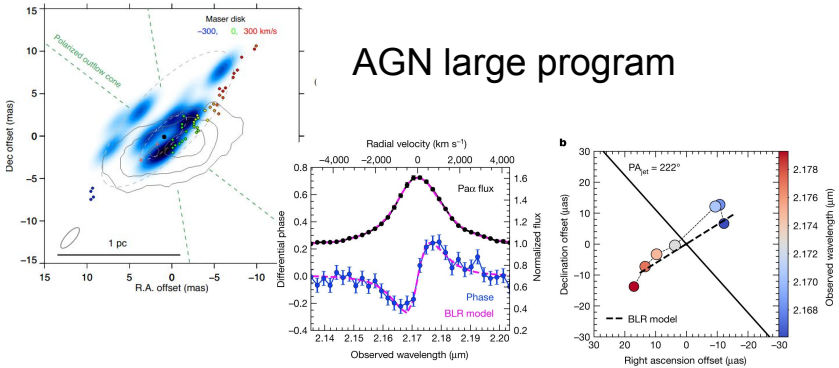
The GRAVITY instrument and its science results

Felix Widmann
on behalf of the GRAVITY Team

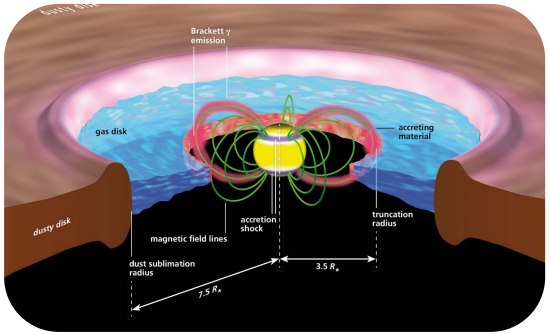
9. June 2021

VLTI Summer School

GRAVITY science results



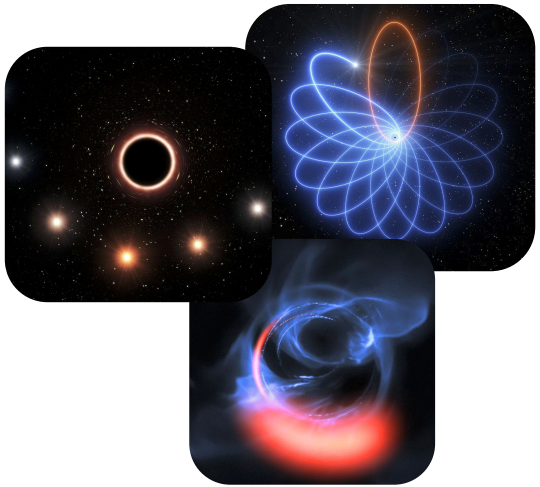
AGN large program



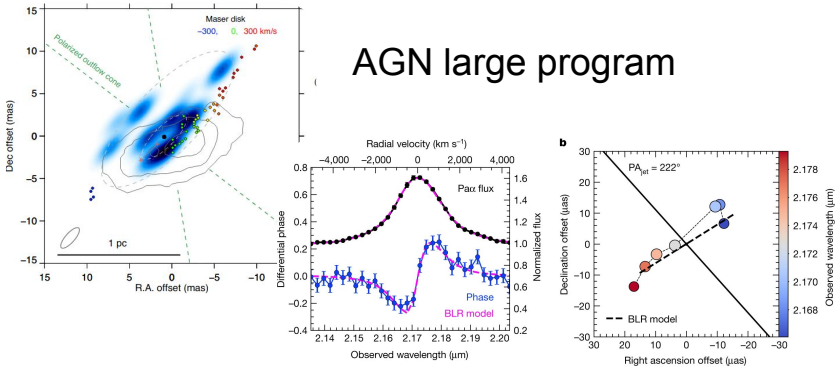
YSO survey

Exoplanet spectroscopy & astrometry

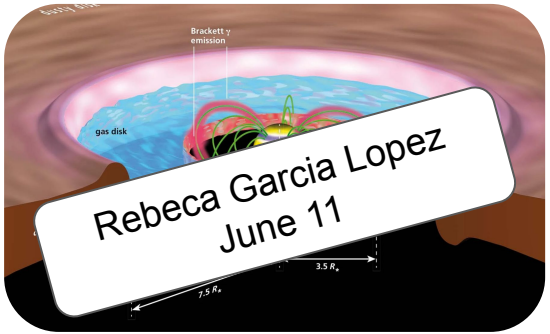
Galactic Center Science



GRAVITY science results



AGN large program



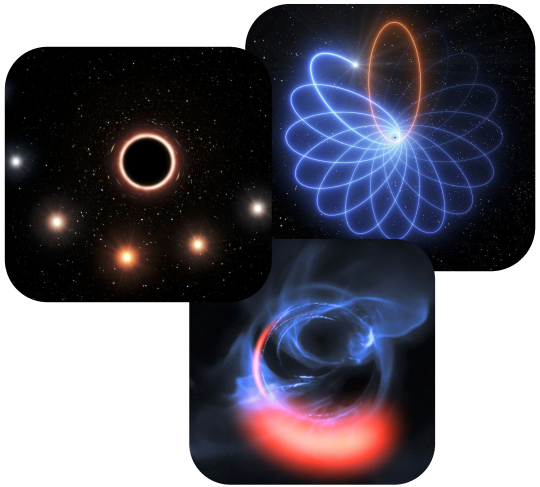
Rebeca Garcia Lopez
June 11

YSO survey

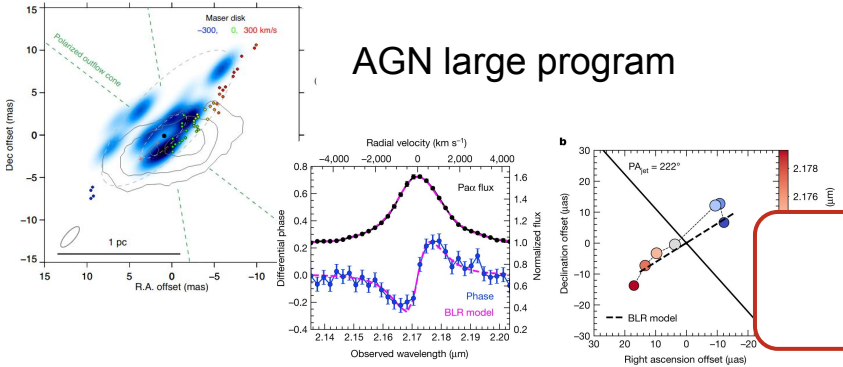
Sylvestre Lacour
June 15

Exoplanet spectroscopy & astrometry

Galactic Center Science



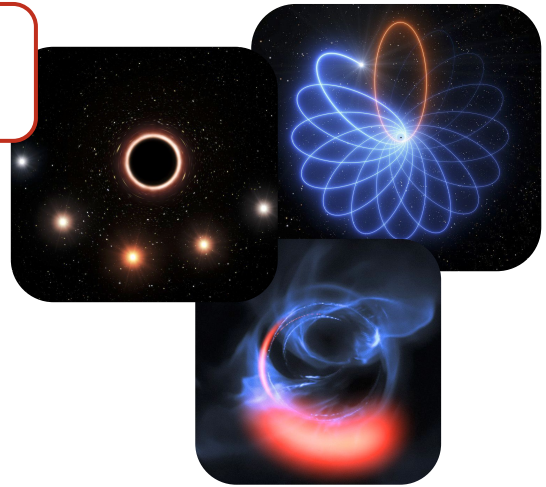
GRAVITY science results

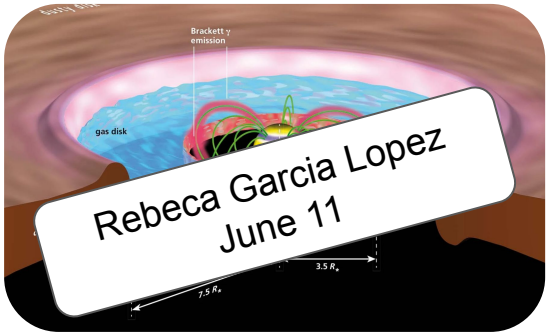


AGN large program

And much more!

Galactic Center Science





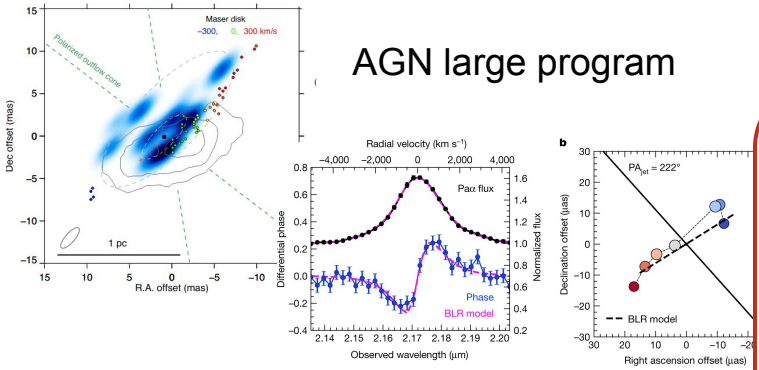
Rebeca Garcia Lopez
June 11

YSO survey

Sylvestre Lacour
June 15

Exoplanet spectroscopy & astrometry

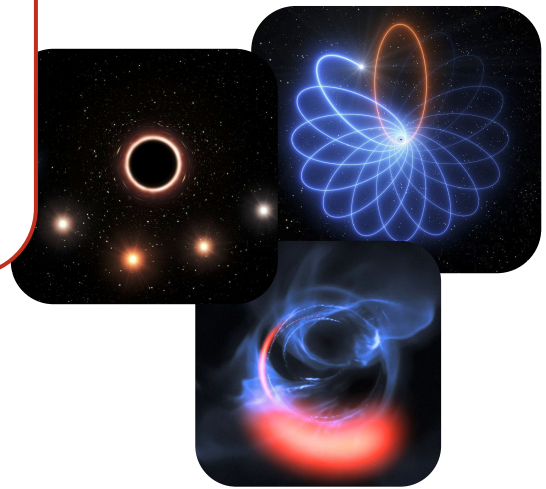
GRAVITY science results

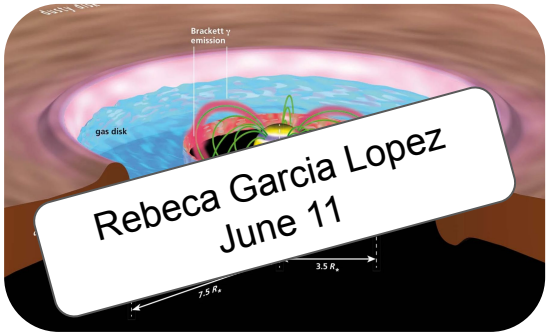


AGN large program

- Few 10 μas astrometry
- mas resolution imaging
- 19+ mag limiting magnitude
- Polarimetry
- Spectroscopy
- μas spectral differential astrometry

Galactic Center Science





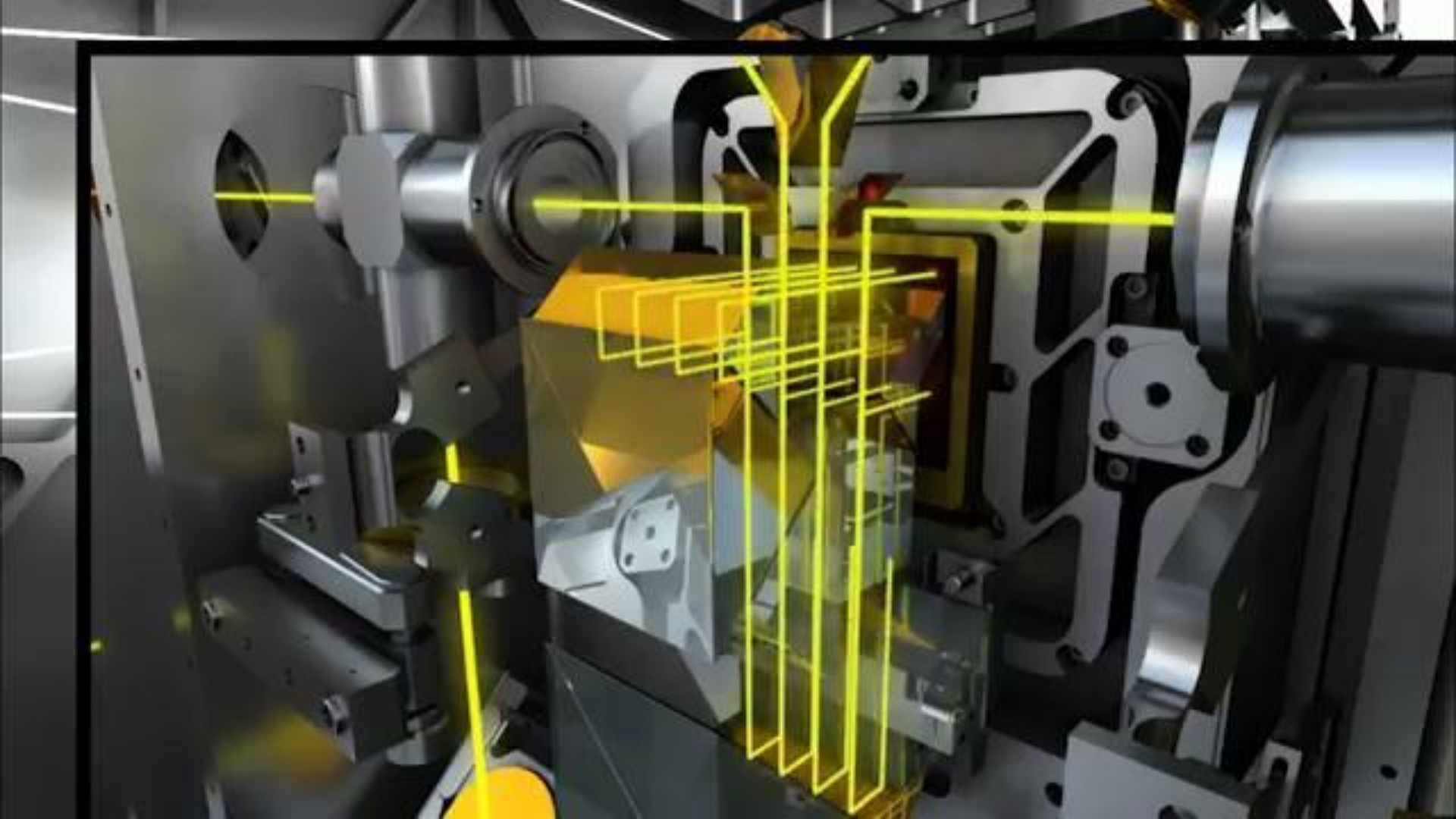
Rebeca Garcia Lopez
June 11

YSO survey

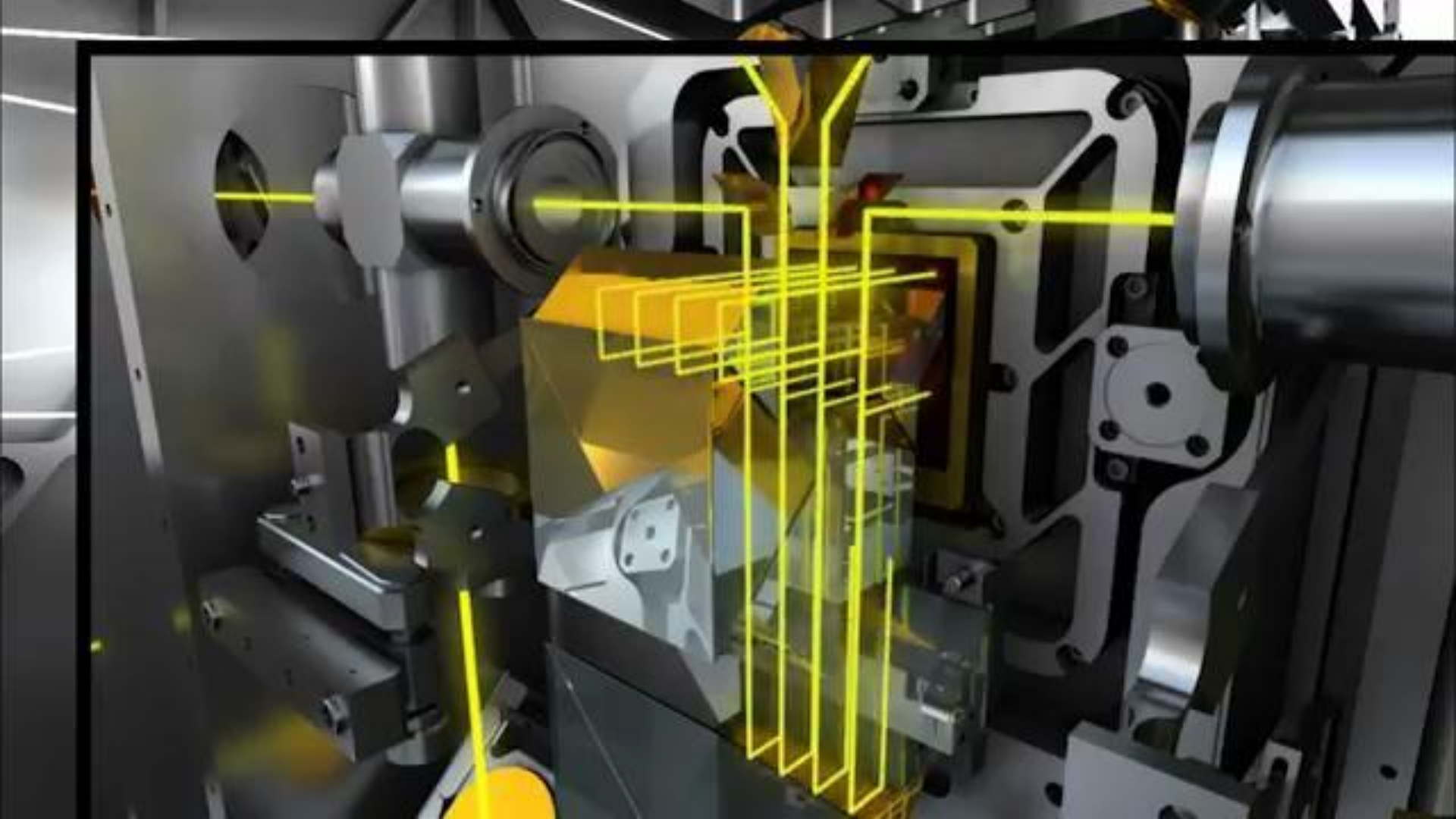
Sylvestre Lacour
June 15

Exoplanet spectroscopy & astrometry

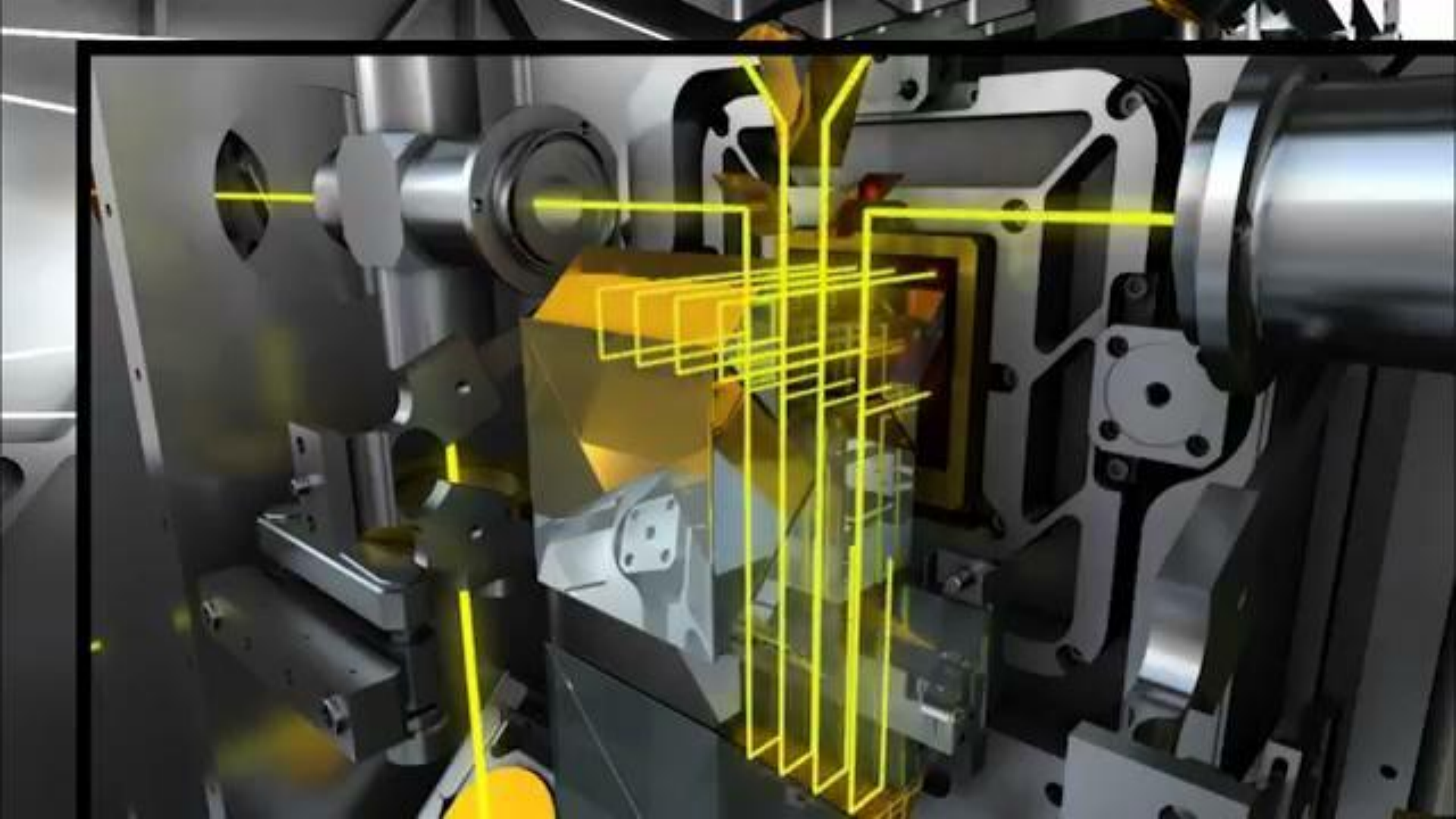
I. GRAVITY technical overview

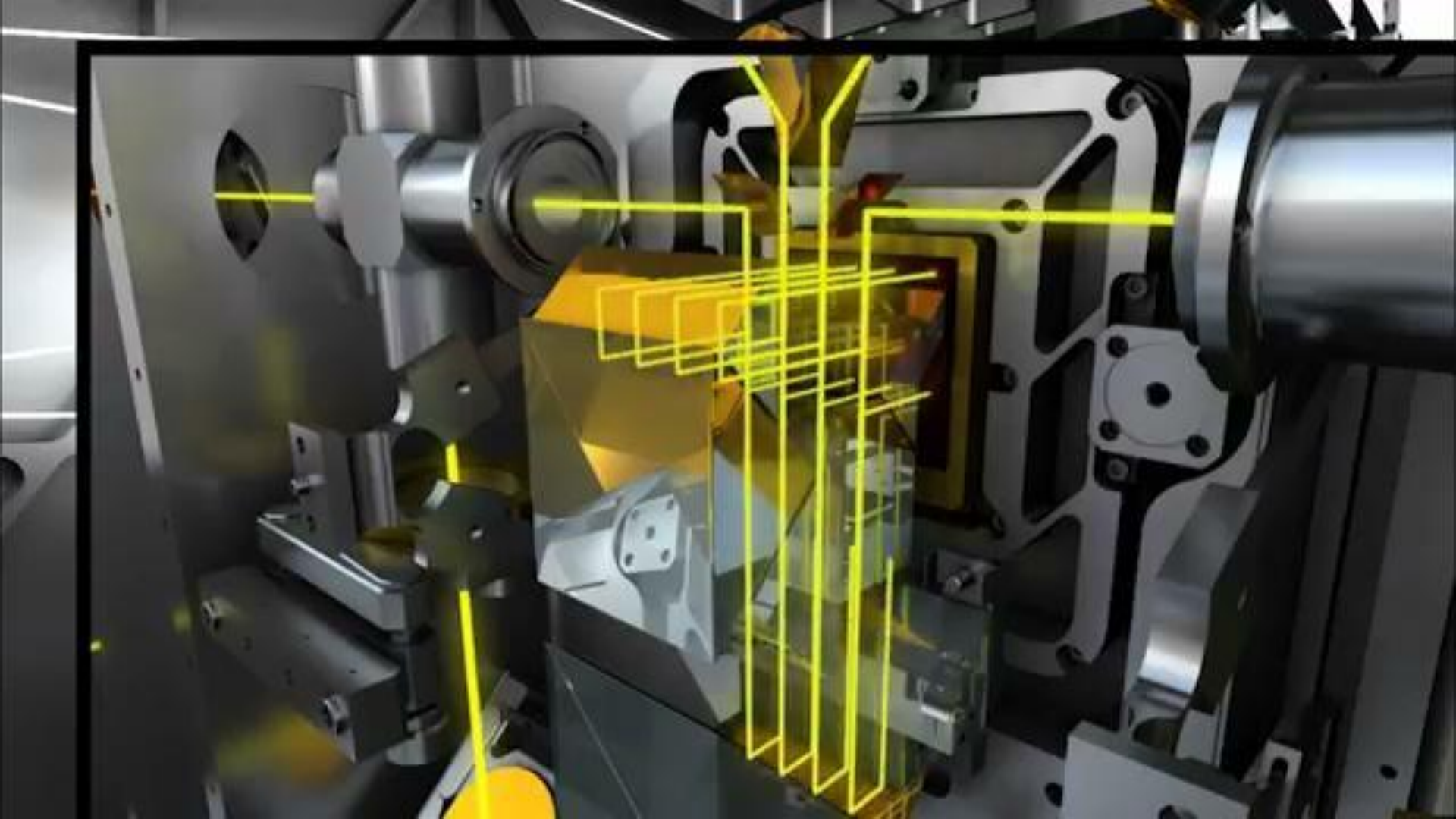


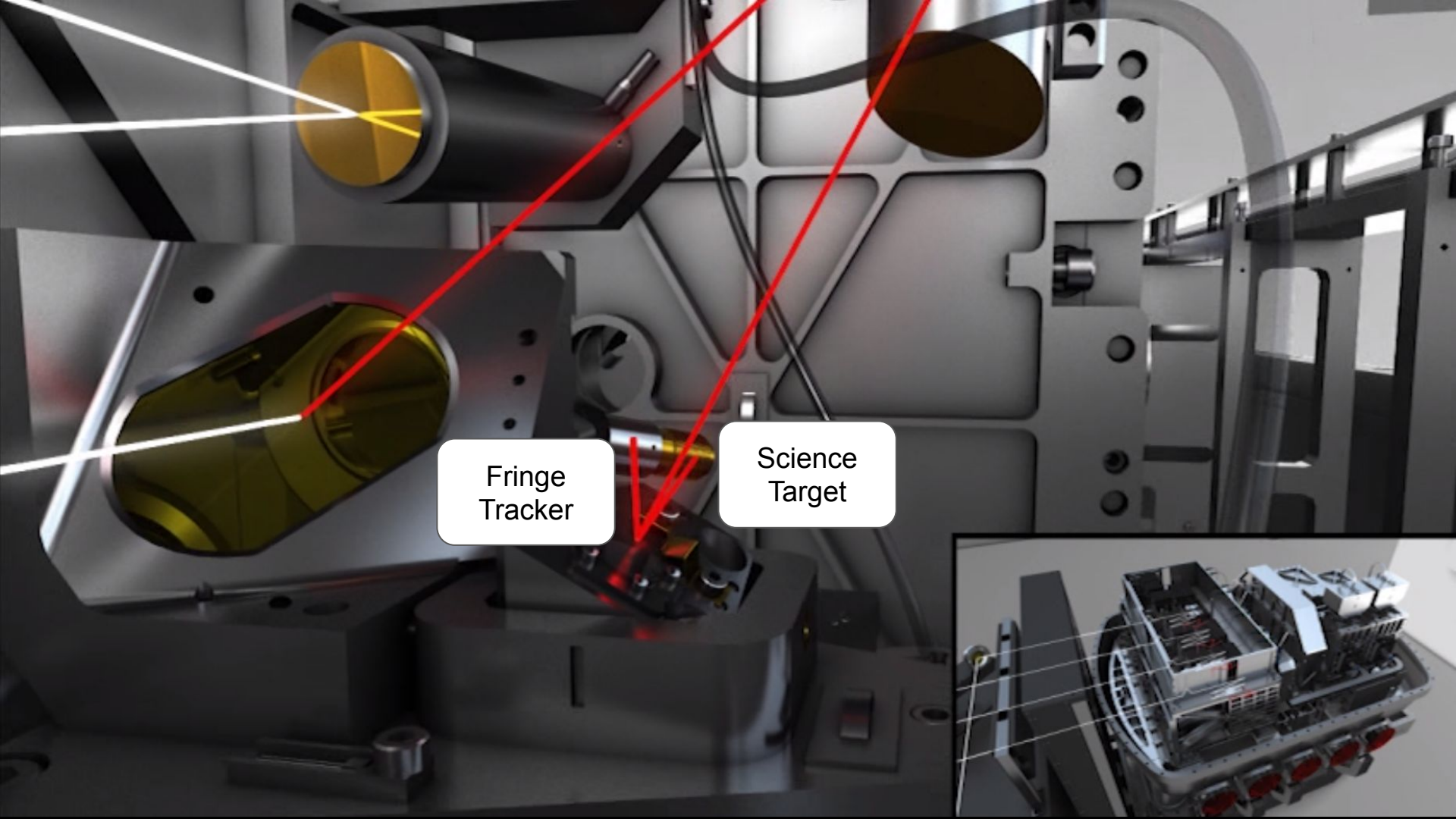

Two adaptive optics systems:
CIAO (NIR)
MACAO (optical)

