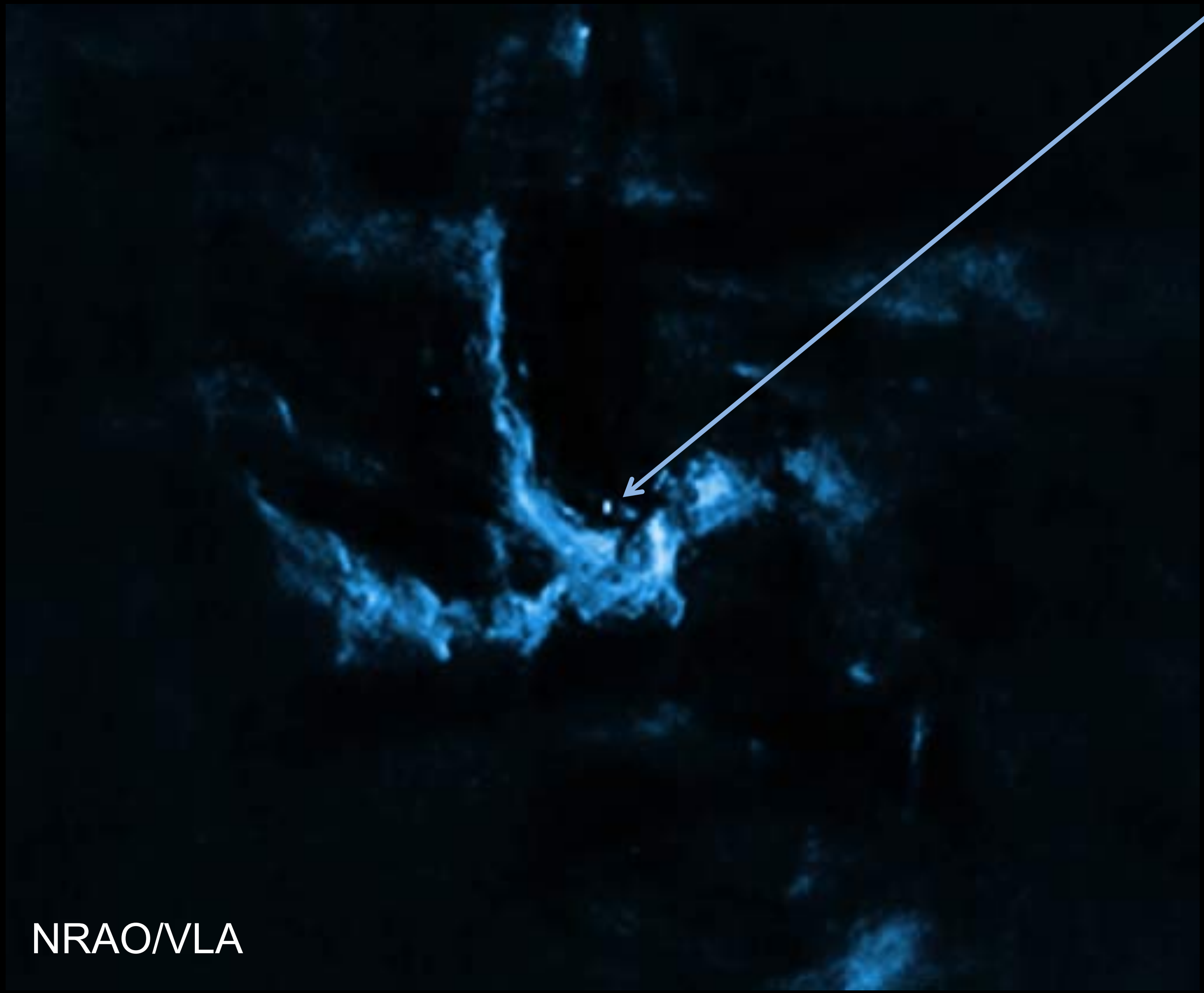
De GRAVITY à GRAVITY+.

Collaboration GRAVITY/+

- Introduction: le Centre Galactique et GRAVITY
- Résultats Centre Galactique
- Résultats AGNs et GRAVITY+
- Quelques mots trous noirs stellaires
- Promesses Centre Galactique

Thibaut Paumard - LESIA CNRS/Observatoire de Paris-PSL

Le parsec central : zone d'influence de Sagittarius A*



Un point (SgrA*, **trou noir** ???)

entouré d'une **minispirale** ionisée…

(découverte : années 70)

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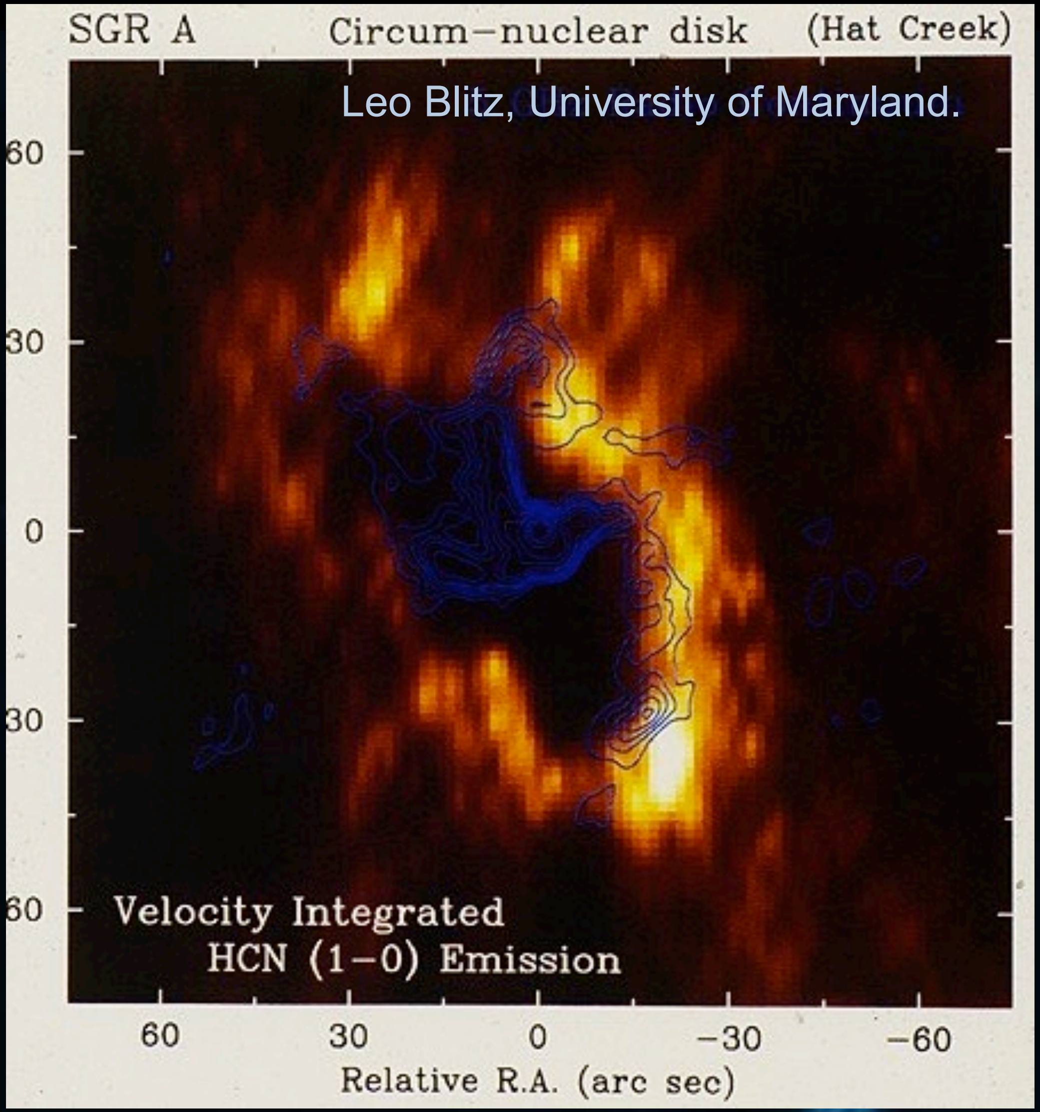

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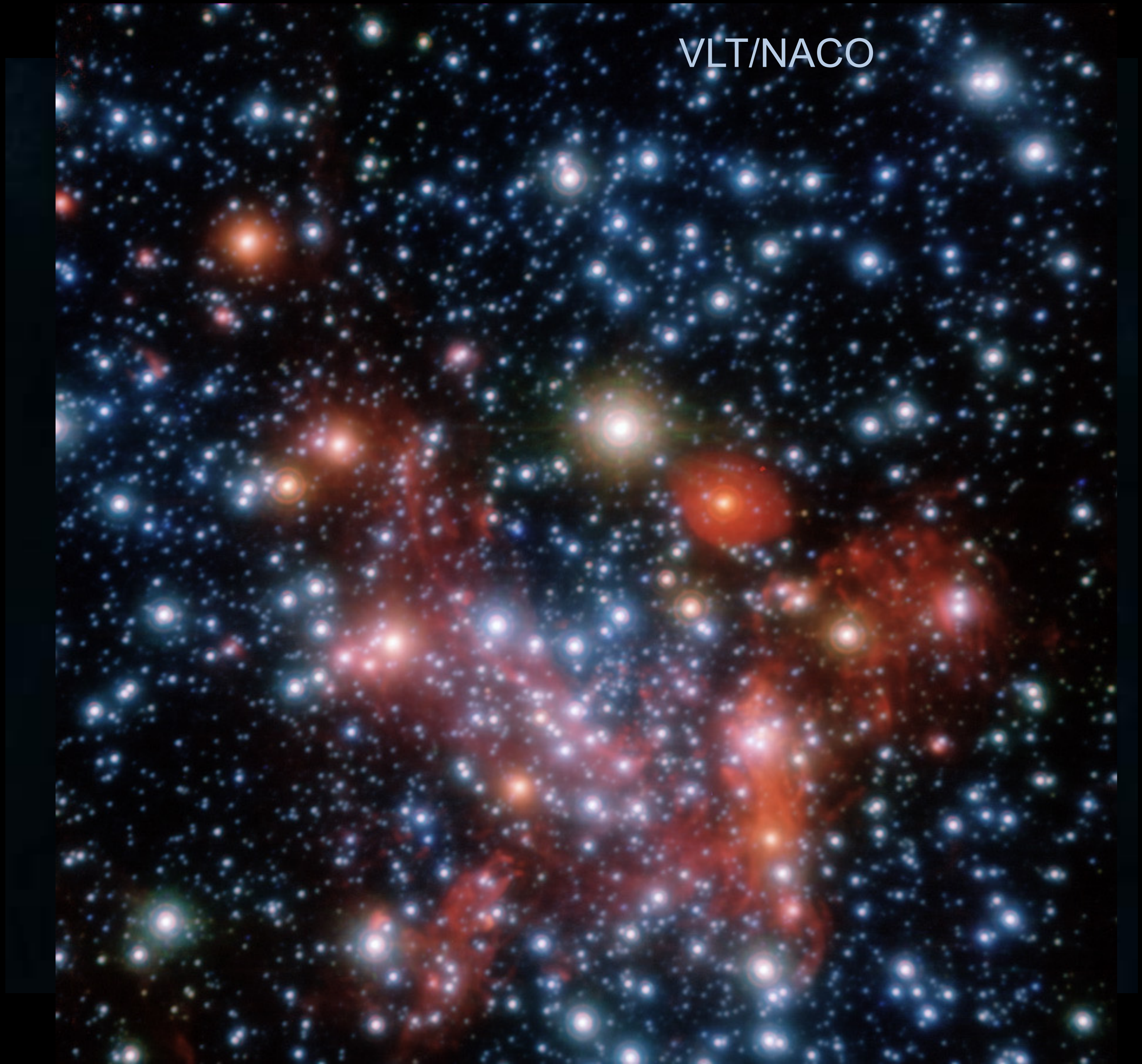

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baignant un amas d'**étoiles** vieilles et **jeunes** malgré les forces de marée

(découverte : années 80)

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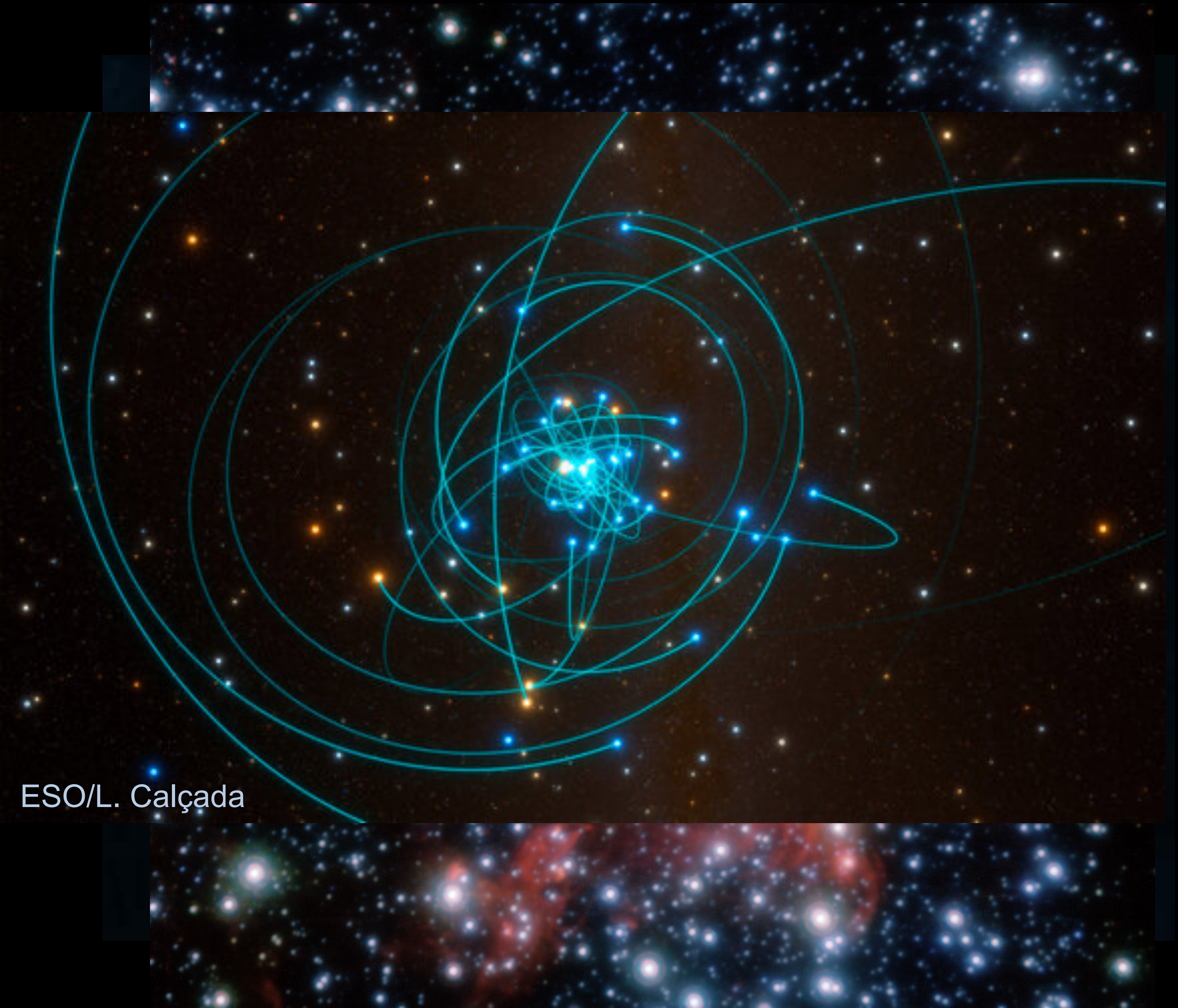

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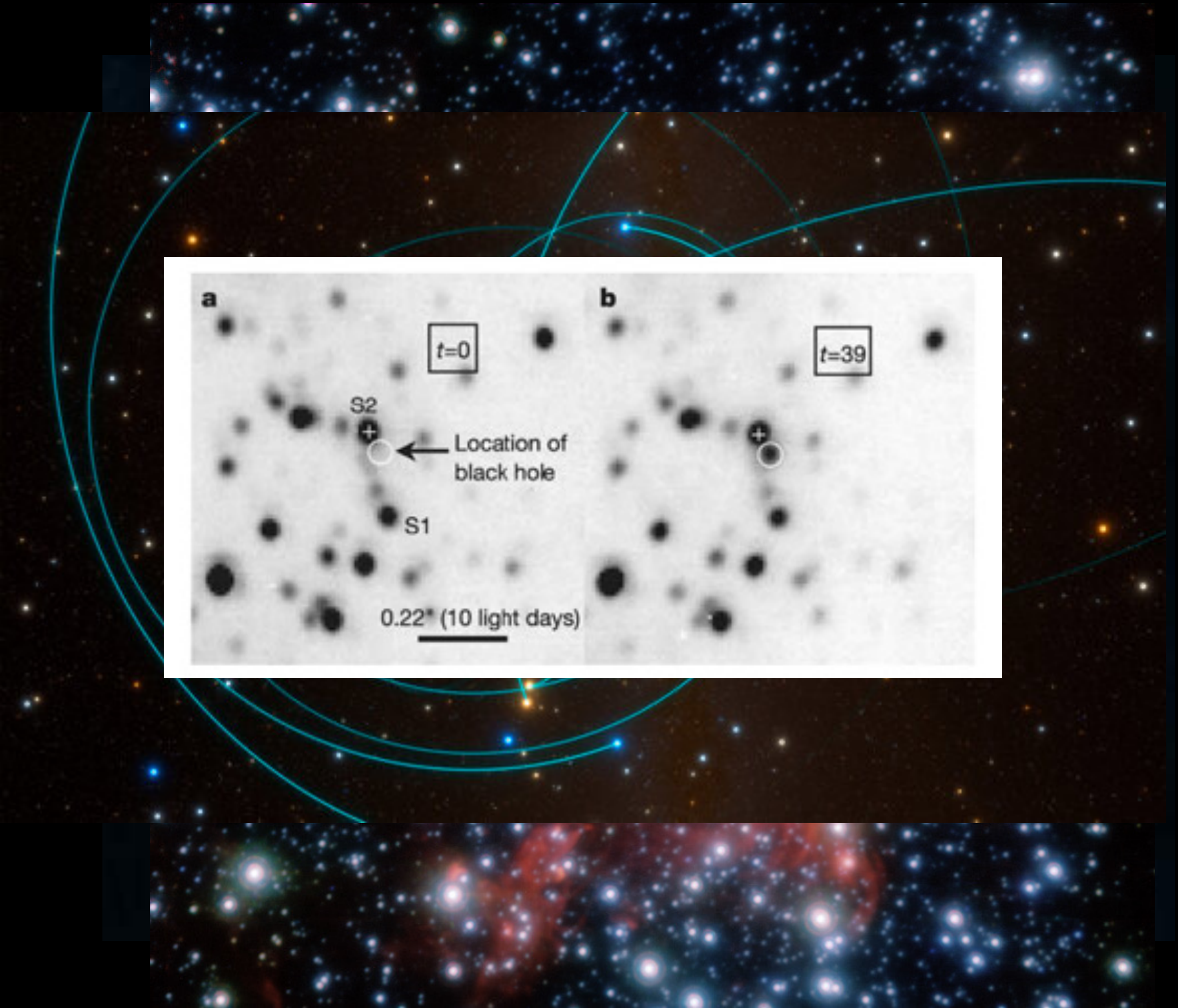
Au cœur, des **étoiles en orbite courte autour de SgrA***

(découverte : années 90)

Le parsec central : zone d'influence de Sagittarius A*



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baignant un amas d'**étoiles** vieilles et **jeunes** malgré les forces de marée

