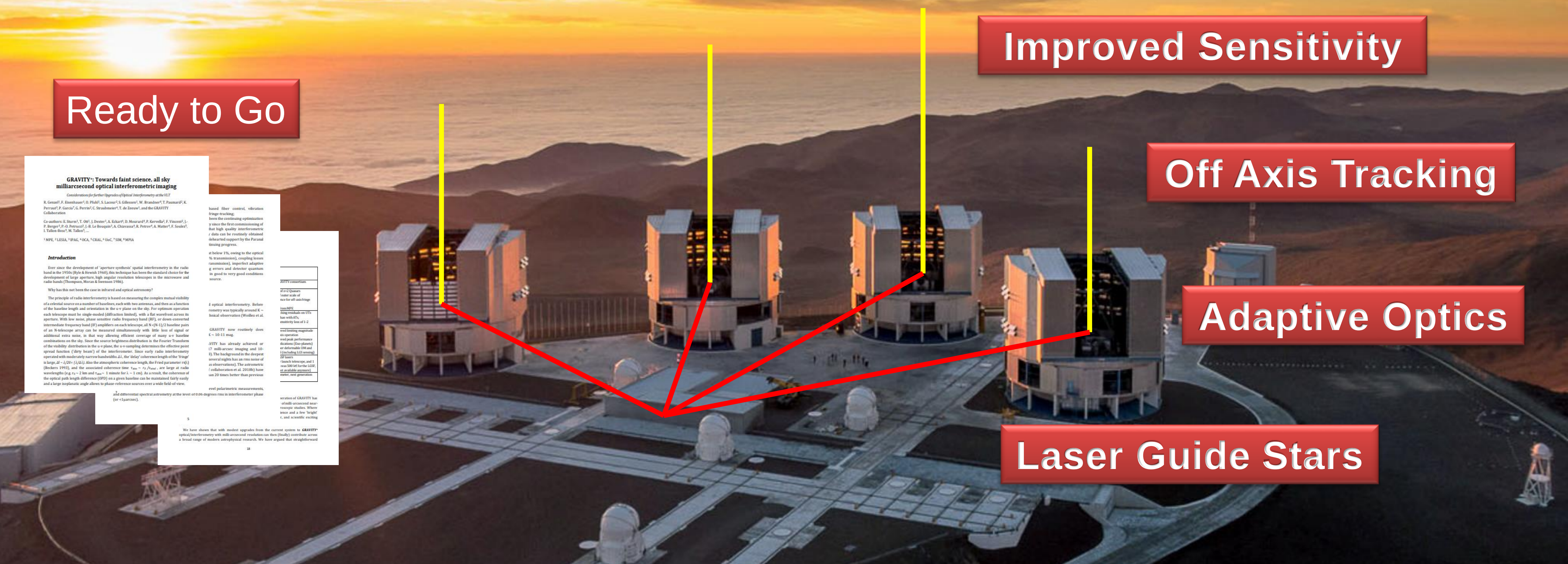
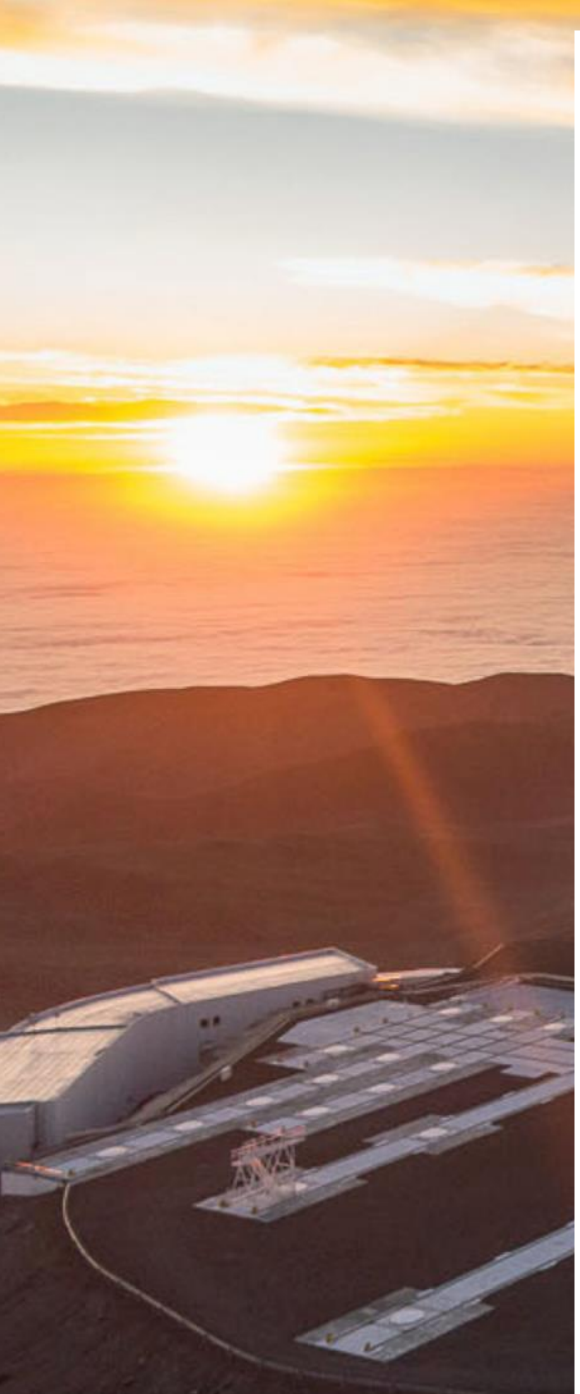
GRAVITY+ : Towards faint science, all sky milliarcsec optical interferometric imaging



Considerations for the Future of Optical Interferometry at the VLT

Credit: ESO, Huedepohl



GRAVITY+: Towards faint science, all sky milliarcsecond optical interferometric imaging