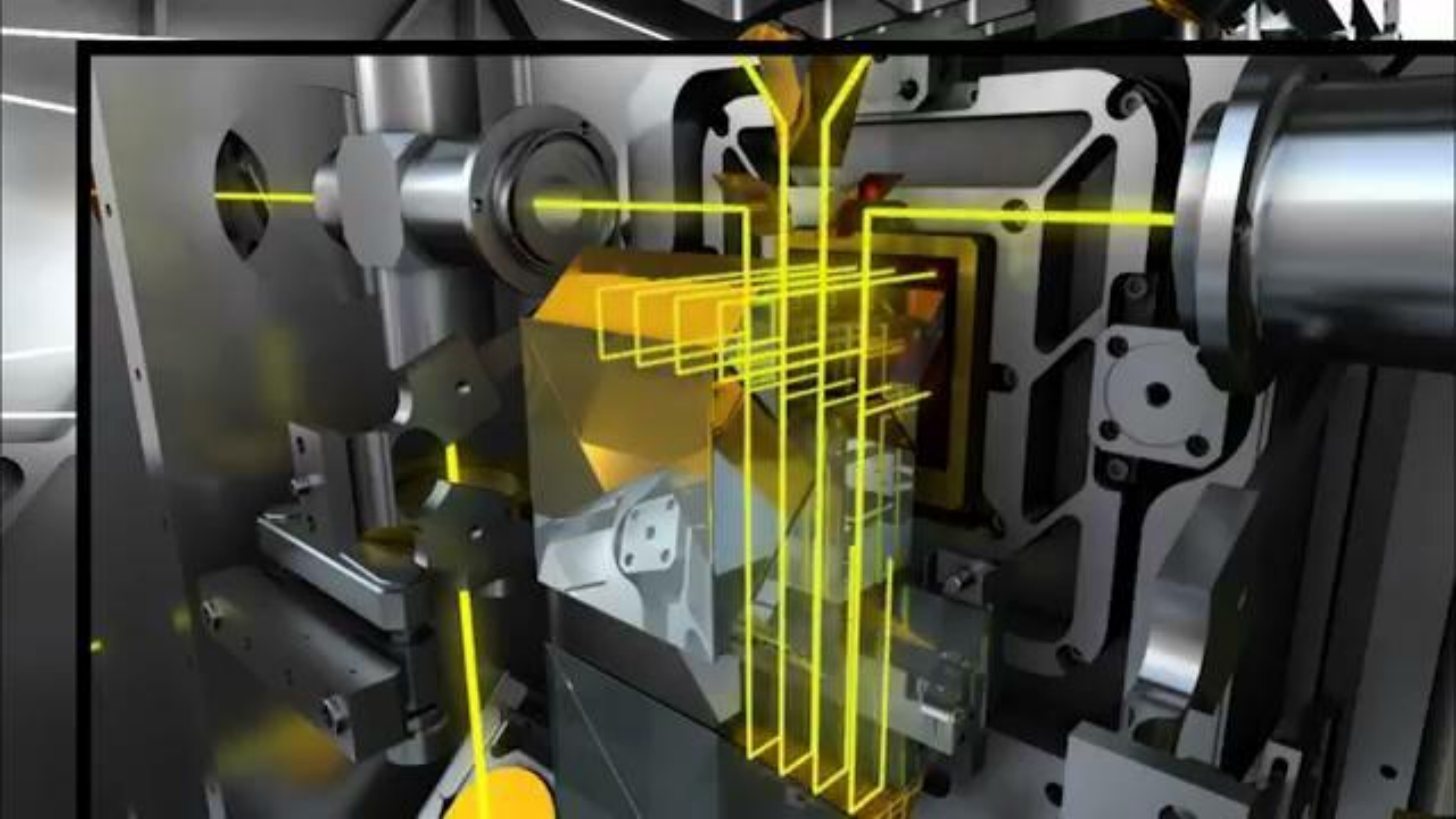


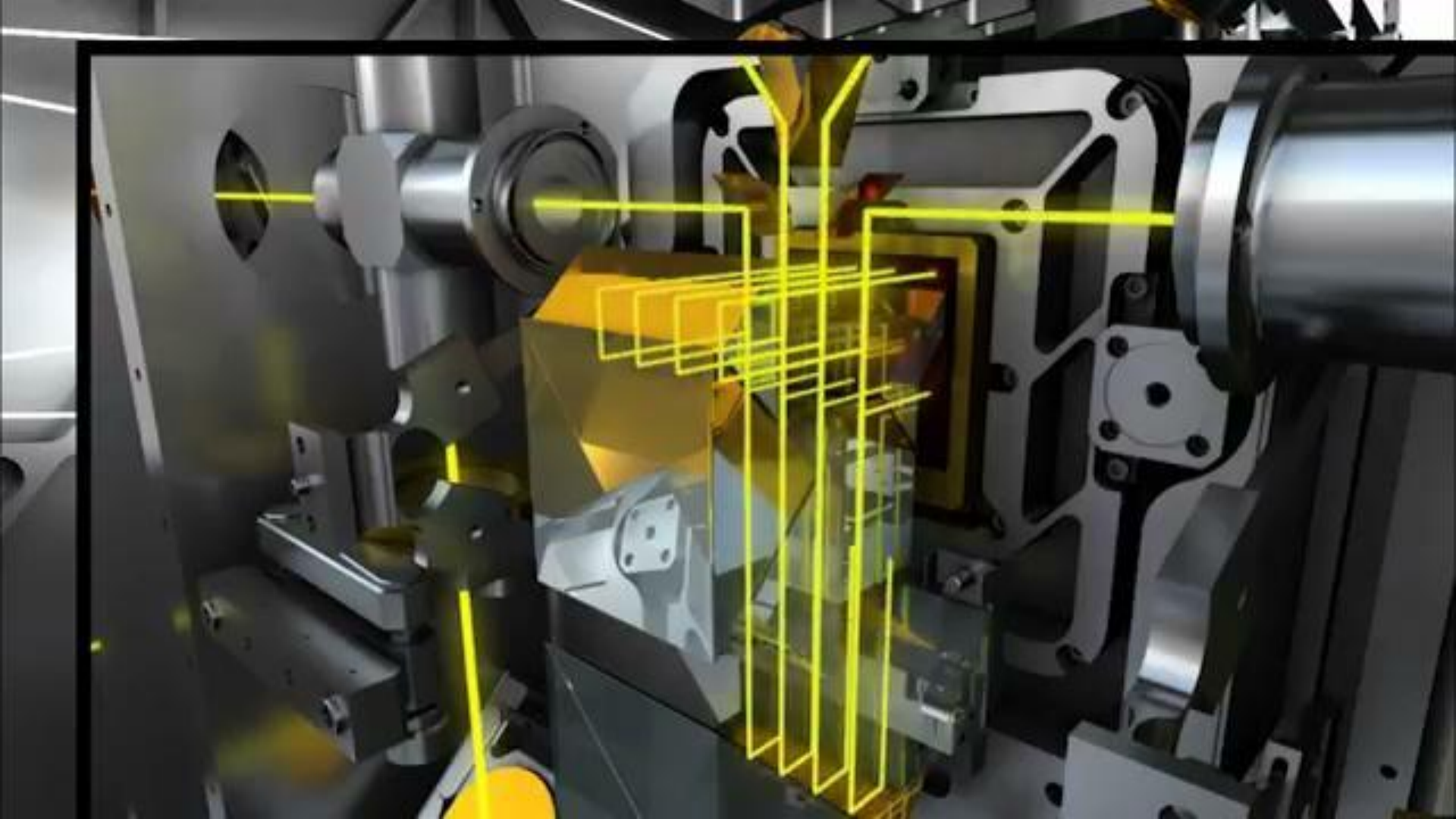
VLTI delay lines



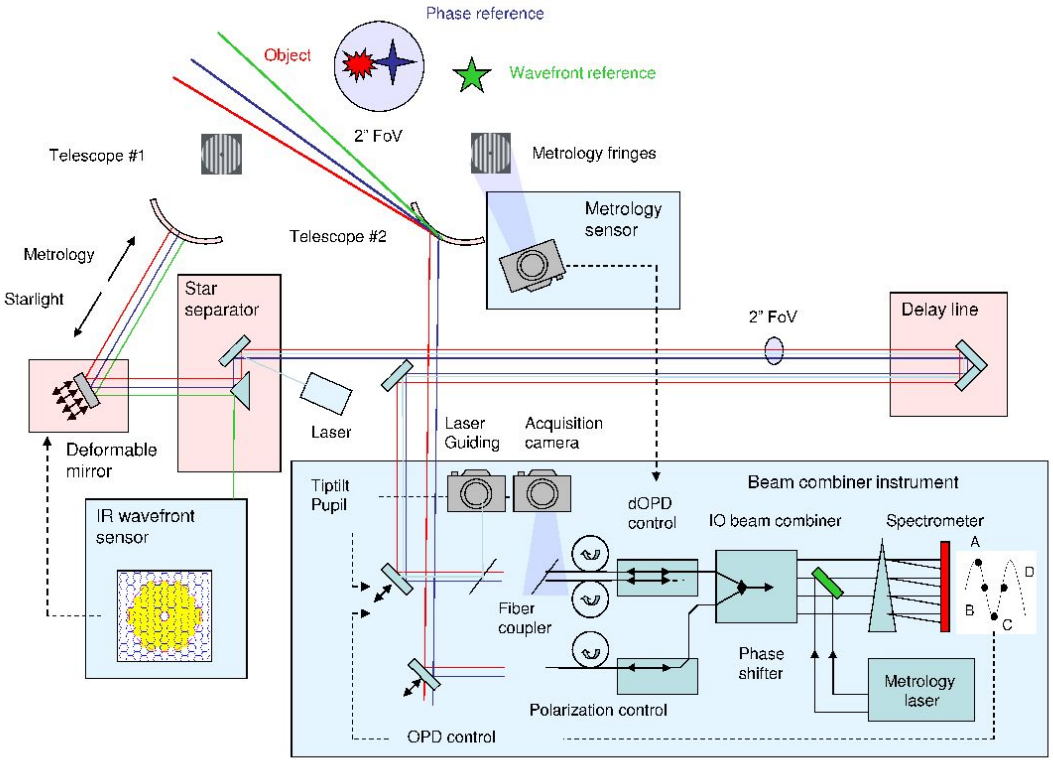



Fringe
Tracker
Science
Target

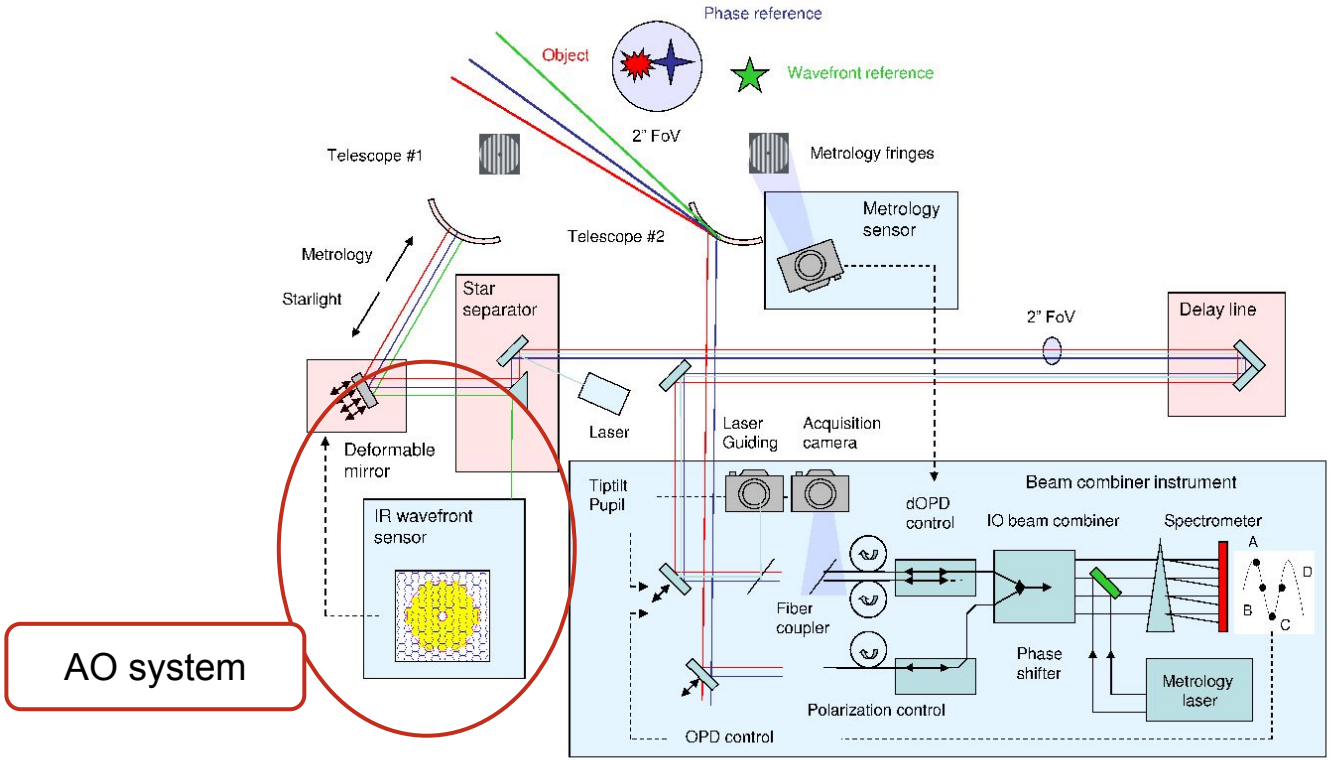




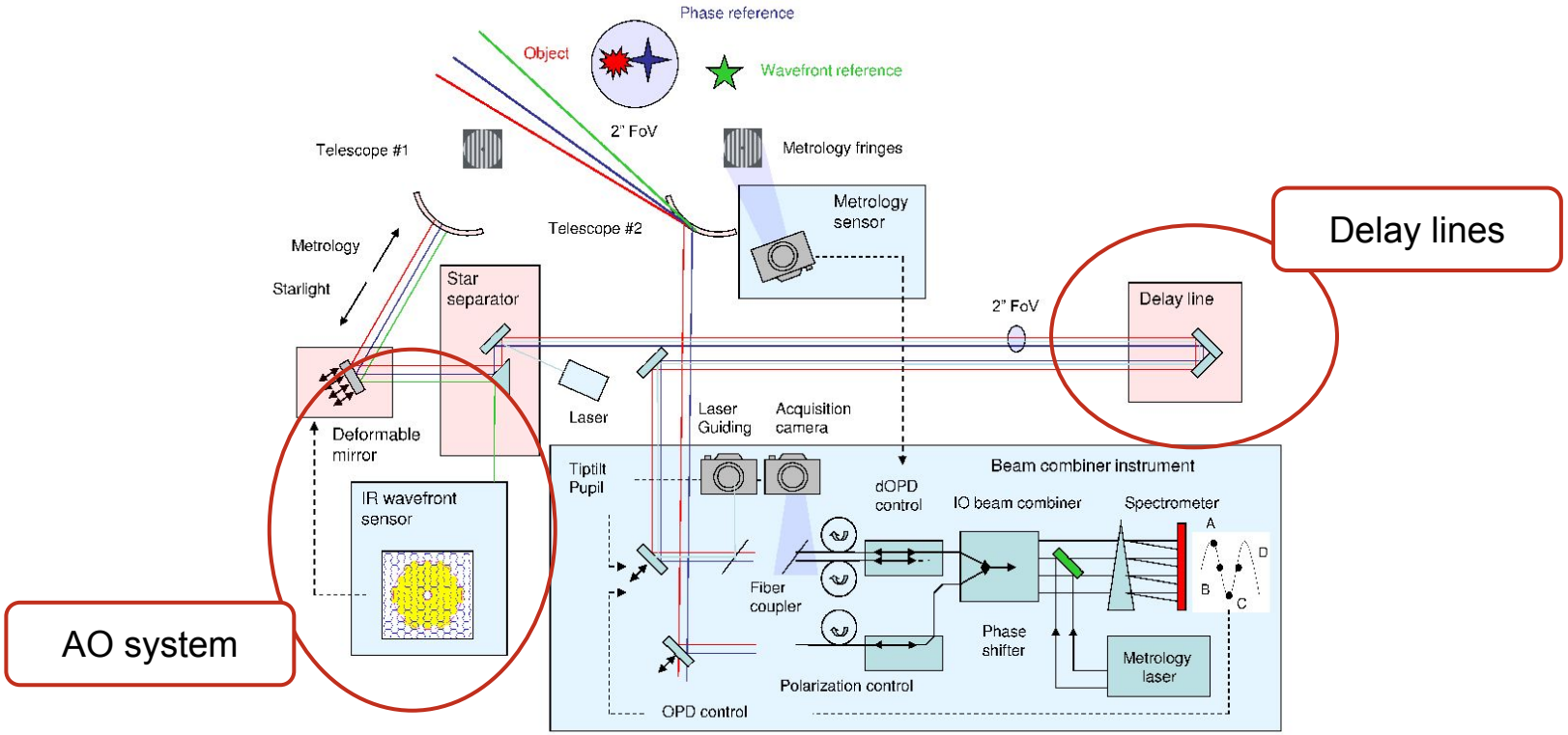
GRAVITY overview



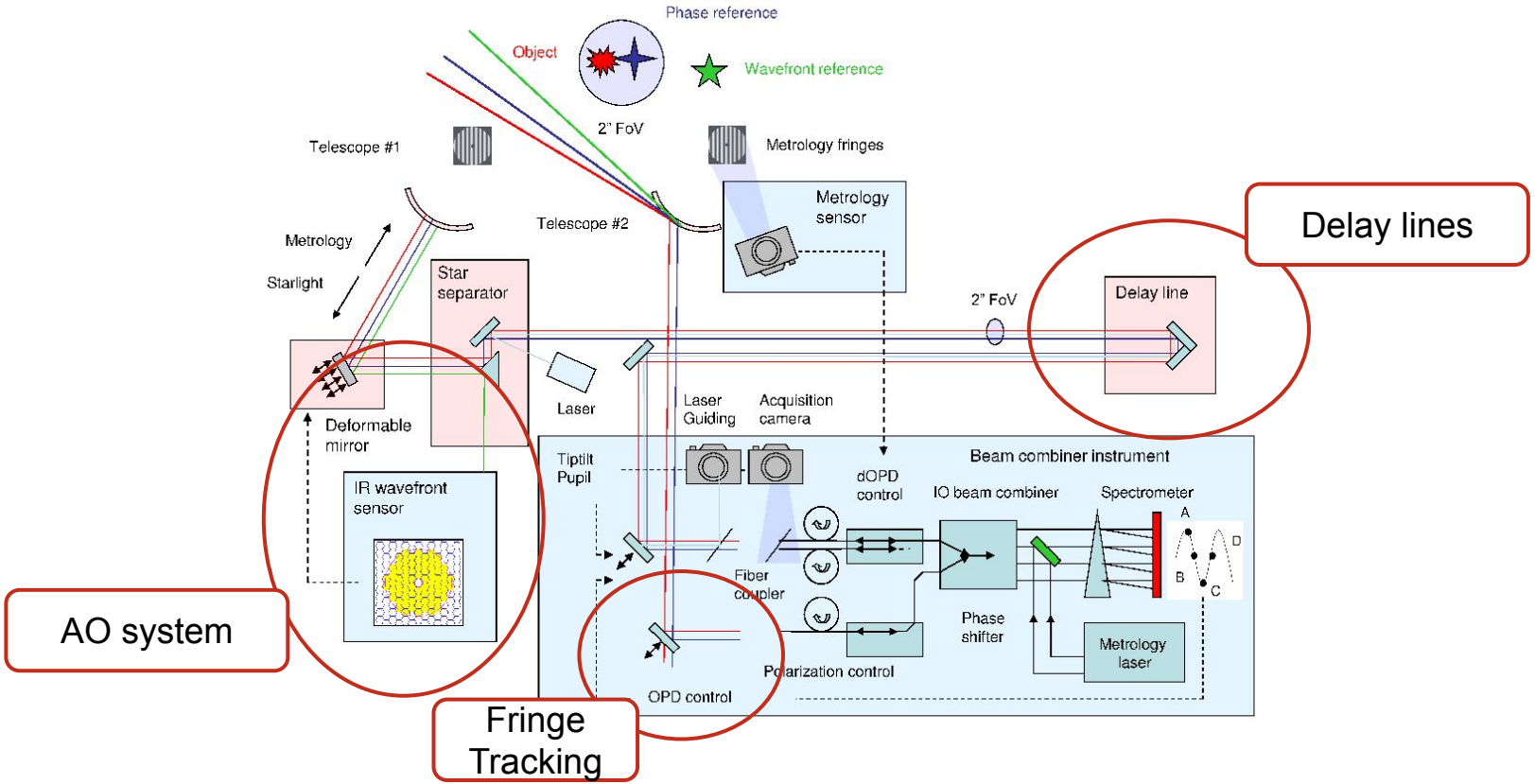
GRAVITY overview



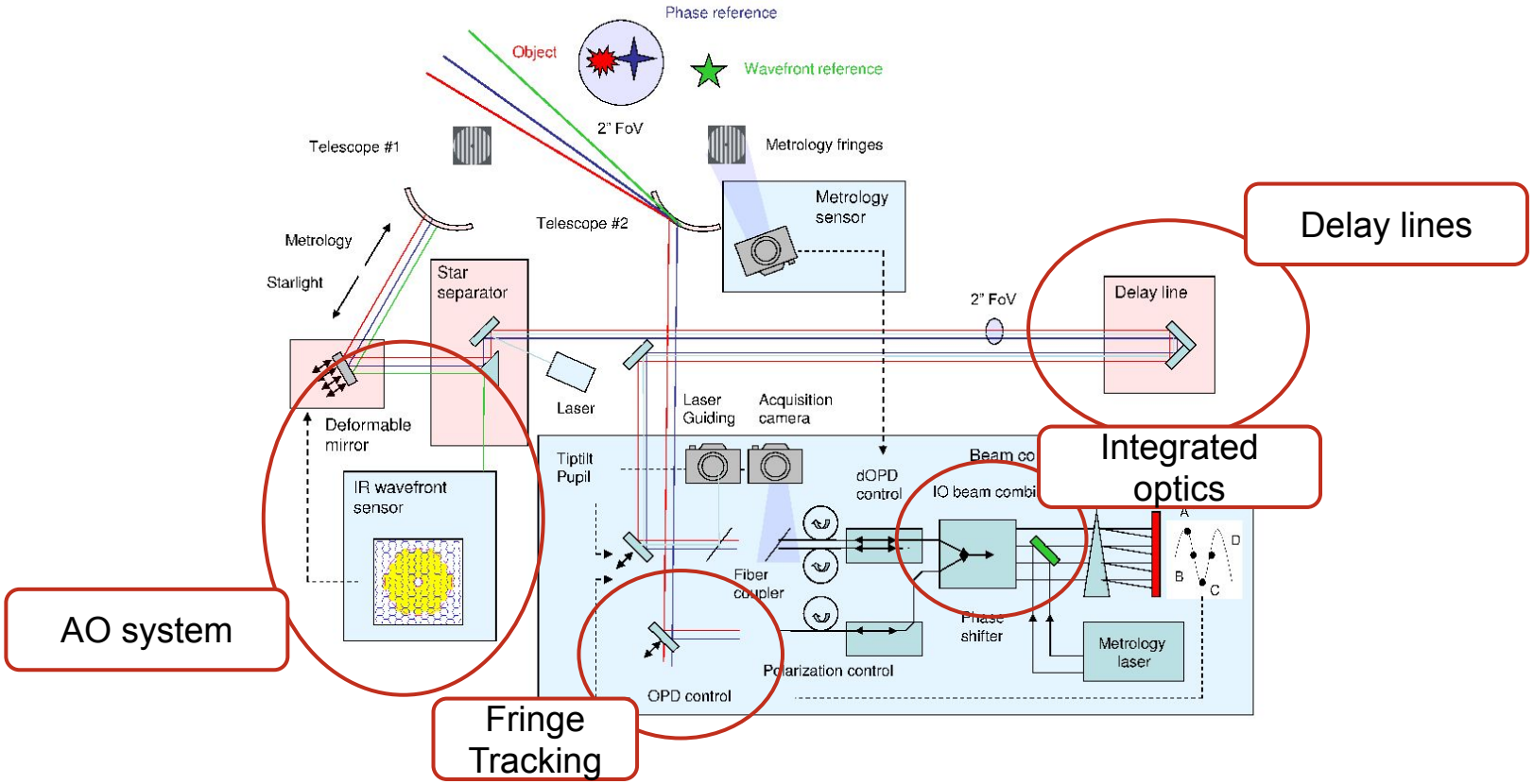
GRAVITY overview



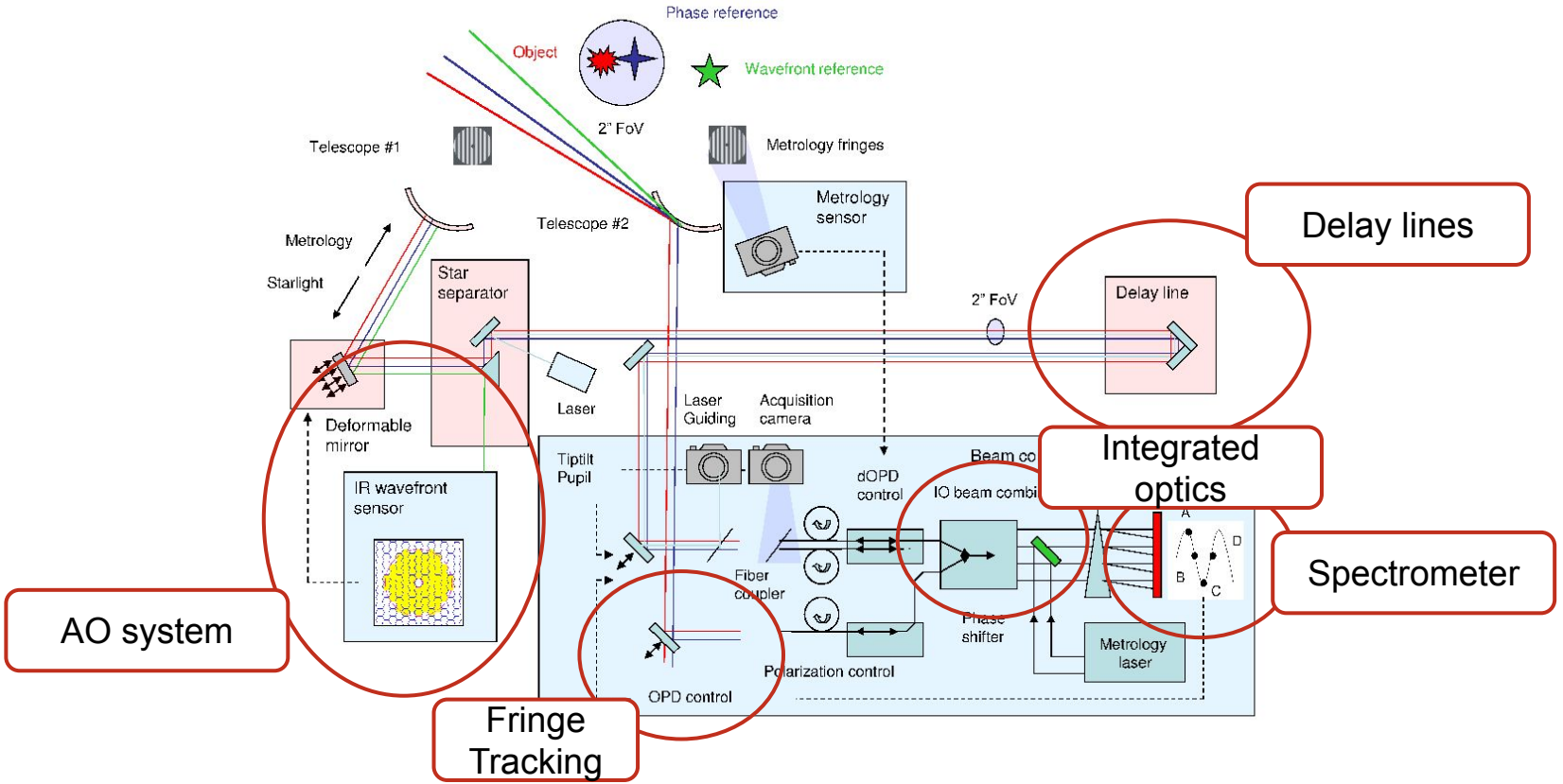
GRAVITY overview



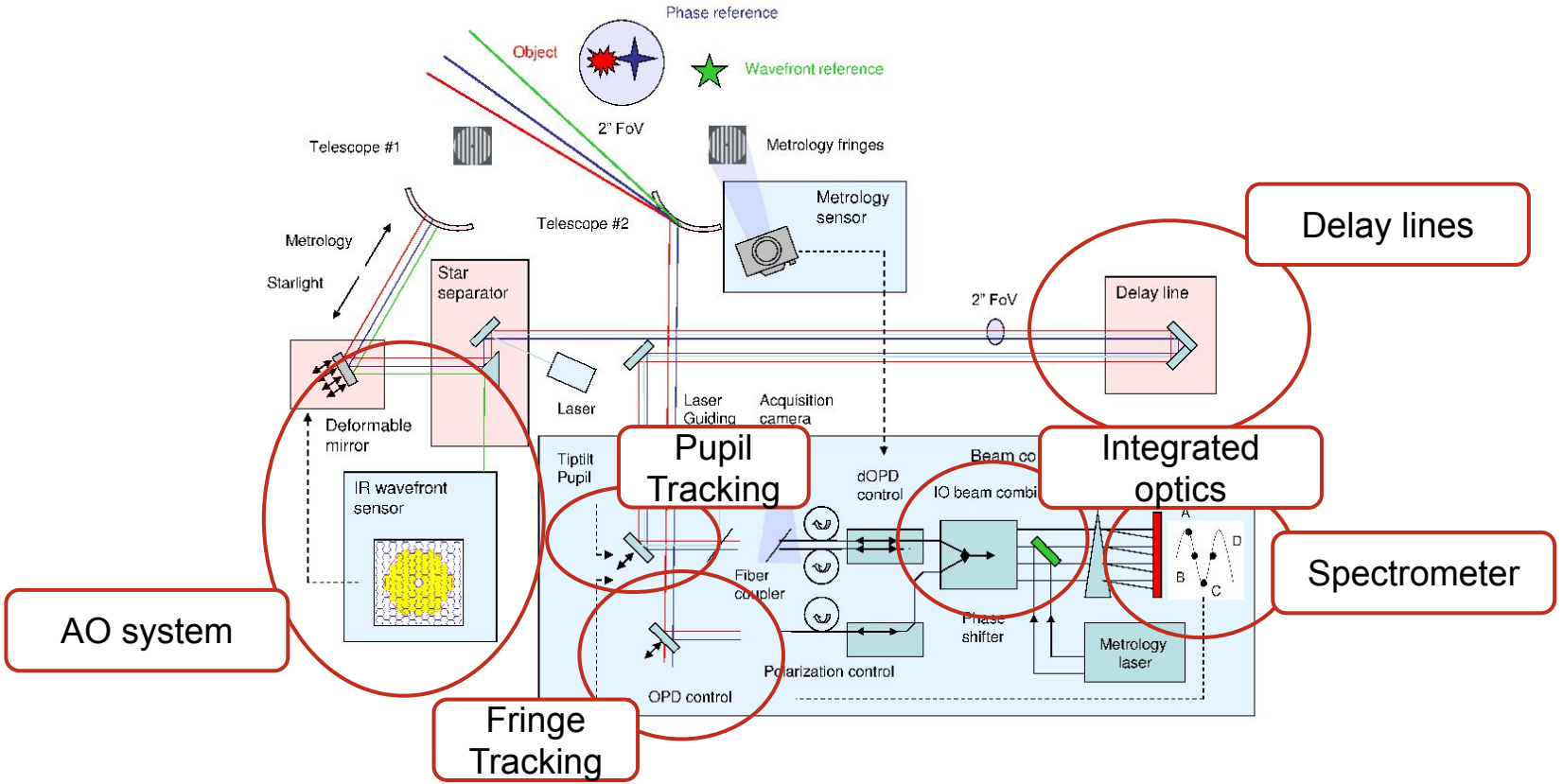
GRAVITY overview



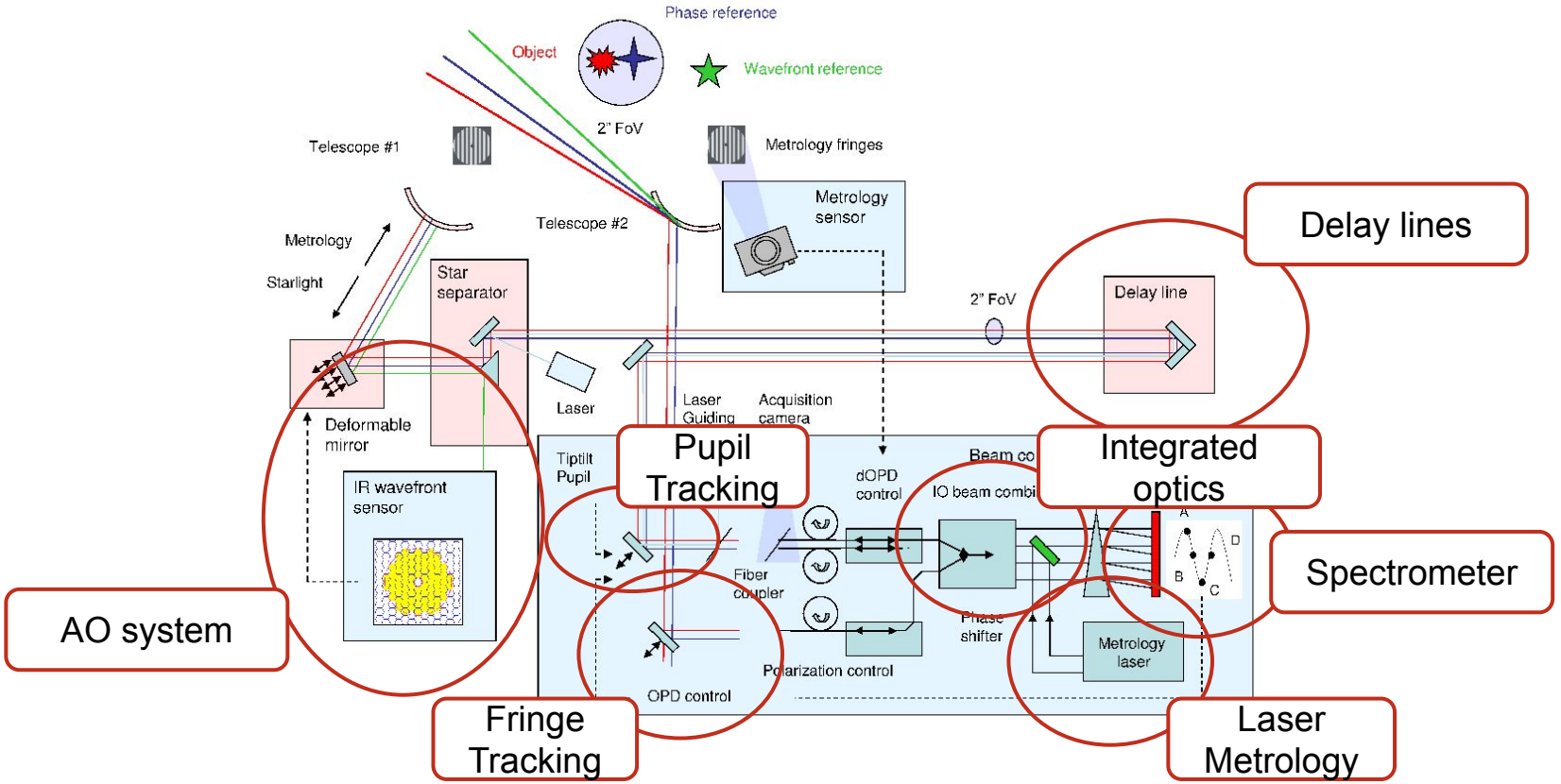
GRAVITY overview



GRAVITY overview

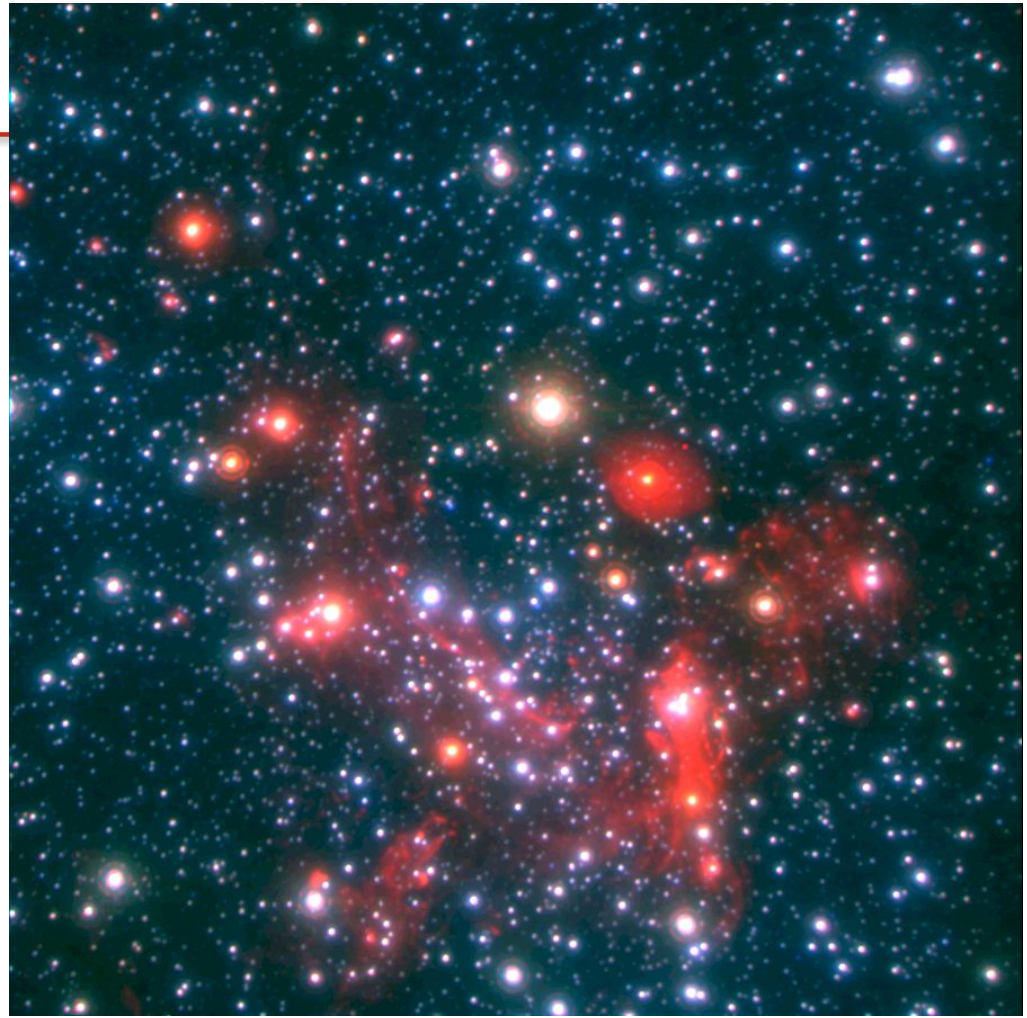


GRAVITY overview

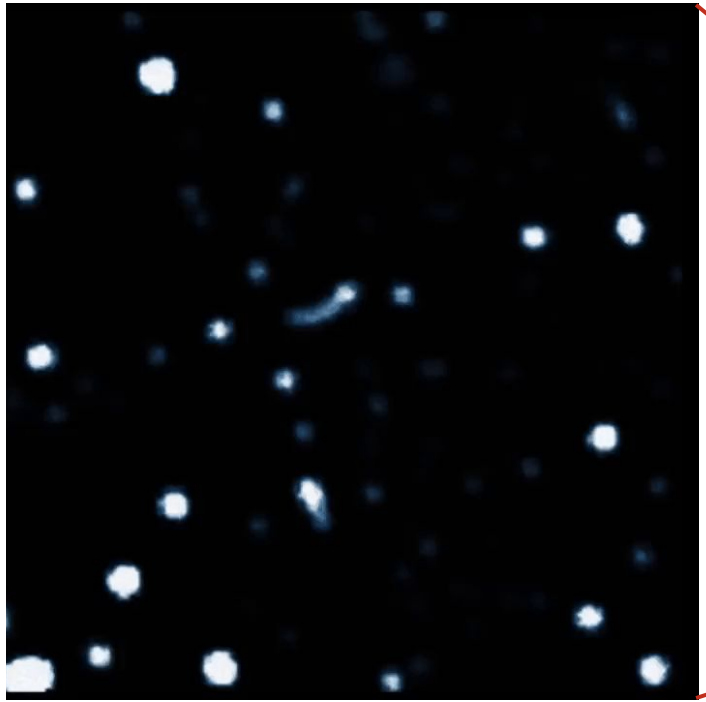


II. Science Examples

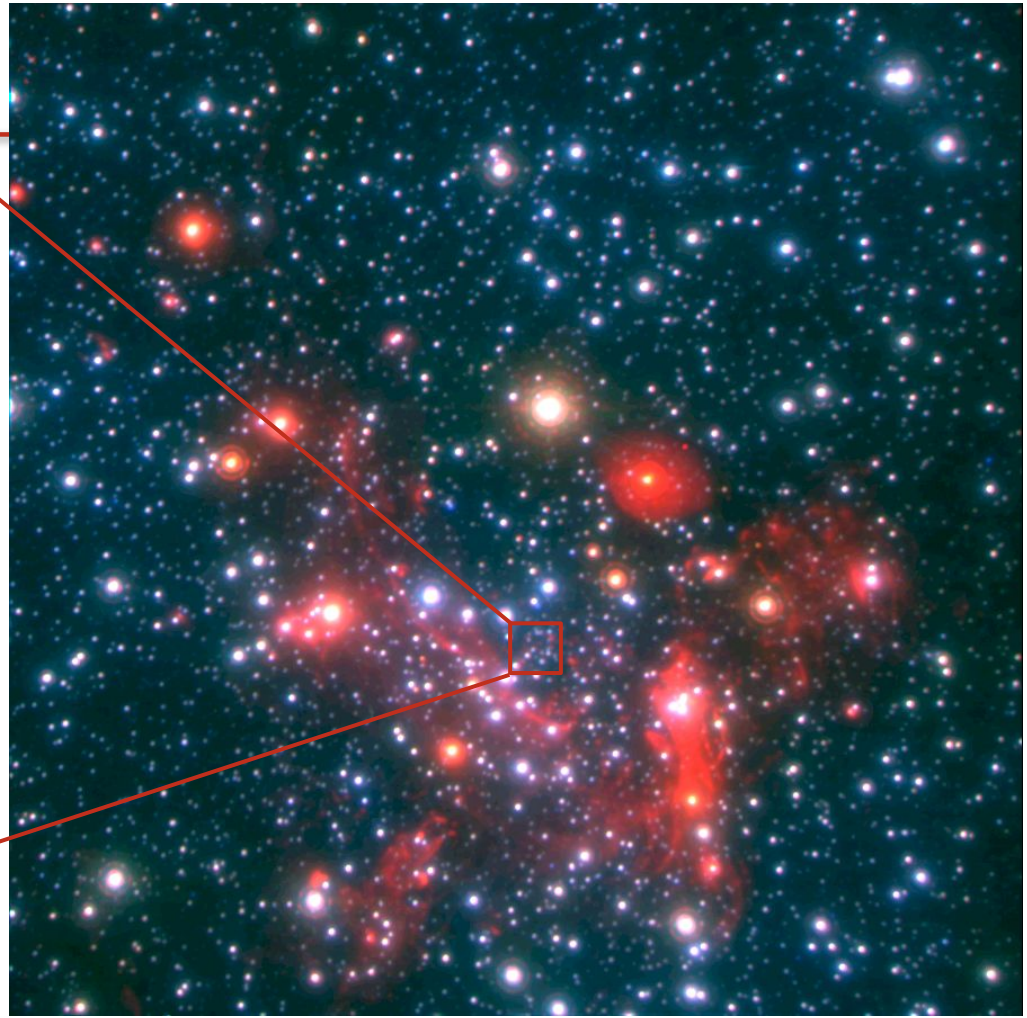
The Galactic Center



The Galactic Center

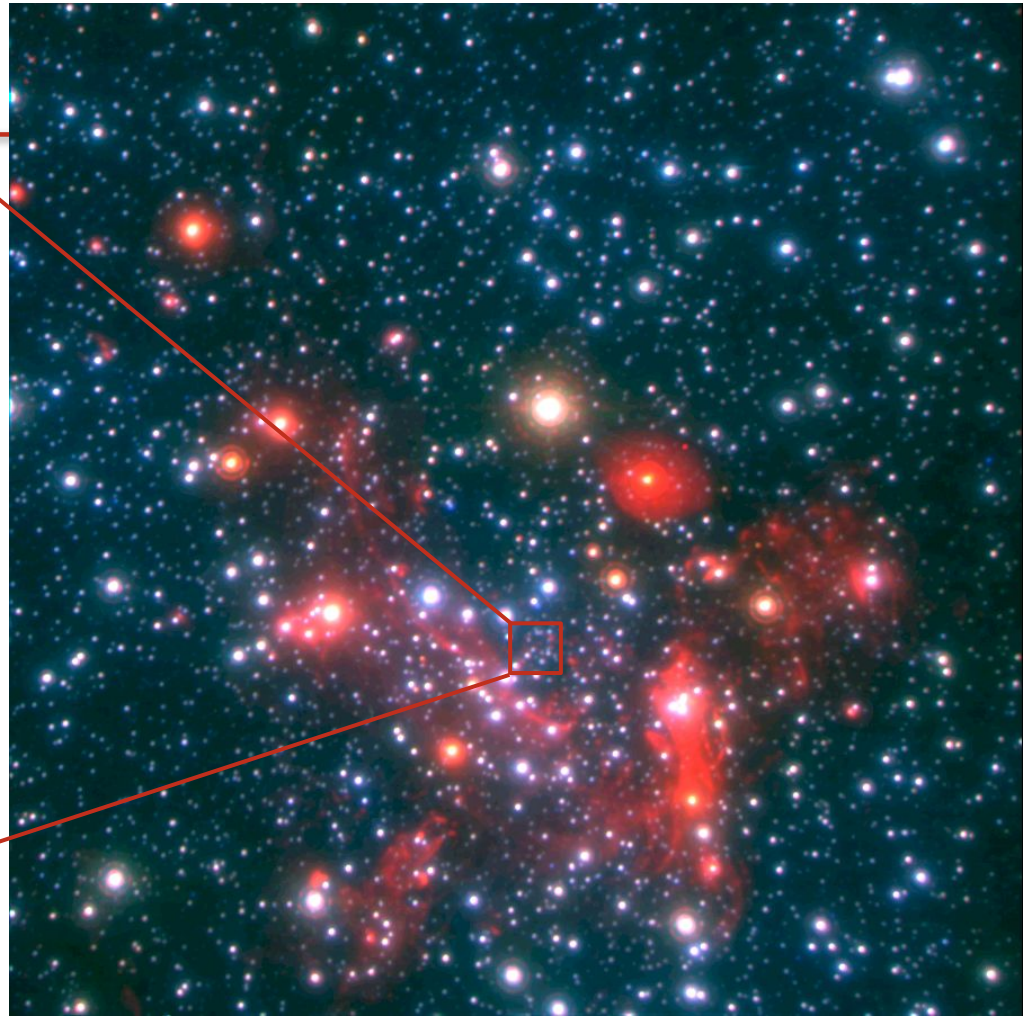


20 years of NACO data
(8m AO supported imaging)

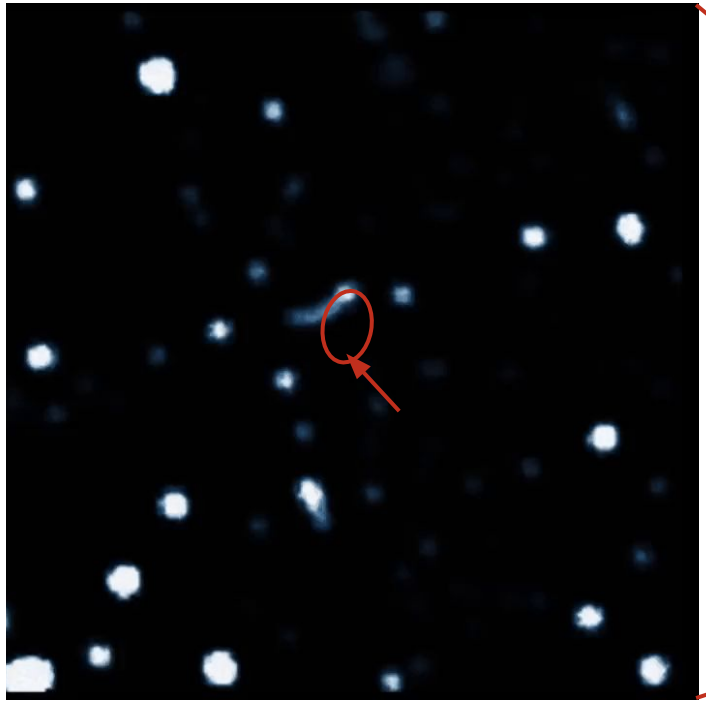