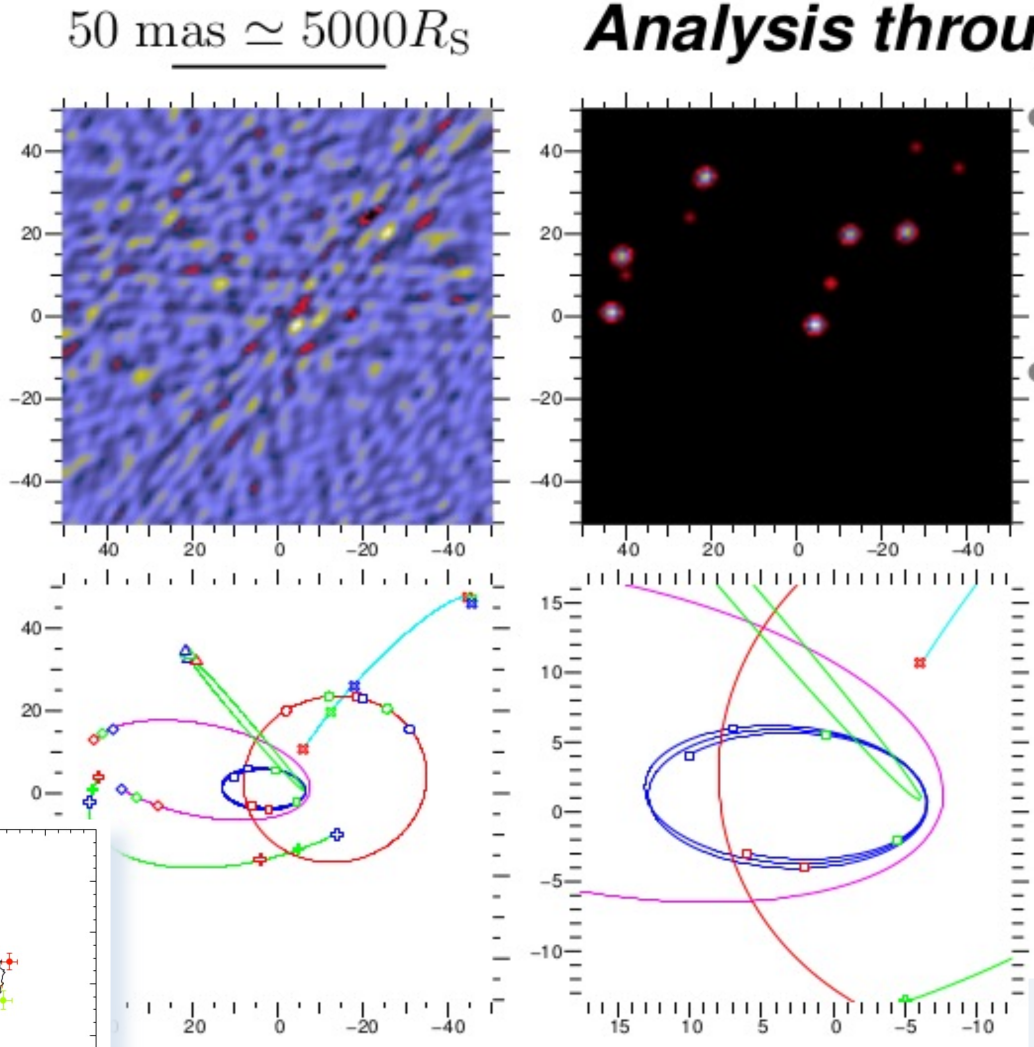
au cœur, des **étoiles en orbite courte autour de SgrA***

Et une émission **variable** (découverte : années 2000)

Dépasser la limite de résolution d'un 8m

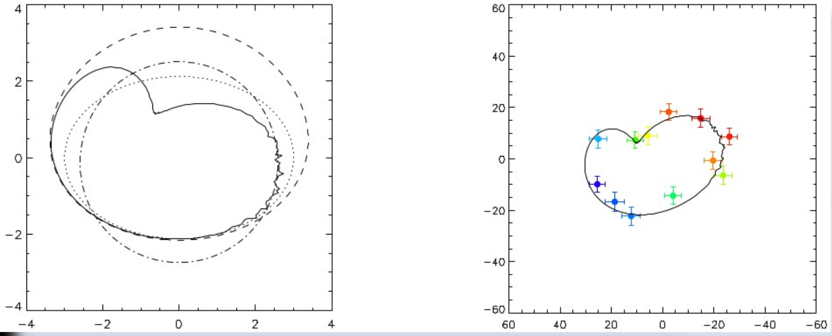
Orbites étoiles

Projet instrumental GRAVITY: General Relativity Analysis through VLT Interferometry



- Section Centre galactique du document ESO « PRIMA reference missions »;
- cas scientifiques GRAVITY, en particulier Centre galactique:
  - ◇ orbites d'étoiles dans la tache de diffraction,
  - ⇒ simulation d'observations interférométriques, synthèse d'images.
  - ◇ flares

Orbite sursauts

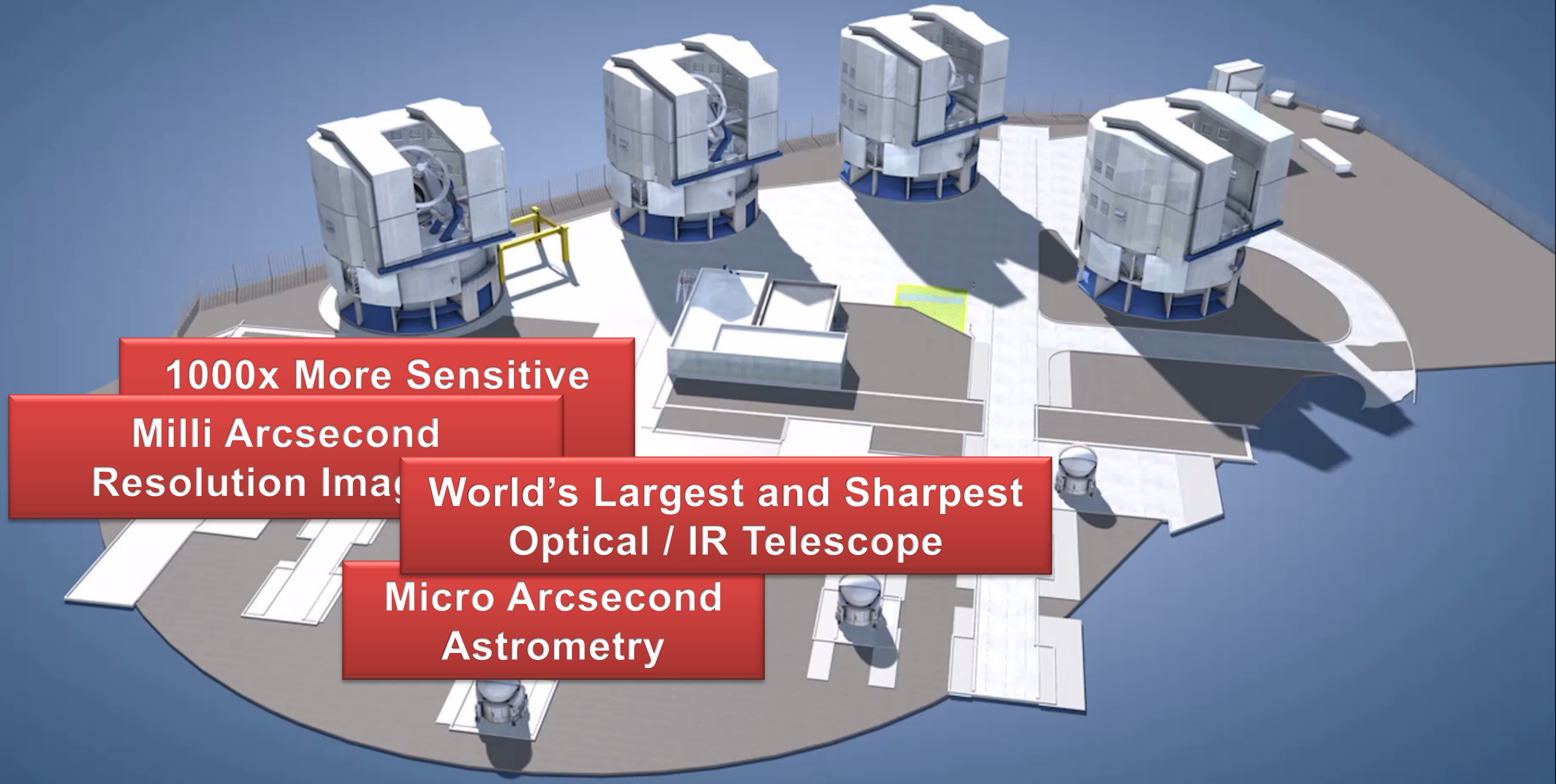


ESO VLTI workshop 2005

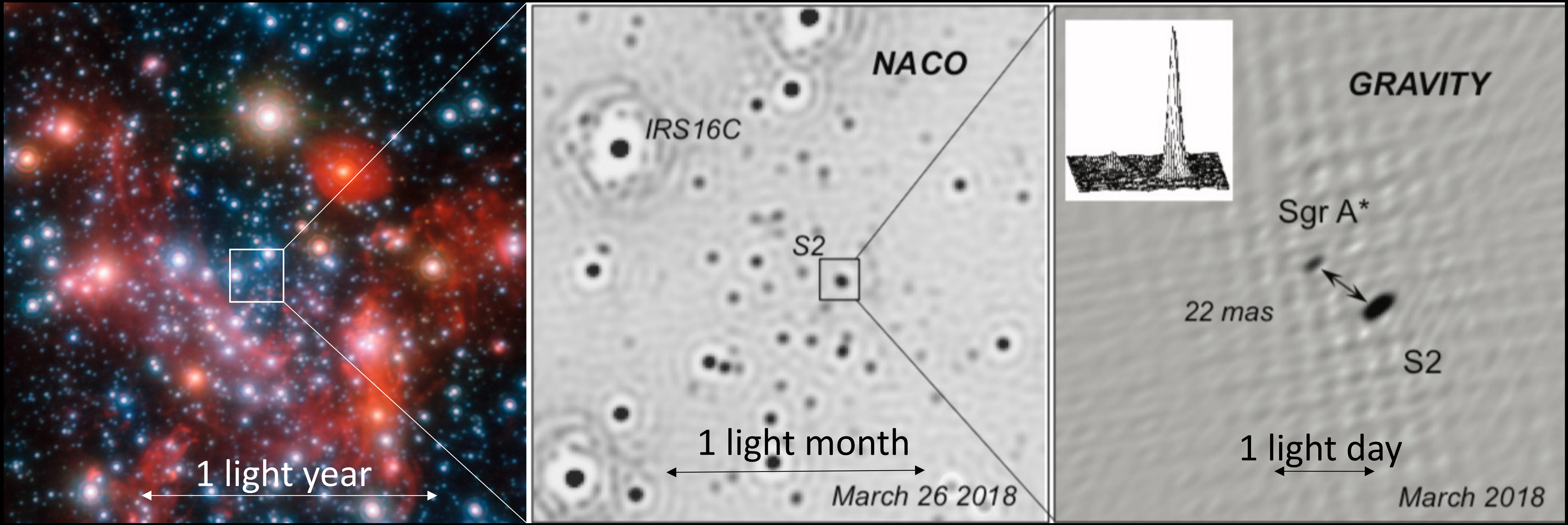
Paumard et al. 2008


GRAVITY Collaboration
l'Observatoire de Paris
IPAG
Institut de Planétologie et d'Astrophysique de Grenoble
SIM
ESO
MPE
ph1
Universität zu Köln
Max-Planck-Institut für Astronomie Heidelberg
Max Planck Institute for Astronomy Heidelberg

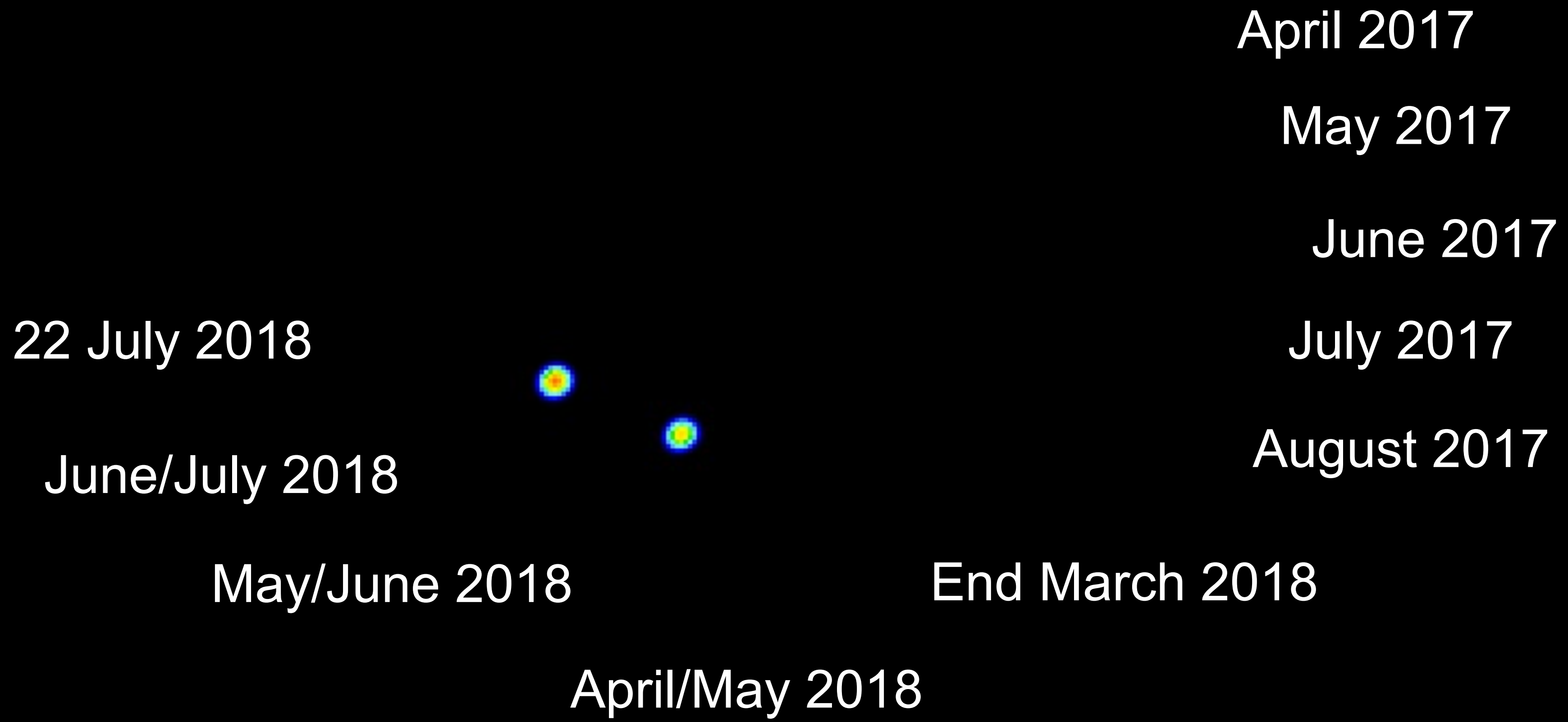
GRAVITY and VLTI



Zooming in with GRAVITY

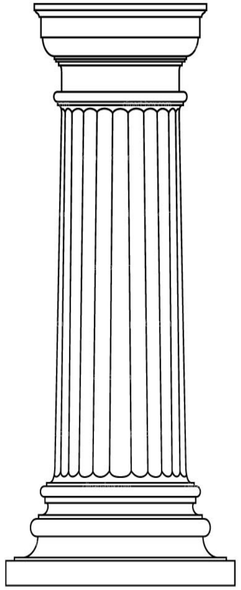


Routine Faint Milli-arcsec Imaging with GRAVITY

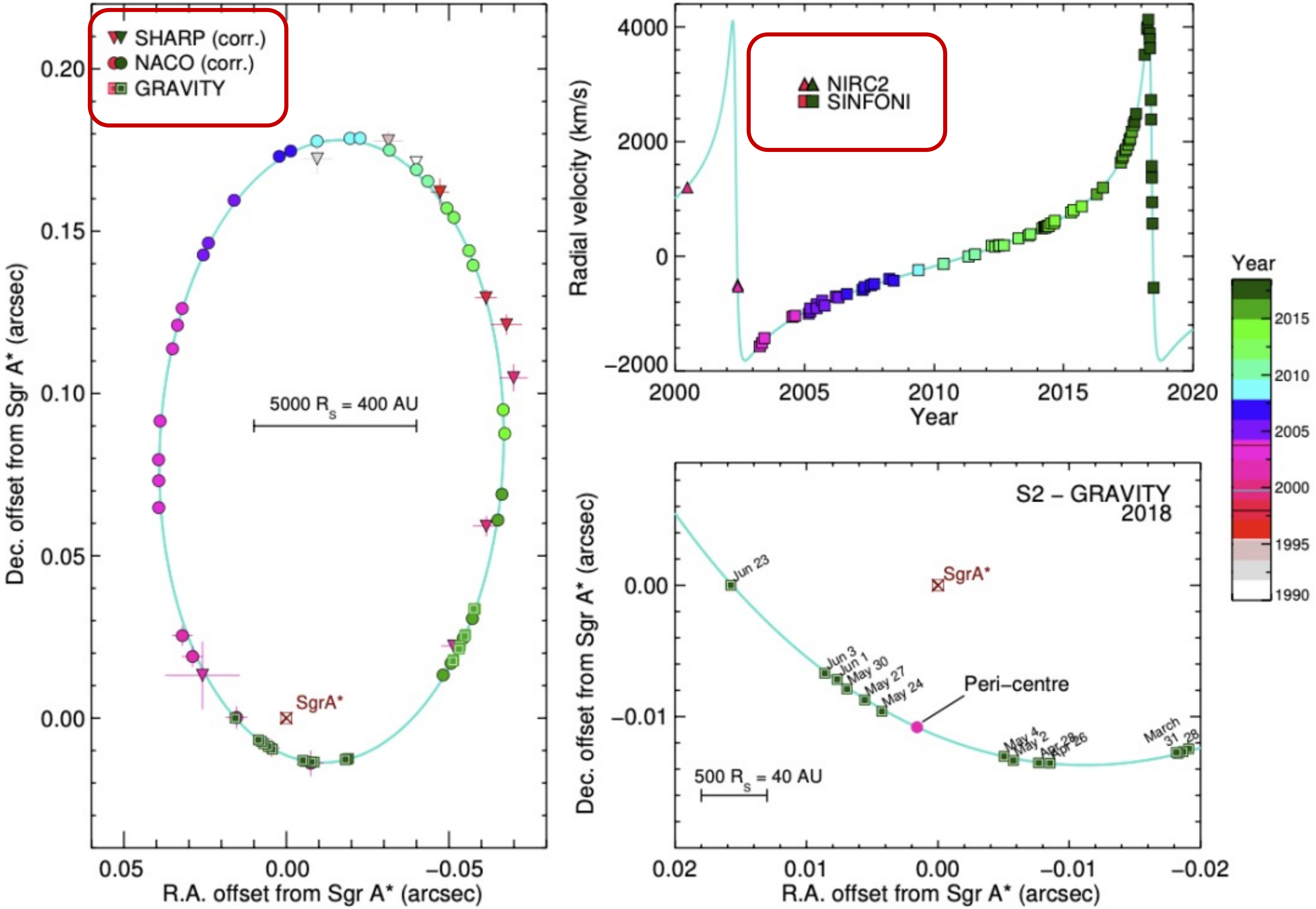


S2 orbit to 20-100µas accuracy (GRAVITY) + SINFONI spectroscopy

Measure Mass



0.3% precision



Eckart & Genzel 96,97, Ghez +98,00,03,08, Schödel+ 02,03, Eisenhauer+ 03,05, Gillessen+ 09,17, Meyer+ 12, Fritz+ 14, Boehle +16, GRAVITY collaboration+ 18,19,20, Do+ 19