Considerations for further Upgrades of Optical Interferometry at the VLT

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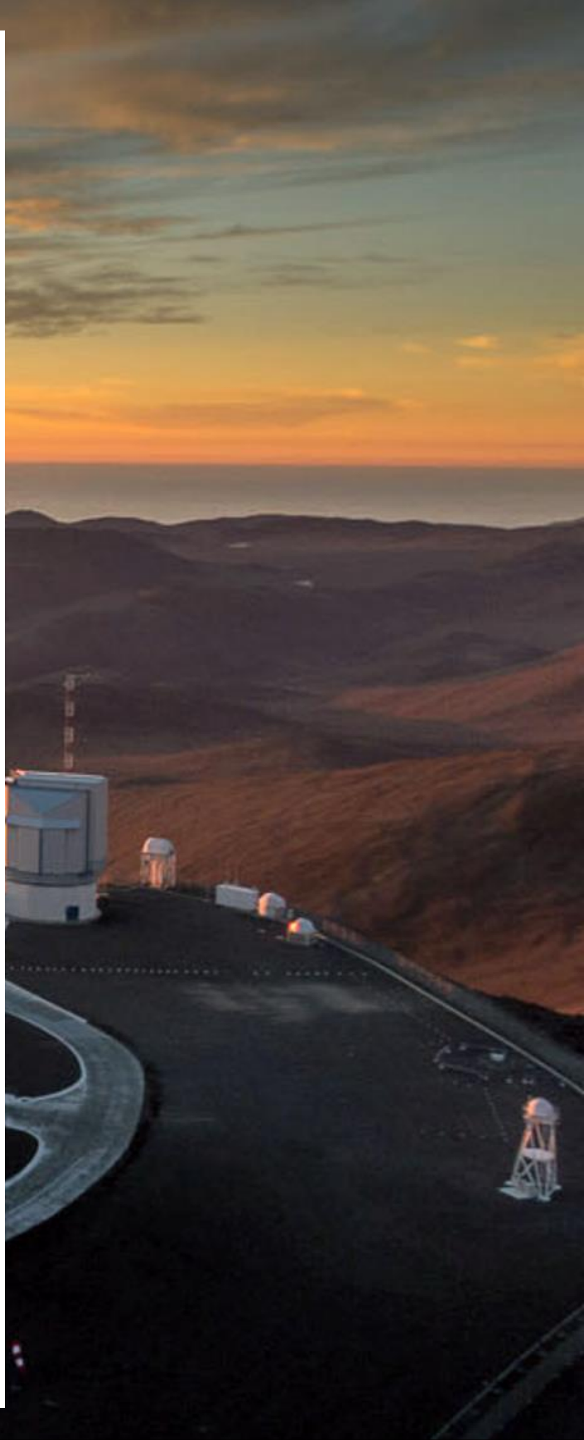
[1] MPE, [2] LESIA, [3] IPAG, [4] OCA, [5] CRAL, [6] UoC, [7] SIM, [8] MPIA, [9] UoE, [10] MPIfR, [11] UoS

Executive Summary

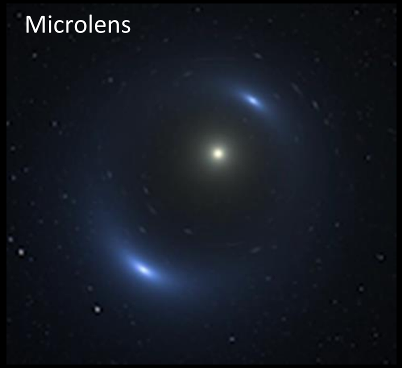
GRAVITY and the VLTI have **transformed** optical interferometry with groundbreaking results on the Galactic Center, Active Galactic Nuclei, and Exoplanets. With modest upgrades to ***GRAVITY+***, the Paranal Observatory will open up the **extragalactic sky** for milliarcsecond resolution interferometric imaging, and give access to **galactic** targets as **faint** as 22 mag. *GRAVITY+* will measure the **black hole masses** of active galactic nuclei **across cosmic times**, establish whether globular clusters harbor **intermediate mass black holes**, and obtain high quality **exo-planet** spectra and orbits. The estimated cost of 13 Mio. € for the upgrade of GRAVITY to ***GRAVITY+*** with off-axis fringe tracking, improved sensitivity, and laser-guide star adaptive optics is relatively modest, and can be divided up into **several phases**. On behalf of a **rapidly growing community**, we propose to conduct in the near future a more detailed study of the feasibility of ***GRAVITY+***, with a goal of implementation in the early 2020s. Most of the upgrades will be **beneficial to all VLTI instruments.**