The Galactic Center

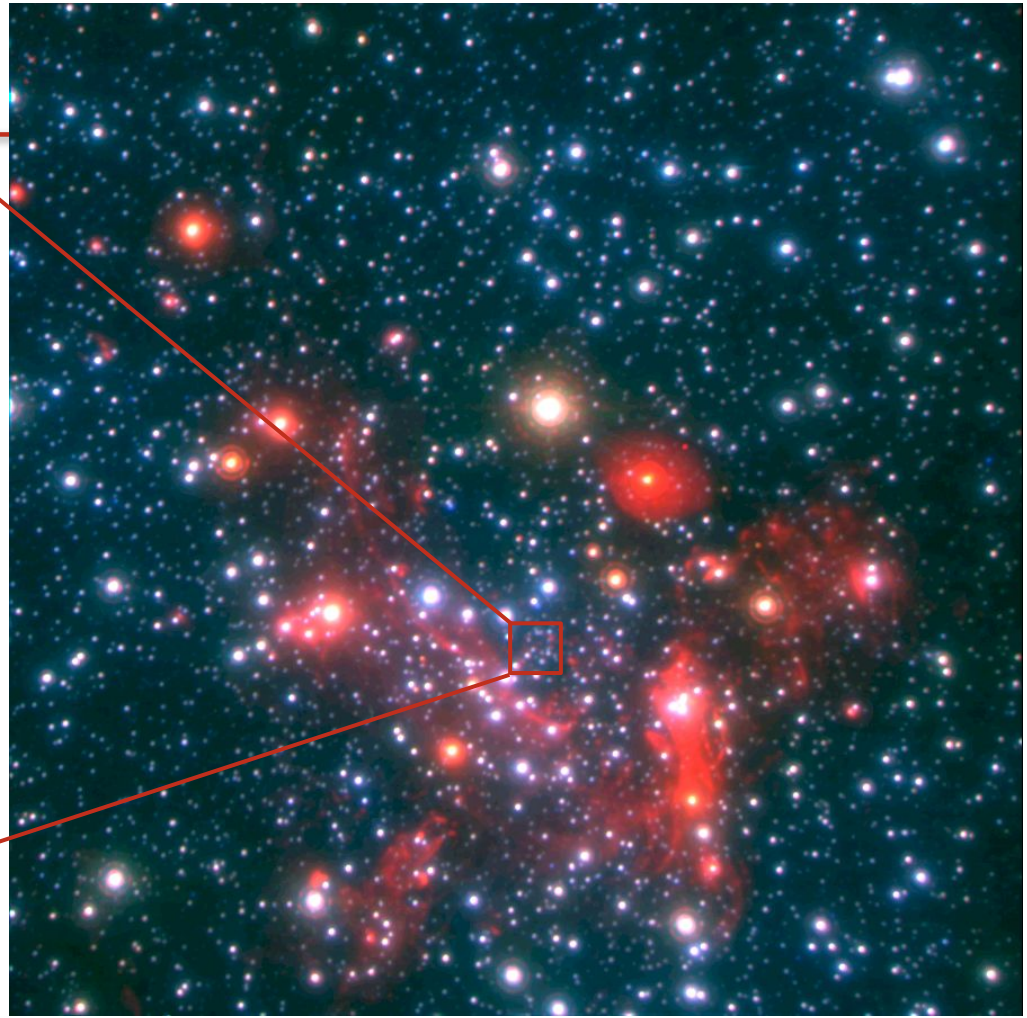
20 years of NACO data
(8m AO supported imaging)



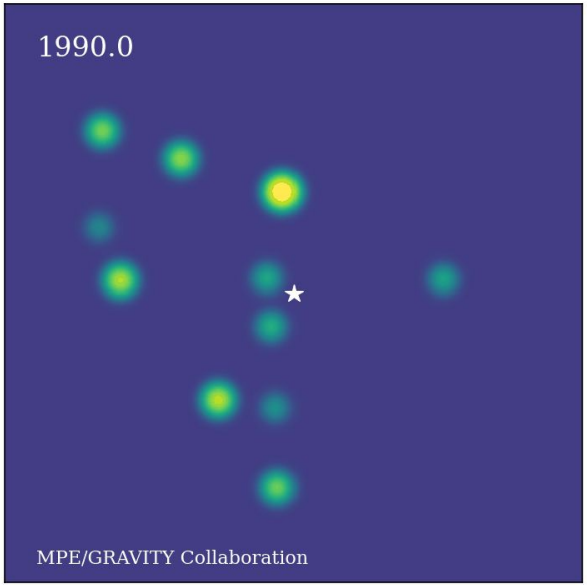
The Galactic Center



20 years of NACO data
(8m AO supported imaging)



The Galactic Center

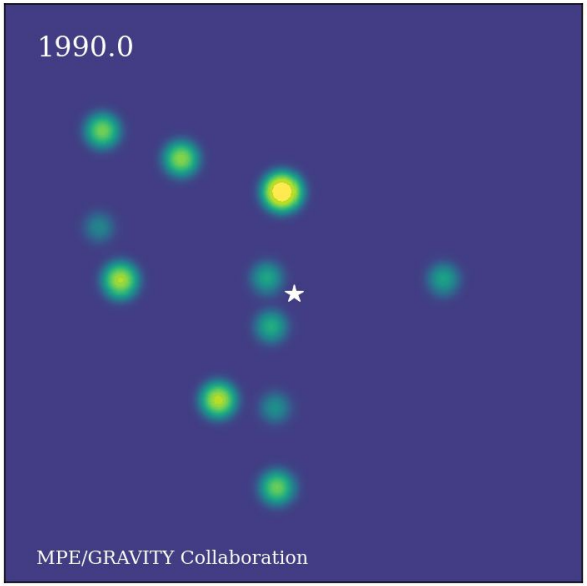


We know ~45 stars which orbit a central object:

- Mostly dark object
- 4 million solar masses heavy
- Very compact

-> Sgr A* is a supermassive black hole

The Galactic Center



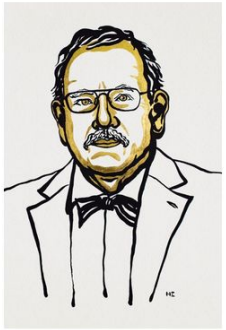
We know ~45 stars which orbit a central object

- Mostly dark object
- 4 million solar masses heavy
- Very compact

-> Sgr A* is a supermassive black hole

Physics Nobel Prize 2020:

"for the discovery of a supermassive compact object at the centre of our galaxy"

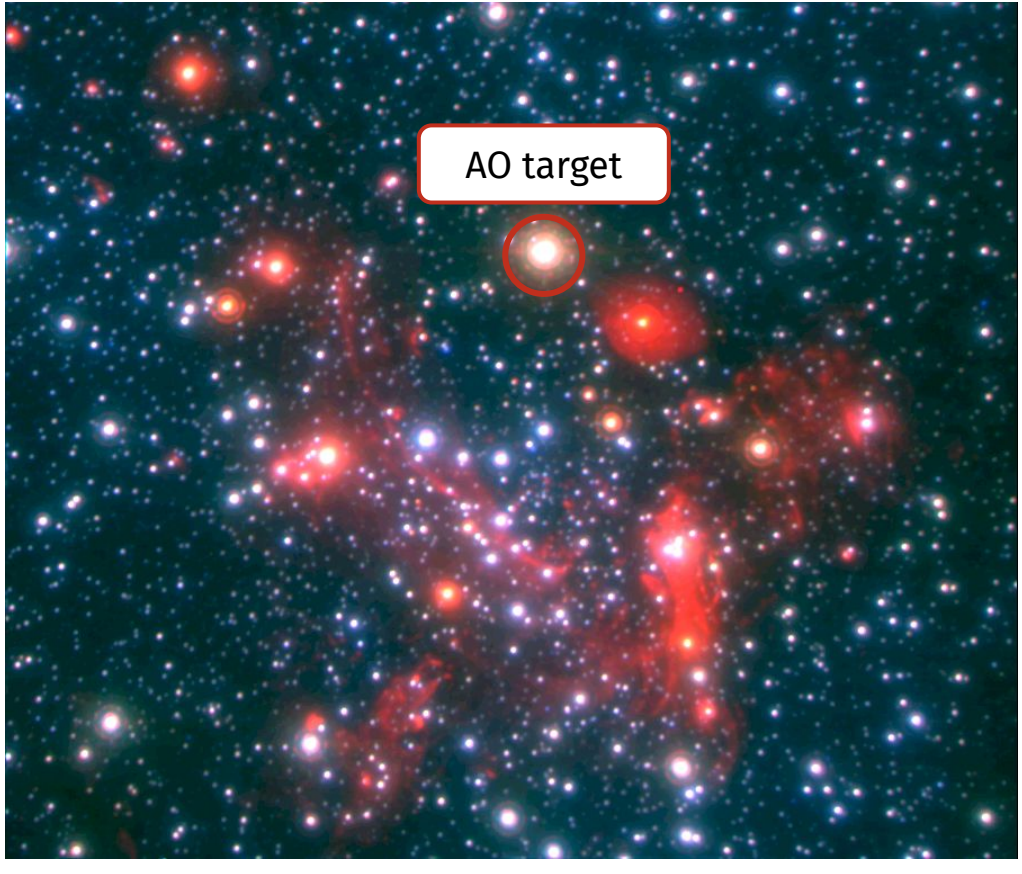


© Nobel Media. Ill. Niklas Elmehed.
Reinhard Genzel

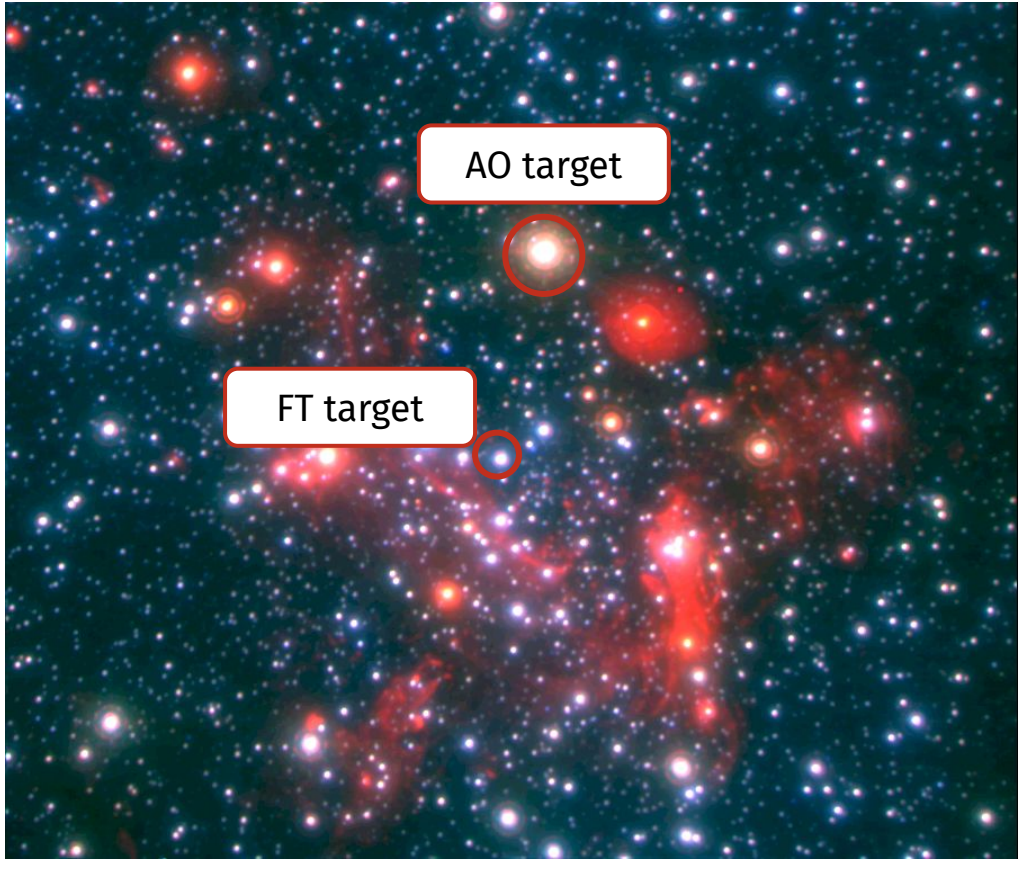
© Nobel Media. Ill. Niklas Elmehed.
Andrea Ghez