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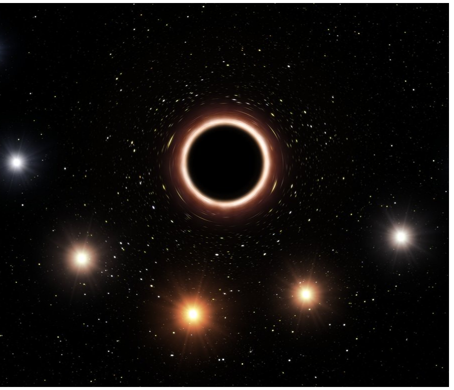
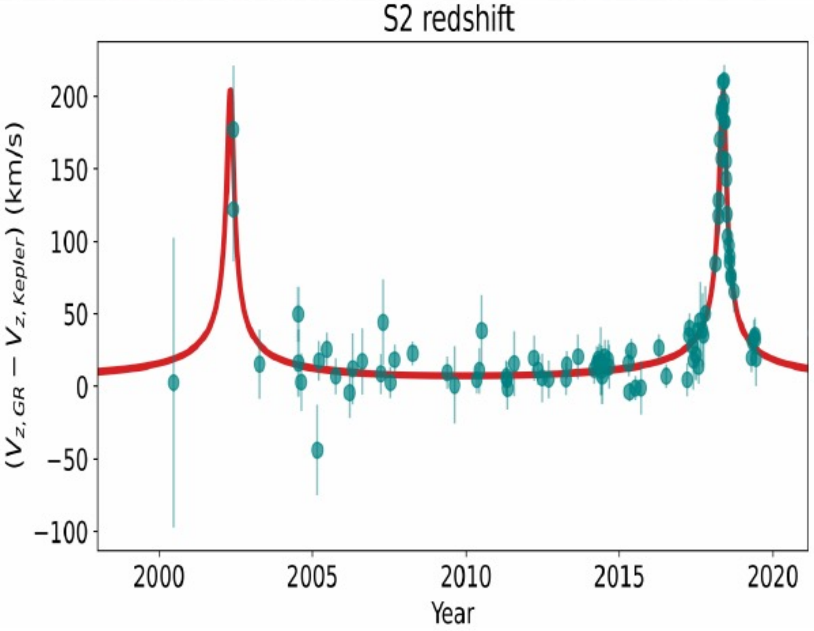
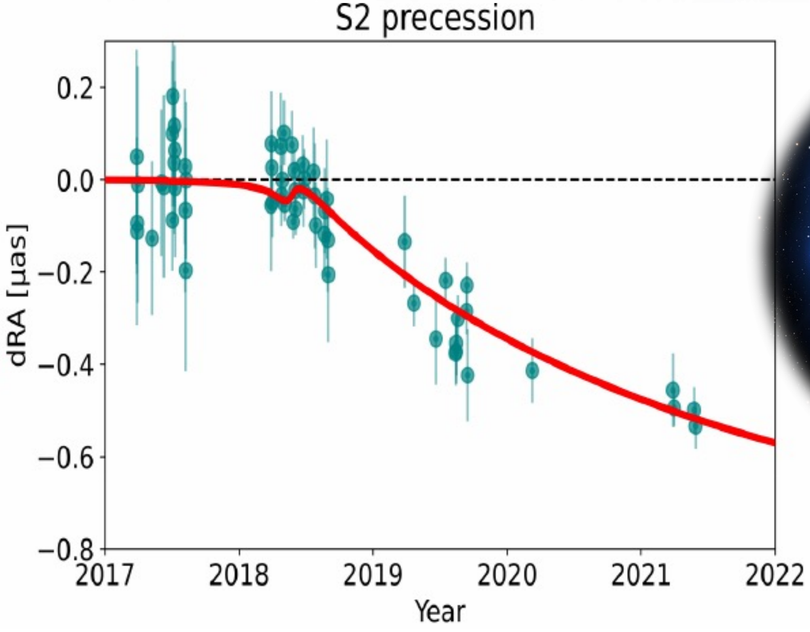
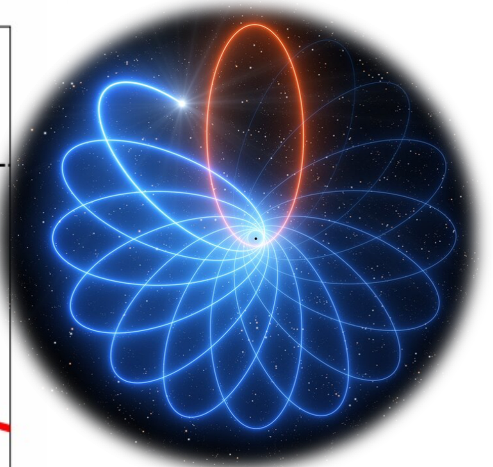
Highly-significant detection of gravitational redshift and GR precession



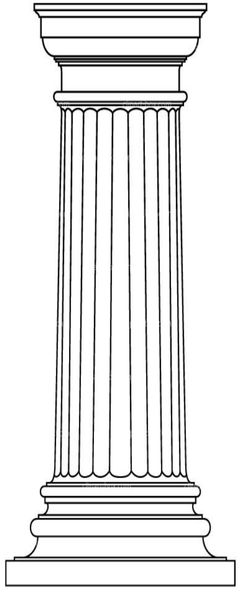






GRAVITY Collab. 2018a, 2019b, 2020

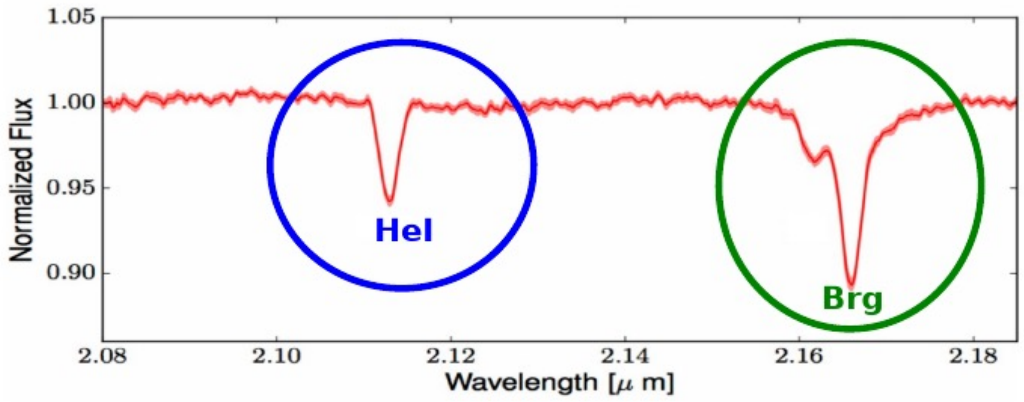
Test GR



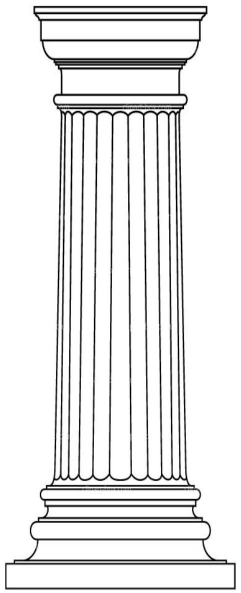
Redshift / Precession (2018-2021)

- f-parameter fit: 0 for Newton, 1 for GR (1PN)
- $f_{\mathrm{redshift}} = 1.04 \pm 0.05 \Rightarrow$ **20**σ grav. redshift detection
  compatible results with Keck: Do,Hees,Ghez+19
- $f_{\mathrm{precession}} = 0.997 \pm 0.144 \Rightarrow$ **7**σ Sch. precession detection
- $\rightarrow$ strong consistency tests of BH paradigm

Redshift => one aspect of Local Position Invariance

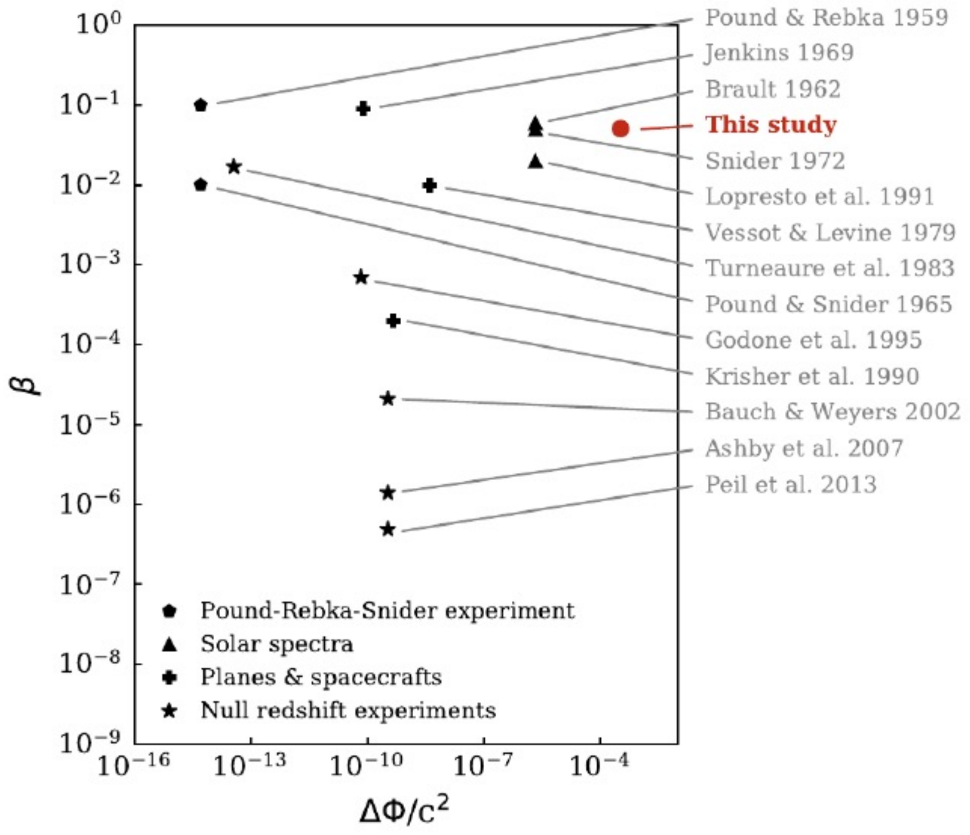


Test GR



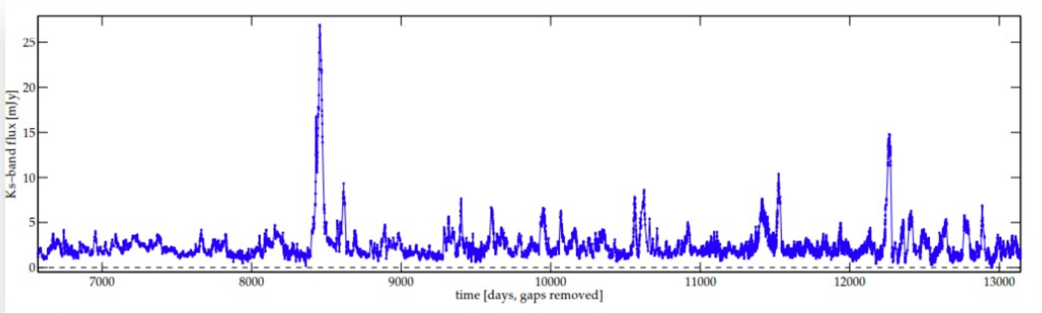
Local position invariance test

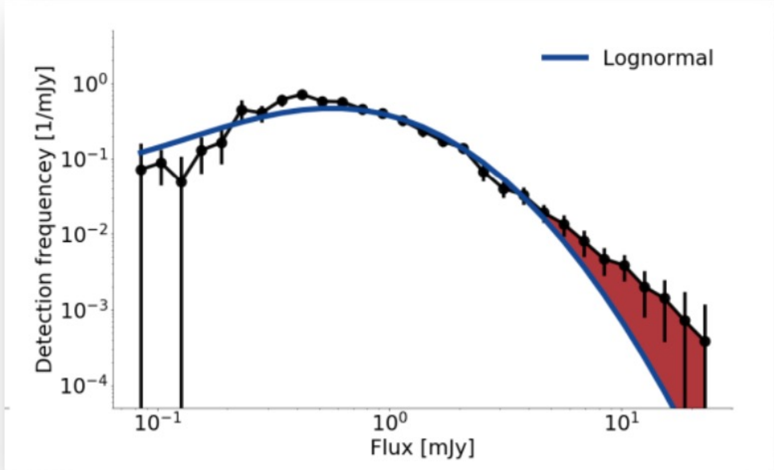
- Frequency shift due to varying potential $\Delta\nu/\nu = (1+\beta)\Delta\Phi/c^2$
- $|\beta_{\rm He} - \beta_{\rm H}| = (2.4 \pm 5.1)\%$
- $\Delta\beta$ not competitive, but very high $\Delta\Phi$!



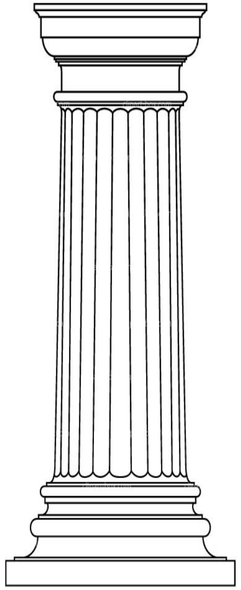
GRAVITY Collab. 2019a

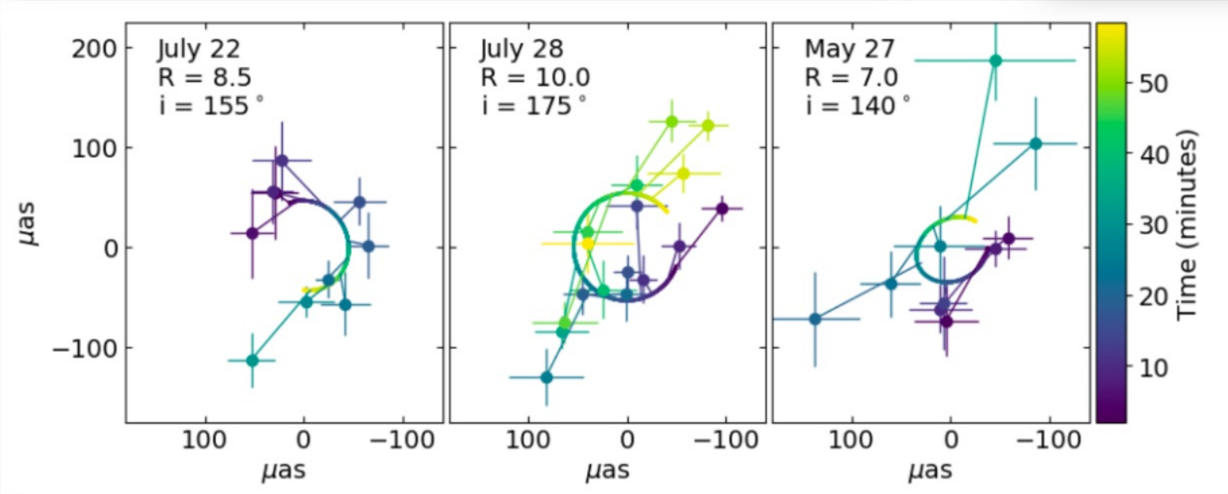
Near ISCO- flare motions in the Galactic Center

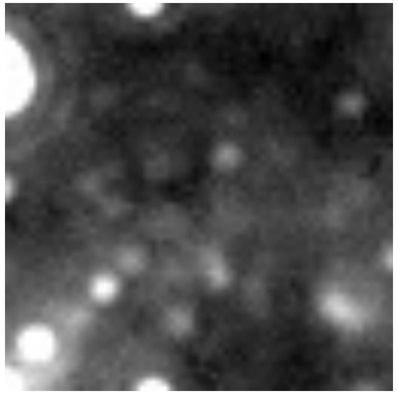




Measure size







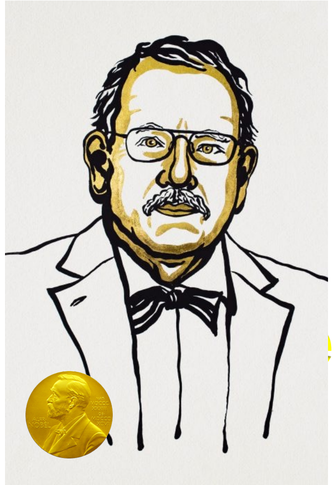
GRAVITY collaboration 2018b, GRAVITY collaboration 2020d, A&A 635, 143, GRAVITY collaboration 2020e,f