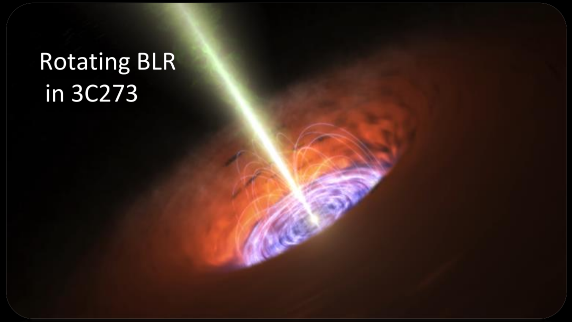


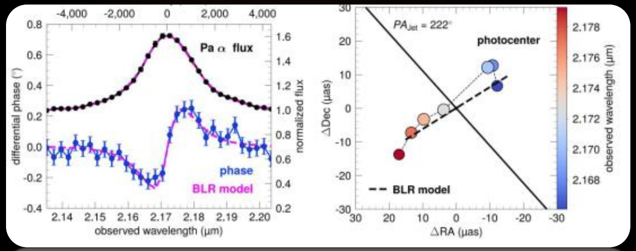
Credit: ESO, Huedepohl

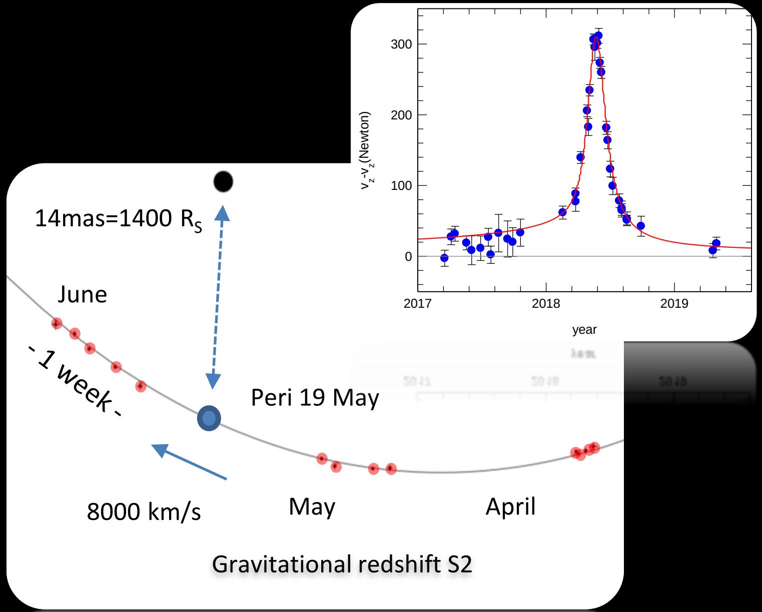
The Harvest of the Last Years

GRAVITY's Firsts



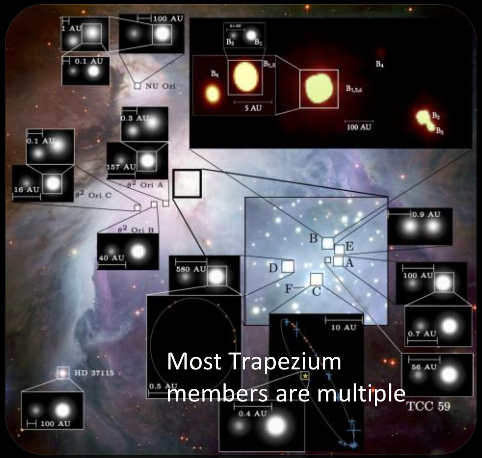


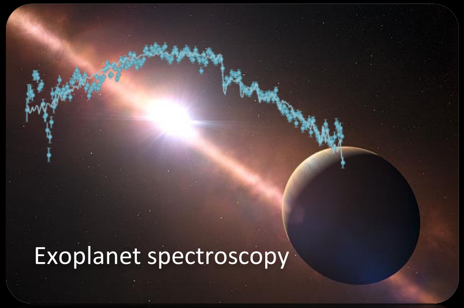




High resolution spectroscopy

19+ mag limiting magnitude & polarimetry





<50 μas imaging astrometry

Micro-arcsec spectral differential astrometry

2 x 4 milli-arcsec resolution imaging

Milliarcsecond Imaging "3D" Spectroscopy of η Carinae

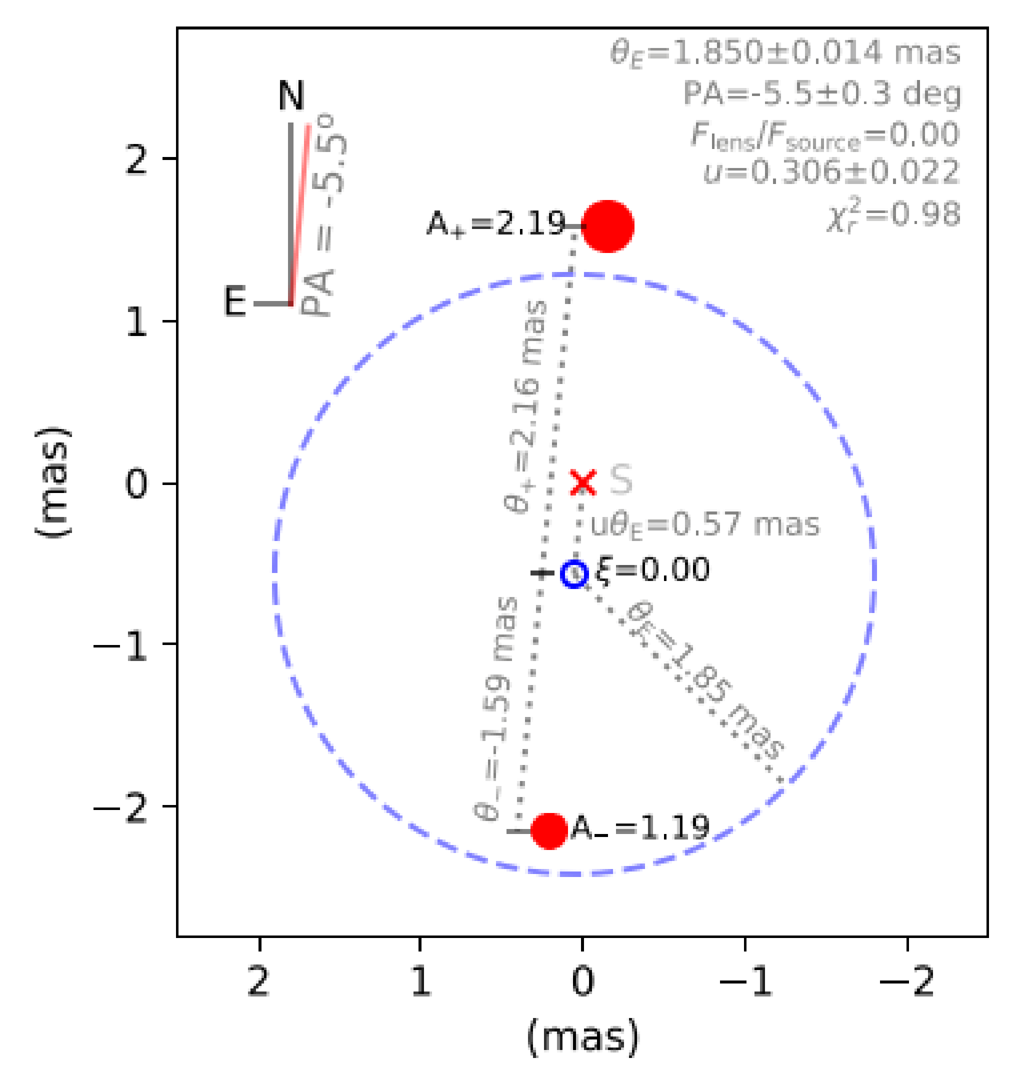
Weigelt+ 16, GRAVITY collaboration+ 18

Hydro dynamic simulations from Madura+13

First Resolution of Microlensed Images

Credit:ESO

$\Theta_E = 1.85 \pm 0.014$ mas

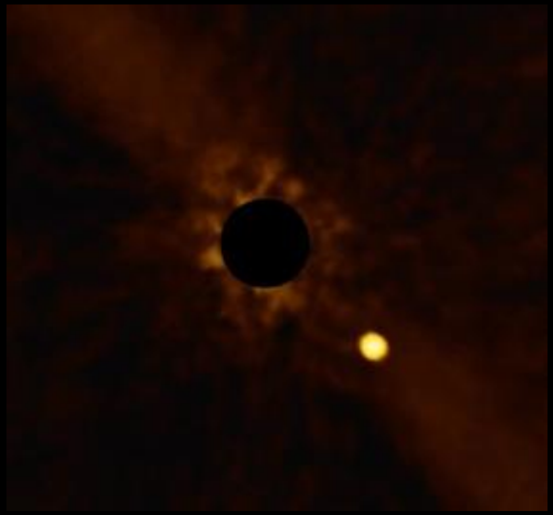


Einstein 1936:

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

Dong, Merand, Delplancke+ 19

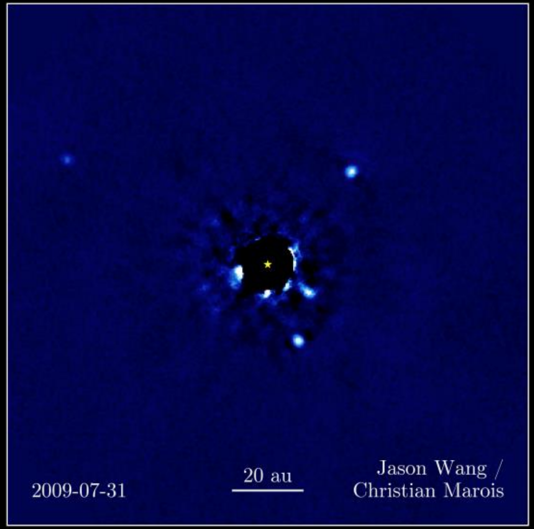
High Resolution Spectra of Exo-Planets



ESO / Lagrange / SPHERE consortium

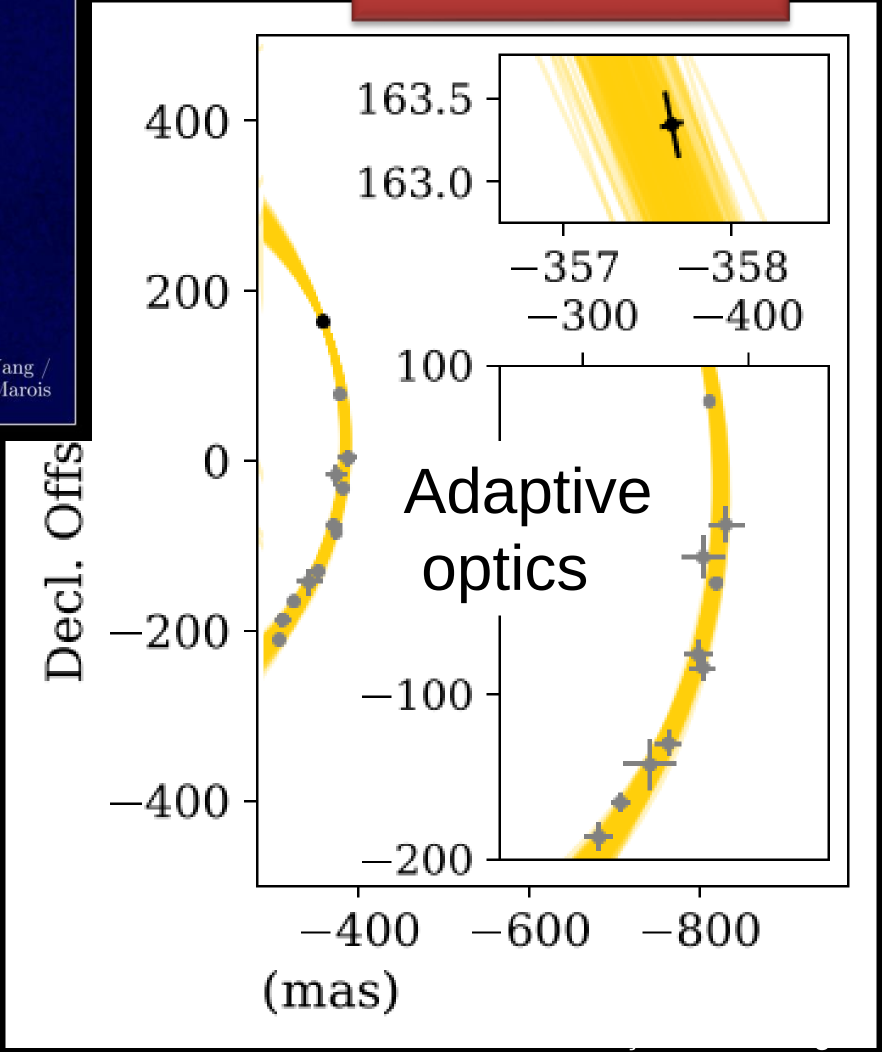
β Pic b

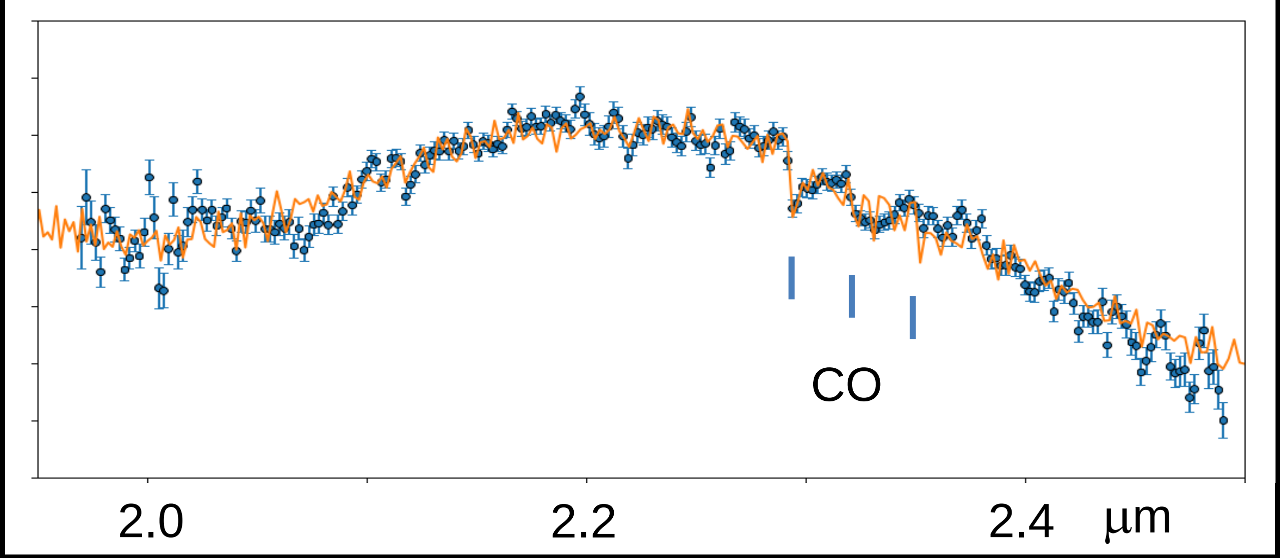
HR 8799 e



GRAVITY

Zoom 100 x





in prep.