Galactic Center with GRAVITY

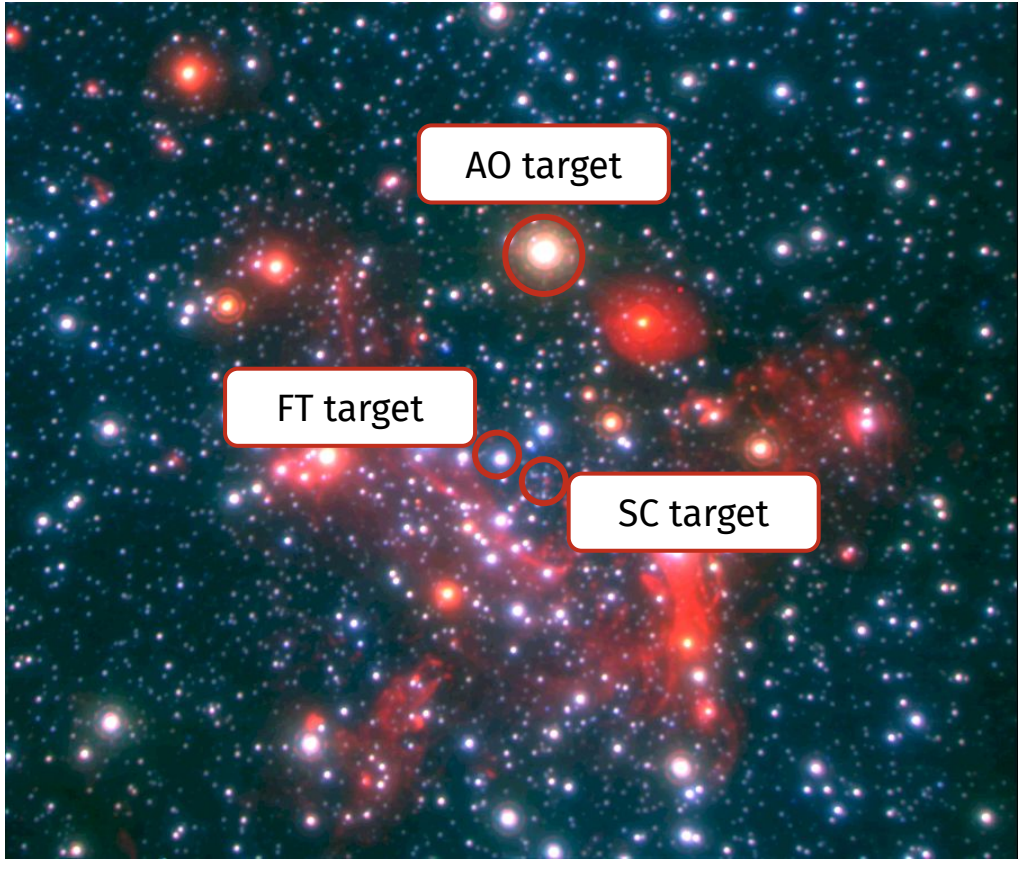
Galactic Center with GRAVITY



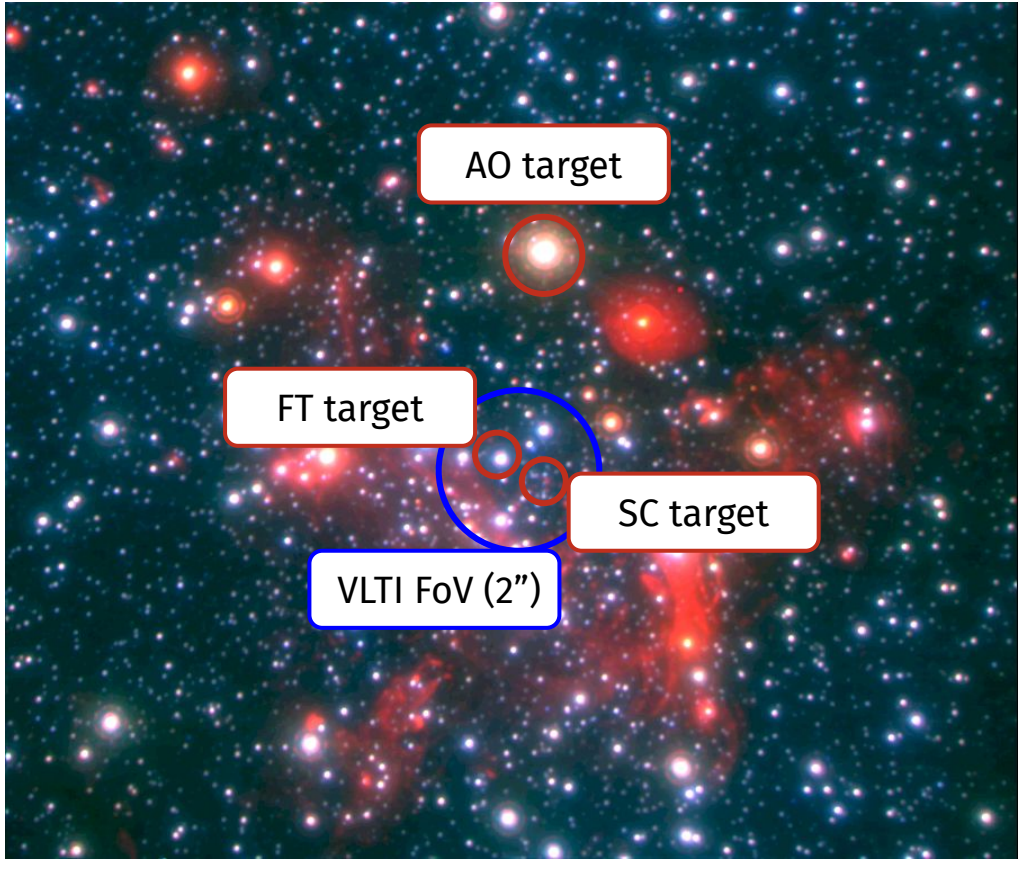
Galactic Center with GRAVITY



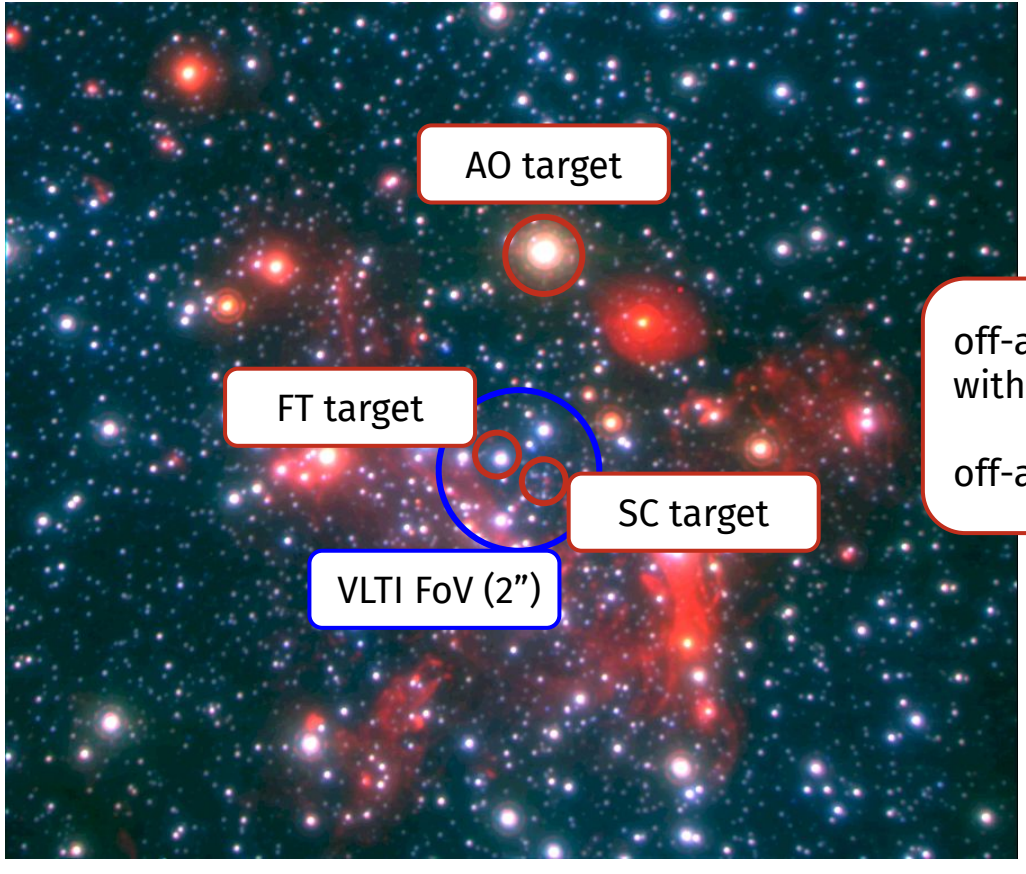
Galactic Center with GRAVITY



Galactic Center with GRAVITY



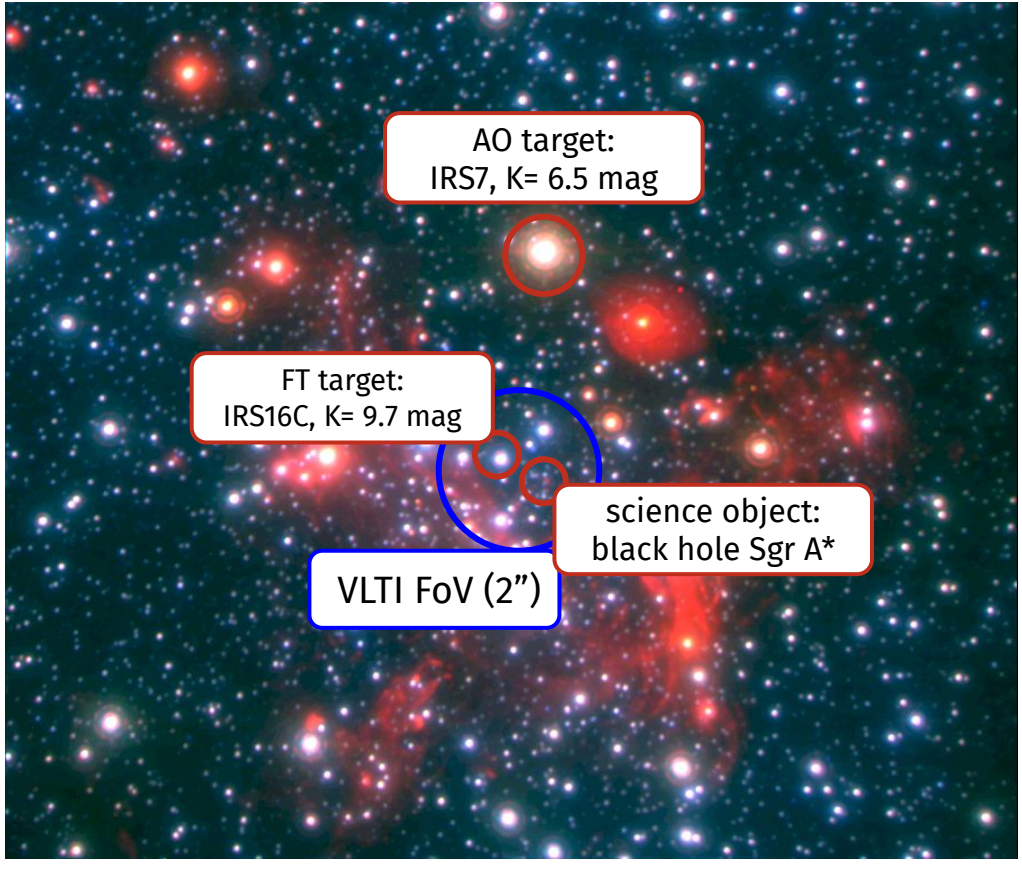
Galactic Center with GRAVITY



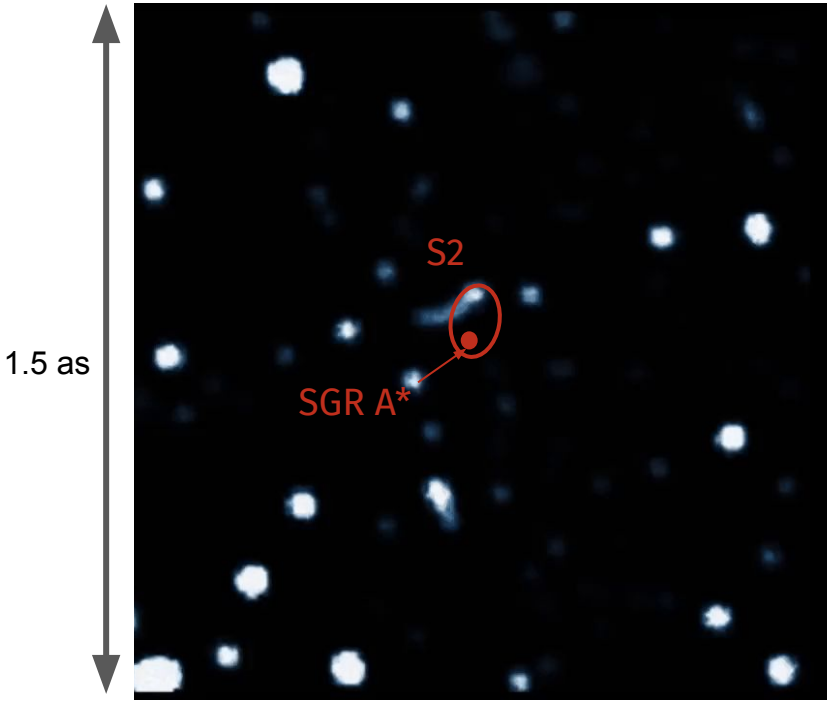
off-axis adaptive optics with CIAO

off-axis fringe tracking

Galactic Center with GRAVITY

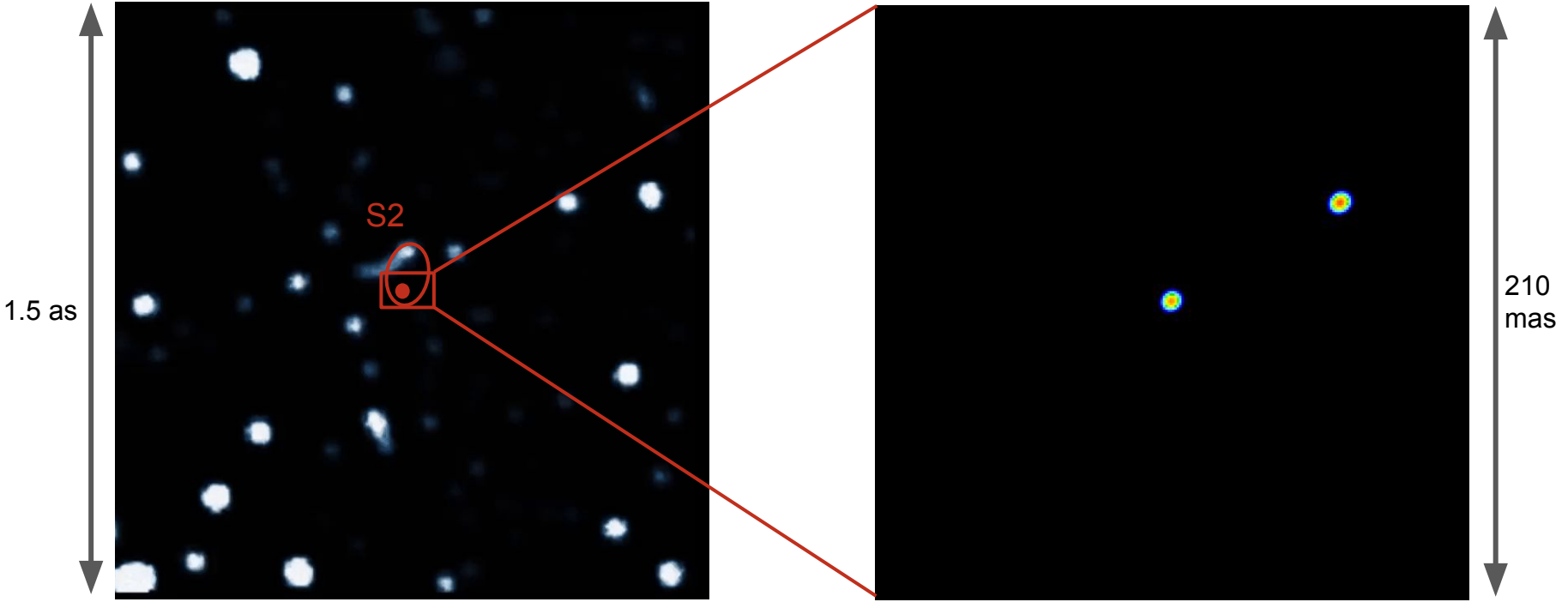


Galactic Center without GRAVITY



20 years of NACO data
(8m AO supported imaging)

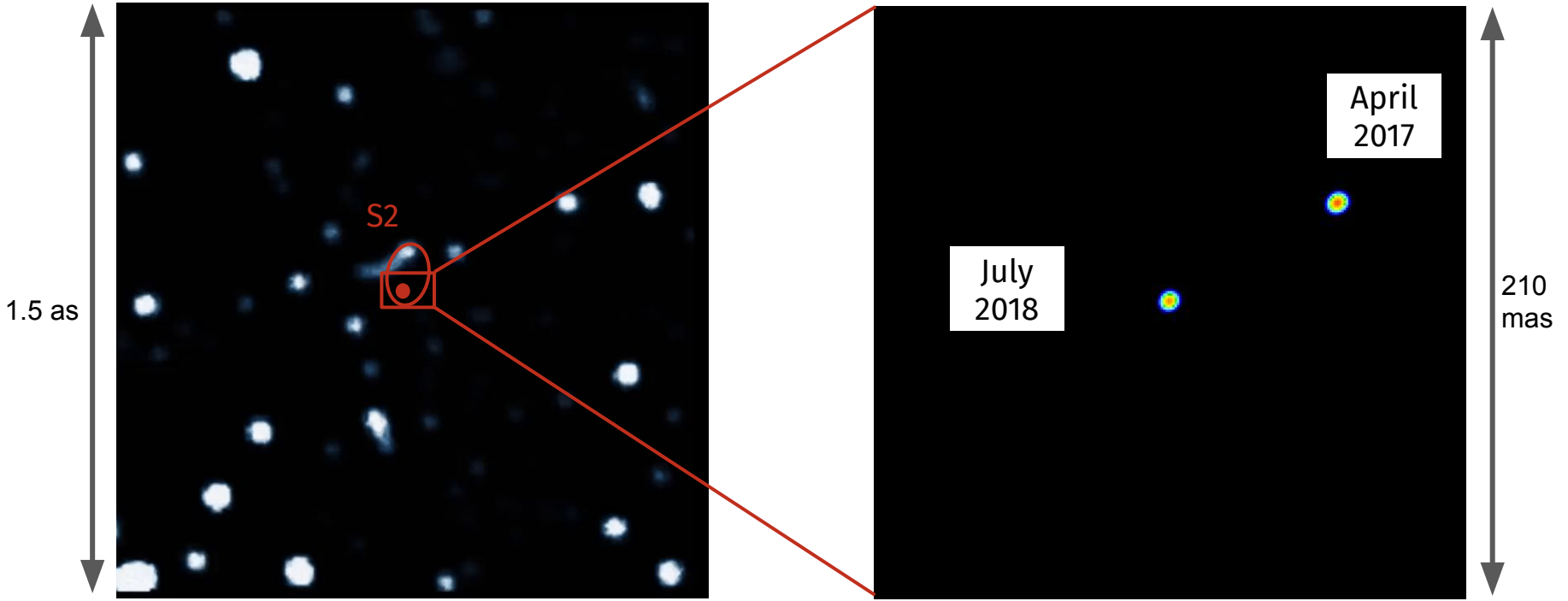
Galactic Center with GRAVITY



20 years of NACO data
(8m AO supported imaging)

1.5 years of GRAVITY data
(reconstructed images)

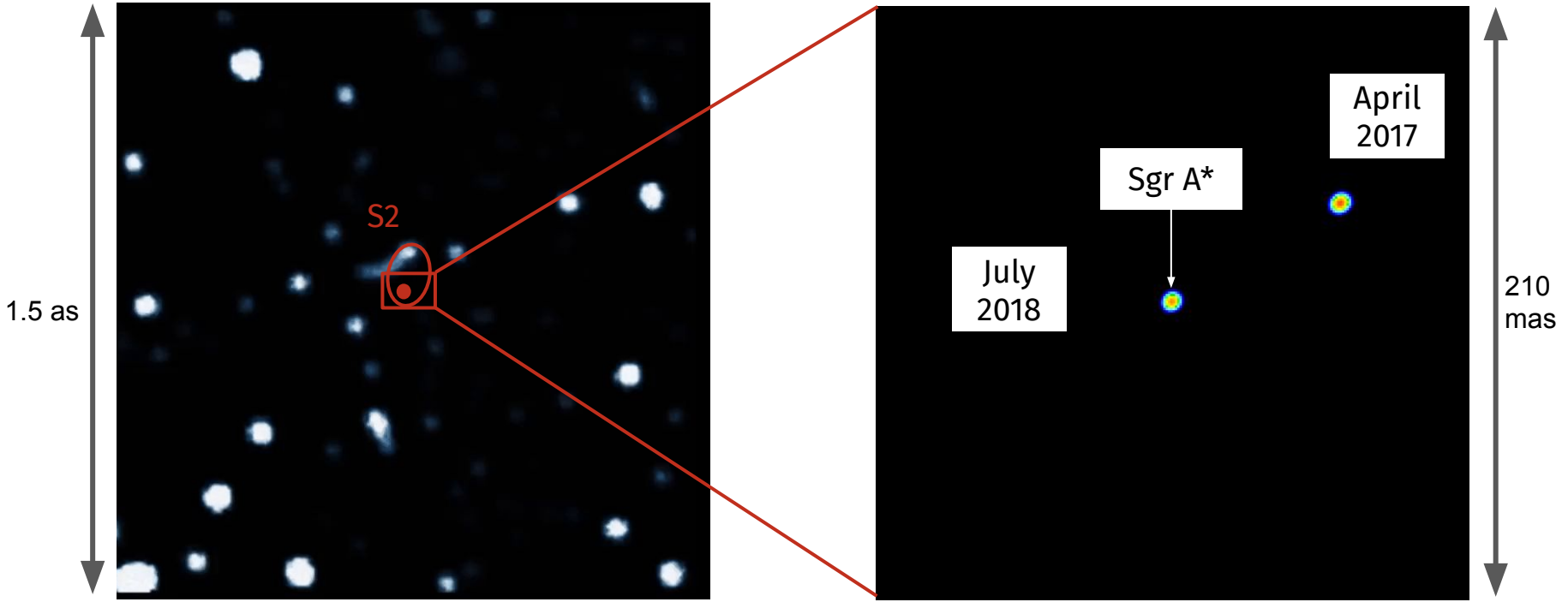
Galactic Center with GRAVITY



20 years of NACO data
(8m AO supported imaging)

1.5 years of GRAVITY data
(reconstructed images)

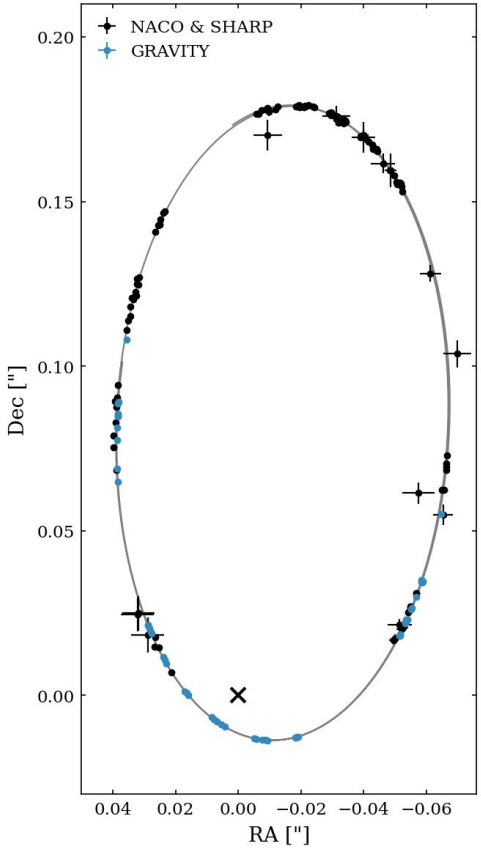
Galactic Center with GRAVITY



20 years of NACO data
(8m AO supported imaging)

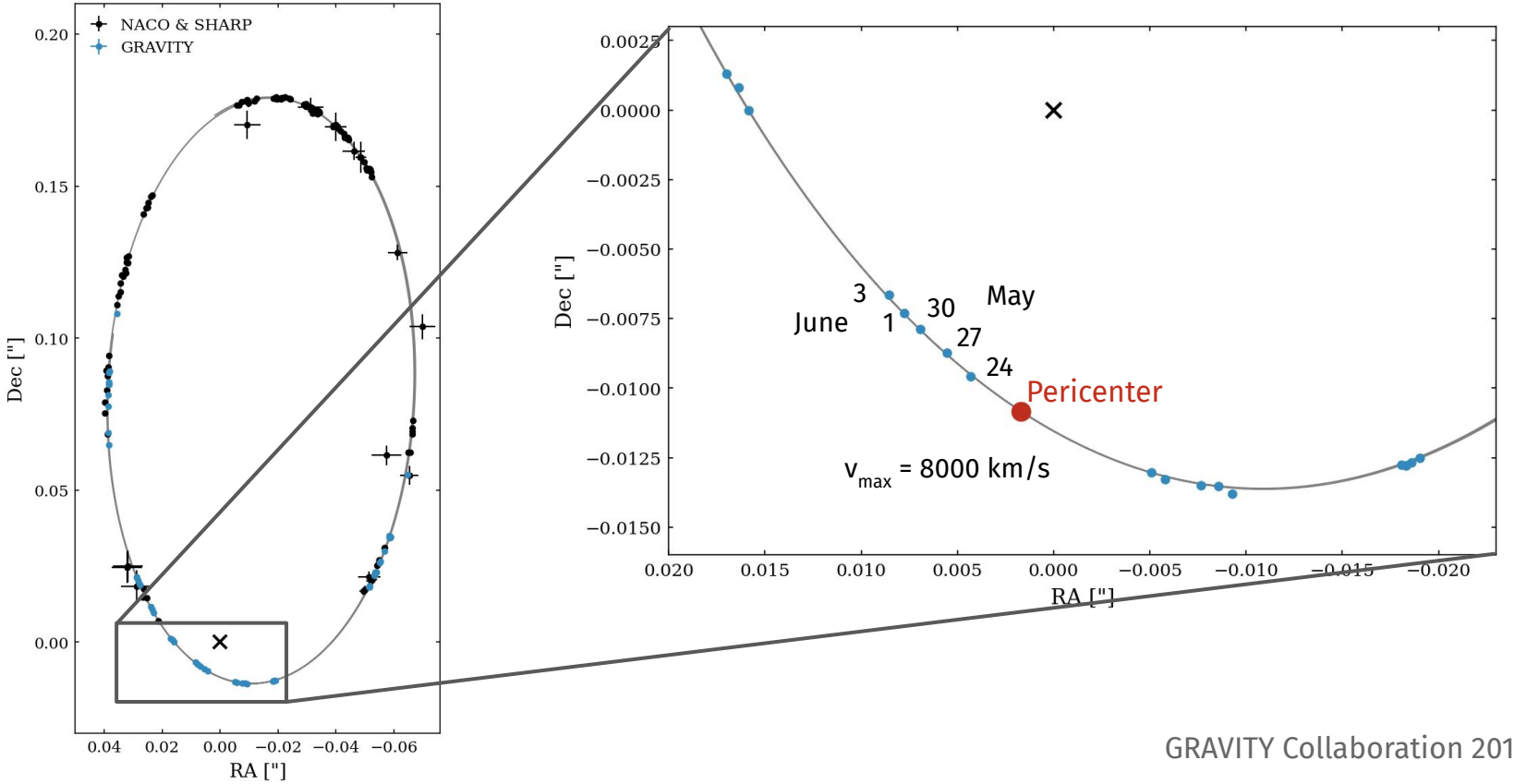
1.5 years of GRAVITY data
(reconstructed images)