Galactic Center Black Hole

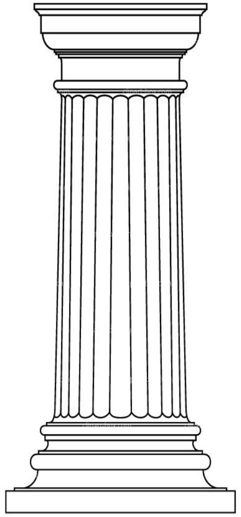
Testing the Black Hole Paradigm

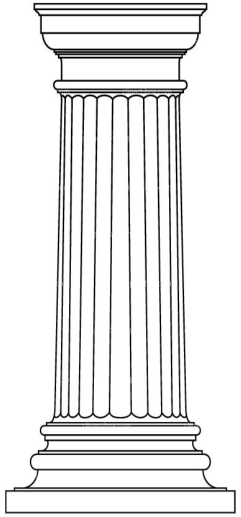
Andrea Ghez

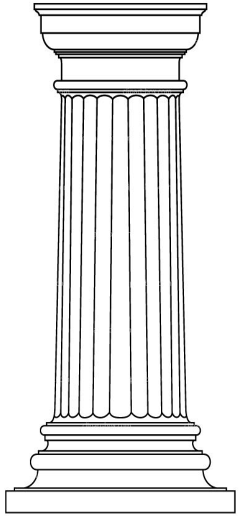
Roger Penrose



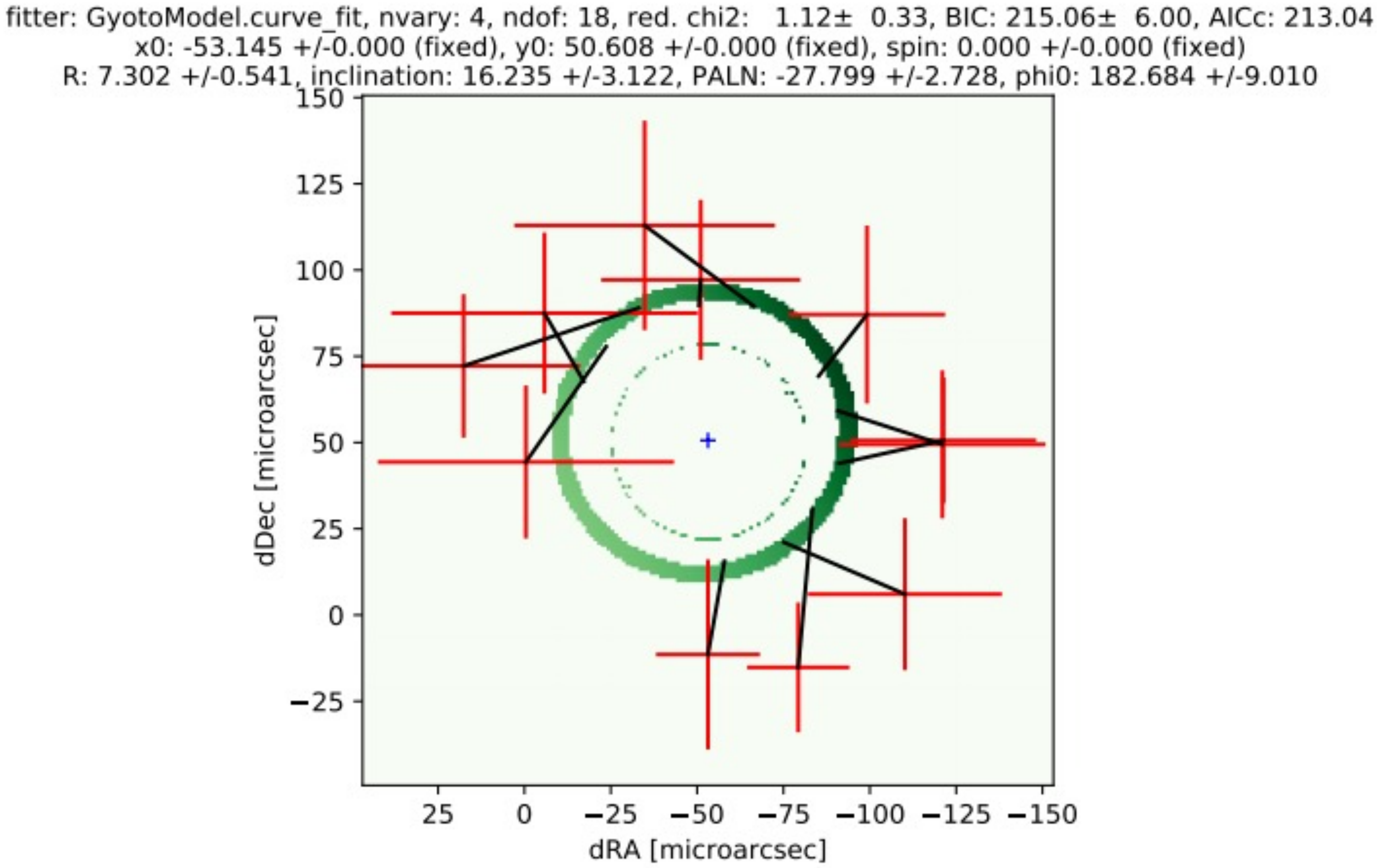
Reinhard Genzel



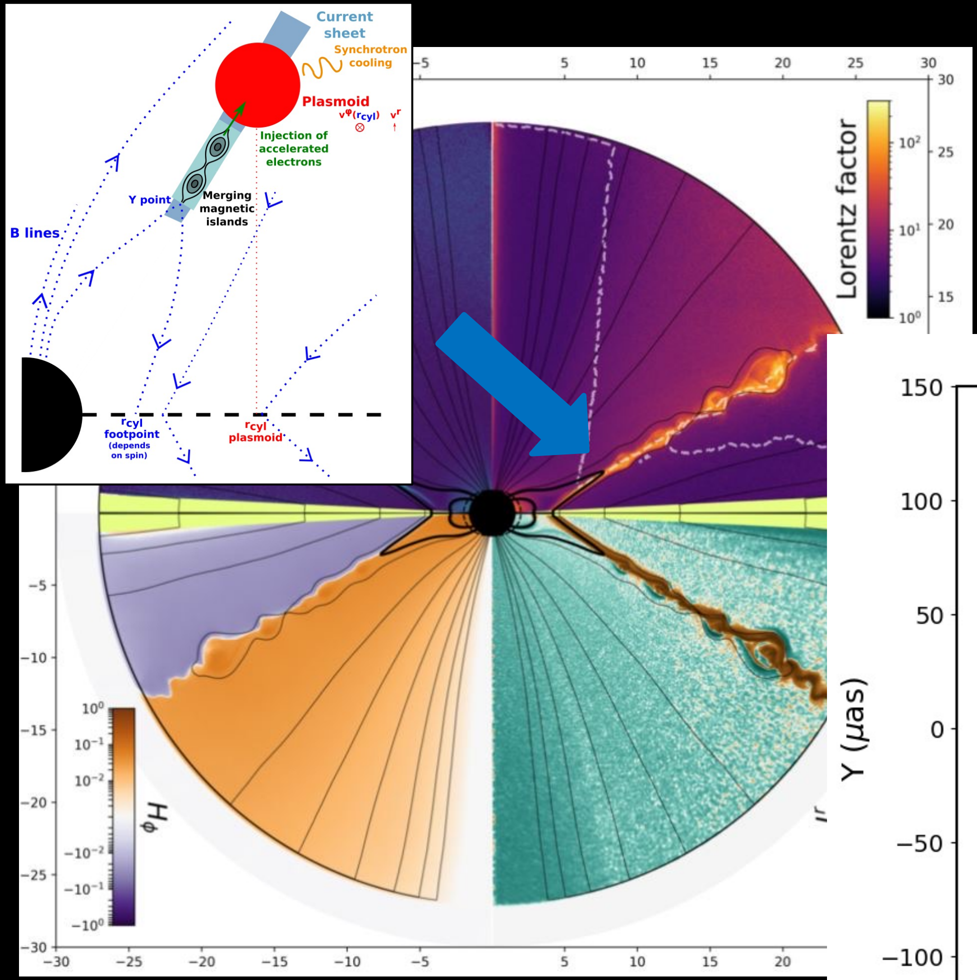




Mouvement des sursauts

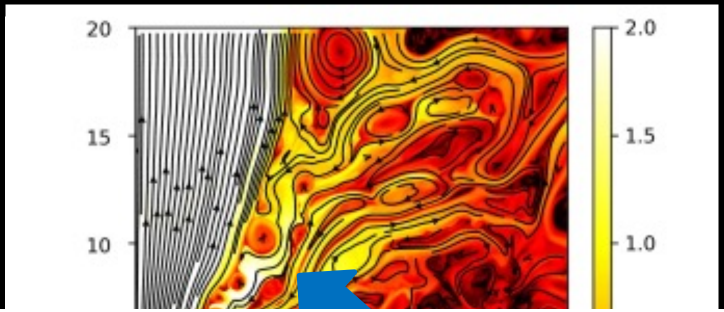


GR-PIC and GR-MHD simulations

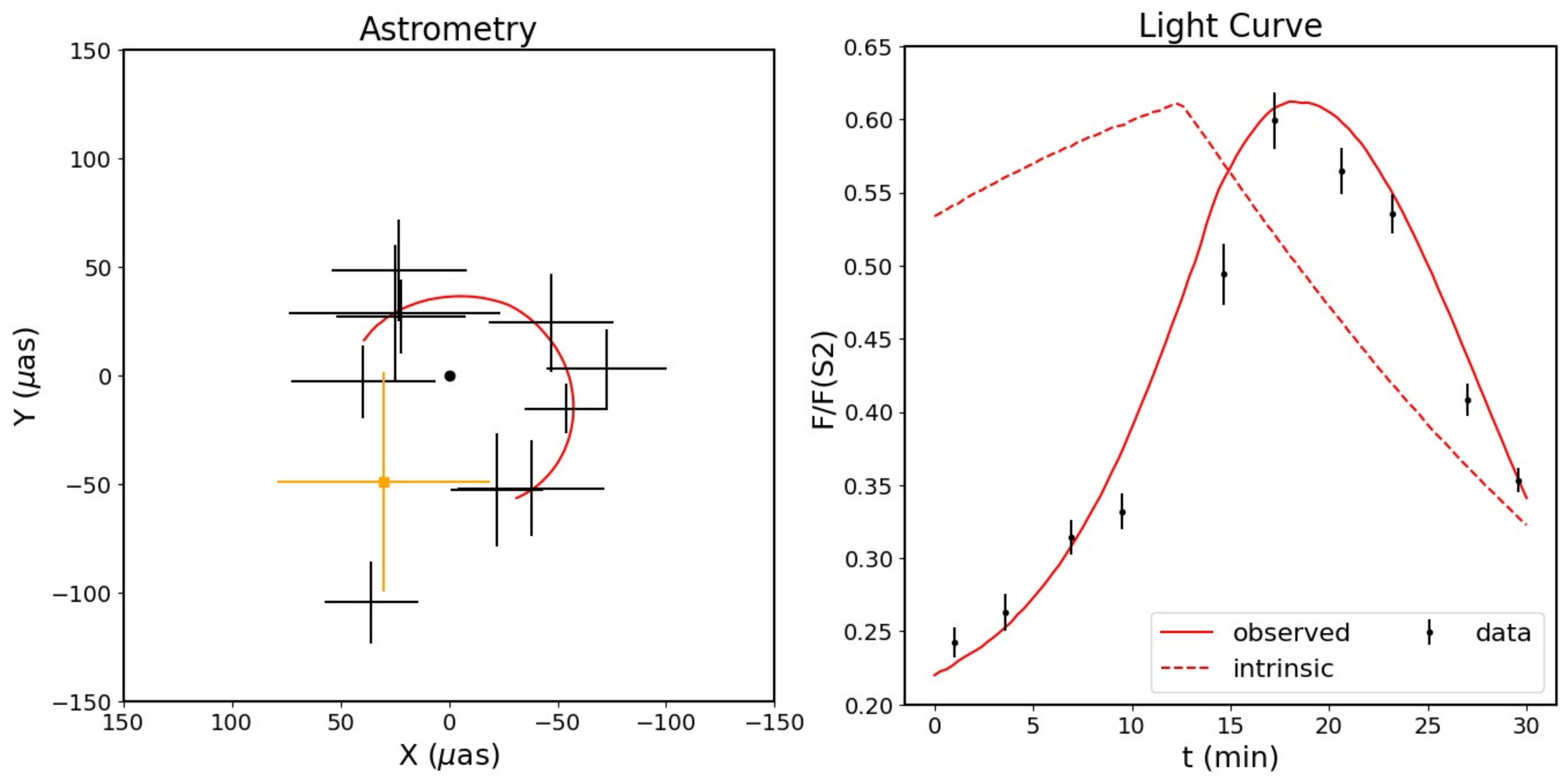


El Mellah et al., A&A 663, A169 (2022) (GR-PIC)

Ripperda et al., ApJ 900, 100 (2020) (GR-MHD)



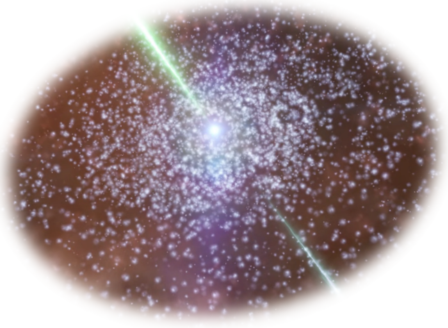
Modeling with Gyoto explains apparent super-Keplerian motion (Aimar et al. 2023, 2023A&A...672A..62A)

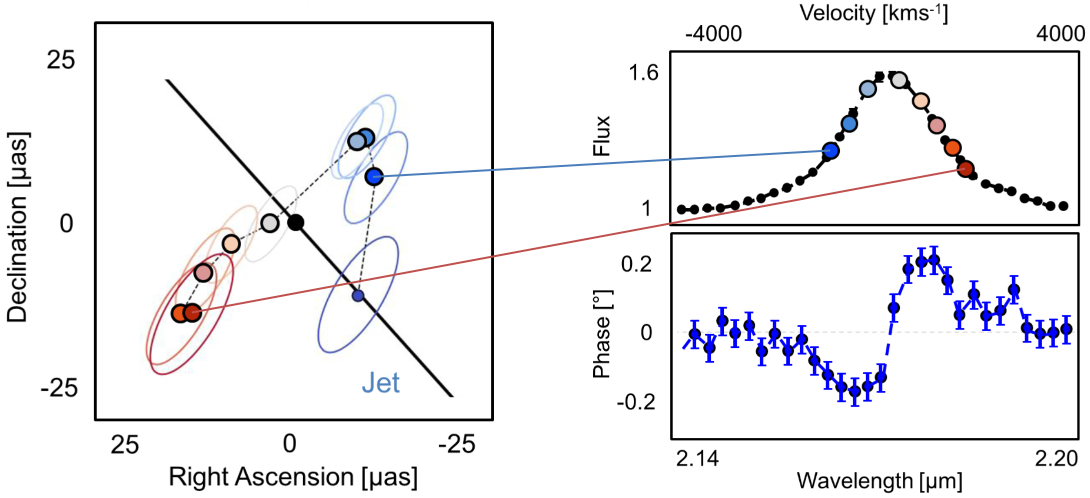


Ambient plasma/electrons fall in X-points w
Accelerated electrons are trapped in small P
Plasmoids merge in flux tubes

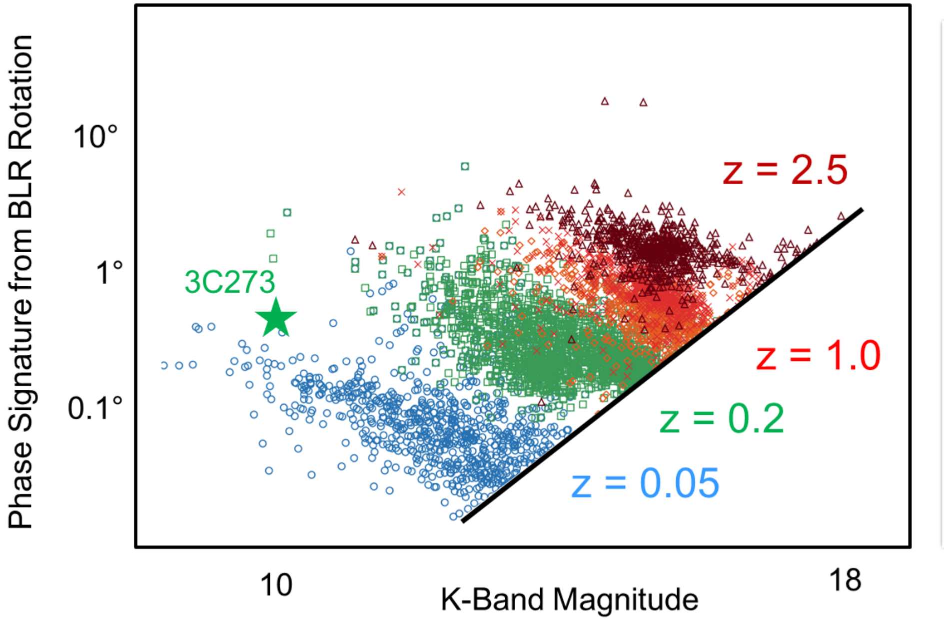

GRAVITY's Firsts
Microlens
Rotating BLR
in 3C273
NGC1068 image
Pa α flux
phase
BLR model
photocenter
observed wavelength (μm)
ΔRA (μas)
ΔDec (μas)
14mas=1400 R_S
June
- 1 week -
Peri 19 May
8000 km/s
May
April
Gravitational redshift
and Schwarzschild
precession
Gravitational Redshift [kms⁻¹]
Date
GRAVITY
Time [yrs]
δRA
19+ mag limiting
magnitude &
polarimetry
Most Trapezium
members are multiple
TCC 59
2 x 4 milli-arcsec
resolution imaging
3 R_S
SgrA* Flare motion at ISCO
η Car & SS433 gas flows
Micro-arcsec spectral
differential astrometry
Exoplanet spectroscopy
<50 μas imaging
astrometry
High resolution
spectroscopy

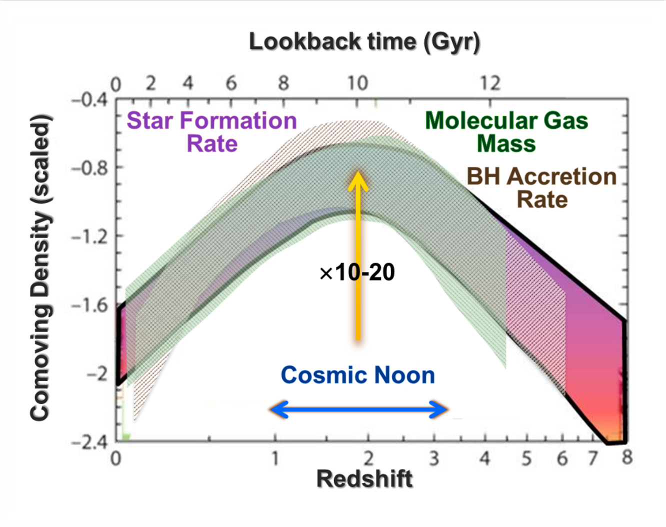
Resolving BLR in Quasars across cosmic times





GRAVITY Collab. 18, 20, 21
3C 273,
IRAS 09149−6206,
NGC3783





Mode	*z = 0*	*z = 0.2*	*z = 1*	*z = 2*	*z = 3*	*All*
Current	*15*	*2*	*0*	*0*	*0*	*17*
Gravity-Wide	2	17	27	10	1	145
On-axis NGS	193	28	3	1	0	249
On-axis LGS	**340**	**227**	19	2	2	1131
Off-axis NGS	0	5	17	12	1	108
Off-axis LGS	2	176	**628**	**542**	**71**	4898

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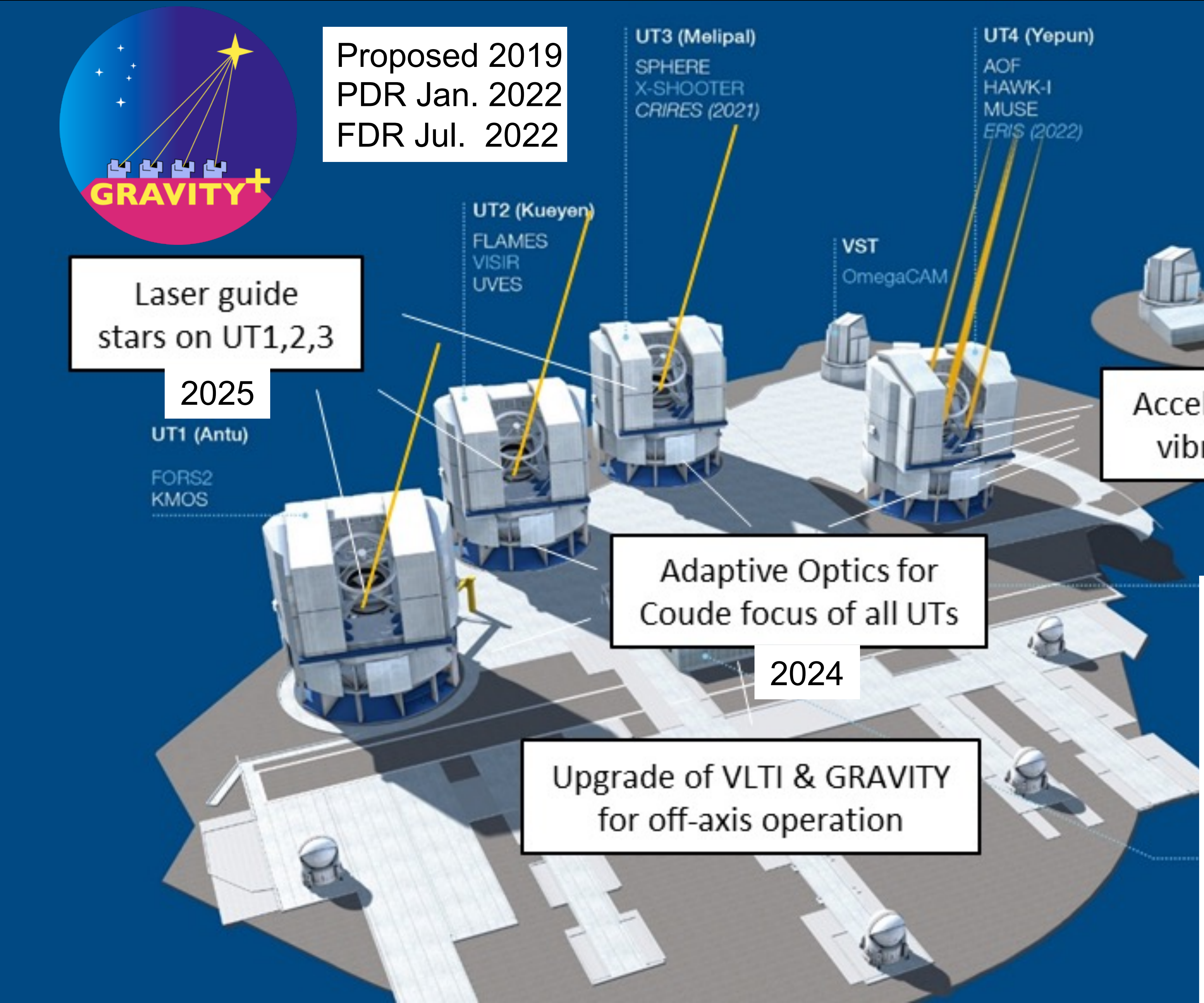
Limit. Mag: K = 22
Resolution: 3 mas
Relative astrometry: 10-50μas
Spectro-astrometry: <10μas