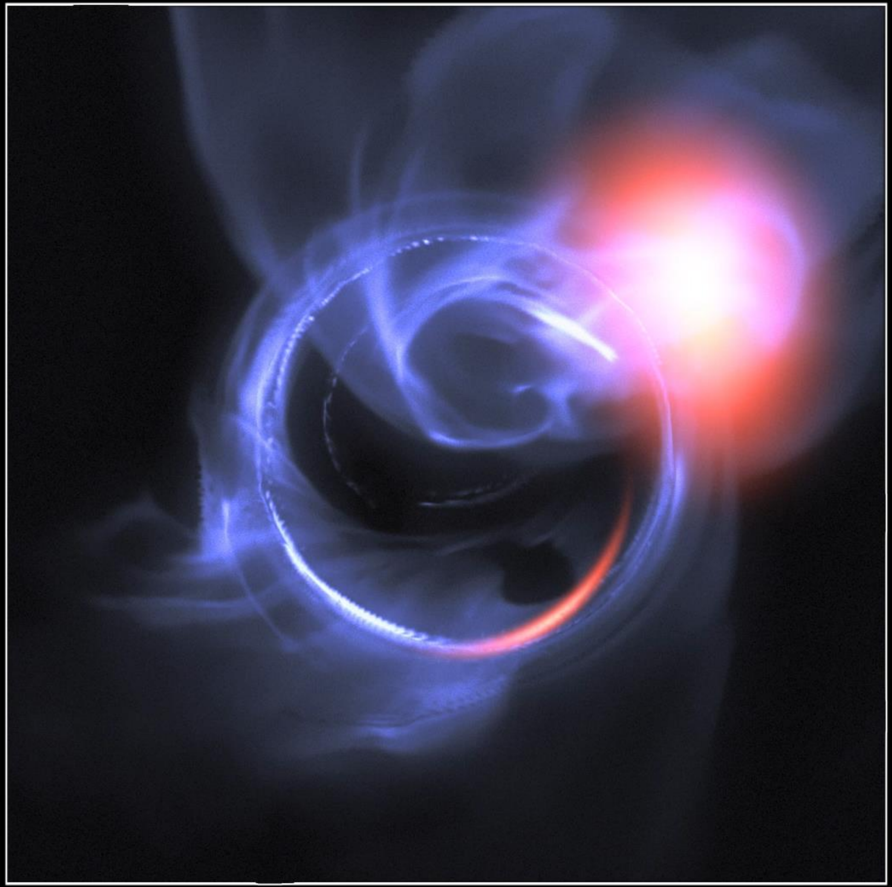
GRAVITY collaboration+ 19

Galactic Center – Black Hole Paradigm

Test of General Relativity

Gravitational redshift
Local position invariance

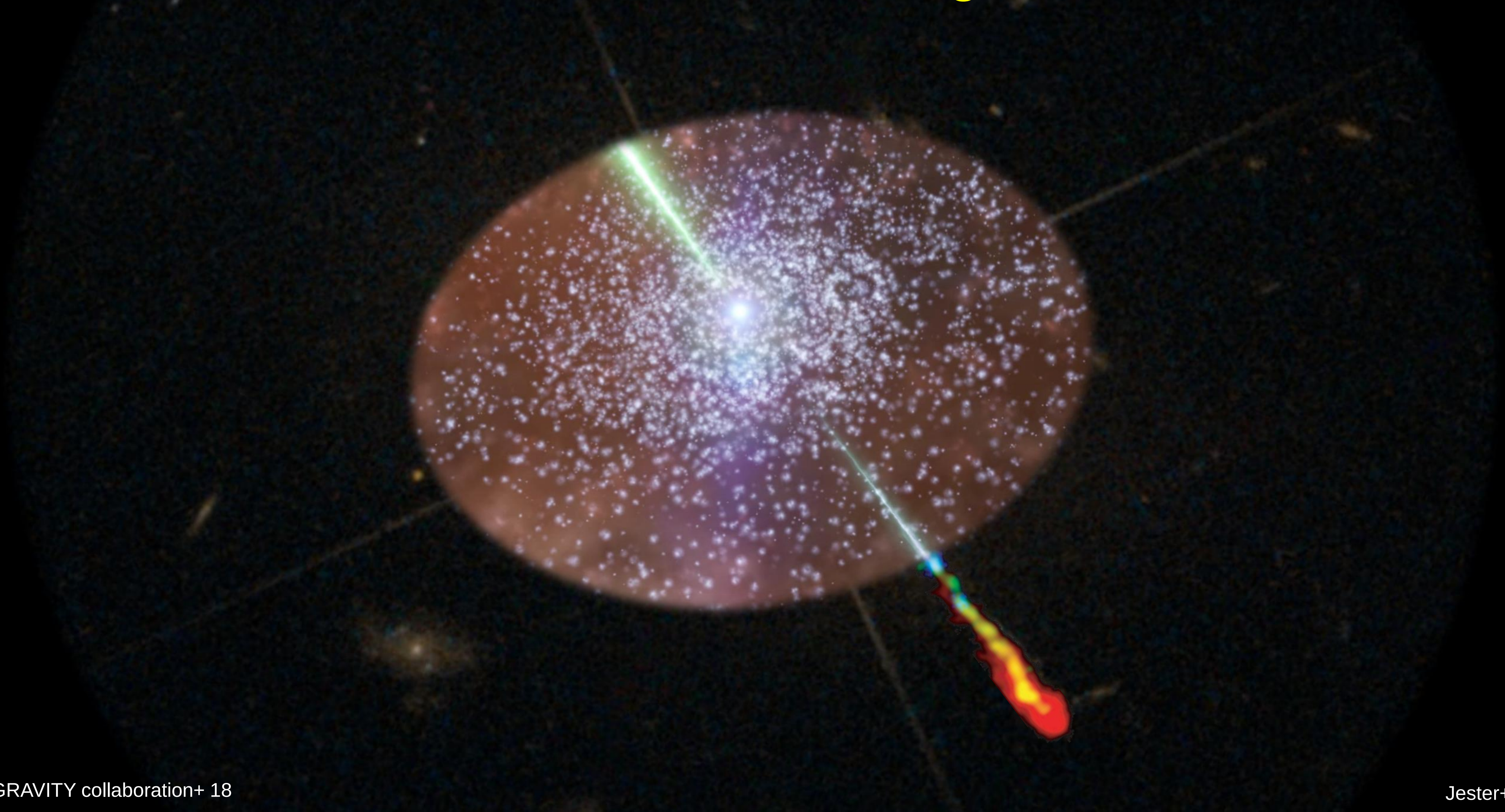
Mass Concentration



Orbiting with 30% the speed of light near the point of no return