Galactic Center - S2 Orbit



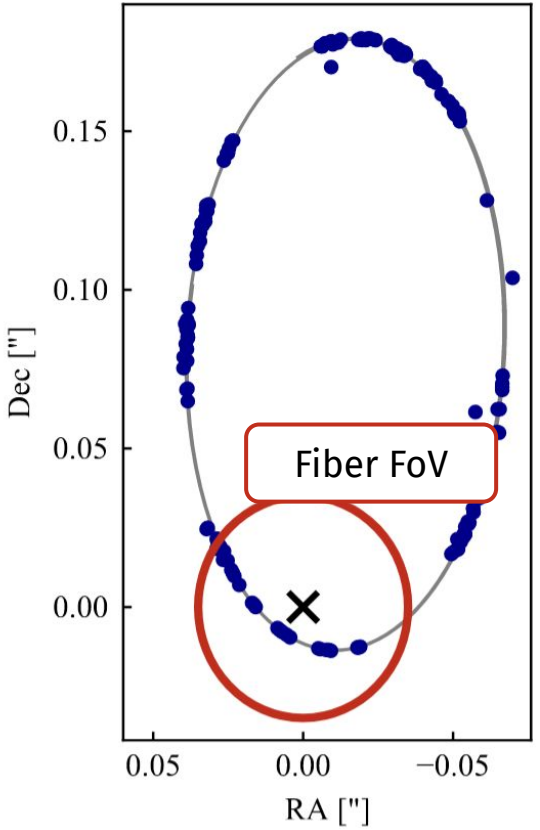
GRAVITY Collaboration 2019, 2020

Galactic Center - S2 Orbit

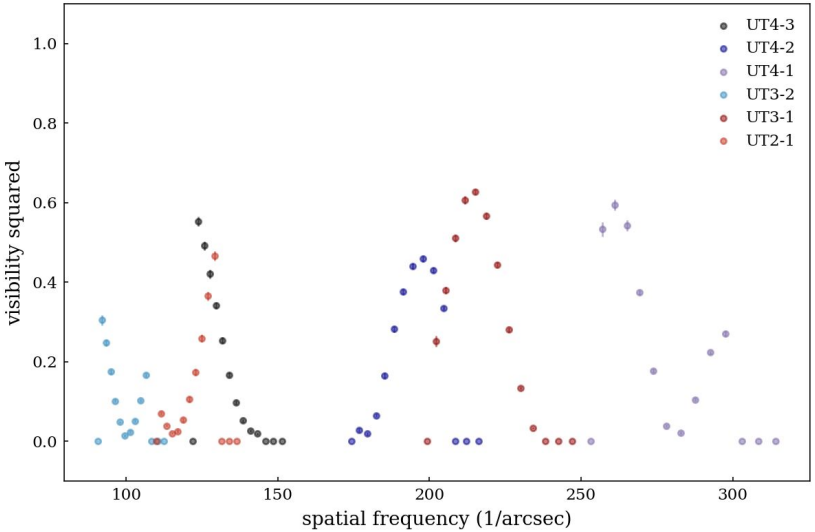


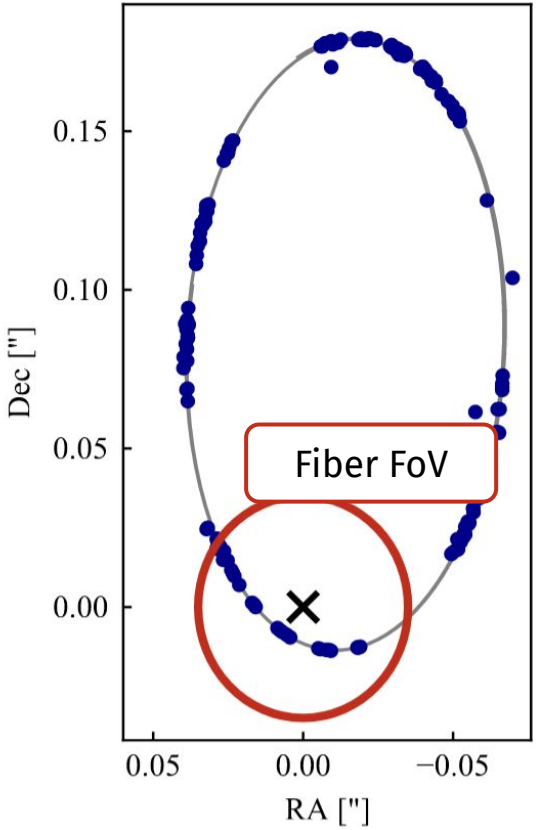
GRAVITY Collaboration 2019, 2020

The Galactic Center

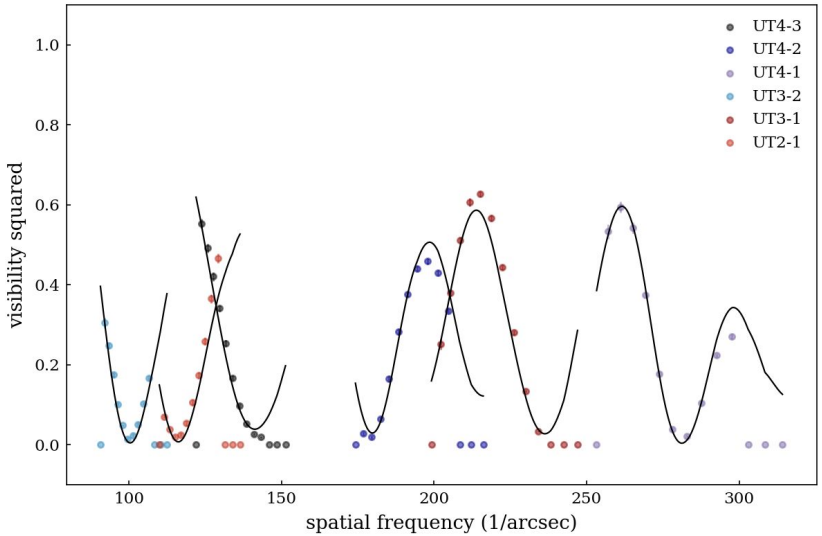


The Galactic Center

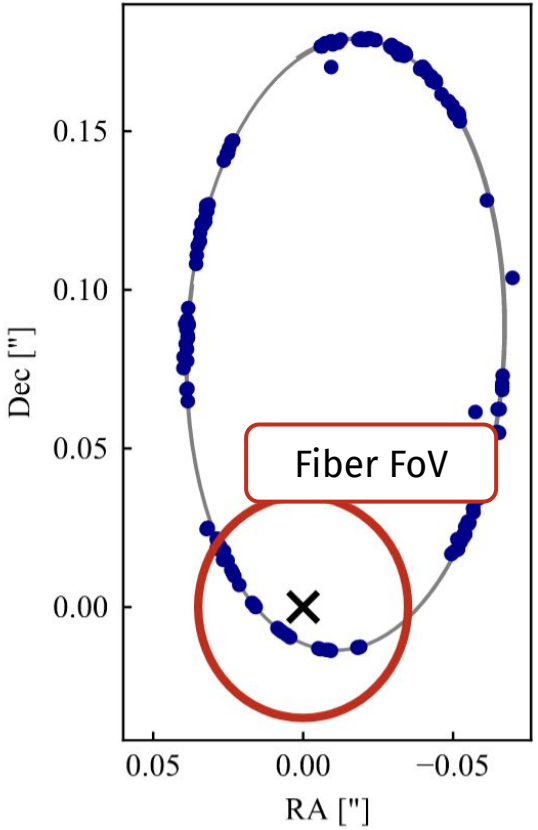




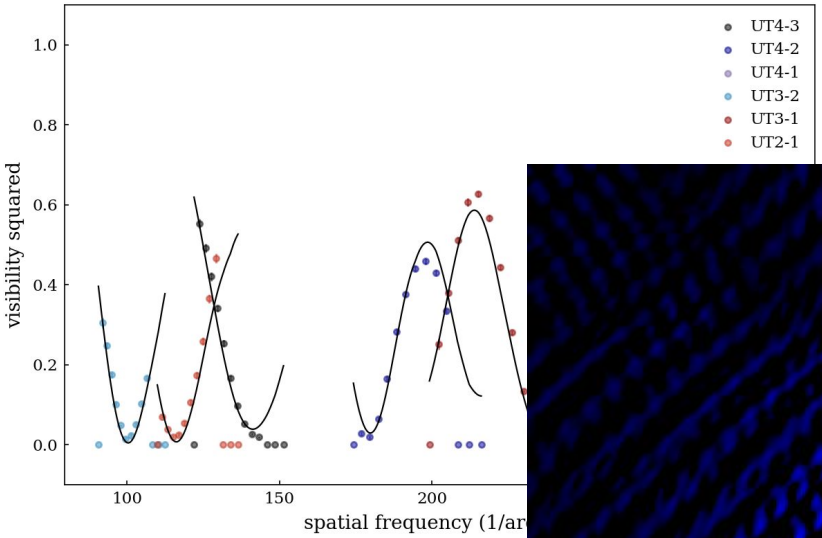
The Galactic Center



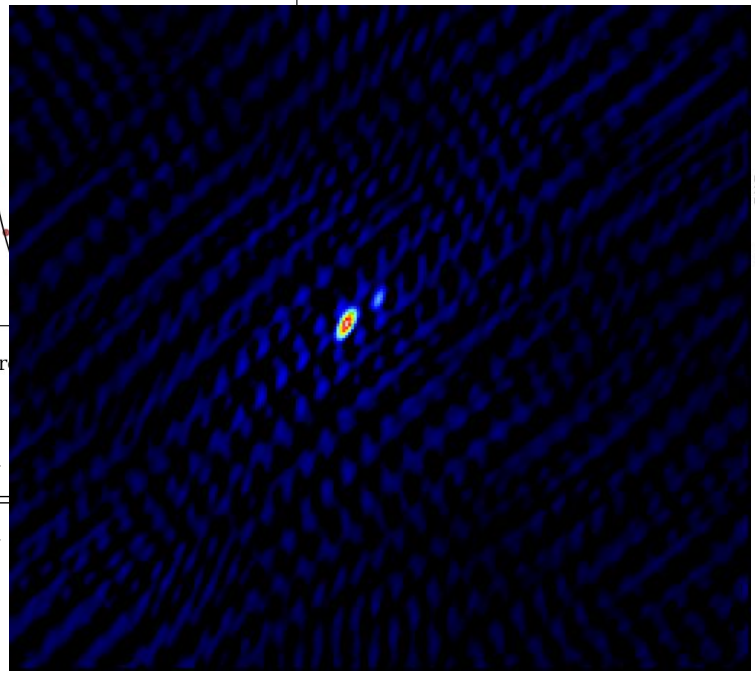
$$V\left(\vec{b}_{i,j}/\lambda\right) = \frac{V_\lambda\left[\left(\vec{b}_{i,j}\cdot\vec{\alpha}_1\right),\nu_1\right] + f^{bin}\cdot V_\lambda\left[\left(\vec{b}_{i,j}\cdot\vec{\alpha}_2\right),\nu_2\right]}{\sqrt{\prod_{x=i,j}\left[V_\lambda\left(\vec{0},\nu_1\right) + f^{bin}\cdot V_\lambda\left(\vec{0},\nu_2\right) + f^{bkg}\cdot V_\lambda\left(\vec{0},\nu_{bkg}\right)\right]}}$$

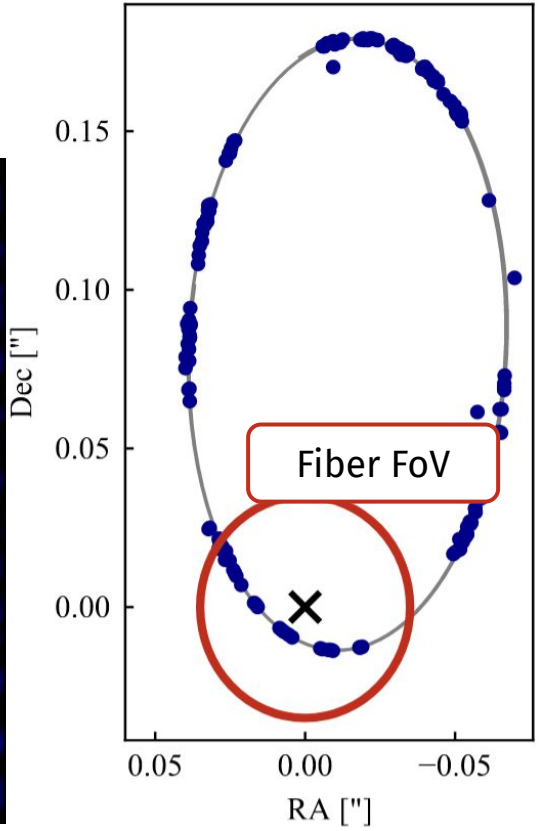


The Galactic Center

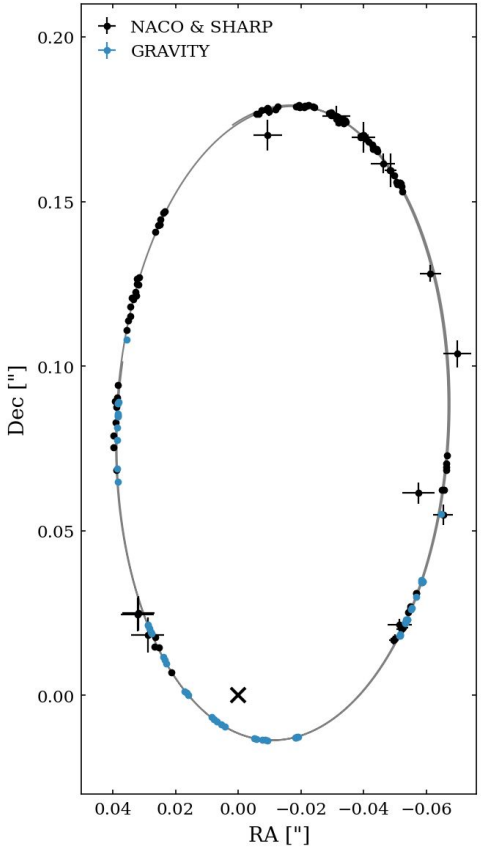


$$V\left(\vec{b}_{i,j}/\lambda\right) = \frac{V_\lambda\left[\left(\vec{b}_{i,j}\cdot\vec{\alpha}_1\right),\nu_1\right]+}{\sqrt{\prod_{x=i,j}\left[V_\lambda\left(\vec{0},\nu_1\right)+f^{bin}\cdot\right.}}$$





The Galactic Center



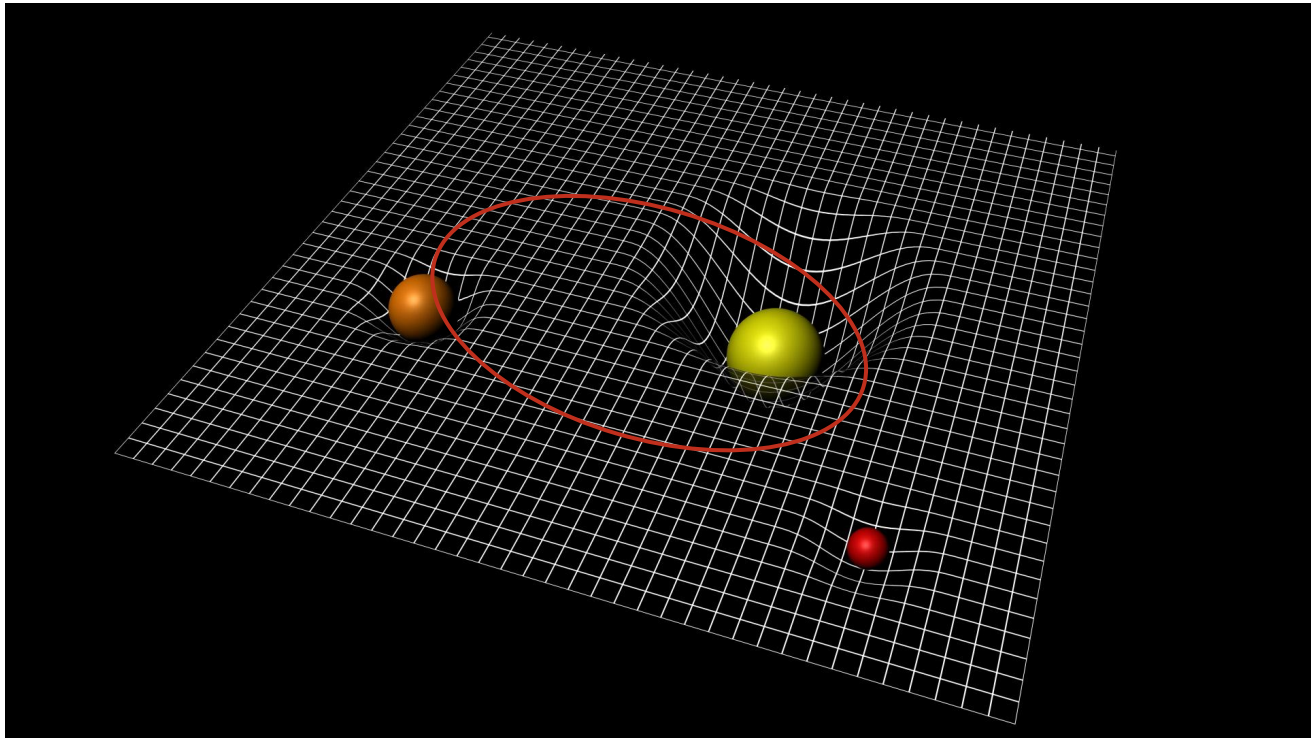
$M = (4.297 \pm 0.013)\ M_{sol}$

$R = (8275 \pm 9_{stat} \pm 33_{sys})$ pc

GRAVITY Collaboration 2019, 2020, 2021

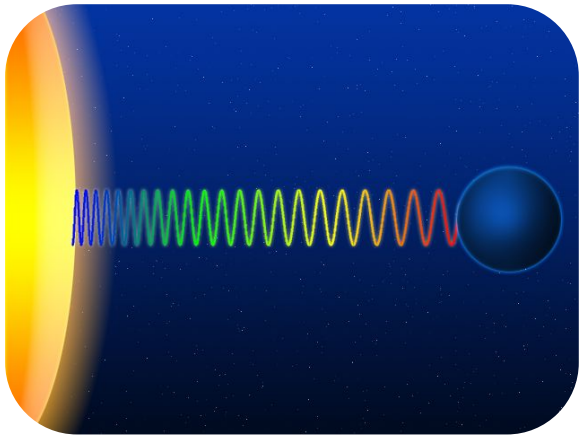
The Galactic Center as a GR laboratory

Stars around SgrA* work as probes to test the gravitational field



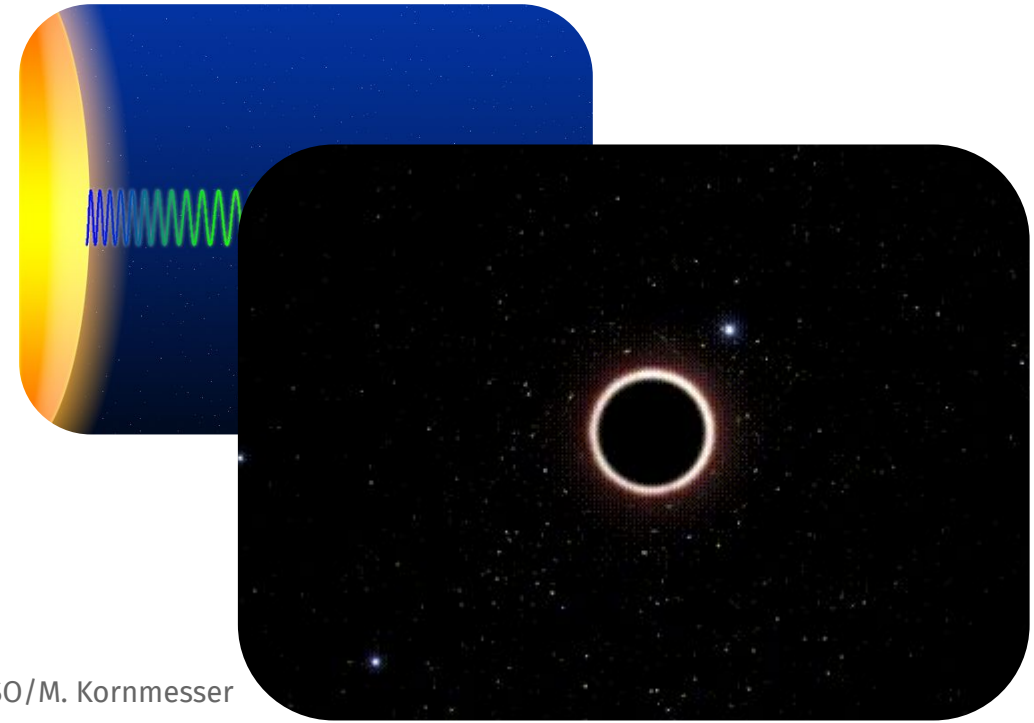
The Galactic Center as a GR laboratory

1. **Gravitational Redshift**



The Galactic Center as a GR laboratory

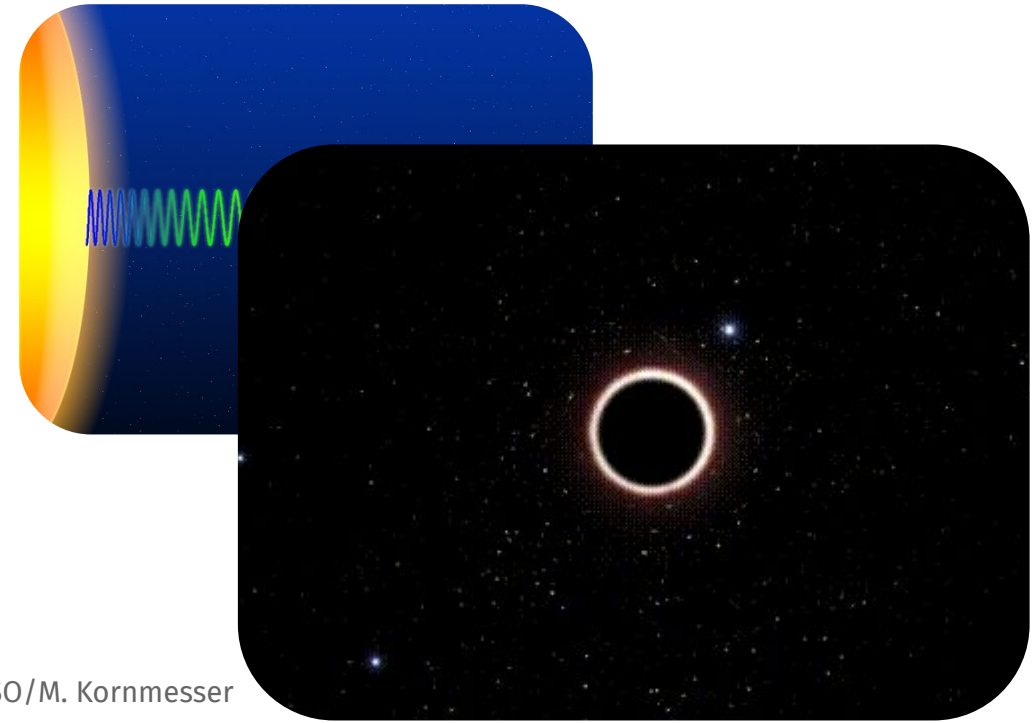
1. **Gravitational Redshift**



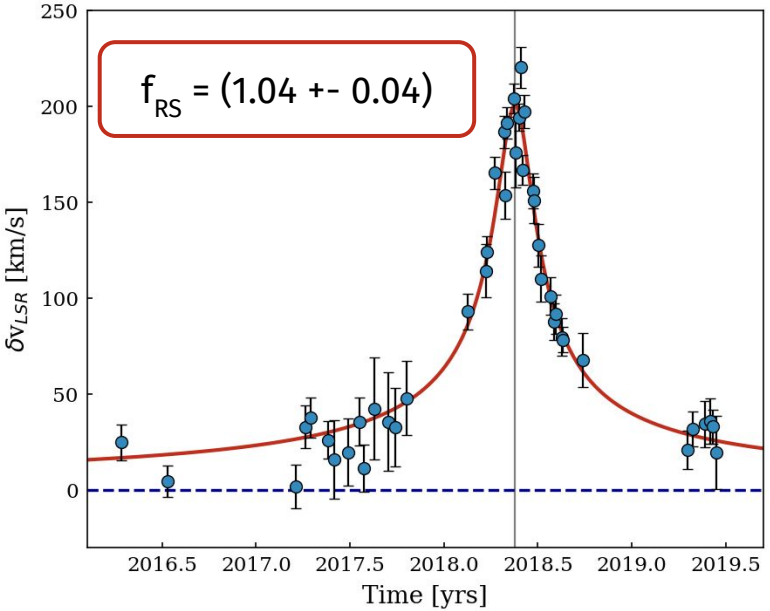
ESO/M. Kornmesser

The Galactic Center as a GR laboratory

1. Gravitational Redshift



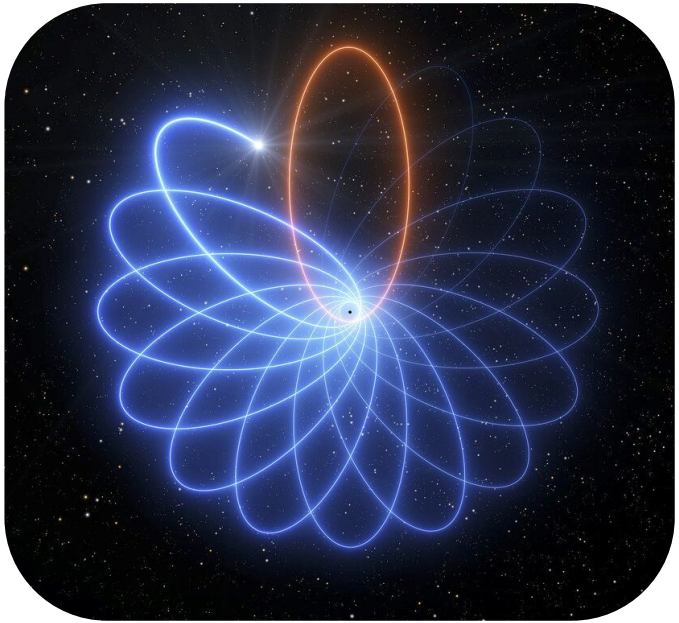
ESO/M. Kornmesser



GRAVITY Collaboration 2018, 2020; Do 2019

The Galactic Center as a GR laboratory

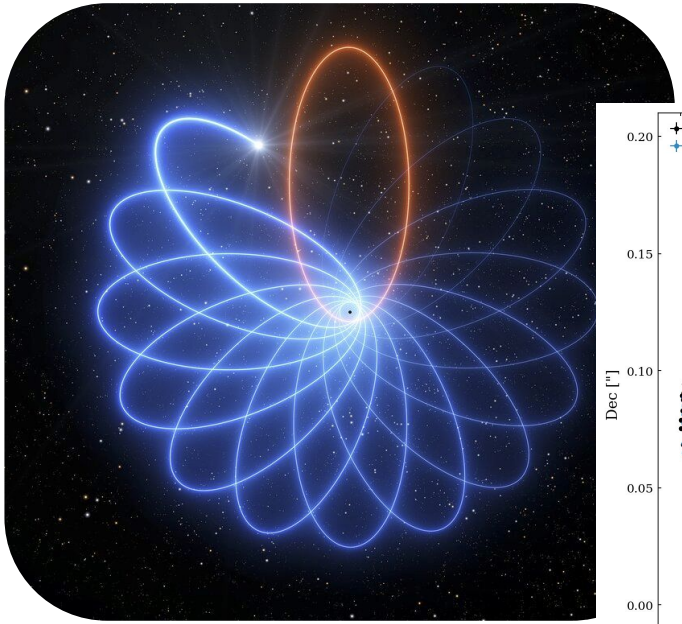
2. Schwarzschild precession

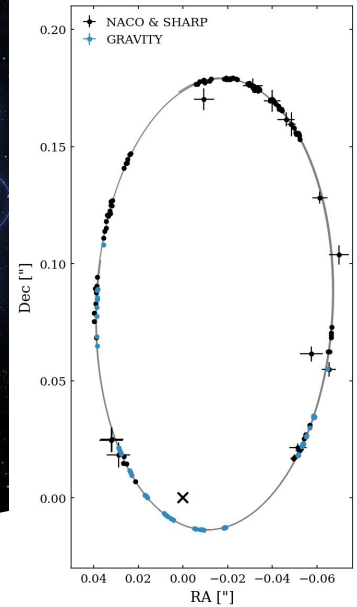


ESO/L. Calçada

The Galactic Center as a GR laboratory

2. Schwarzschild precession

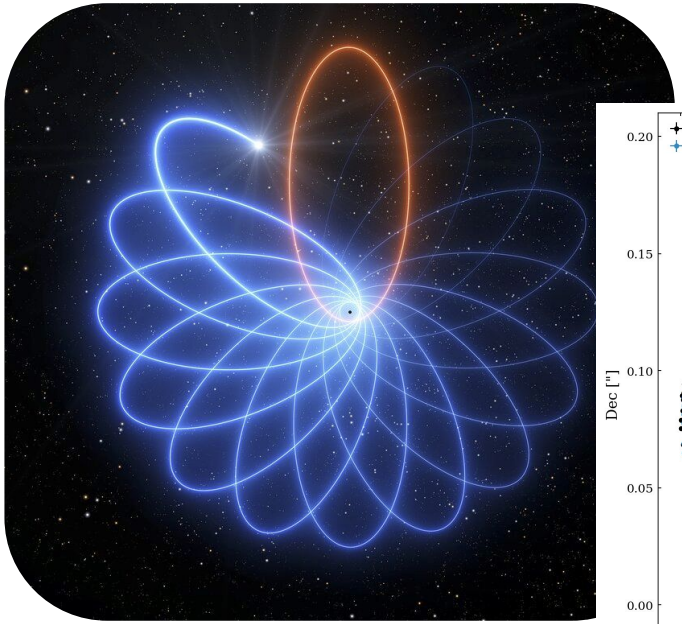




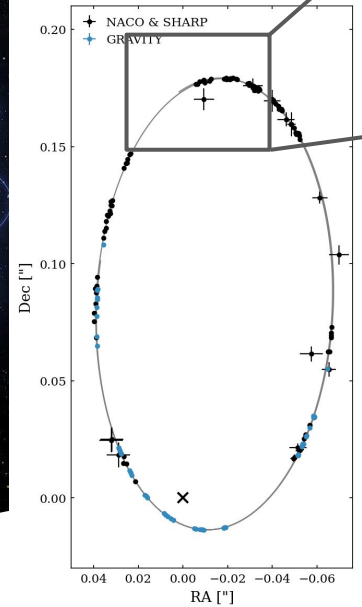
ESO/L. Calçada

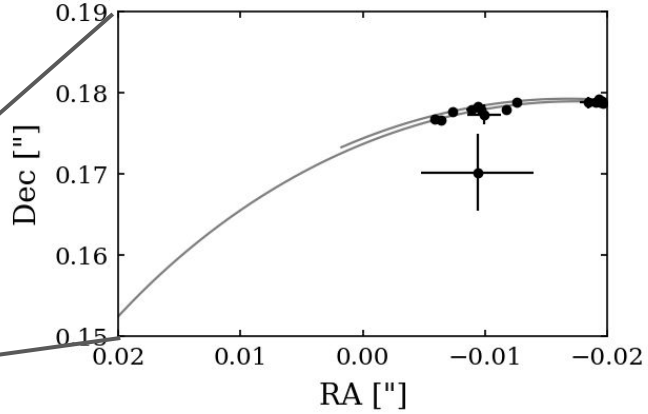
The Galactic Center as a GR laboratory

2. Schwarzschild precession



ESO/L. Calçada

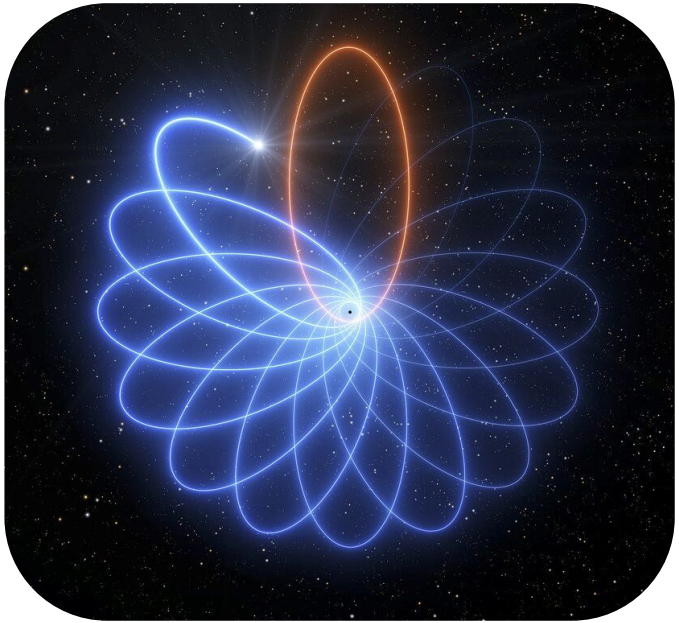




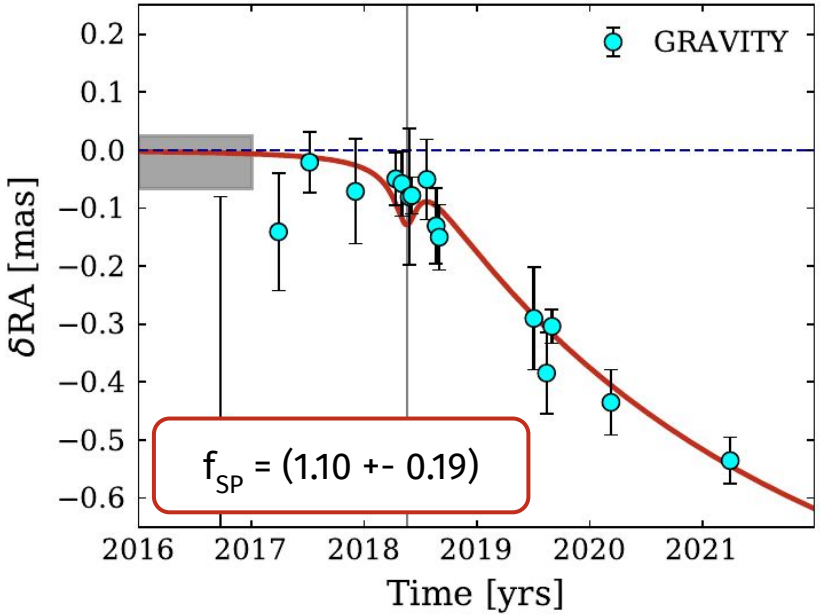
=> Rotation of orbit by 12’
per orbital period