Proposed 2019
PDR Jan. 2022
FDR Jul. 2022

Sensitivity and Robustness

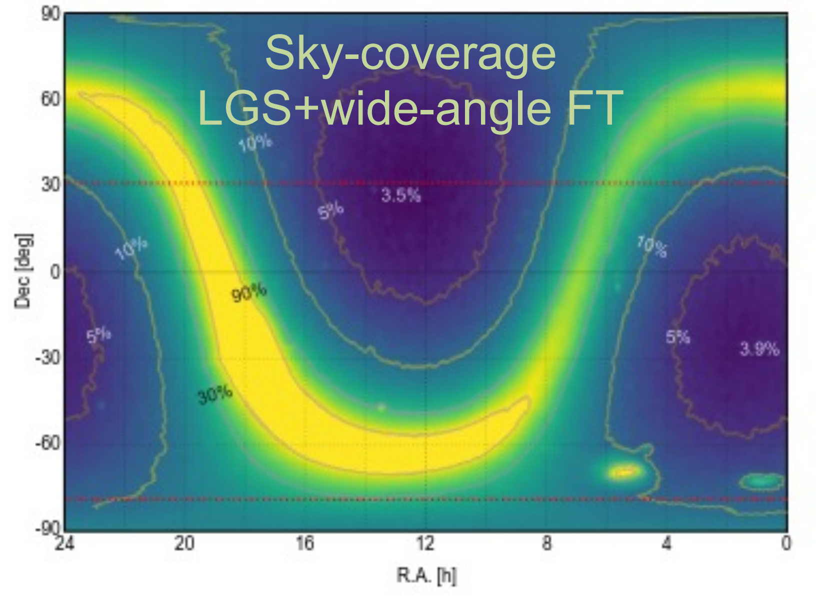


Laser guide stars on UT1,2,3
2025

Accelerometers and vibration control

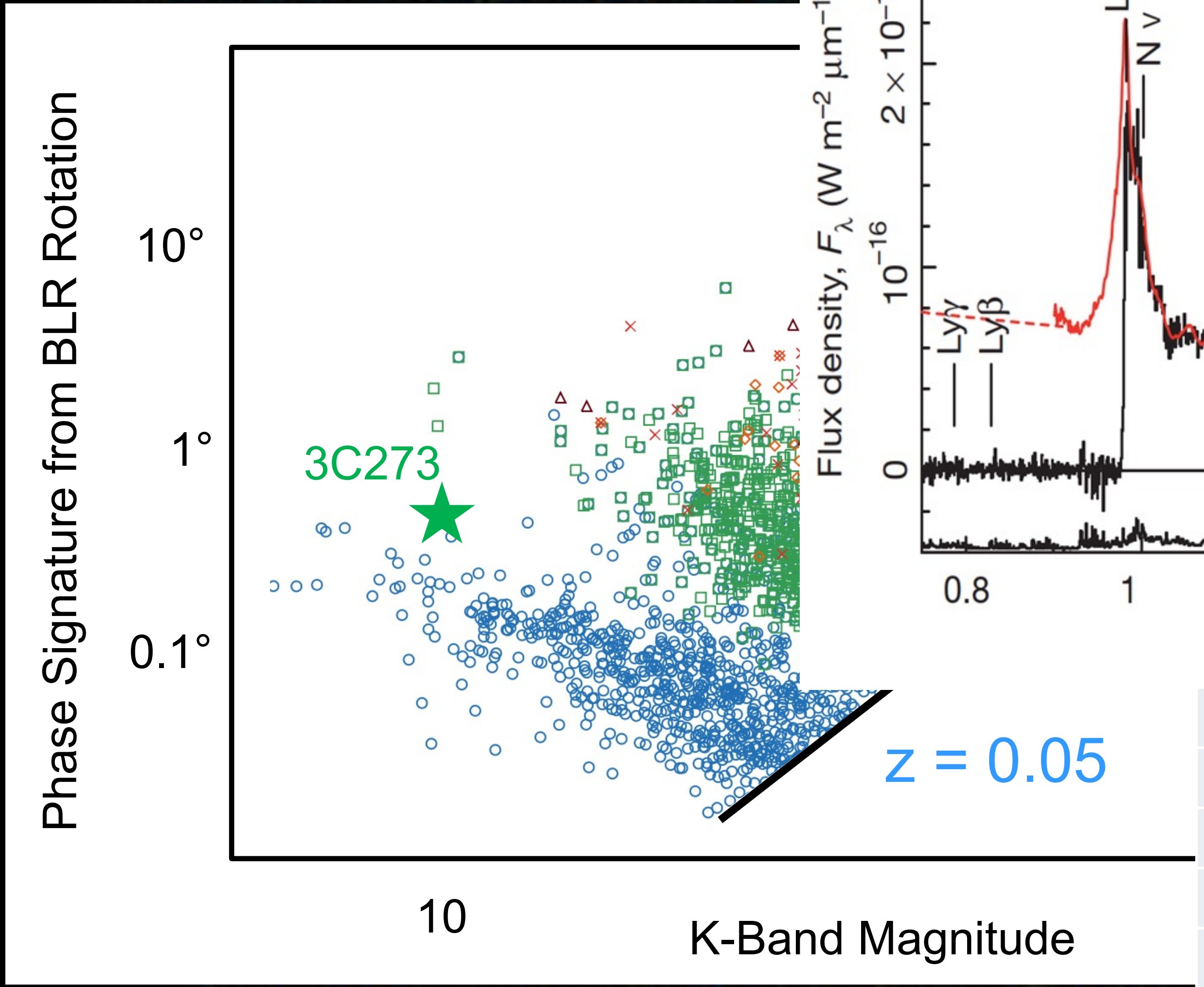
Adaptive Optics for Coude focus of all UTs
2024

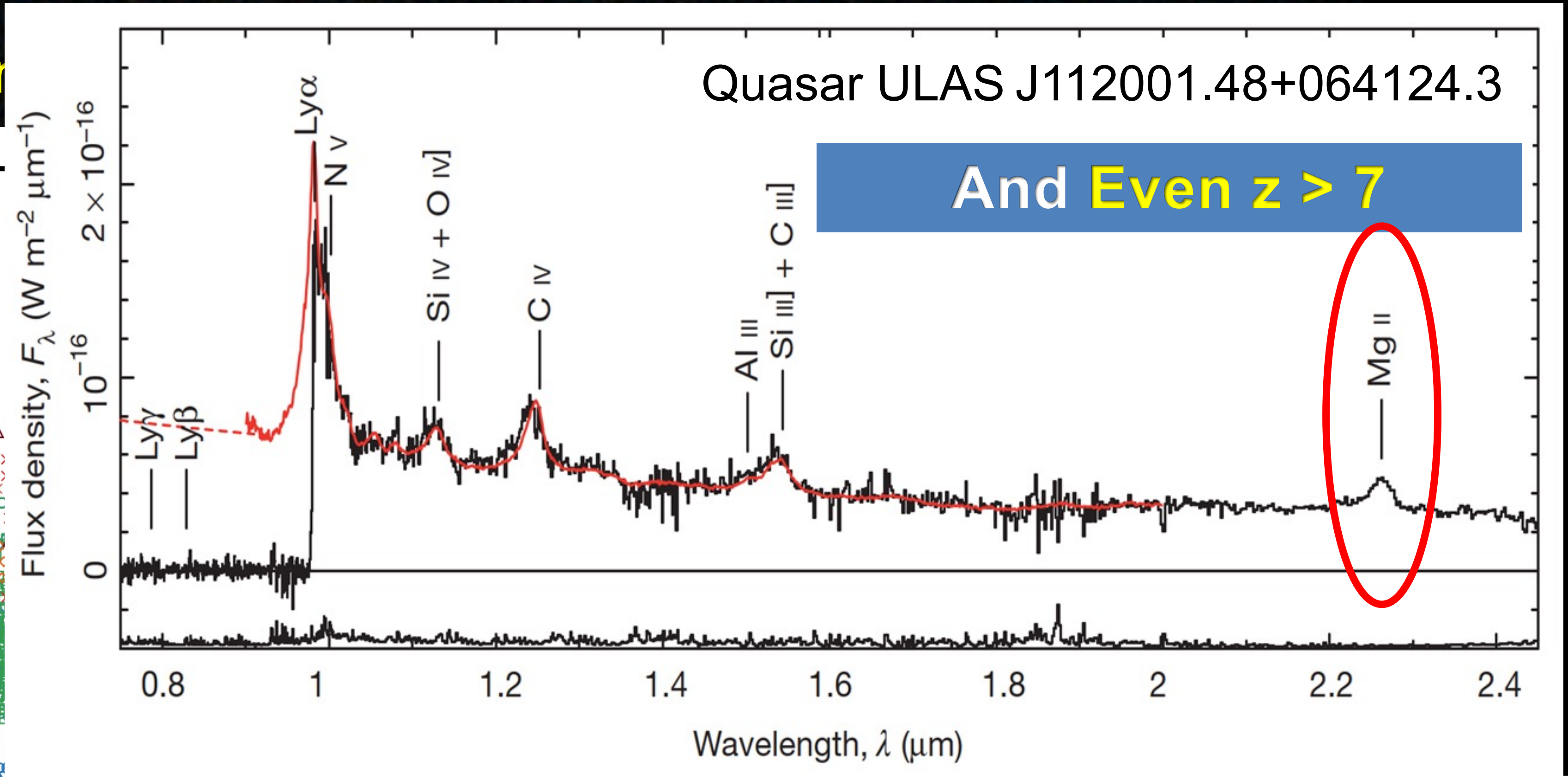
Upgrade of VLTI & GRAVITY for off-axis operation



Resolving BLR in Quasars at High-z

Up to redshift 2 – Cosr





Mode	*z = 0*	*z = 0.2*	*z = 1*	*z = 2*	*z = 3*	*All*
Current	*15*	*2*	*0*	*0*	*0*	*17*
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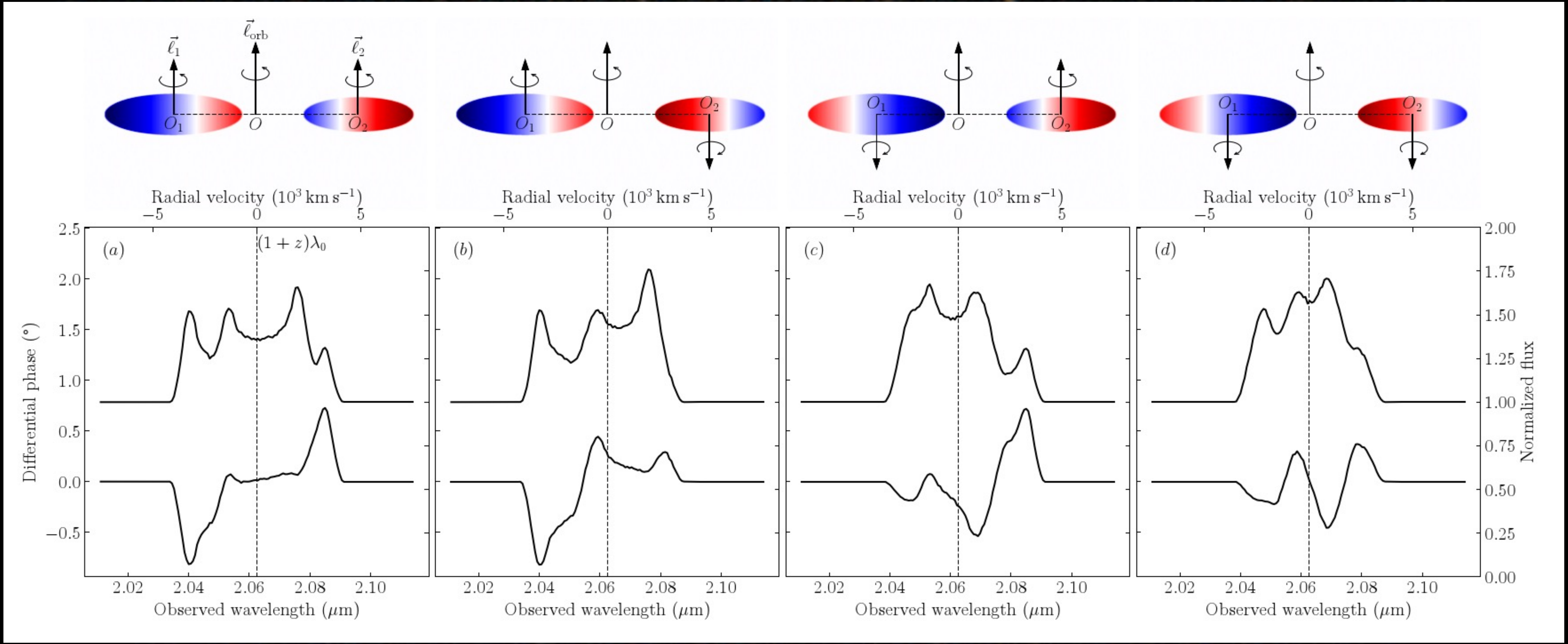
Supermassive Binary Black Holes – Final Parsec Problem



Yu-Yang Songsheng, Jian-Min Wang, Yan-Rong Li, Pu Du

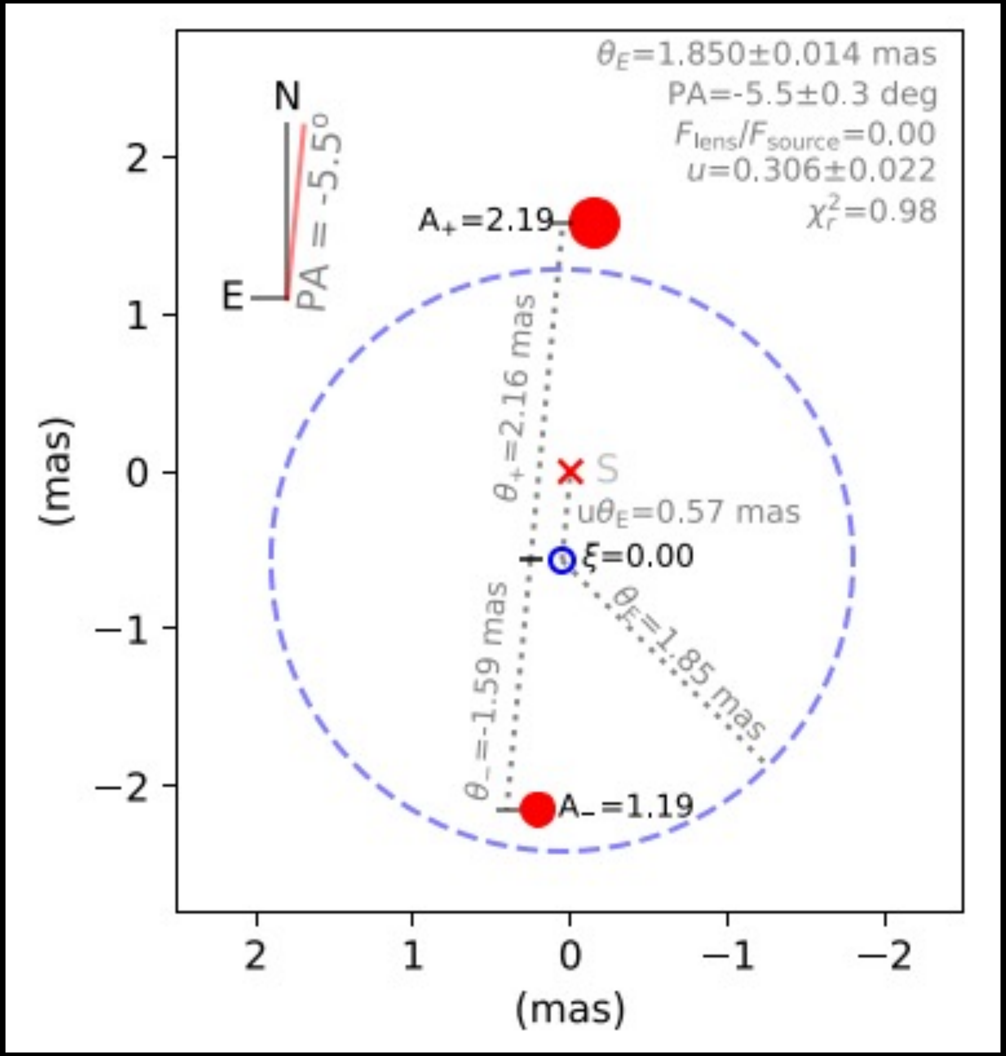
First Resolution of Microlensed Images

Credit:ESO

LENS-LIKE ACTION OF A STAR BY THE DEVIATION OF LIGHT IN THE GRAVITATIONAL FIELD

Einstein 1936

QE = 1.85 ± 0.014 mas

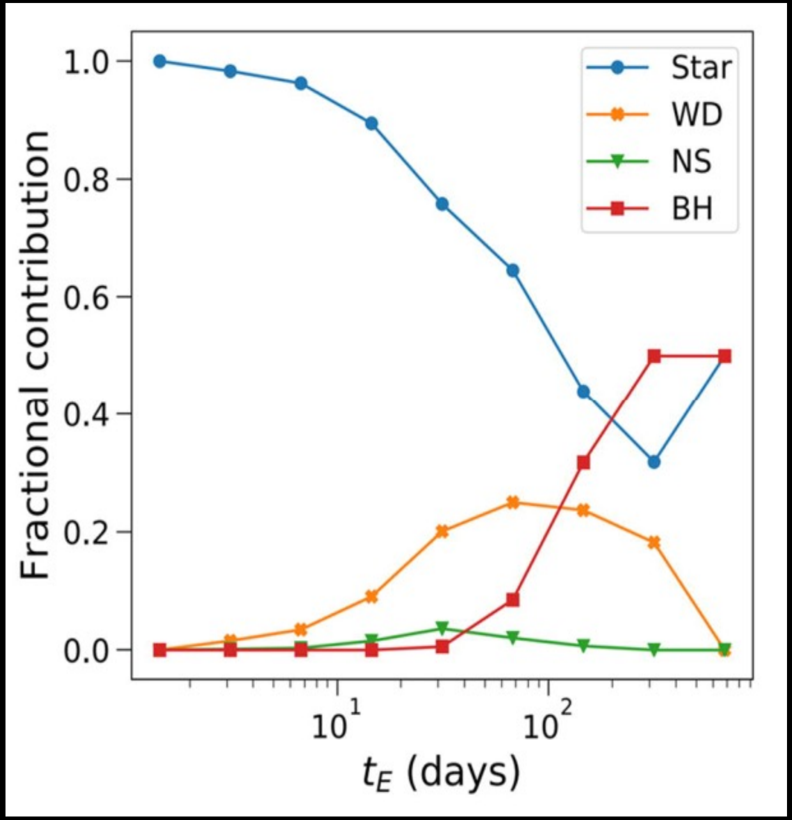


Dong+ 19

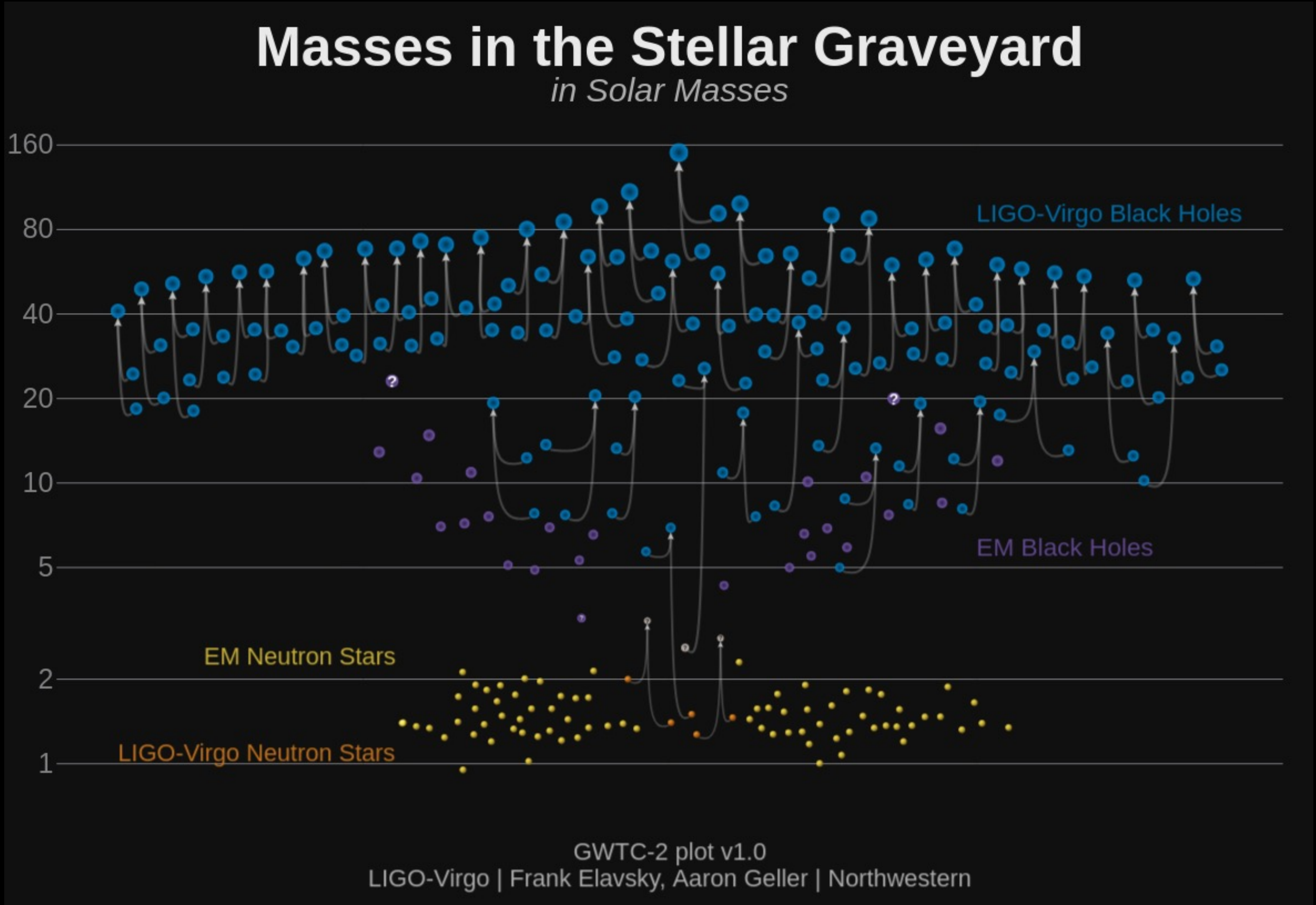
Isolated Stellar Black Holes from Microlensing