GRAVITY collaboration+18a,b,19a,b

Active Galactic Nuclei – Rotating BLR in 3C273

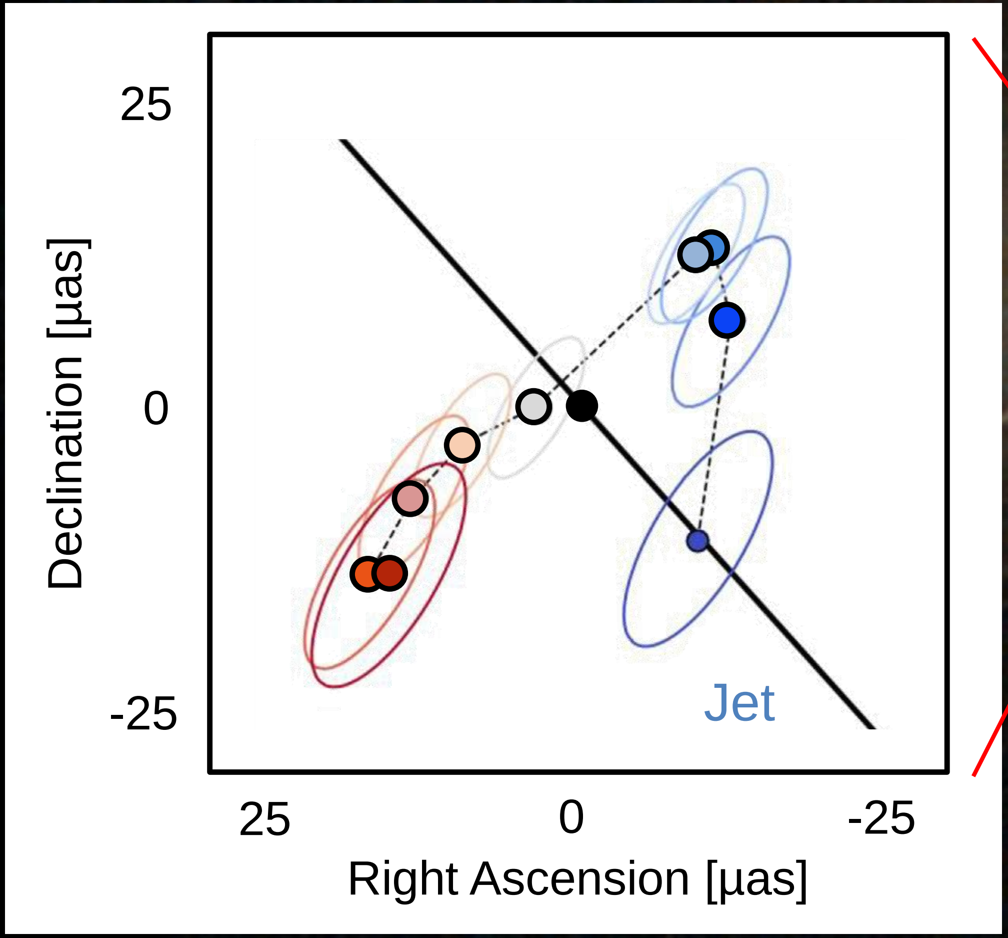


GRAVITY collaboration+ 18

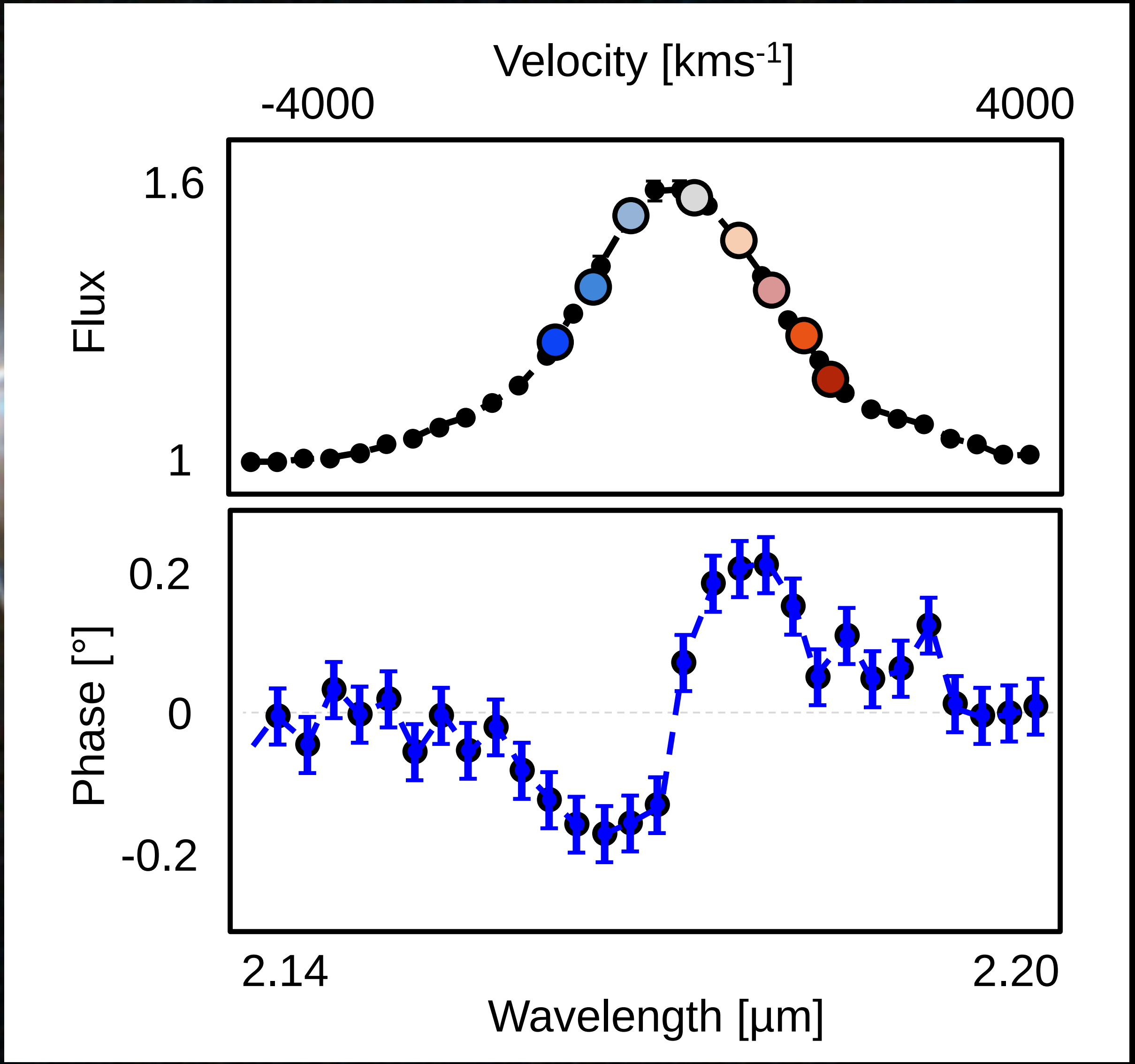
Jester+ 06

Active Galactic Nuclei – Rotating BLR in 3C273