The Galactic Center as a GR laboratory

2. Schwarzschild precession



ESO/L. Calçada

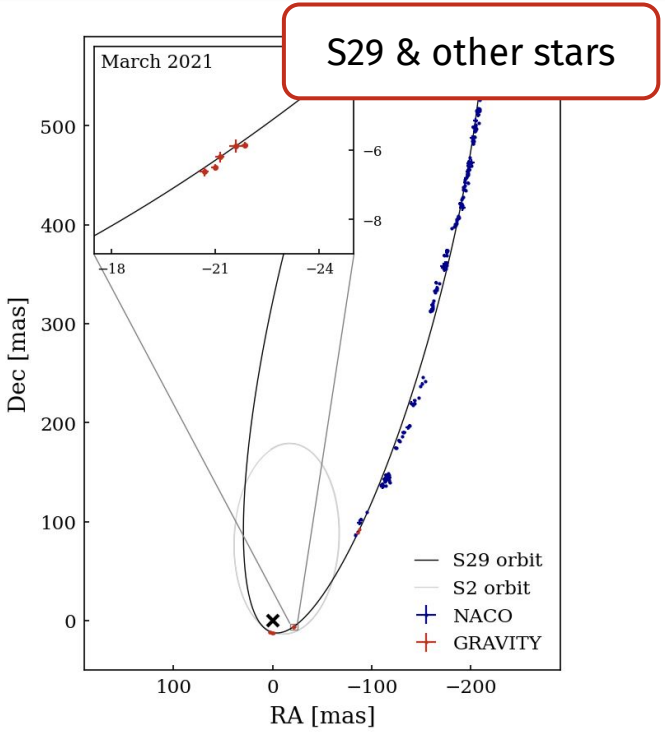


GRAVITY Collaboration 2020

The Galactic Center as a GR laboratory

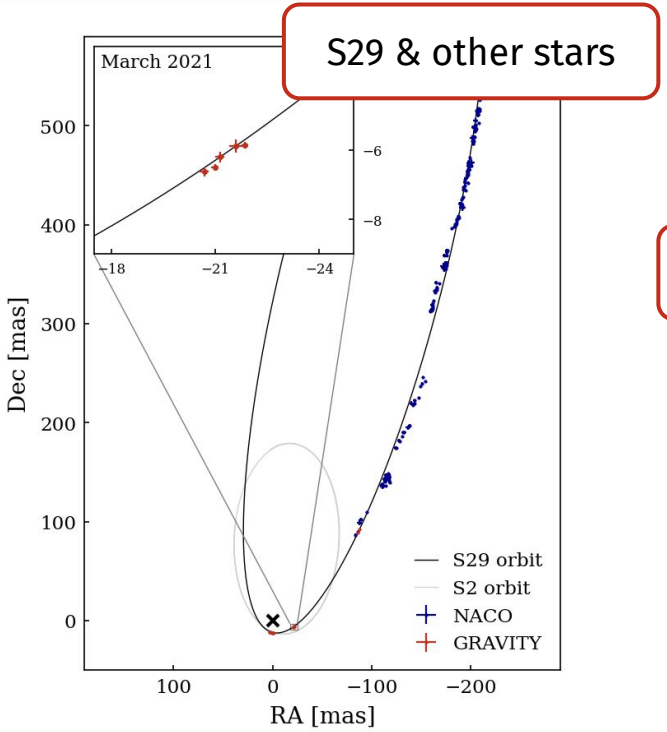
What's next?

The Galactic Center as a GR laboratory



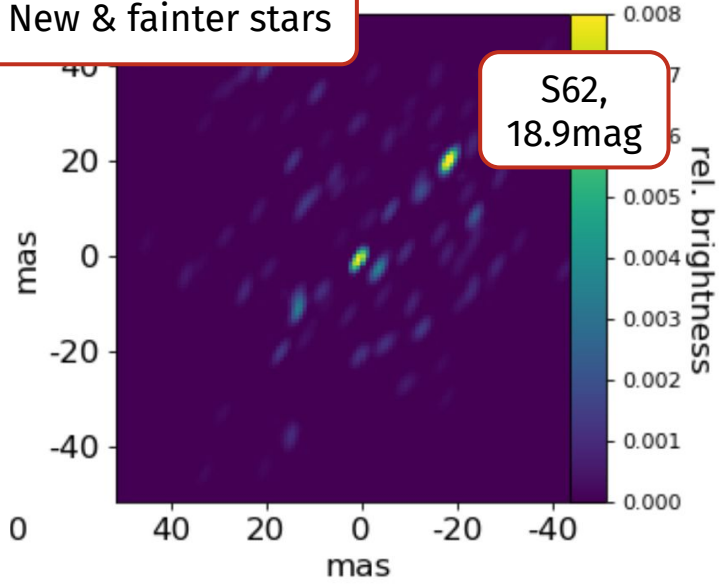
The Galactic Center as a GR laboratory

S29 & other stars



New & fainter stars

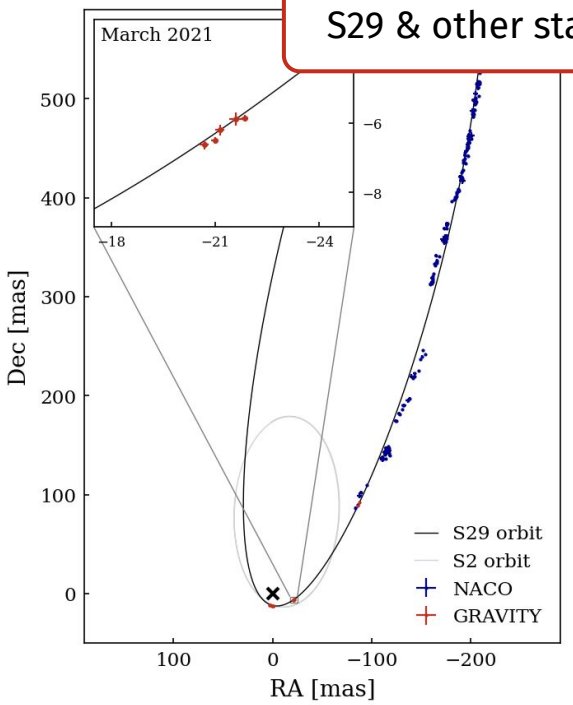
S62, 18.9mag



GRAVITY Collaboration 2021

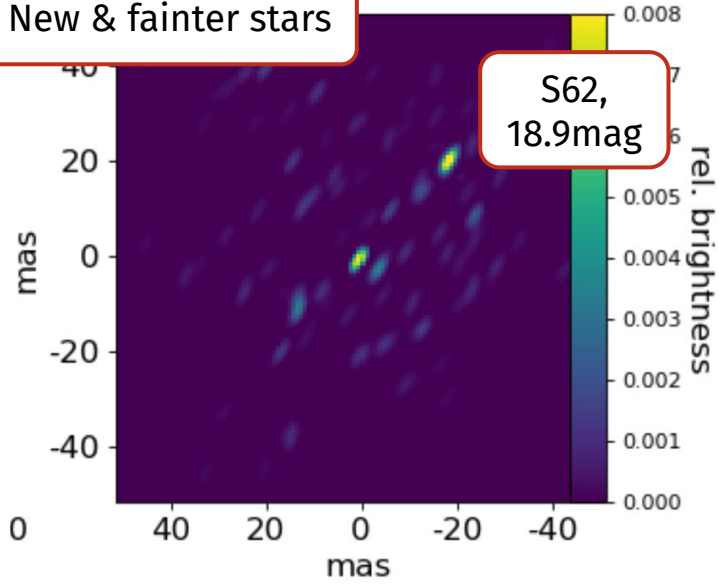
The Galactic Center as a GR laboratory

S29 & other stars

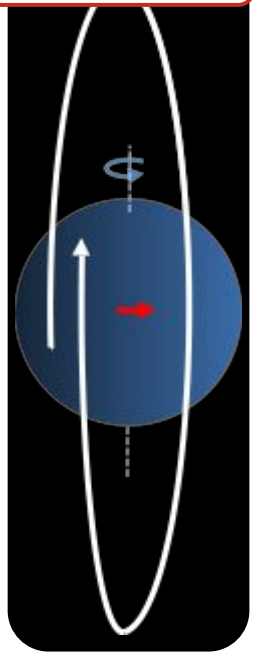


New & fainter stars

S62, 18.9mag

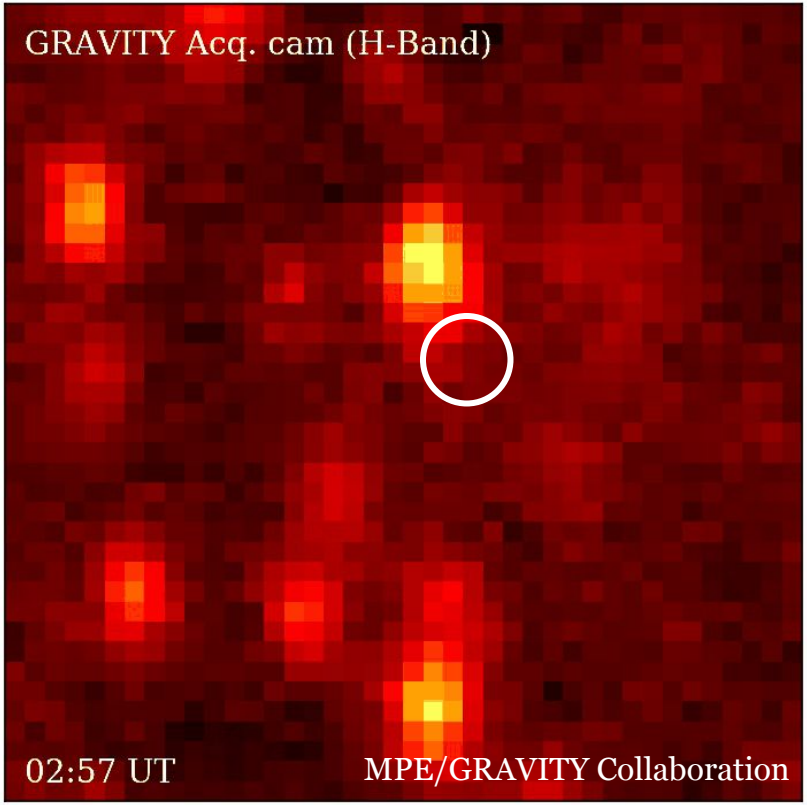


Measure spin of SgrA*

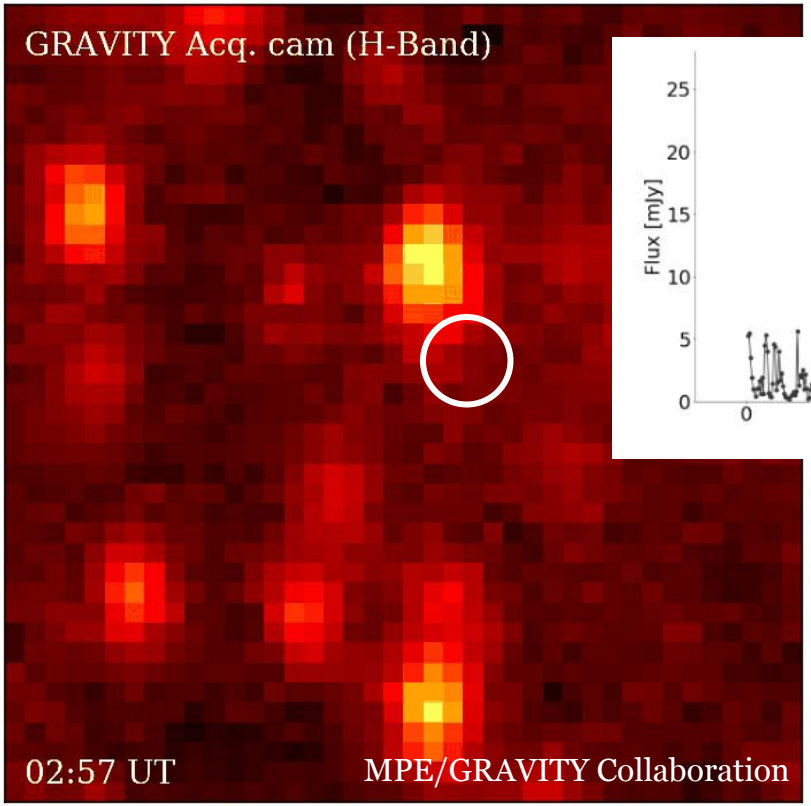


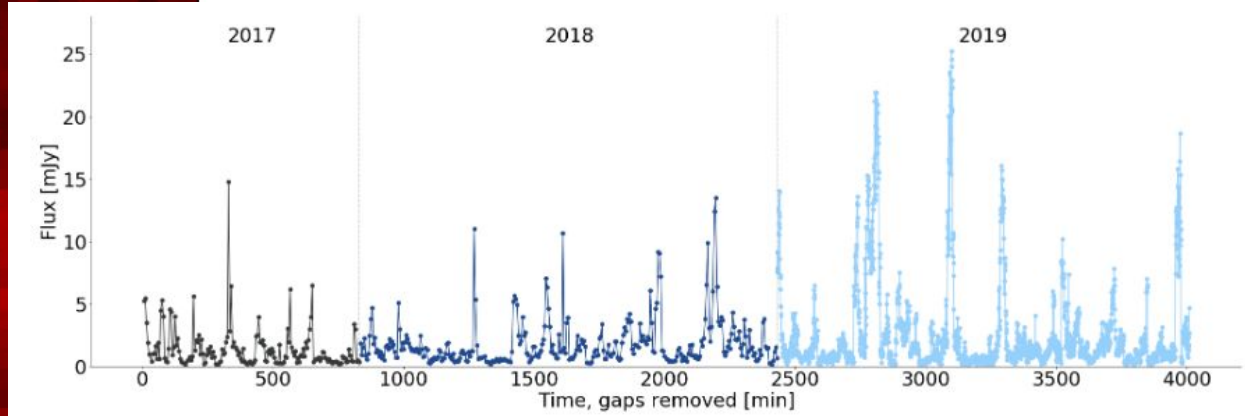
GRAVITY Collaboration 2021

The Galactic Center to study black holes



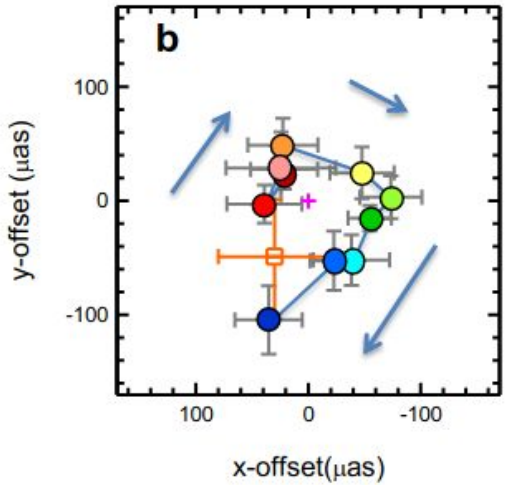
The Galactic Center to study black holes





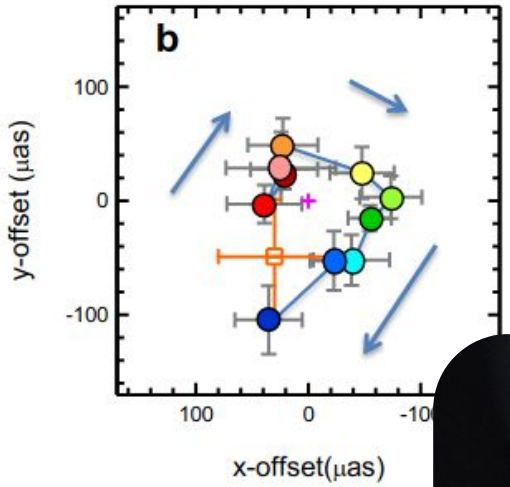
GRAVITY Collaboration 2020

The Galactic Center to study black holes



GRAVITY Collaboration 2018, 2020

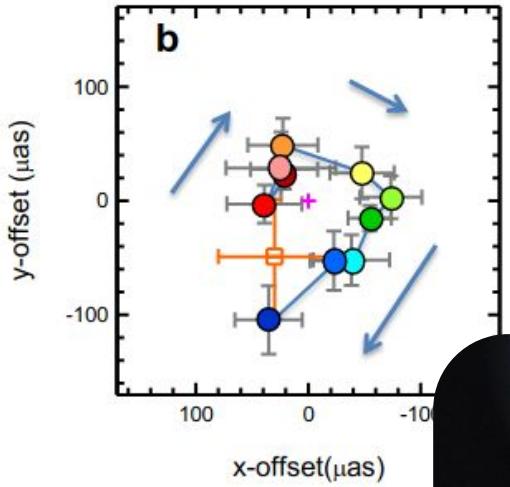
The Galactic Center to study black holes

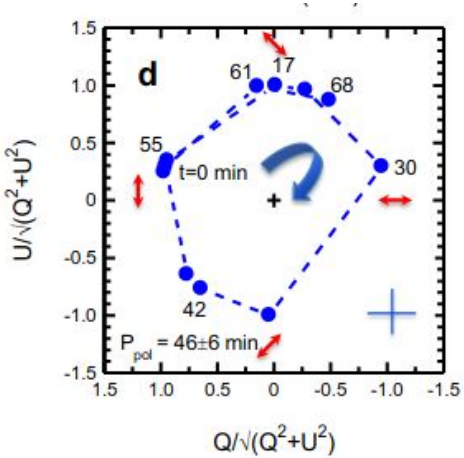


ESO/Gravity Consortium/L. Calçada

GRAVITY Collaboration 2018, 2020

The Galactic Center to study black holes

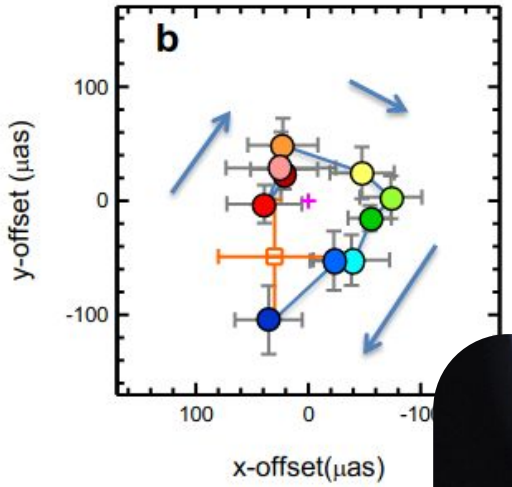




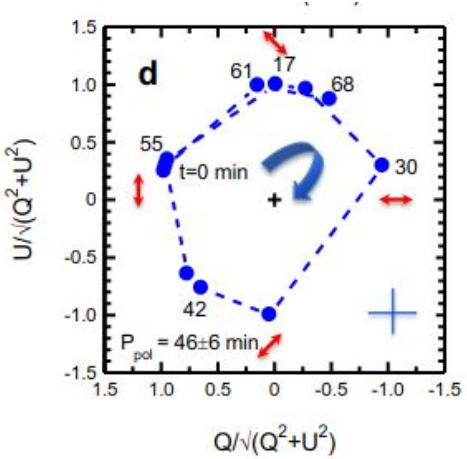
ESO/Gravity Consortium/L. Calçada

GRAVITY Collaboration 2018, 2020

The Galactic Center to study black holes



magnetic reconnection in predominantly vertical magnetic field!

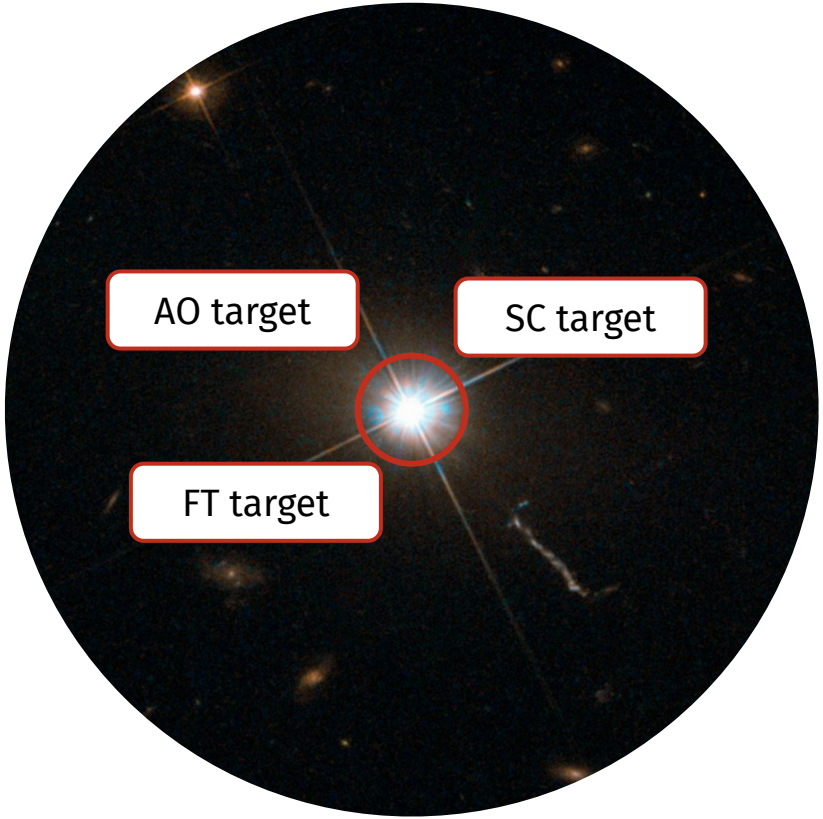


ESO/Gravity Consortium/L. Calçada

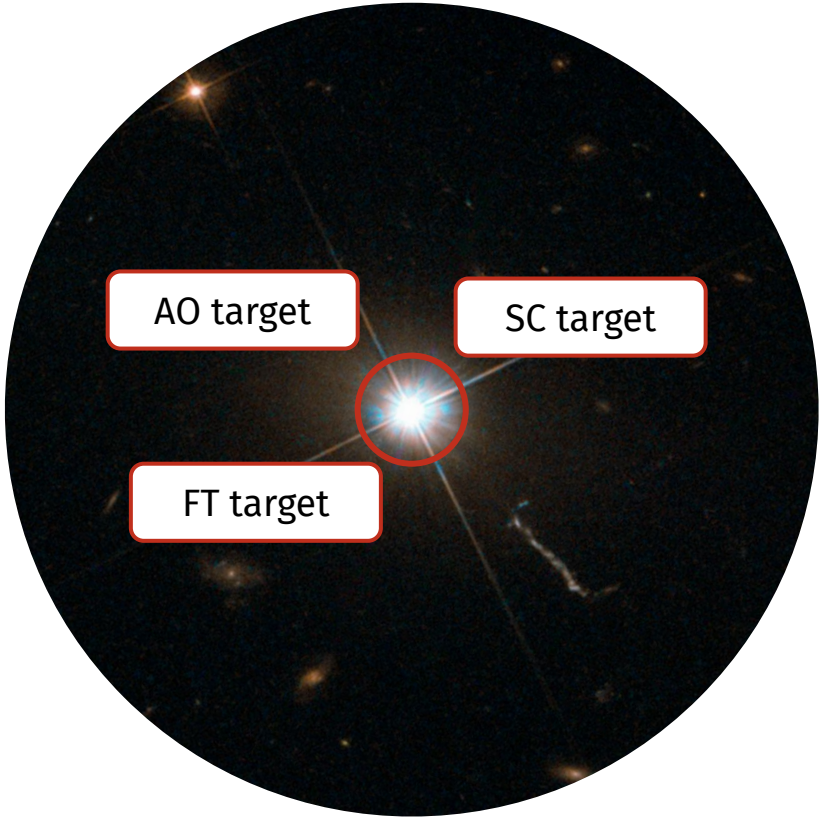
GRAVITY Collaboration 2018, 2020

AGN science

AGN science



AGN science



on-axis adaptive optics with MACAO

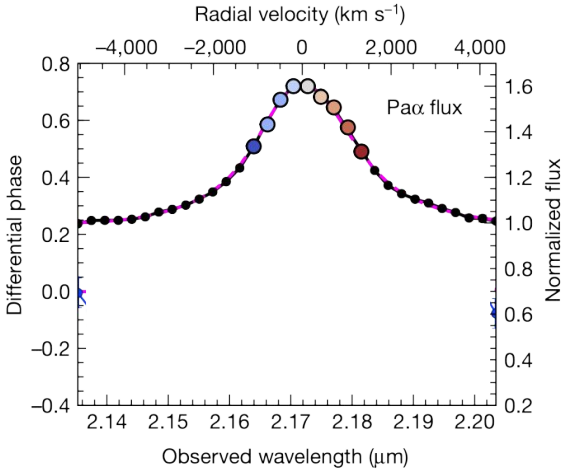
on-axis fringe tracking

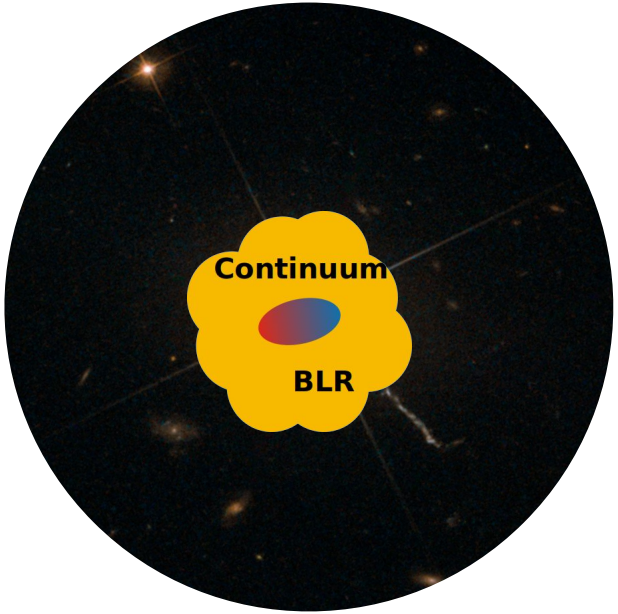
First detection of BLR kinematics for 3C 273

First detection of BLR kinematics for 3C 273

$$\Delta\phi = -2\pi \frac{f(\lambda)}{1+f(\lambda)} [\vec{u}(\lambda) \cdot \vec{\epsilon}(\lambda)]$$

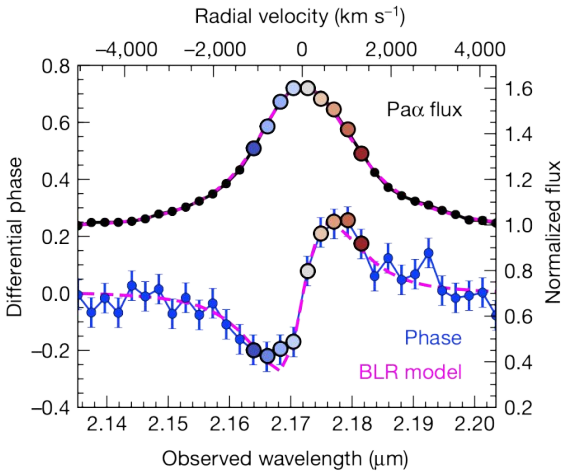
Differential Phase — *Line Strength* — *Baseline* — *Photocenter Offset*