Model-free Determination of **Mass** for Dark Lens

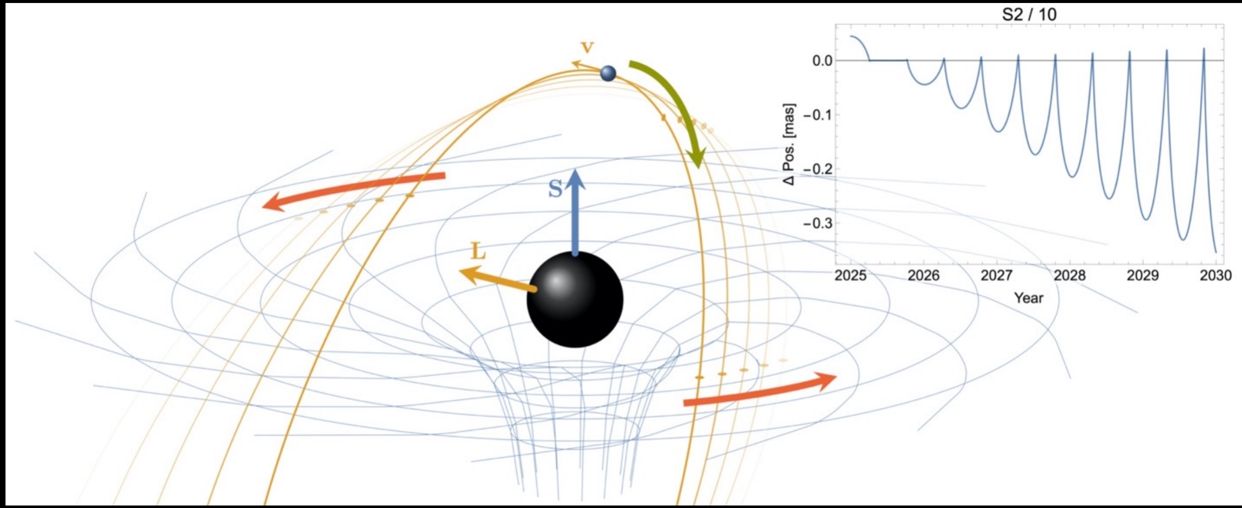
Most **long duration** lensing events will be **black holes**



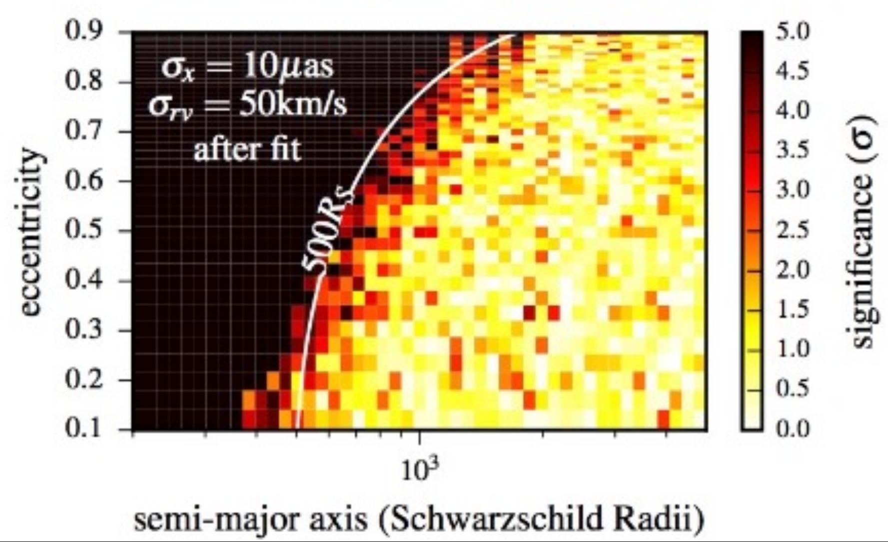
Lam+ 20



Towards measuring the spin of Sgr A*



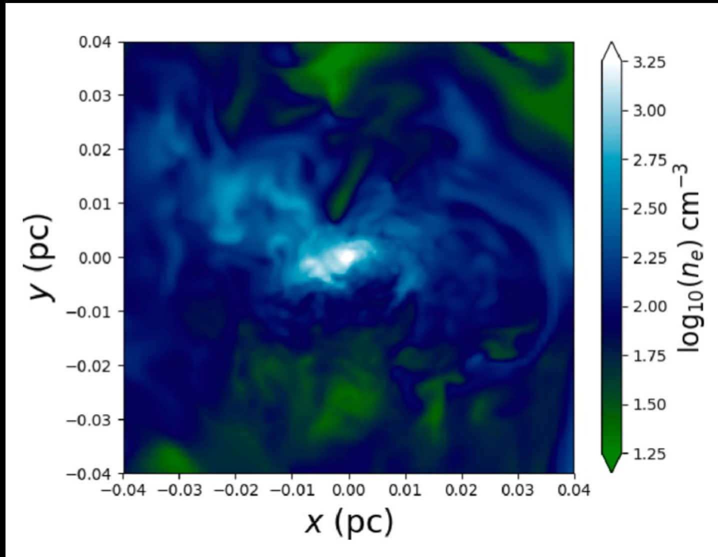
Possibly test $Q = -J^2/M$
Test no-hair theorem (Will 2008)



Waisberg ea 2018

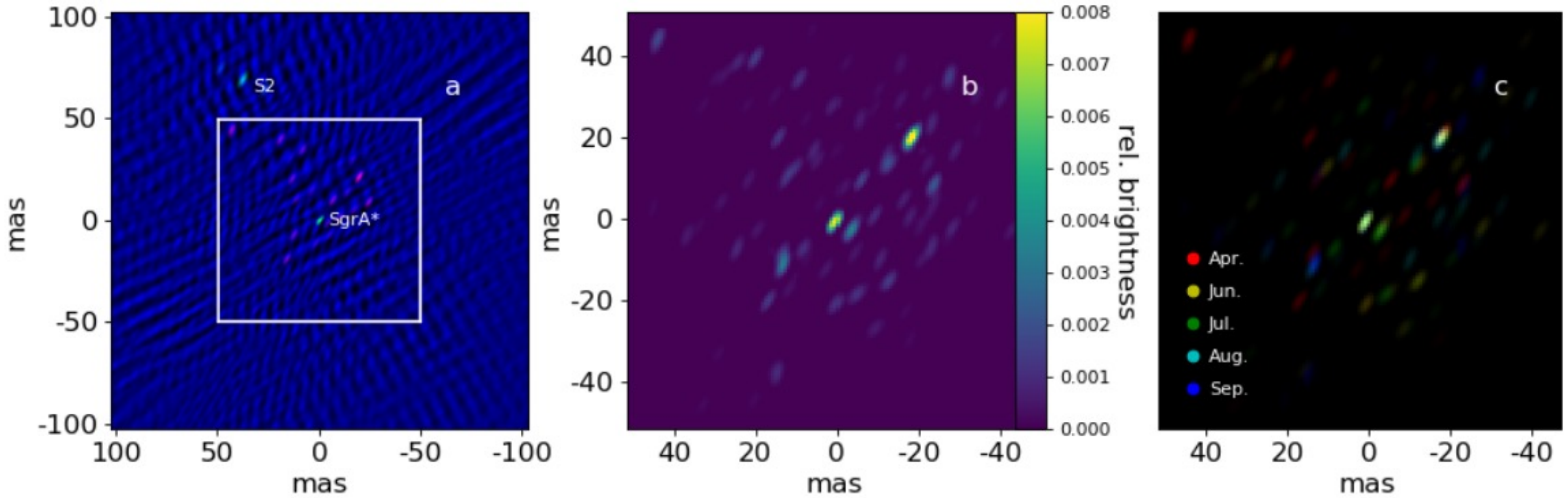
- Cleanest probe: Stellar orbit
  - Needs a star on very close, high eccentricity orbit

- Closest probe: Flares
  - Gas phyiscs & magnetic fields
  - Using a combination of light curves, 10μas astrometry & polarimetry
  - Accretion physics might be against us

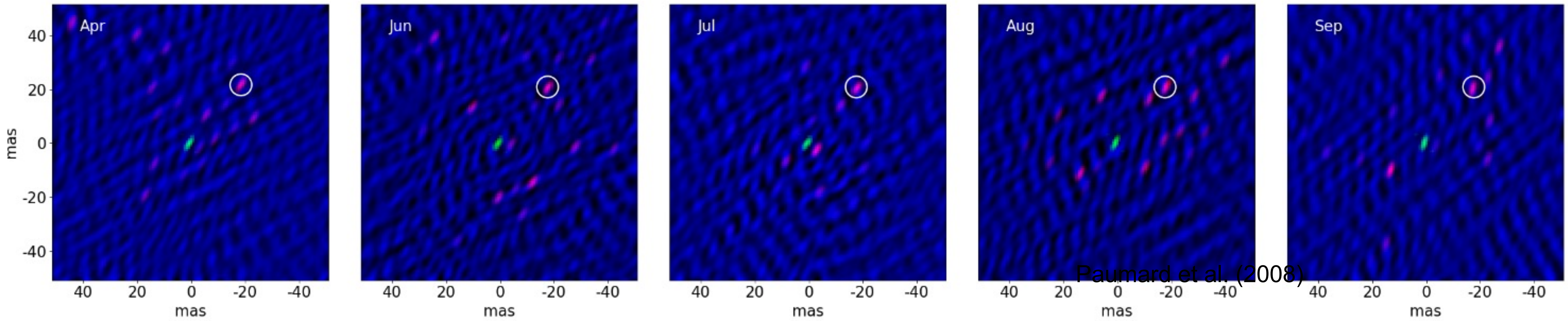


Ressler ea 2018

Original science case: detect close faint stars

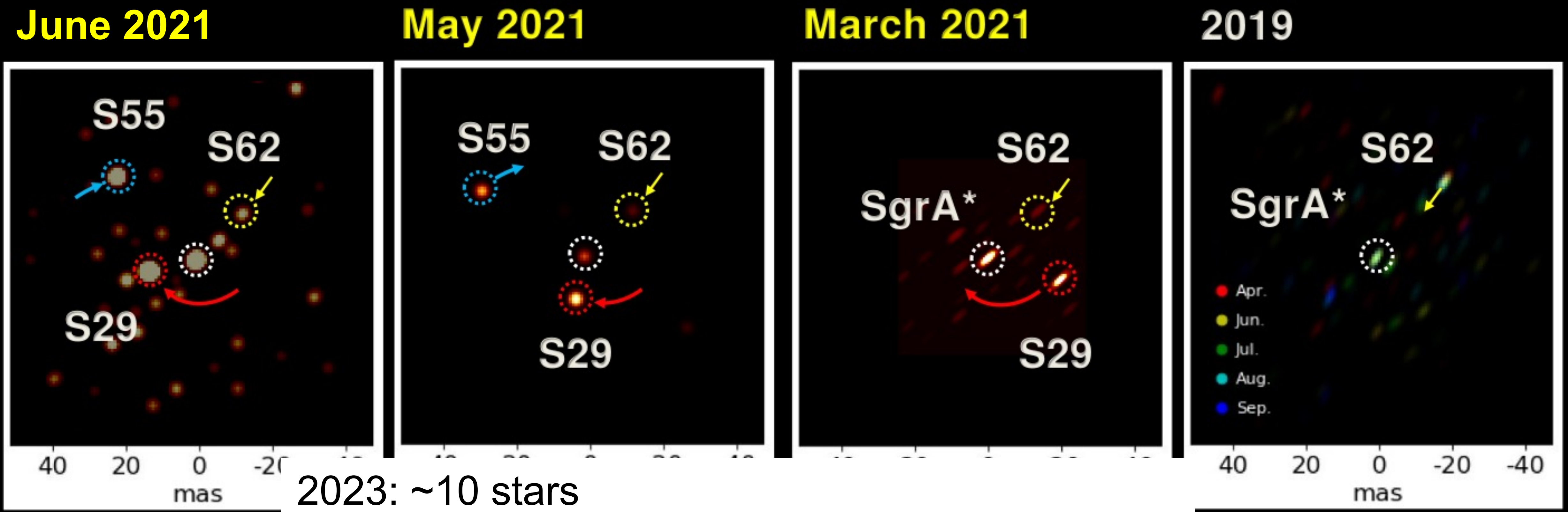


Detection of a K=19 star near SgrA* (in projection), GRAVITY collaboration et al. 2020



Paumard et al. (2008)

Just the Beginning



GRAVITY Collaboration+ 20

Quick look image re

00x fainter than S2

S2

2023: ~10 stars

GRAVITY+ :

increased sensitivity,

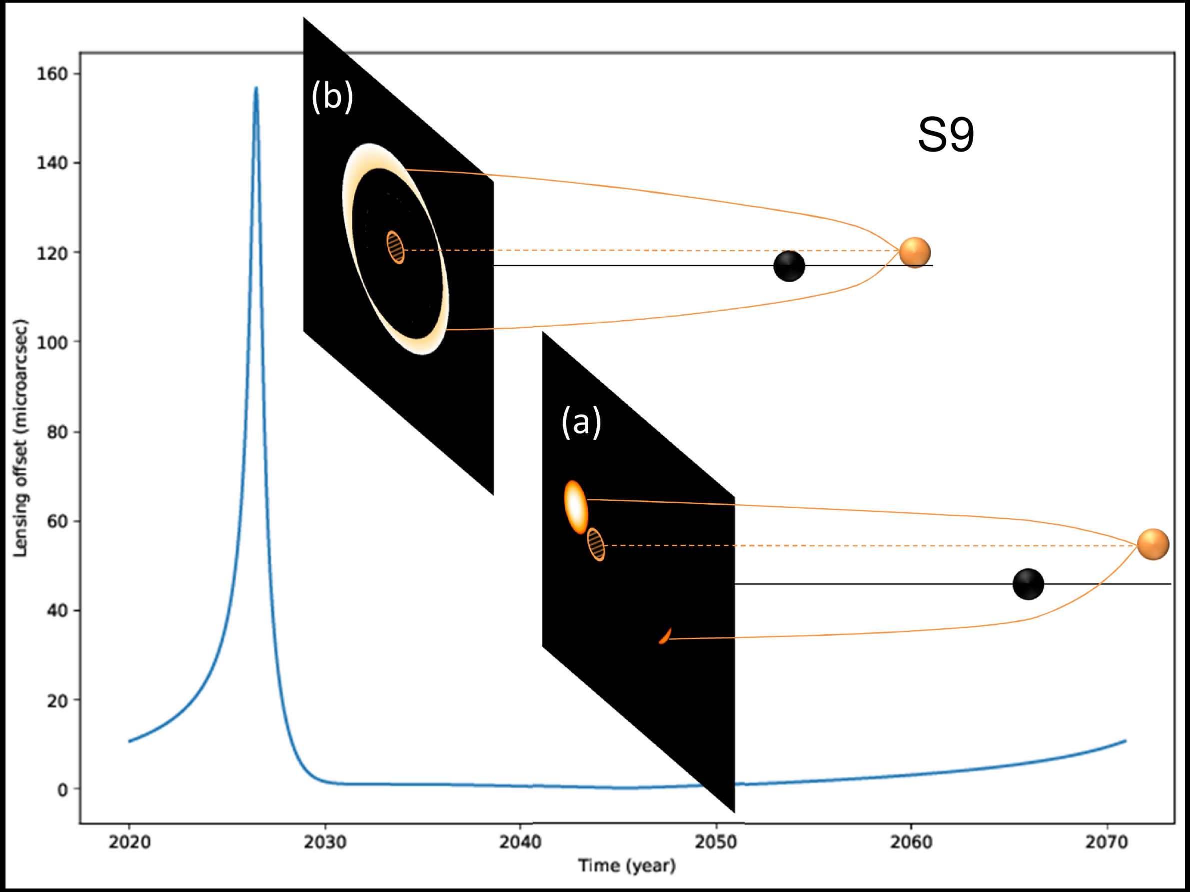
more stable, higher performance (LGS)

detect and monitor more faint stars (K=22)

detect more flares

Probe the potential well around SgrA*

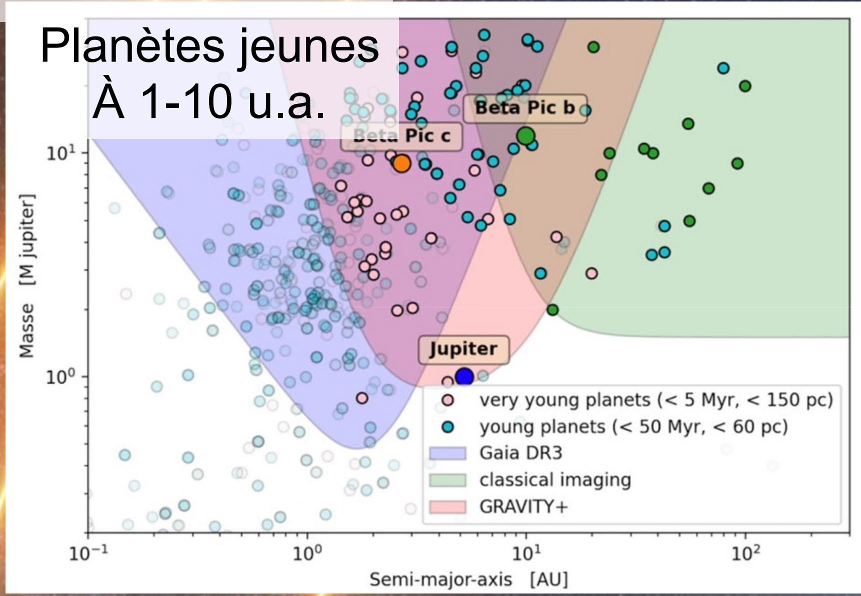
- Mass distribution around Sgr A*:
  - (faint) stars
  - Sea of stellar mass to intermediate mass
- Signatures:
  - Enclosed mass for many stars
  - Orbital precession
  - Statistics of orbital elements (Tep et al. 2021)
  - Changes in orbits from 2 body encounters
  - Caustic crossings in "weak" lensing events

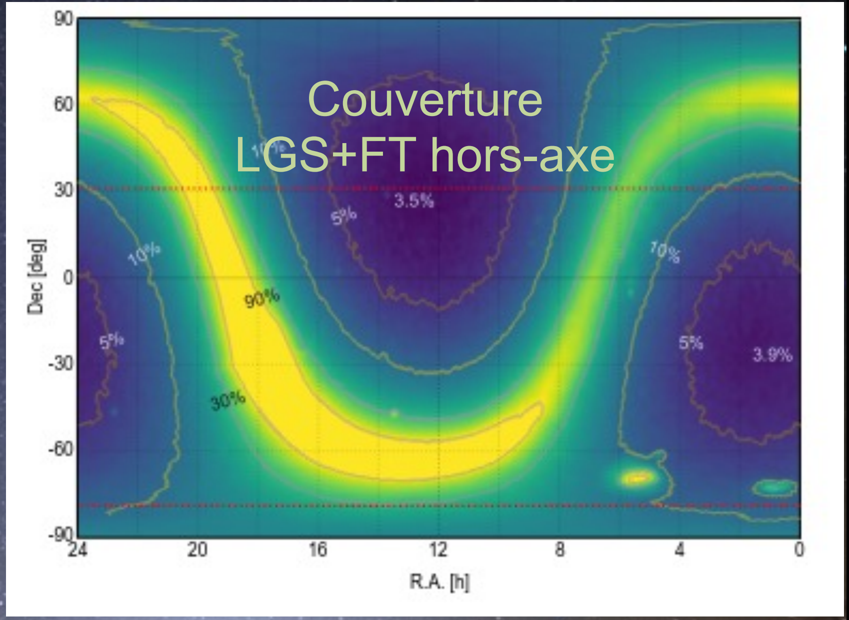


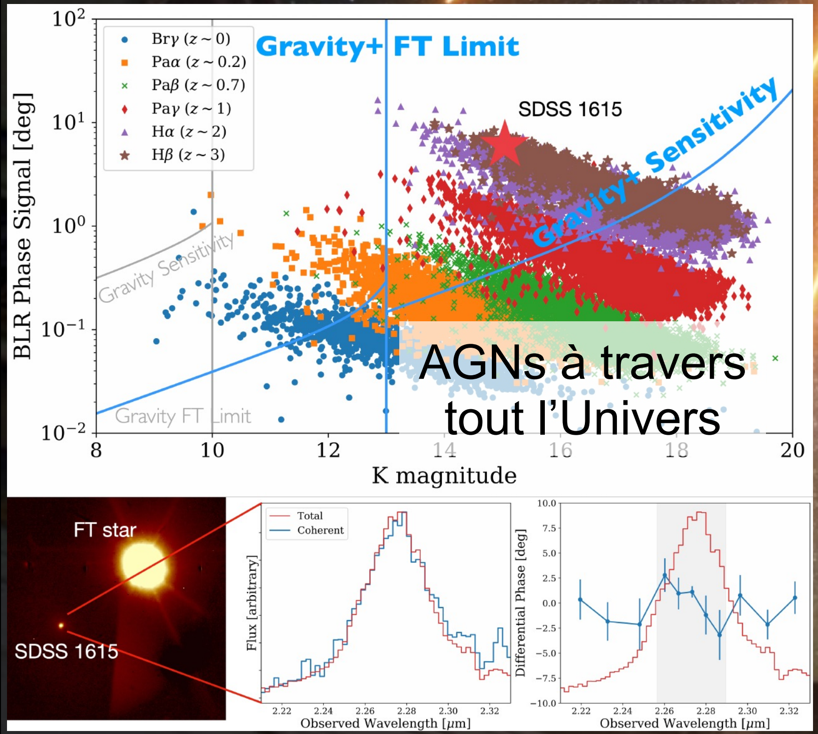
Lensing detectable within first years of operation

Mise en service communauté :
2022: GRAVITY-wide
2022: FT upgrade
2023: GRAVITY-faint
2024: GPAO NGS
2026: GPAO LGS

Participation française: lead Gravity Plus AO (GPAO)
- LESIA: coordination nationale G+, RTC, FT upgrade
- IPAG: système AO, qualification DM
- Laboratoire Lagrange: intégration
- CRAL: DRS







Calendrier de GPAO (Gravity Plus AO):
- 2019: Présentation à VLT2030
- 2020: Lettre d'intention/sélection ESO
- 2022: Jan: PDR, jul: FDR, nov : début AITs
- **2024: PAE, commissioning mode NGS**
- 2025: Commissioning LGS

Performance cible: K=22,
Tout le disque galactique, beaucoup d'AGNs

Vue d'artiste des étoiles laser. Crédits: Luis Calçada

Fundamental Physics at the Galactic Centre

15 & 18 December, 2023

https://gravity2023.sciencesconf.org/
Deadline: November 10th (next Friday!)