1 µas = 500 AU @ 1.8 Billion ly



Dynamical Mass

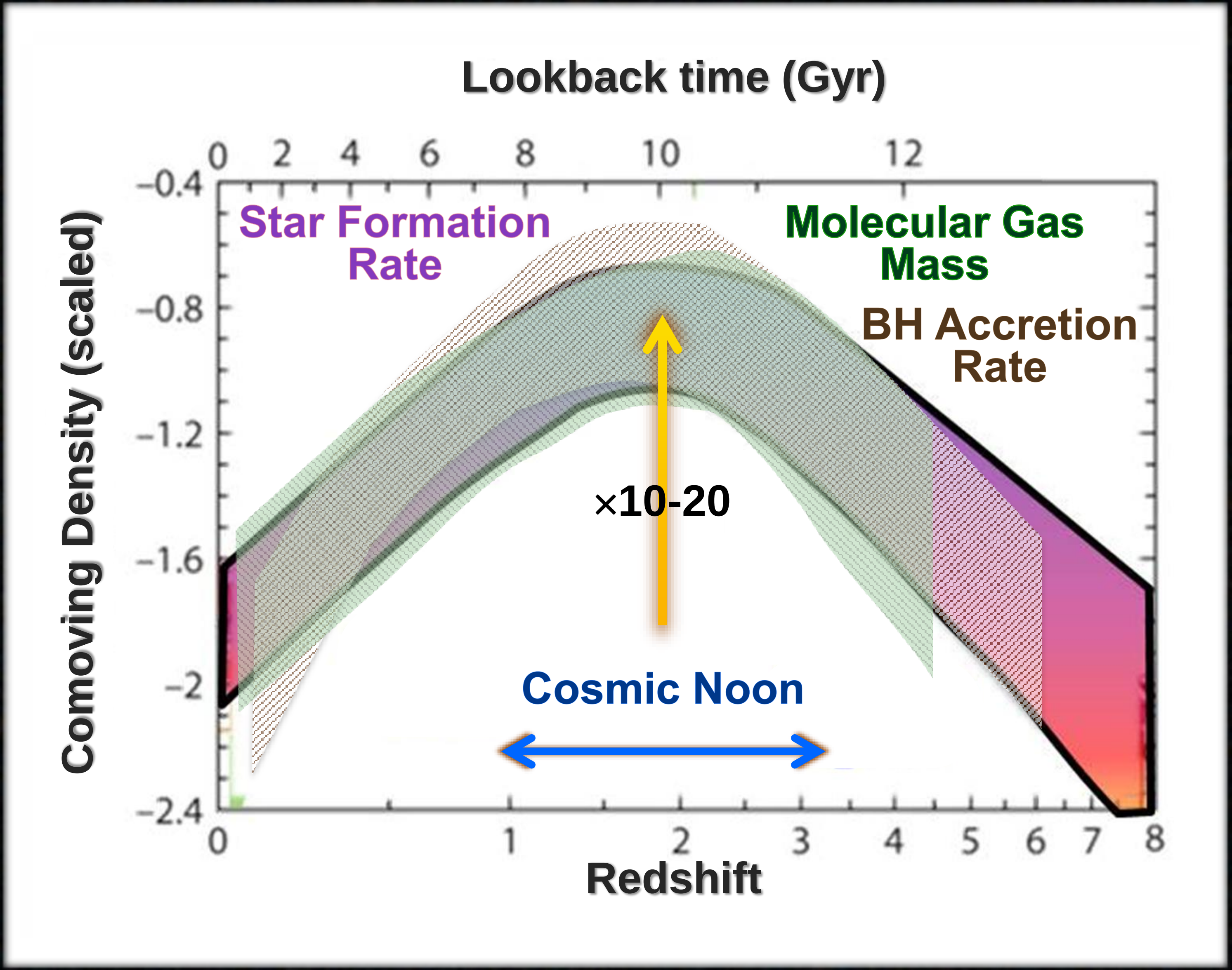


GRAVITY collaboration+ 18

The Future – GRAVITY ➕

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

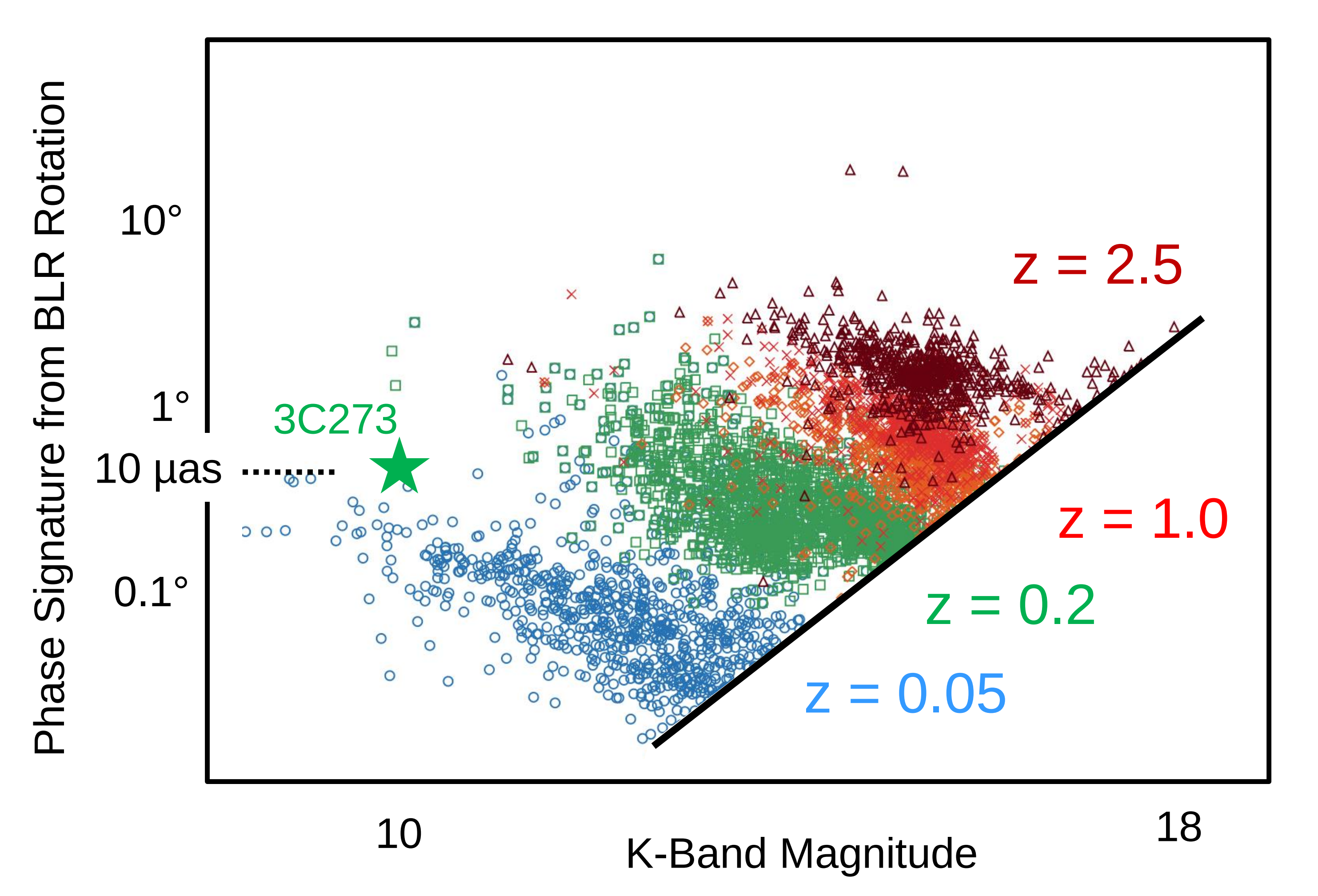
Active Galactic Nuclei – at Cosmic Noon