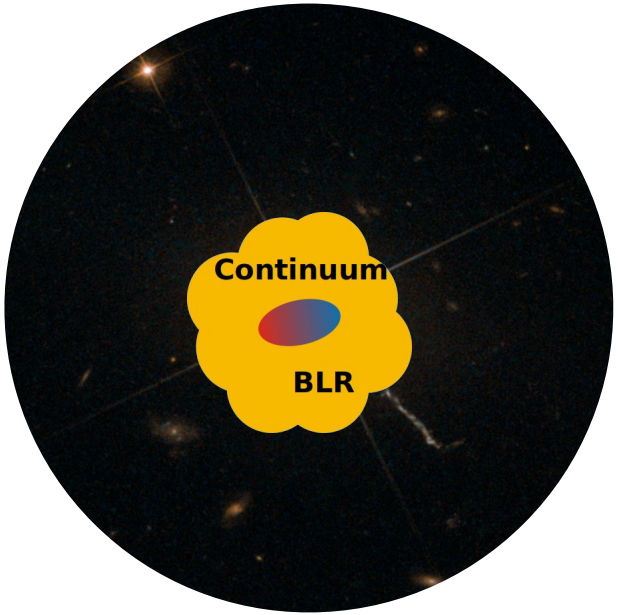




First detection of BLR kinematics for 3C 273

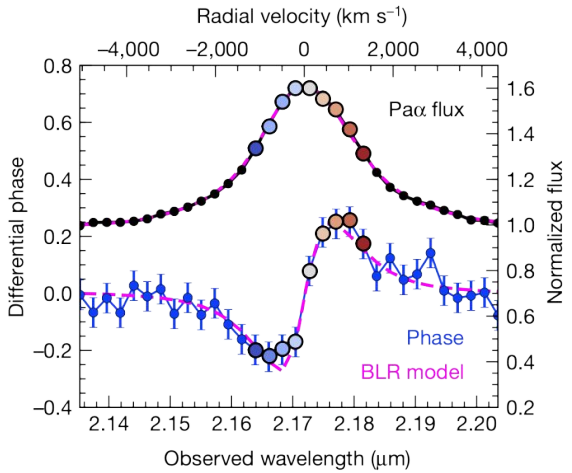
$$\Delta\phi = -2\pi \frac{f(\lambda)}{1+f(\lambda)} [\vec{u}(\lambda) \cdot \vec{\epsilon}(\lambda)]$$

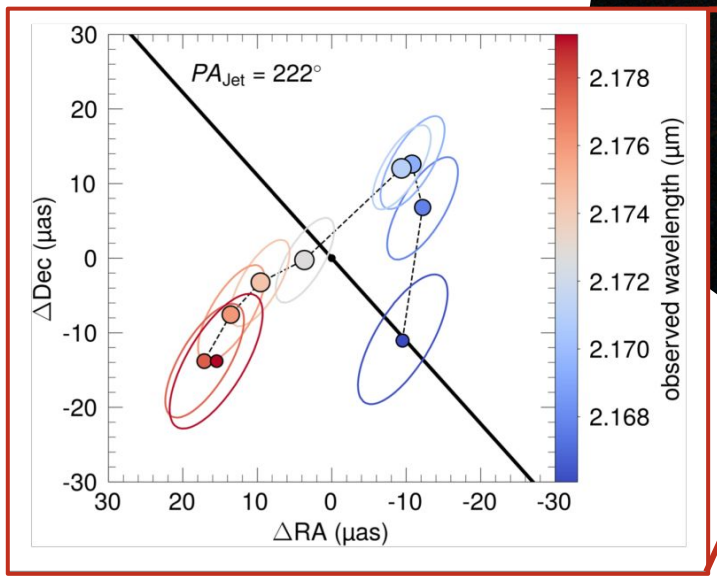


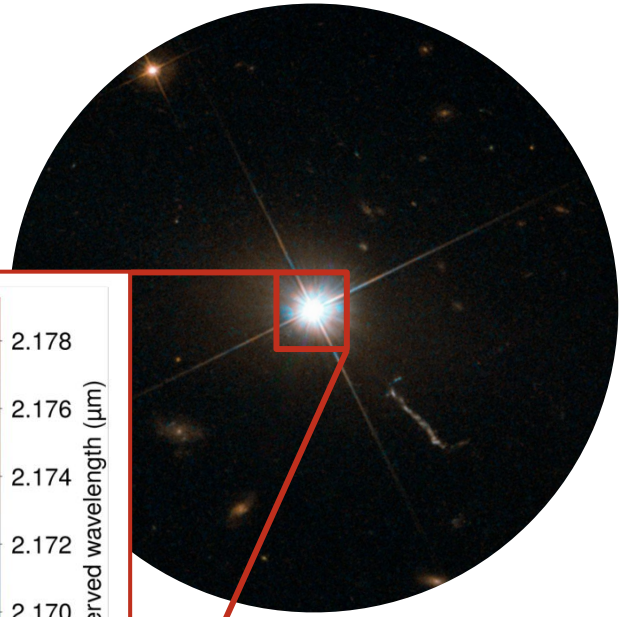


First detection of BLR kinematics for 3C 273

$$\Delta\phi = -2\pi \frac{f(\lambda)}{1+f(\lambda)} [\vec{u}(\lambda) \cdot \vec{\epsilon}(\lambda)]$$

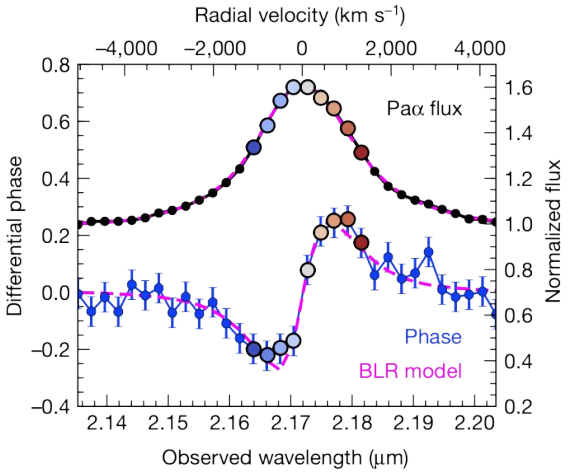


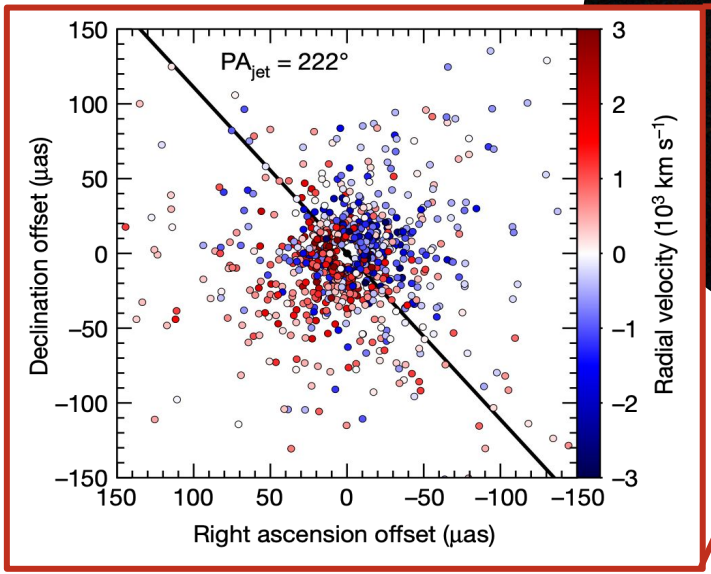


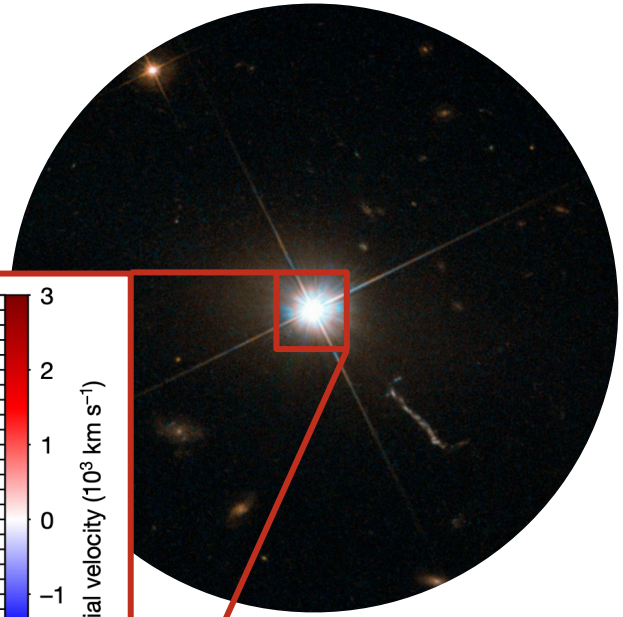


First detection of BLR kinematics for 3C 273

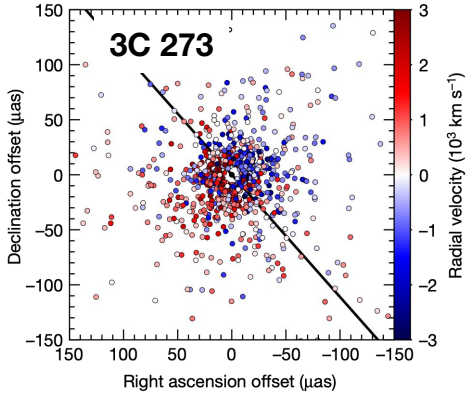
$$\Delta\phi = -2\pi \frac{f(\lambda)}{1+f(\lambda)} [\vec{u}(\lambda) \cdot \vec{\epsilon}(\lambda)]$$

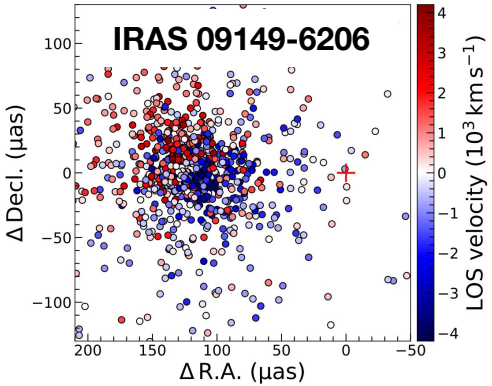


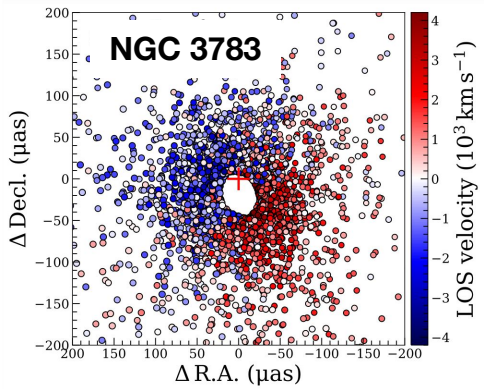




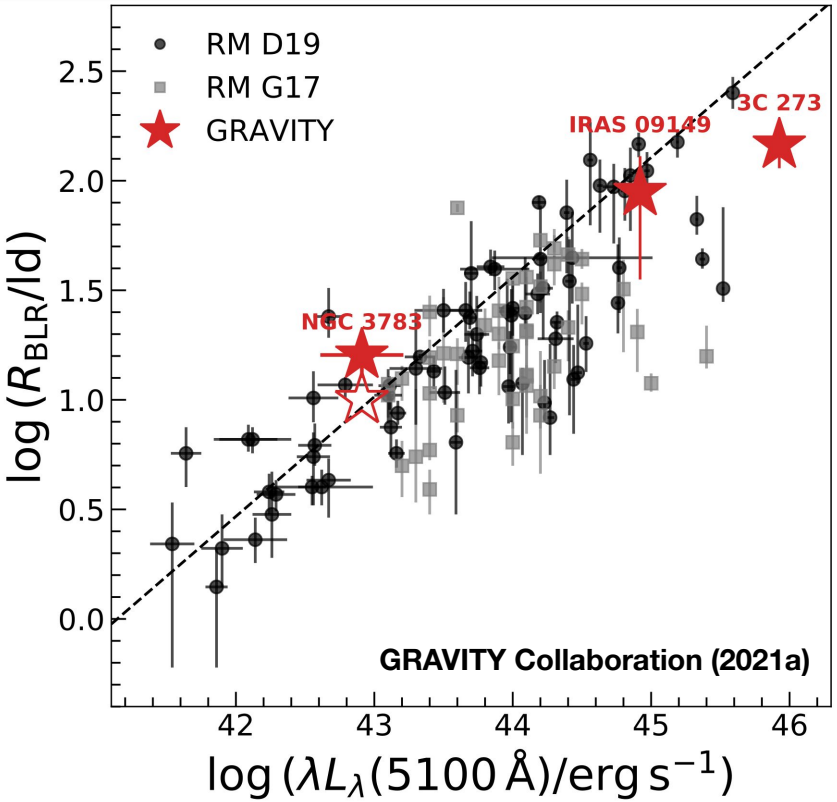
Comparison with reverberation mapping results

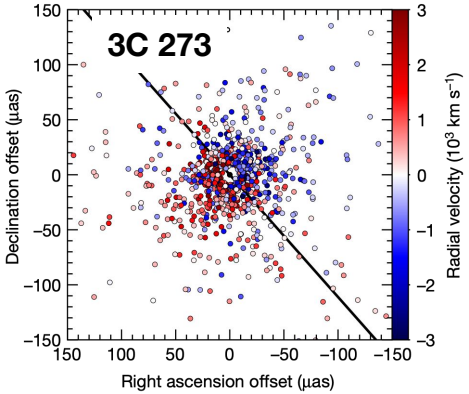


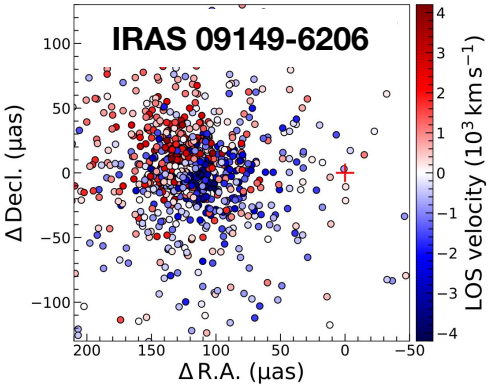


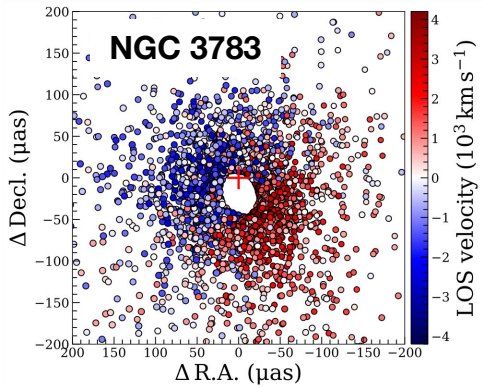


Comparison with reverberation mapping results



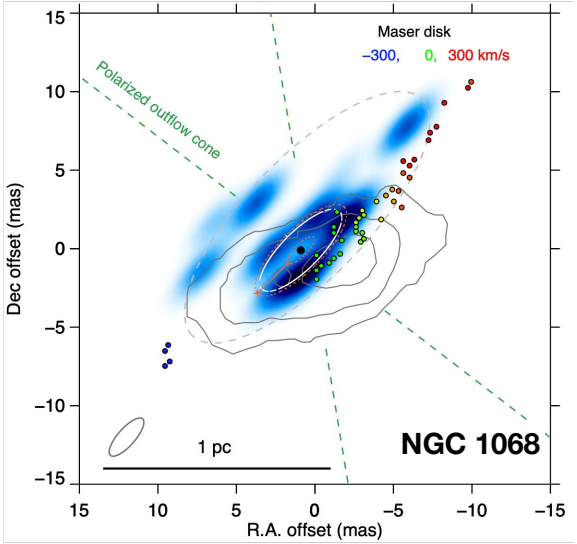




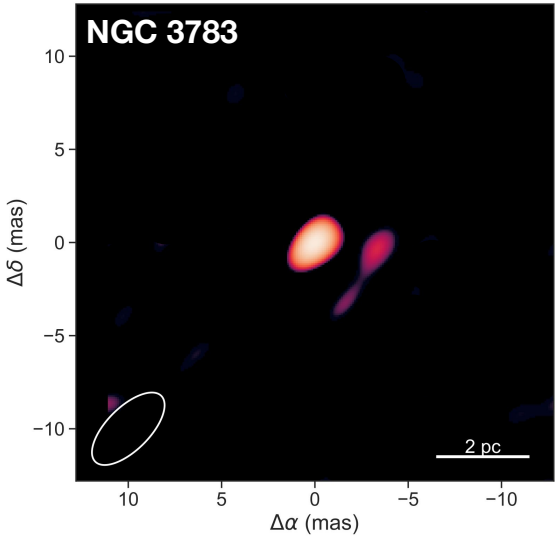


Hot dust continuum surrounding the BLR

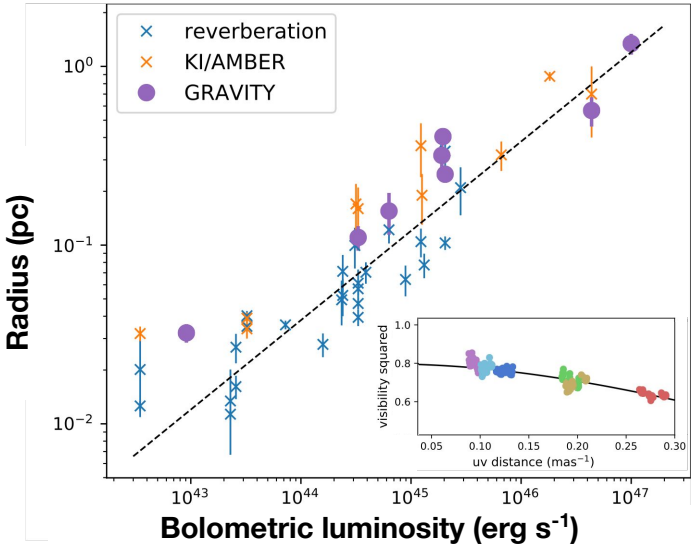
Nearby type 2 AGN



Nearby type 1 AGN



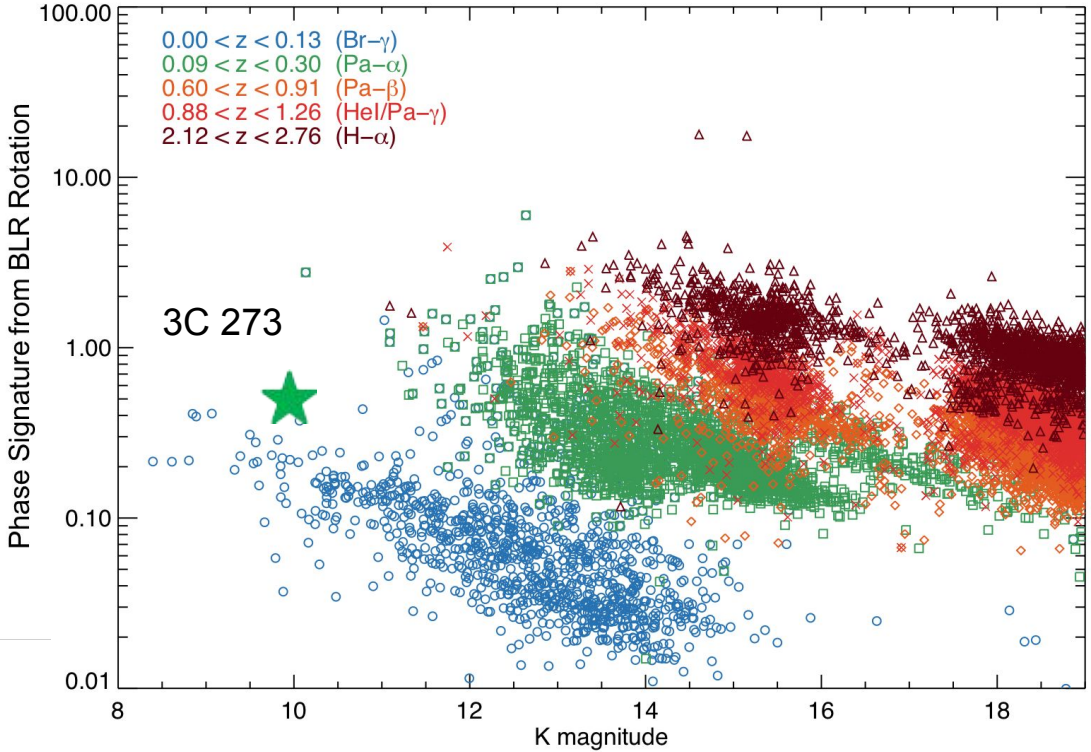
Continuum R-L relation



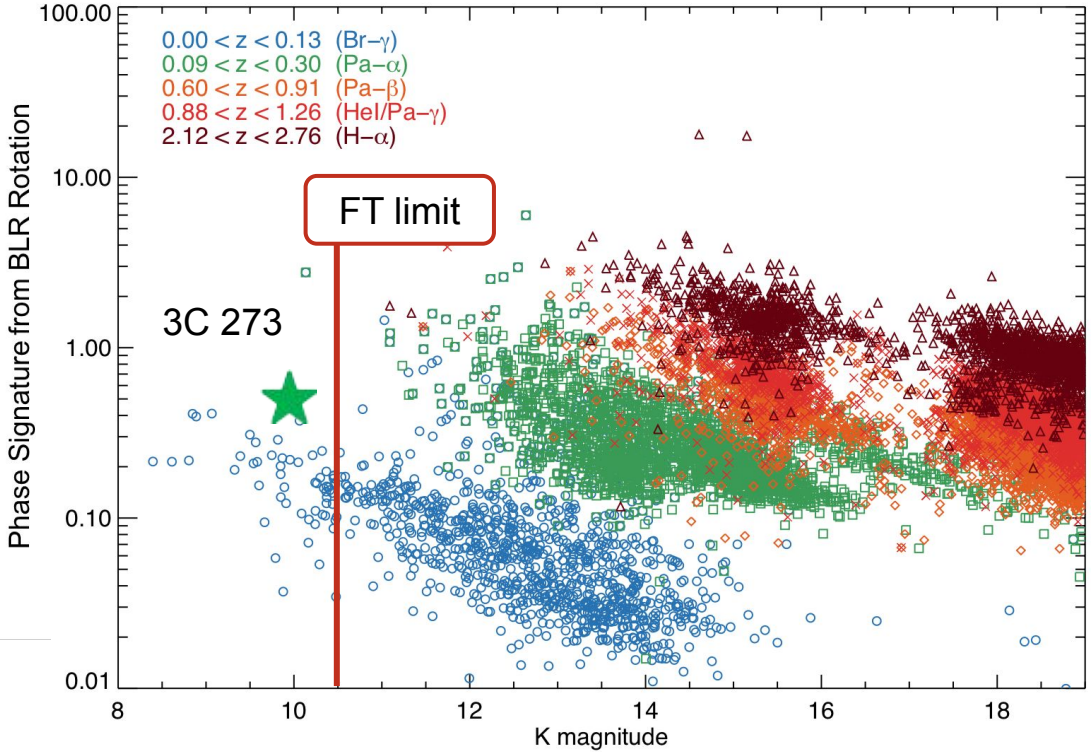
GRAVITY Collaboration (2020a)
GRAVITY Collaboration (2020b)
GRAVITY Collaboration (2021a)

III. Future of GRAVITY+

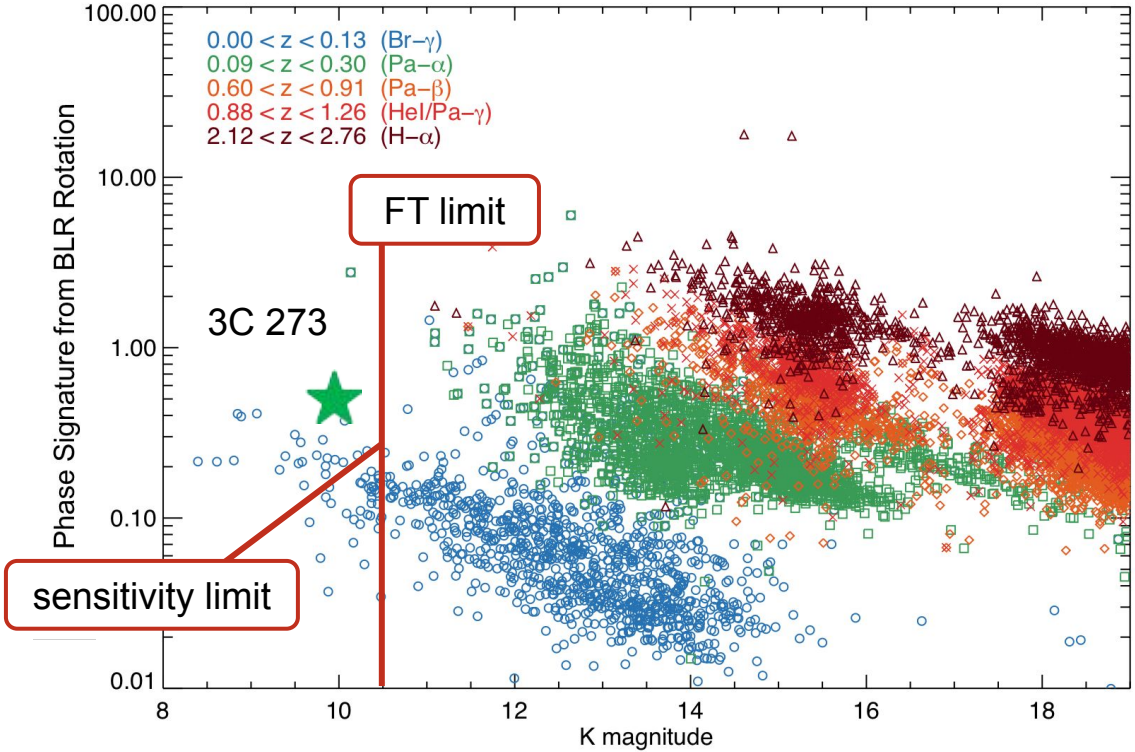
Possible improvements



Possible improvements

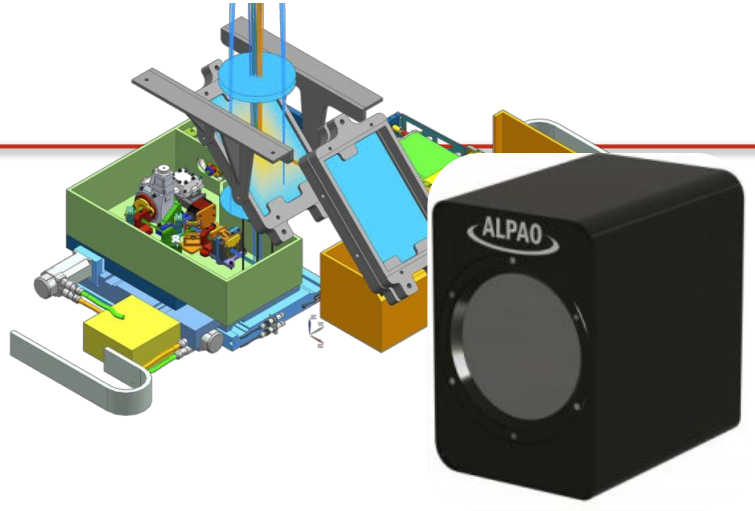


Possible improvements



GRAVITY+ improvements

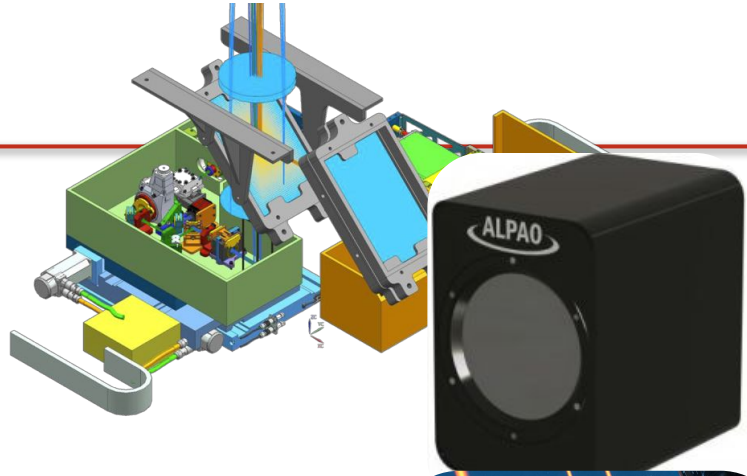
Sensitivity increase by:
- state of the art AO

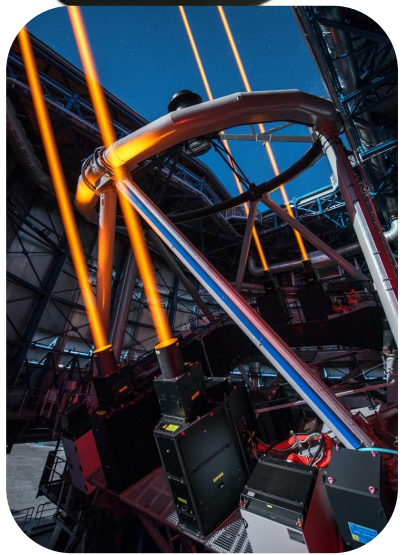


GRAVITY+ improvements

Sensitivity increase by:

- state of the art AO
- Laser Guide Stars

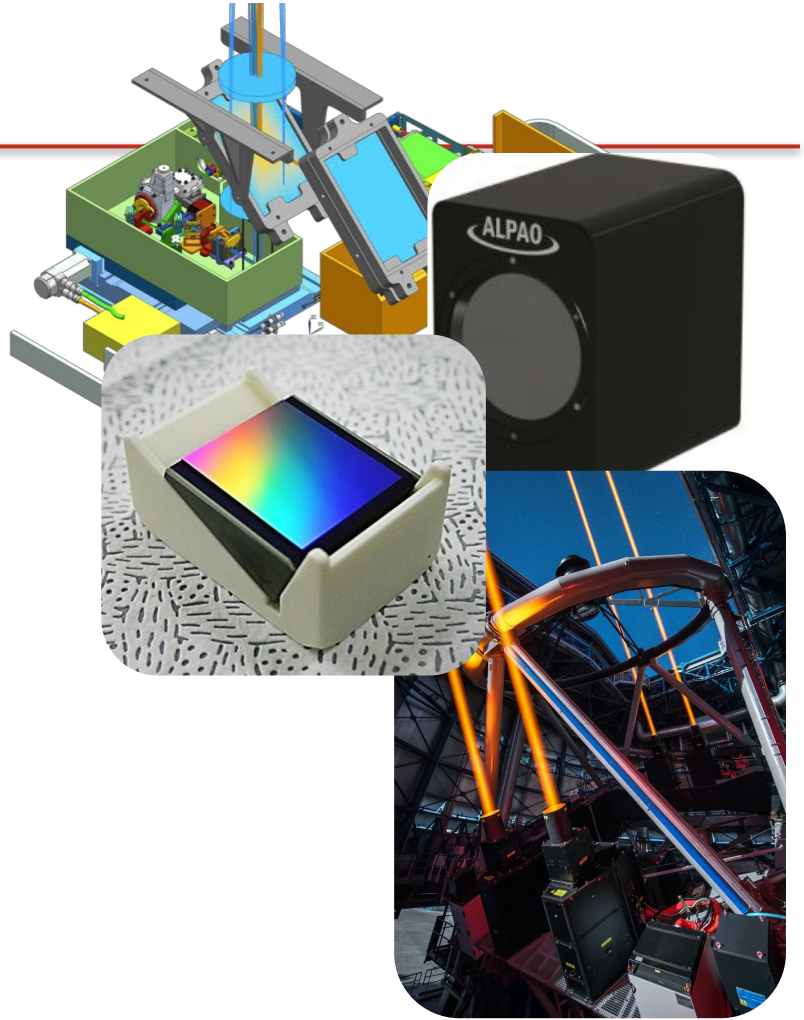




GRAVITY+ improvements

Sensitivity increase by:

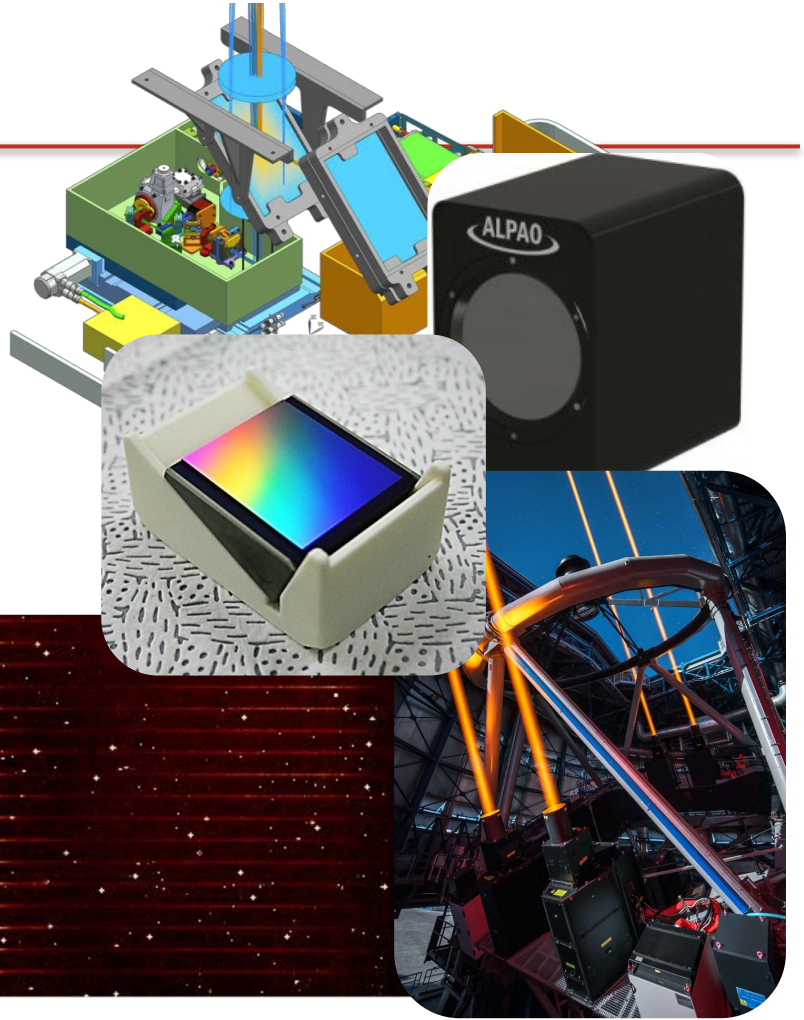
- state of the art AO
- Laser Guide Stars
- higher throughput prisms



GRAVITY+ improvements

Sensitivity increase by:

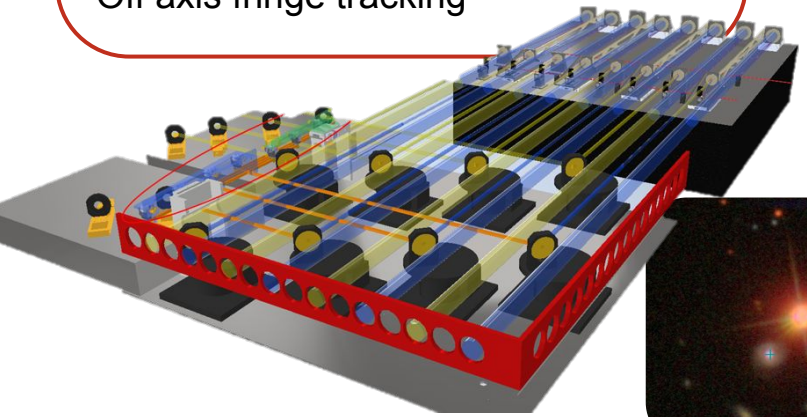
- state of the art AO
- Laser Guide Stars
- higher throughput prisms
- Laser background suppression
- Lower vibrations

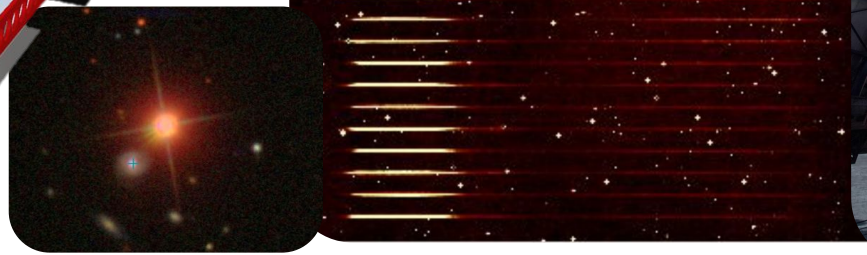


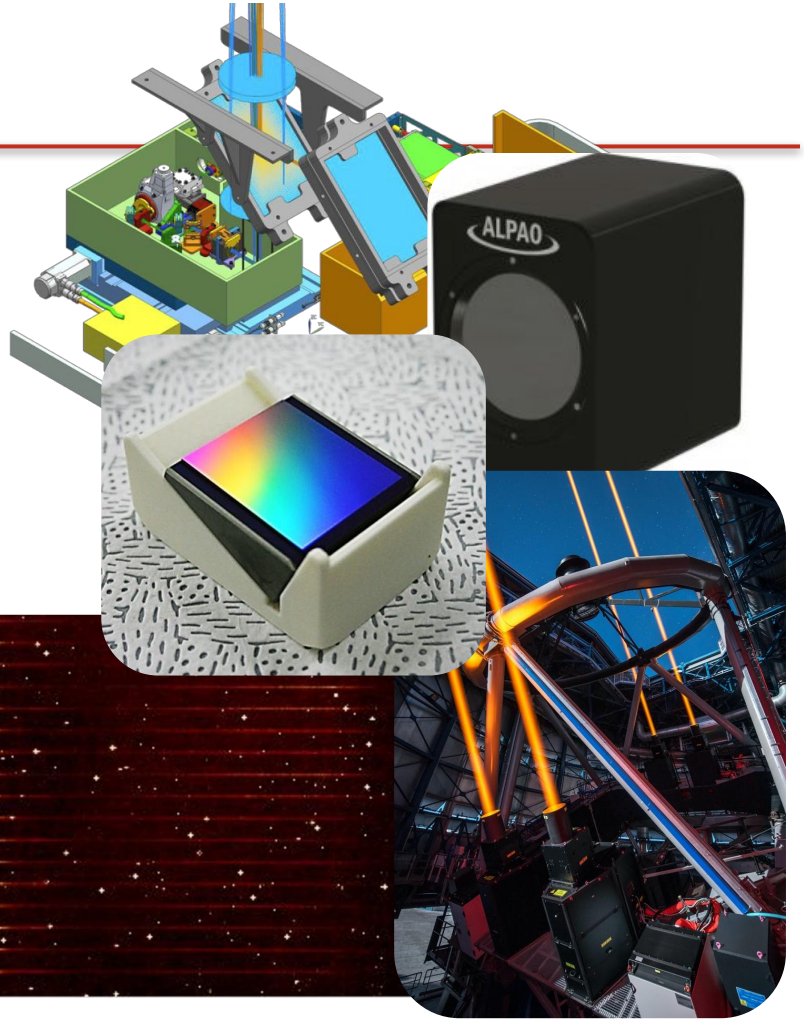
GRAVITY+ improvements

Sensitivity increase by:
- state of the art AO
- Laser Guide Stars
- higher throughput prisms
- Laser background suppression
- Lower vibrations

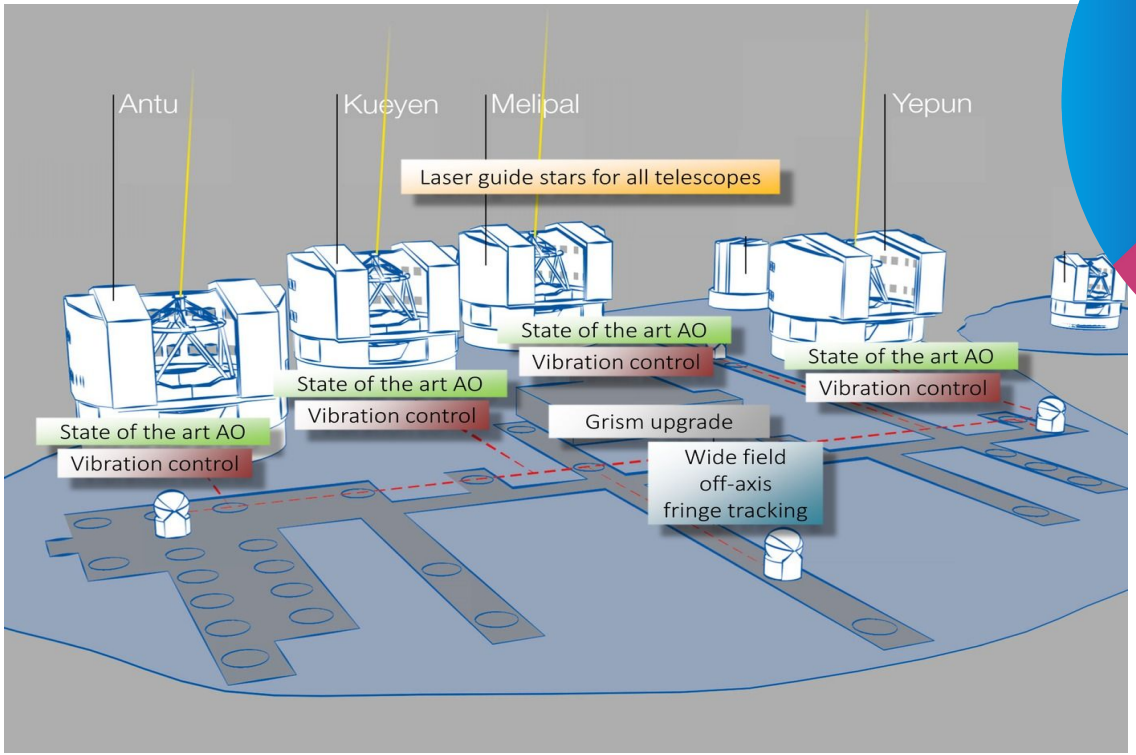
Off axis fringe tracking

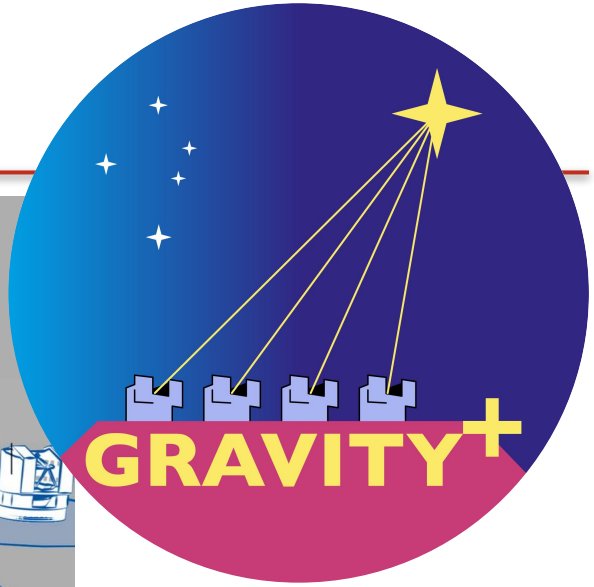






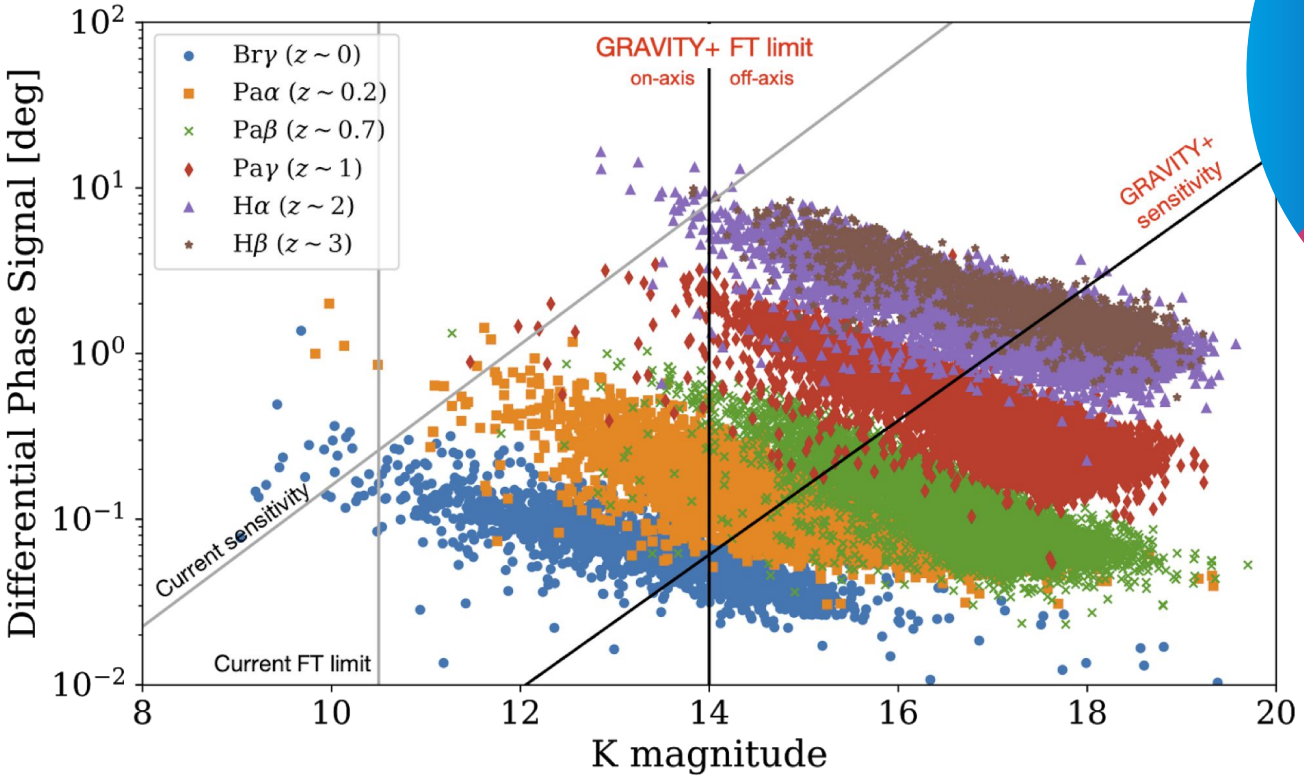
GRAVITY+

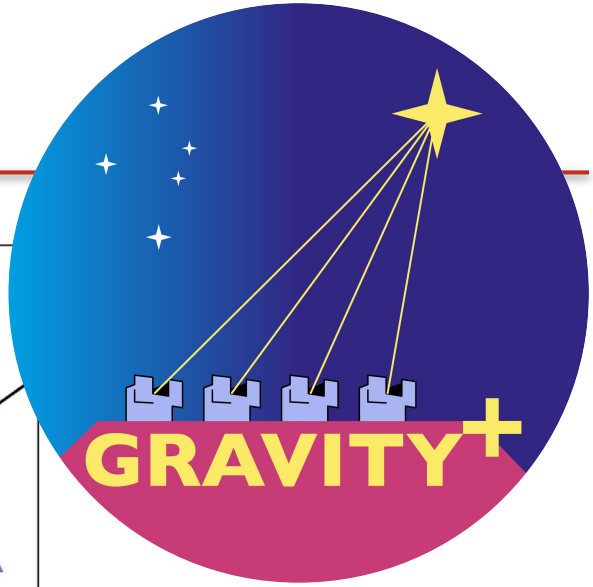




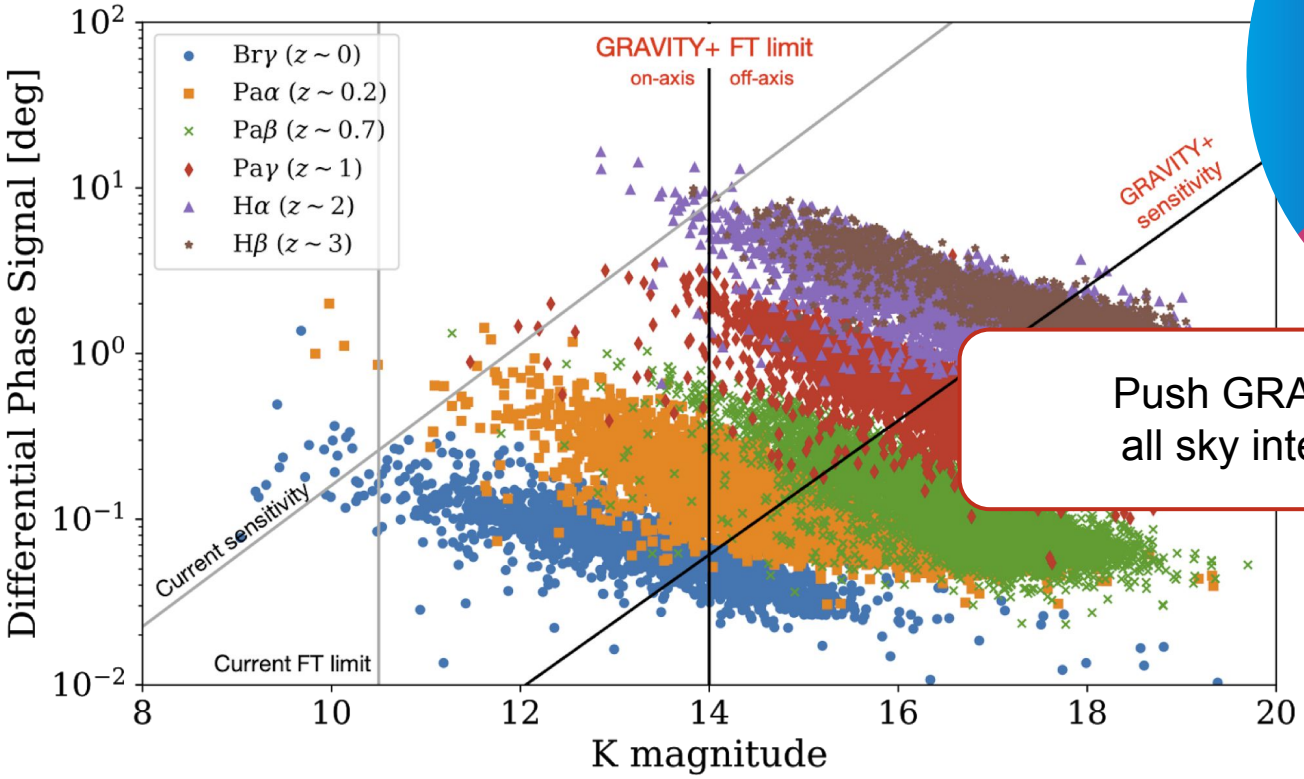
MPE LESIA l'Observatoire de Paris | PSL LAGRANGE IPAG pht Southampton centra KU LEUVEN ESO

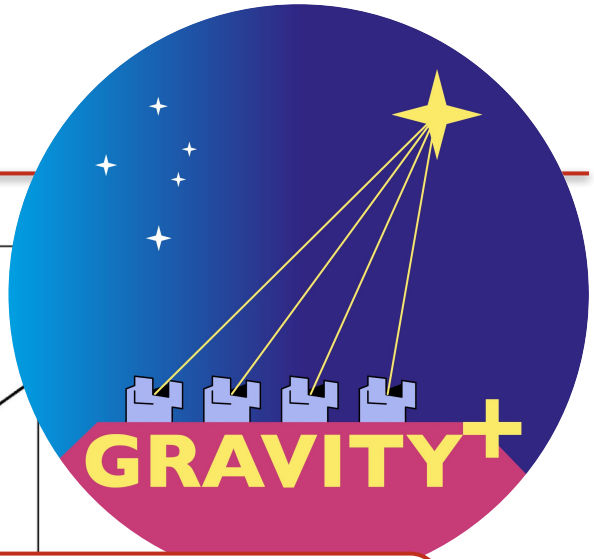
GRAVITY+ improvements





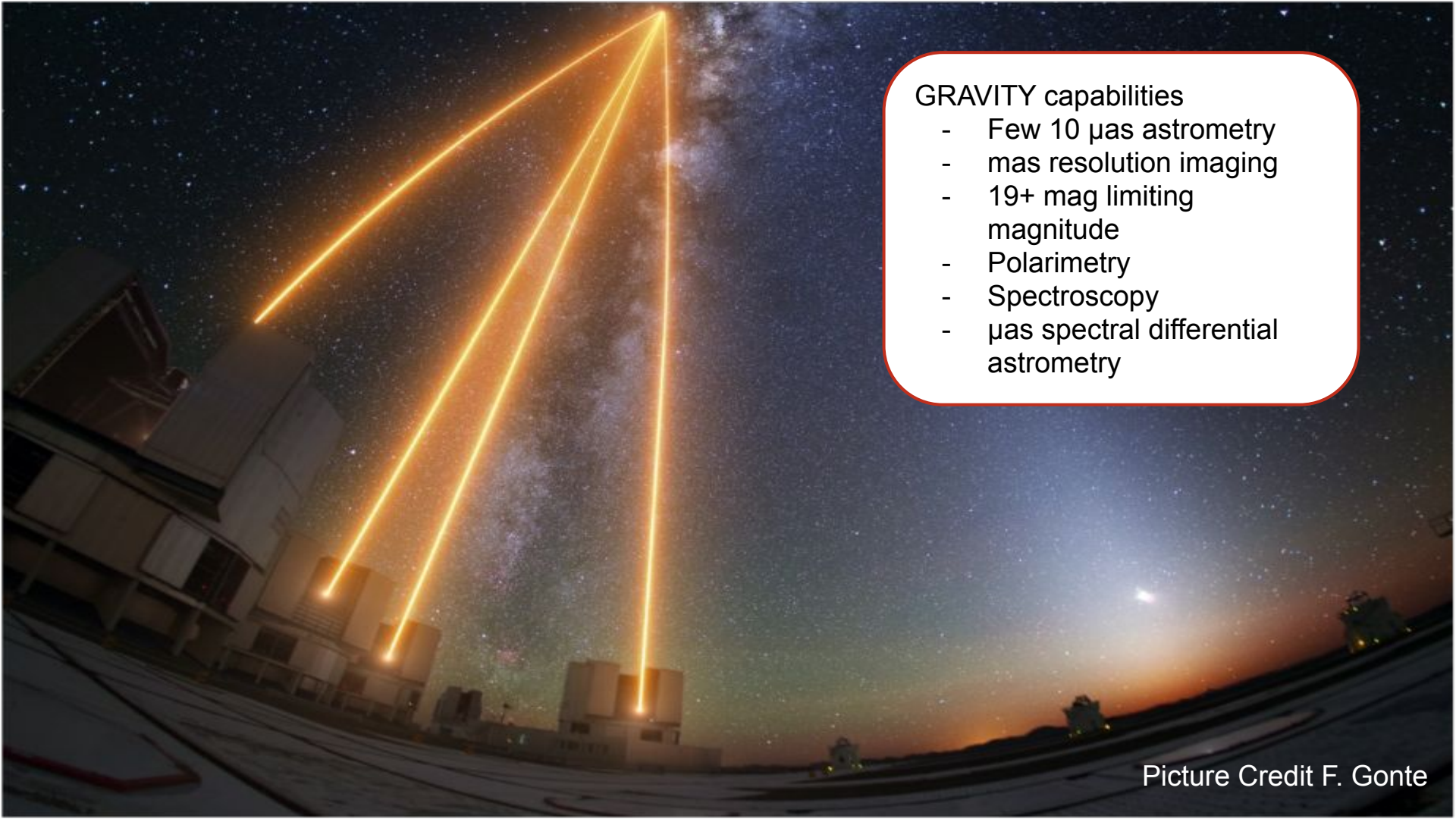
GRAVITY⁺ improvements

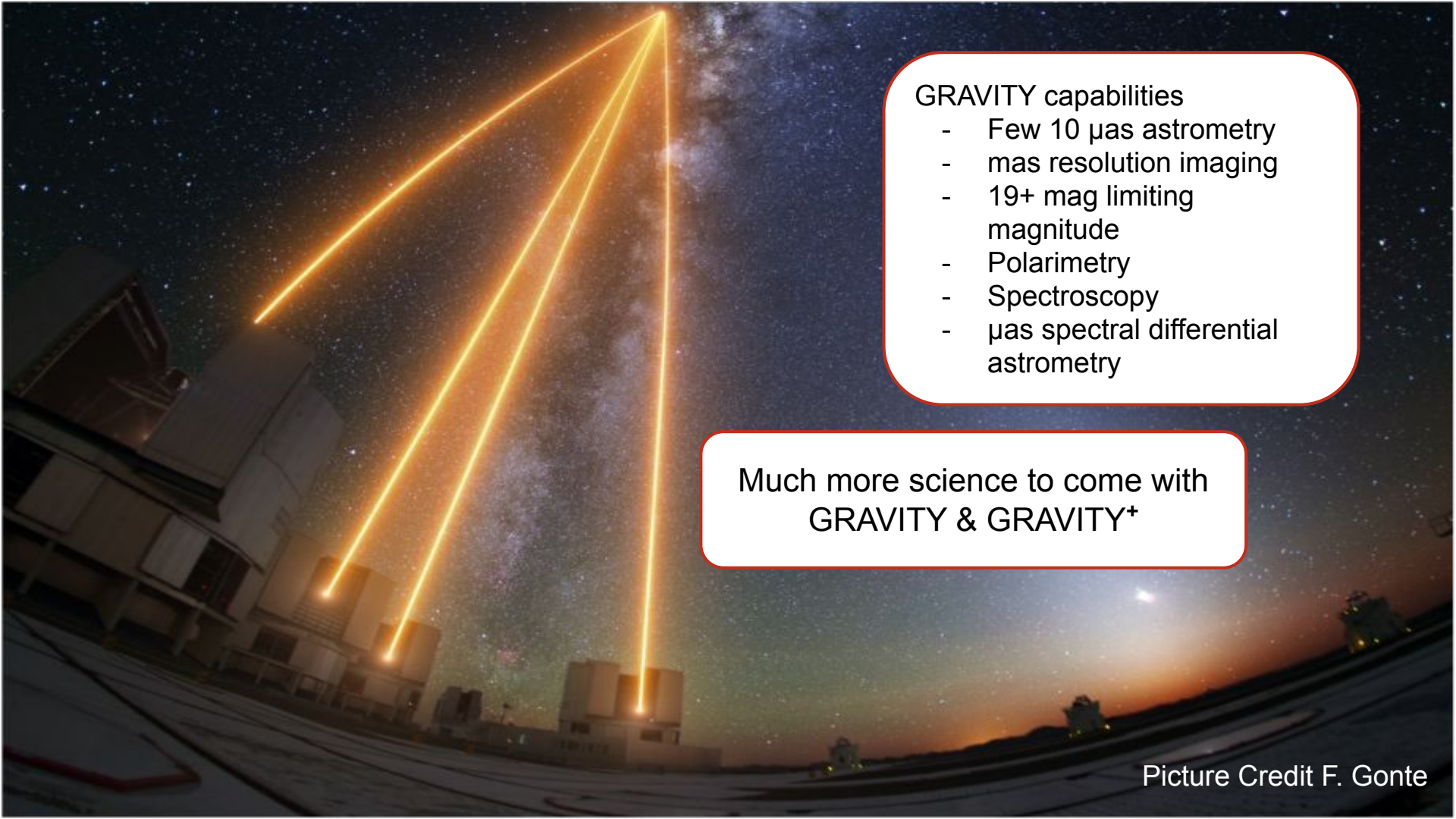




Push GRAVITY⁺ to an all sky interferometer


Picture Credit F. Gonte


GRAVITY capabilities
- Few 10 μas astrometry
- mas resolution imaging
- 19+ mag limiting magnitude
- Polarimetry
- Spectroscopy
- μas spectral differential astrometry
Picture Credit F. Gonte



GRAVITY capabilities

- Few 10 μas astrometry
- mas resolution imaging
- 19+ mag limiting magnitude
- Polarimetry
- Spectroscopy
- μas spectral differential astrometry

Much more science to come with GRAVITY & GRAVITY^{+}

Picture Credit F. Gonte