Porto, Portugal

Login

MAIN MENU

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WELCOME

The Galactic Centre and SgrA* is a unique laboratory for fundamental physics studies. Being the nearest supermassive compact object to planet Earth, it allows for probing the smallest spatial scales with high angular resolution instrumentation such as adaptive optics at the Keck and VLT telescopes, (sub-)mm long baseline interferometry with the EHT and infrared long baseline interferometry with Gravity/VLTI, space telescopes such as the James Webb or NuSTAR satellites. Its low accretion rate allows for a relatively minor astrophysical complexity concerning other counterparts.

A wealth of measurements and fundamental physics results has been obtained in its context, from the celebrated 2020 Nobel prize to the EHT images, from General Relativity tests to alternative theories of gravity and dark matter. The general understanding is that the compact object at SgrA* is a black hole. Johann Wolfgang von Goethe once wrote, "*We only see what we know*". Black holes have been known theoretically since 1915 and are obvious candidates for what we see at SgrA*. But is this all that there is?

Strong community support, P0 of INSU 2019 prospective

Off Axis Fringe Tracking

Laser Guide Stars

GRAVITY+: Towards Faint Science, All Sky, High Contrast, Milli-Arcsecond Optical Interferometric Imaging

White Paper and Proposal

Improved Sensitivity

Adaptive Optics

GRAVITY+

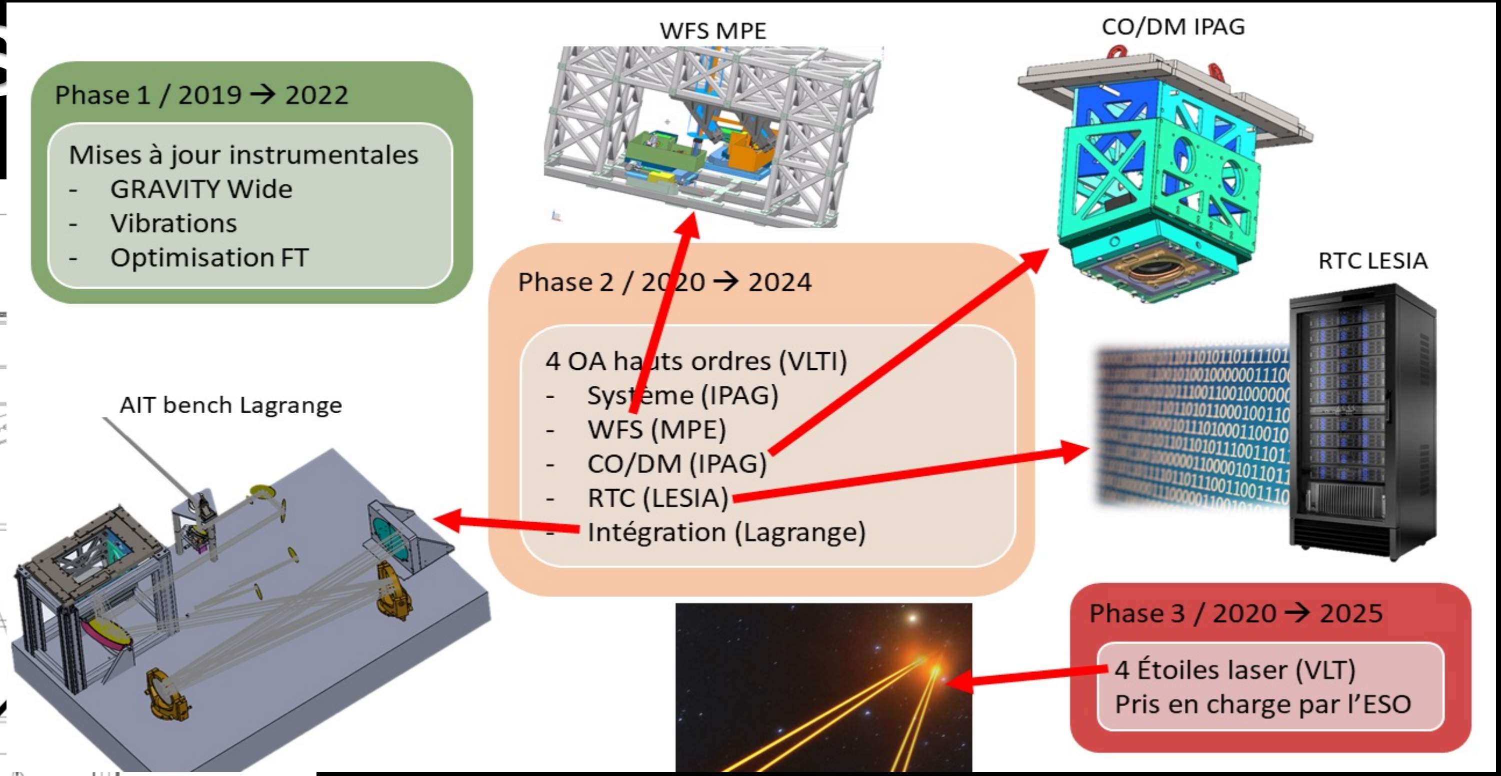
Faint All Sky Milli Arcsecond Imaging and Micro Arcsecond (Spectro) Astrometry

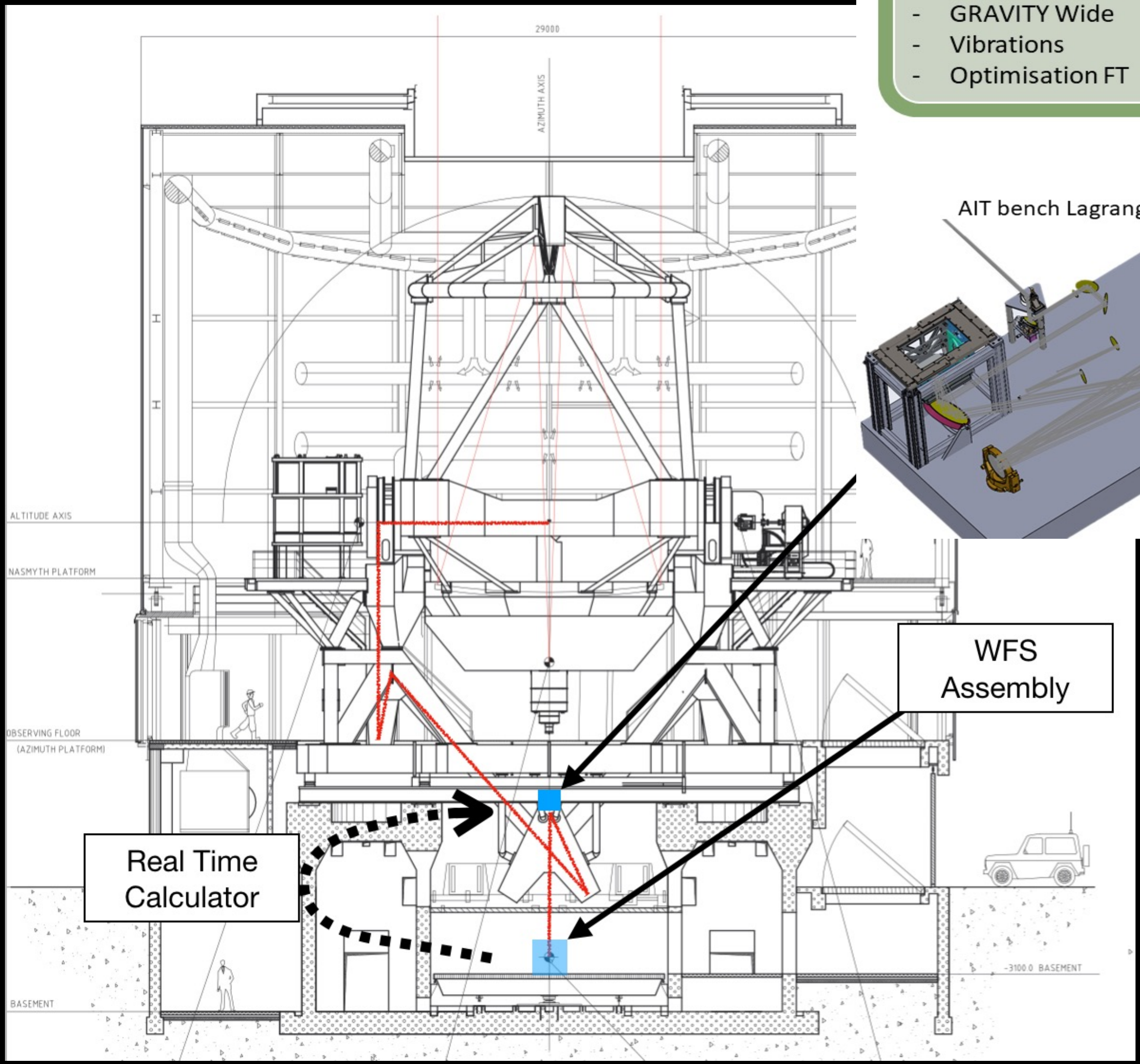
We are happy to inform you that the STC recommended GRAVITY+ as the highest priority project to be pursued in the coming years. ESO is now considering adopting GRAVITY+ as the next VLT facility instrument after a thorough Phase A process, which is also requested by the STC.

Currently being integrated in Nice, first light next year!

Credit: ESO, Luis Calçada

INS

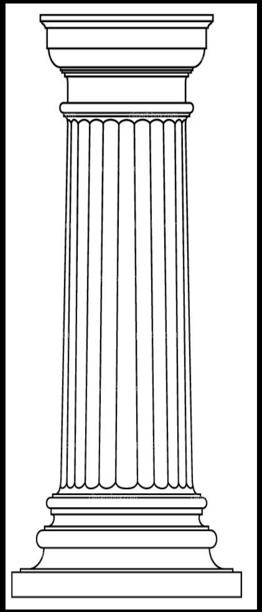


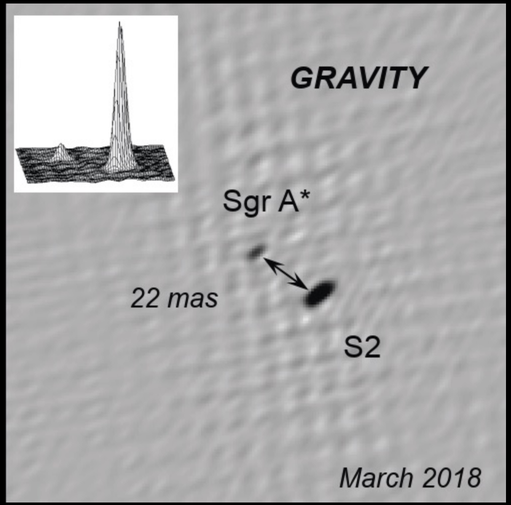


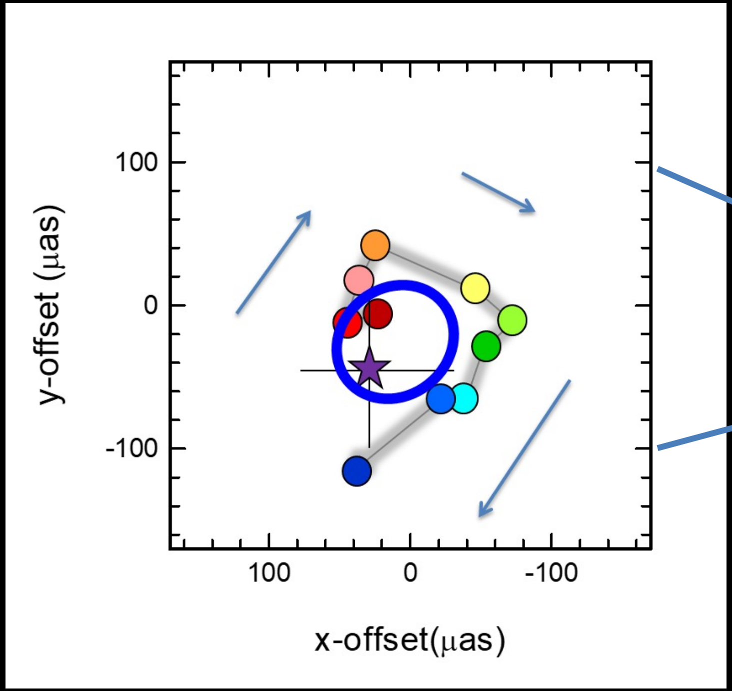
LESIA l'Observatoire de Paris | PSL IPAG Institut de Planétologie et d'Astrophysique de Grenoble LAGRANGE CRAL

