---|---|---|---|
| FWHM (mas) | 95 | 75 | 70 | 65 | 62 |
| Strehl (maoppy) | 0.6% | 3.1% | 6.5% | 13.4% | 19.2% |

- Such lensed quasar was not observable with the previous IRLOS
- It's now straight forward, in the bright regime of IRLOS+
- Visible correction radius consistent with the correction of 850 modes
- Despite conditions, probably the highest spatial resolution image of this object

# Next: PSF Reconstruction




*Credit: Fernando Selman and Johanna Hartke*

PhD of Arseniy Kuznetsov on self-learning AO: stay tuned …

# Status and next steps

- The only LTAO system in operation delivers high performance and robust science
- GALACSI NFM now goes 4 magnitude fainter (Goal was 2)
- Before the upgrade 7<Jmag<15 → After the upgrade 0.5<Jmag<19
- Off axis guiding has been pushed to 5'' radius
- NFM performance is now less sensitive to Tau0 and seeing, also better and more robust performance on extended targets
- Next steps:
  - Commissioning report and PAC
  - Dissemination of the results
  - Further improvement of the LTAO: technical time in November 2021
  - PSF reconstruction and improvement of MUSE NFM optical quality

# The IRLOS+ team