Galactic Center Black Hole

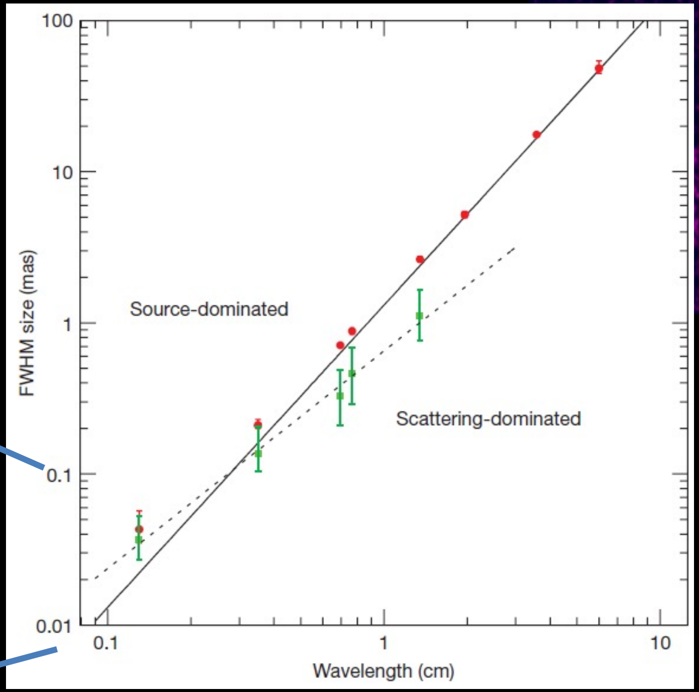
Measure Size



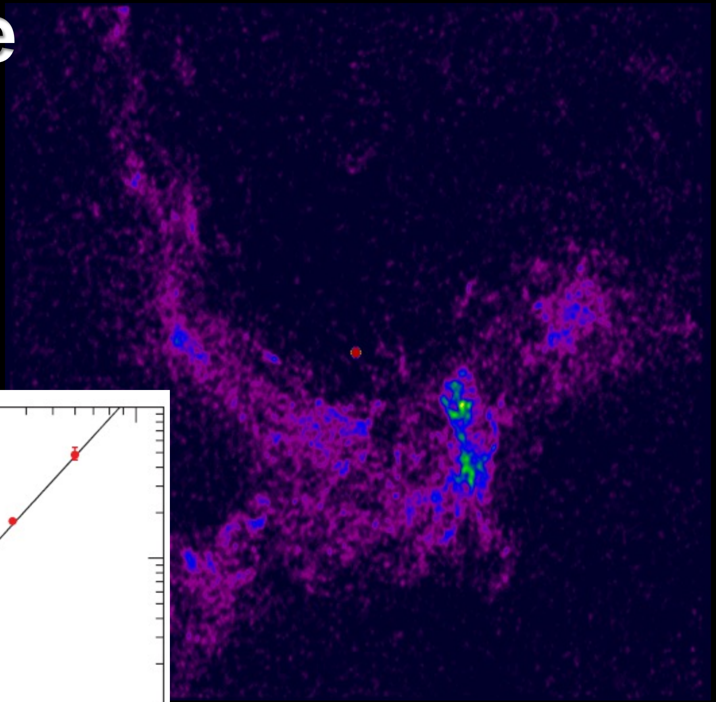




GRAVITY Collaboration+ 18,19,20

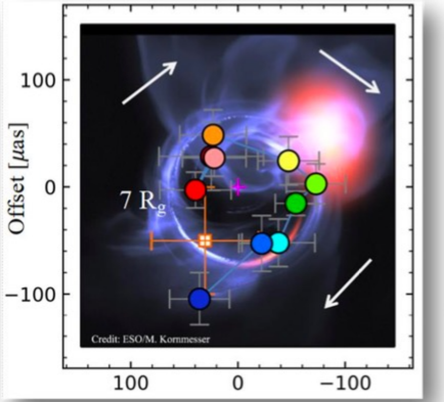


Fish+ 11, Doeleman+ 08
Bower+ 06,04, Shen+ 05
Krichbaum+ 98

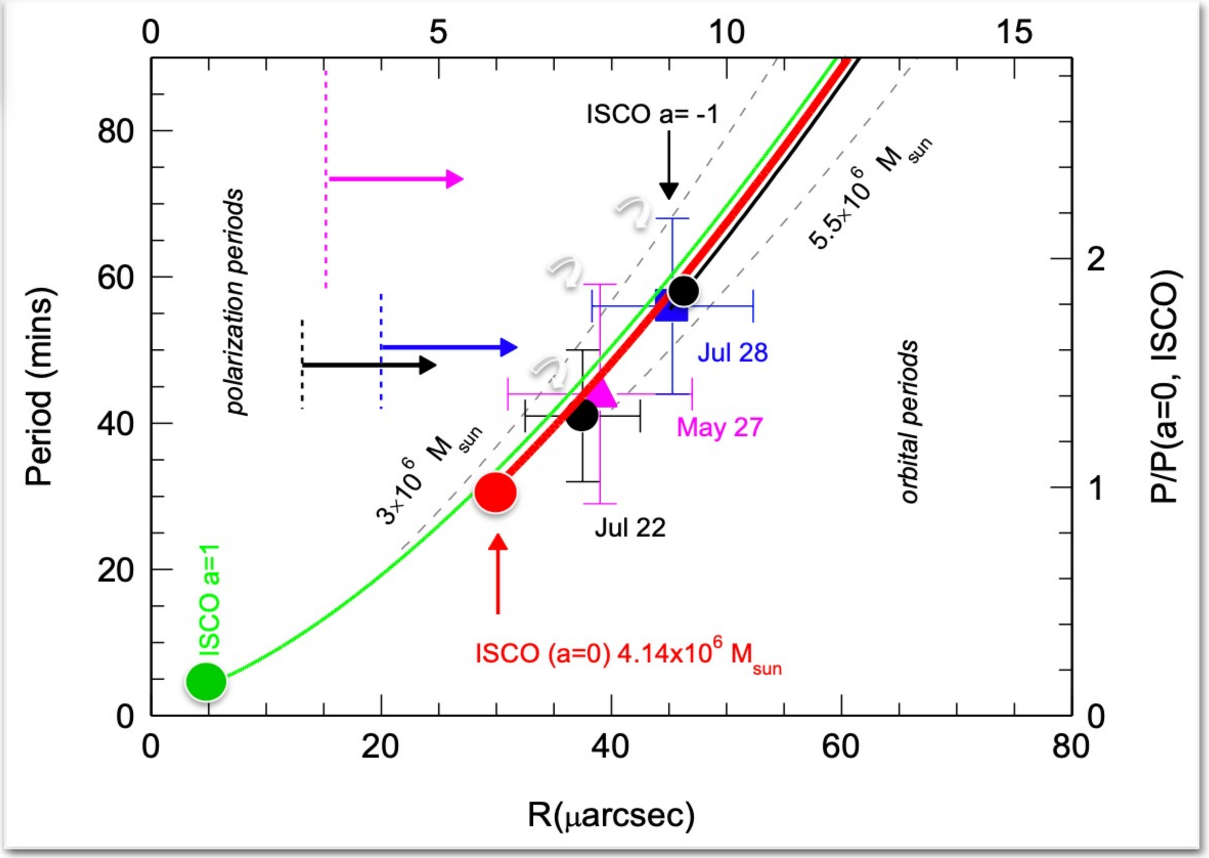


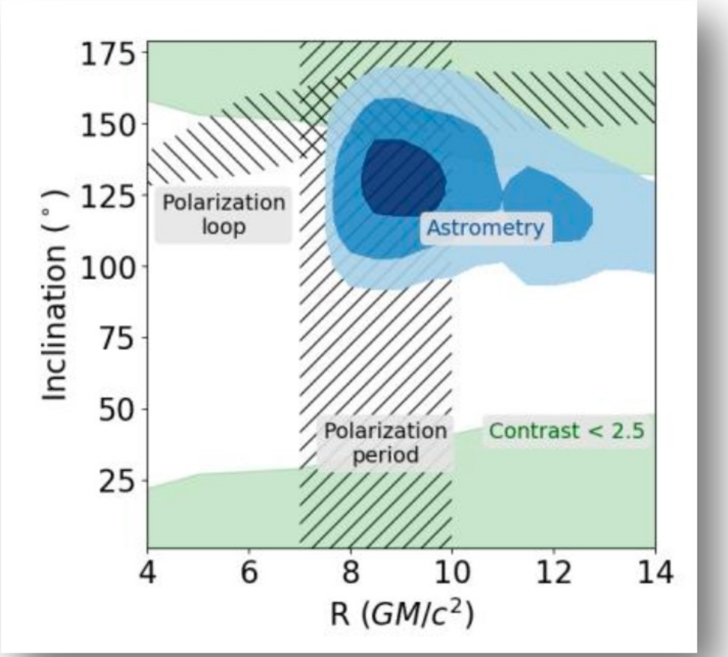
Yusef-Zadeh+ 86
Roberts & Goss 93

Orbital motions in relativistic zone are consistent with hypothesis that SgrA* is a Kerr Black Hole



R/R_g

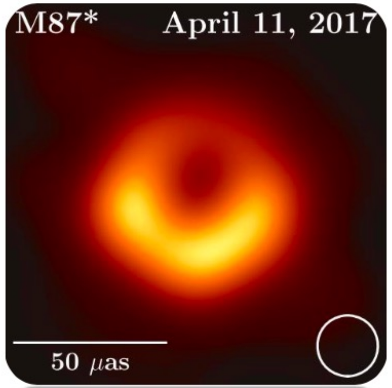


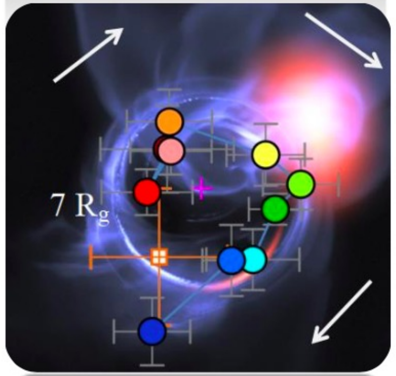


GRAVITY collaboration 2018b, A&A, 618, L10;
GRAVITY collaboration 2019c, MNRAS, 489, 4604;
GRAVITY collaboration 2020, A&A, 635, 143

Dreaming about the Future: Are '(Massive) Black Holes' described by the Kerr Space-Time ?

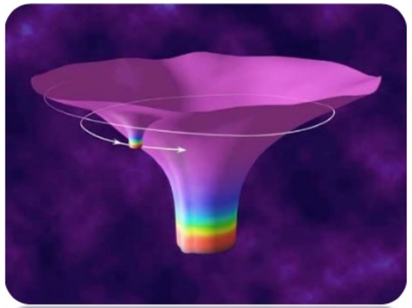
(and can other theories of gravity, boson-stars, grava-stars etc. be excluded ?)





$$\left(\frac{q}{M}\right) = -\left[(a')^2 + \varepsilon\right] \quad \text{(no hair)}$$

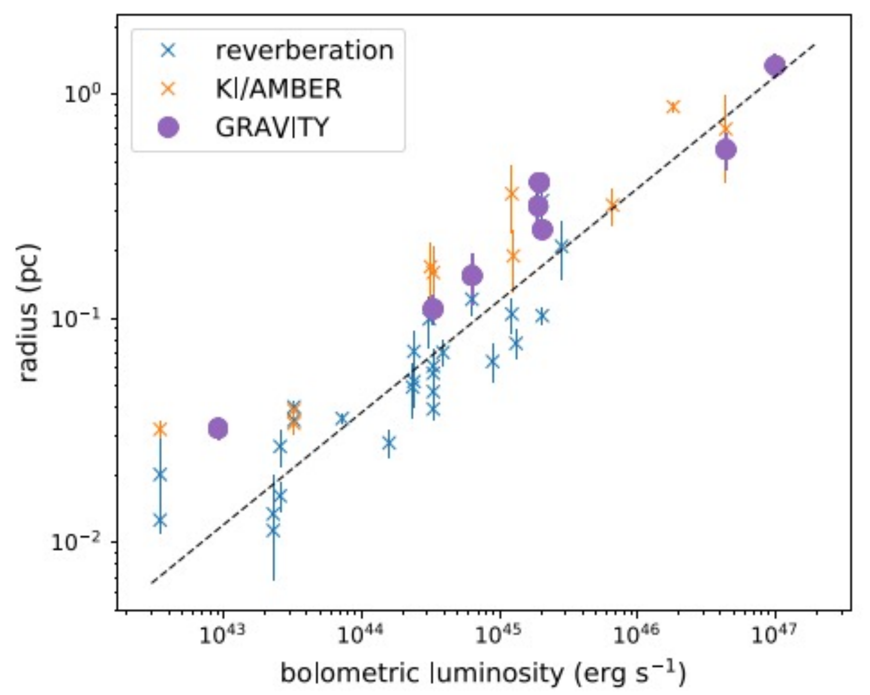
object	measurement	limit on ε
AGN	Kα line width/reverberation	a few
GW150914	in-spiral/ring down	0.4-0.7
SgrA*	GRAVITY hot spots near ISCO	1
SgrA*	**EHT ring & mass from stars**	**0.5**
SgrA*	**GRAVITY faint star R~10mas**	**0.3**
SgrA*	**GRAVITY & EHT**	**0.1**
SgrA*	**pulsar in central 10 mas**	**0.1**
SgrA*	**MICADO spectroscopy**	**0.05**
distant MBH	**LISA EMR in-spiral**	**0.01**



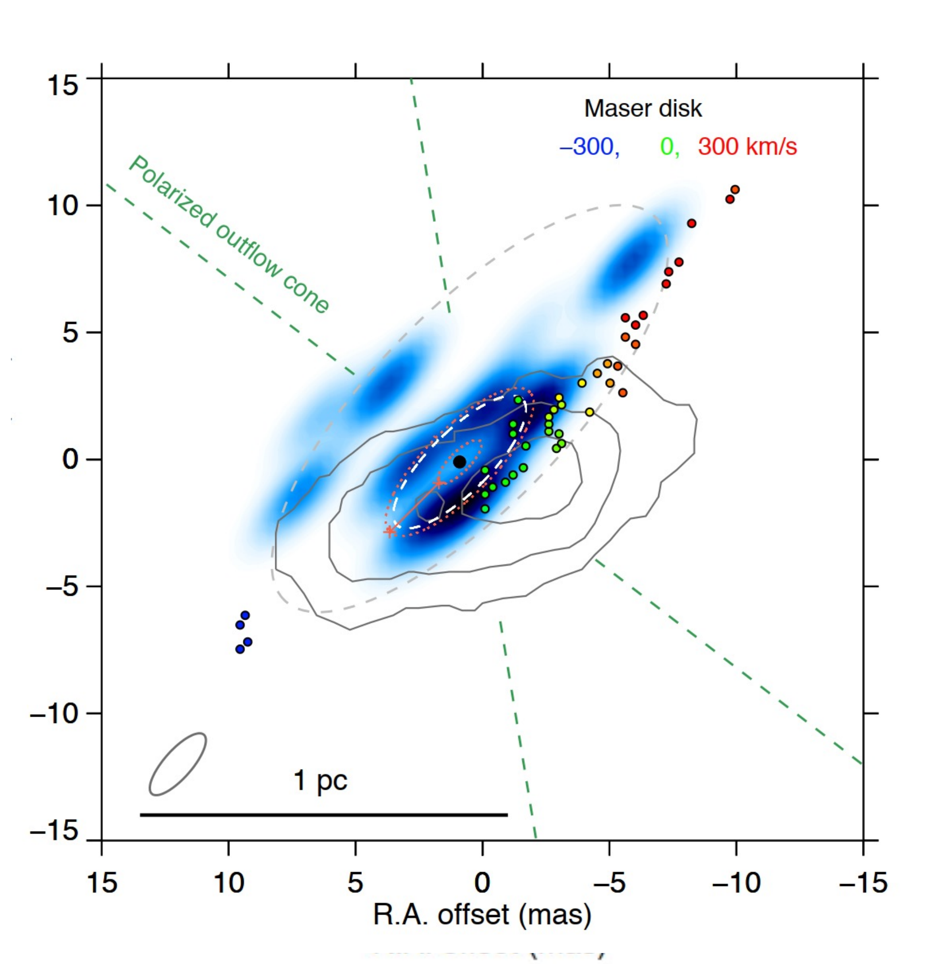
Johannsen & Psaltis 2010 a,b, Will 2014, Johannsen 2016, Psaltis, Wex & Kramer 2016, Johannsen et al. 2016, Zhang et al. 2015, Waisberg et al. 2018 , GRAVITY collaboration et al. 2018c, EHT collaboration et al. 2019, Cardoso & Pani 2019

Active Galactic Nuclei – Imaging NGC 1068

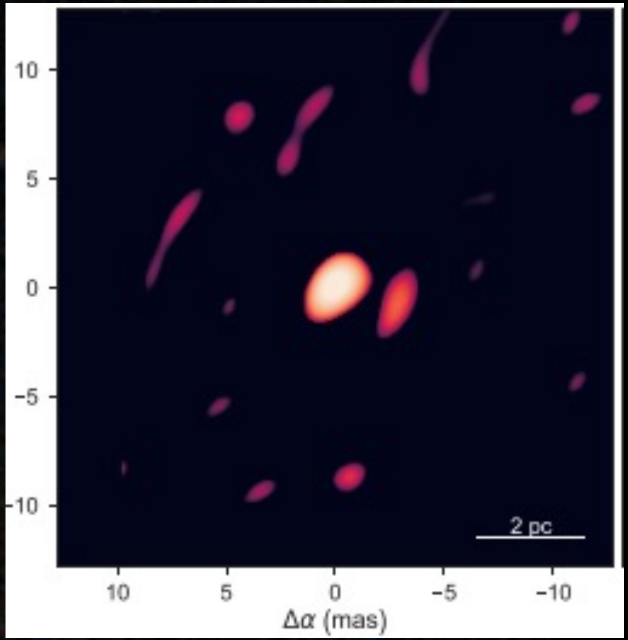
Size-Luminosity Relation



Thin Ring aligned with Maser Disc



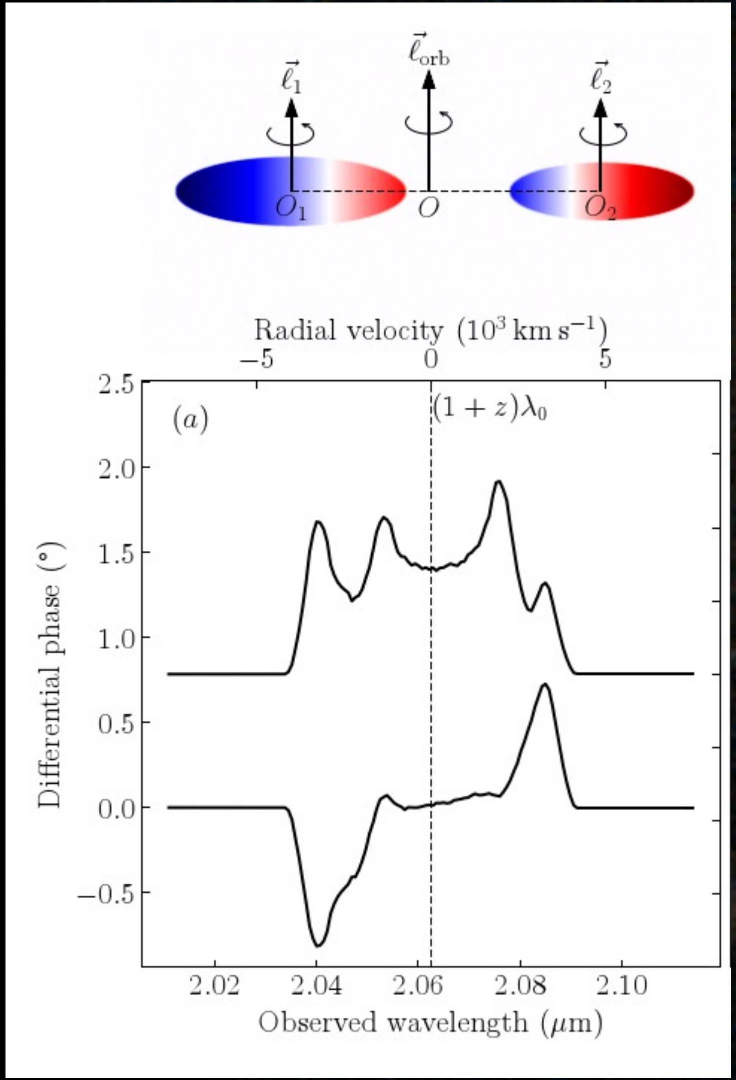
and NGC3783



GRAVITY collaboration+ 20+, subm.

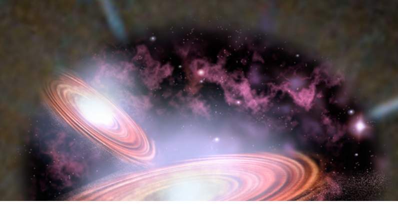
Supermassive Binary Black Holes – Final Parsec Problem

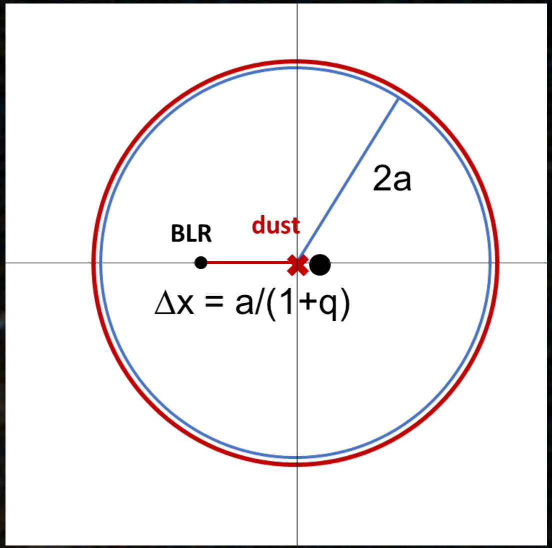
Dual Broad Line Region

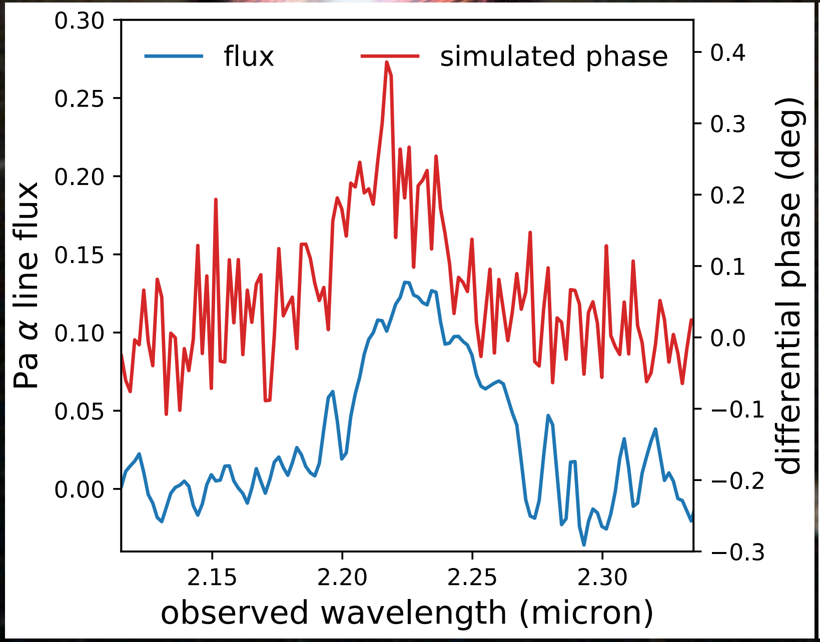


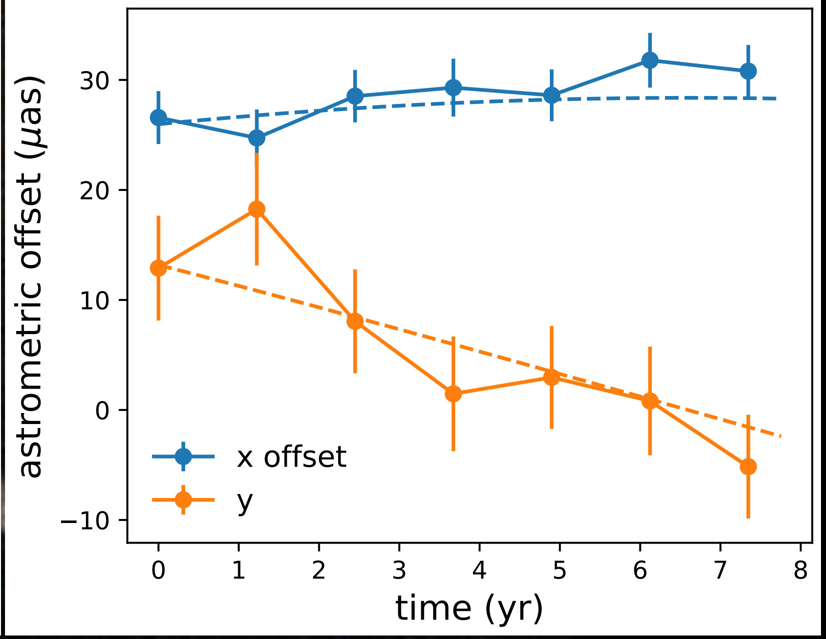
Songsheng+ 19

Single Broad Line Region









Dexter+ 20