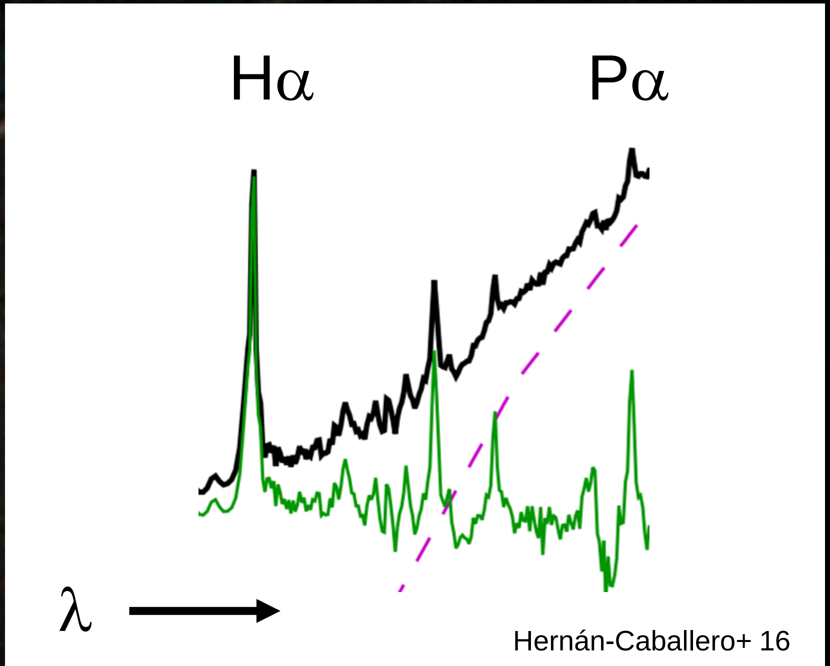
Adapted from Madau & Dickinson 14, Combes 18, Tacconi+ 18

Resolving BLR in Quasars at High-z

No Problem of Astrometric Signature



Ever Larger Line / Continuum Ratio



Resolving BLR in Quasars at High-z

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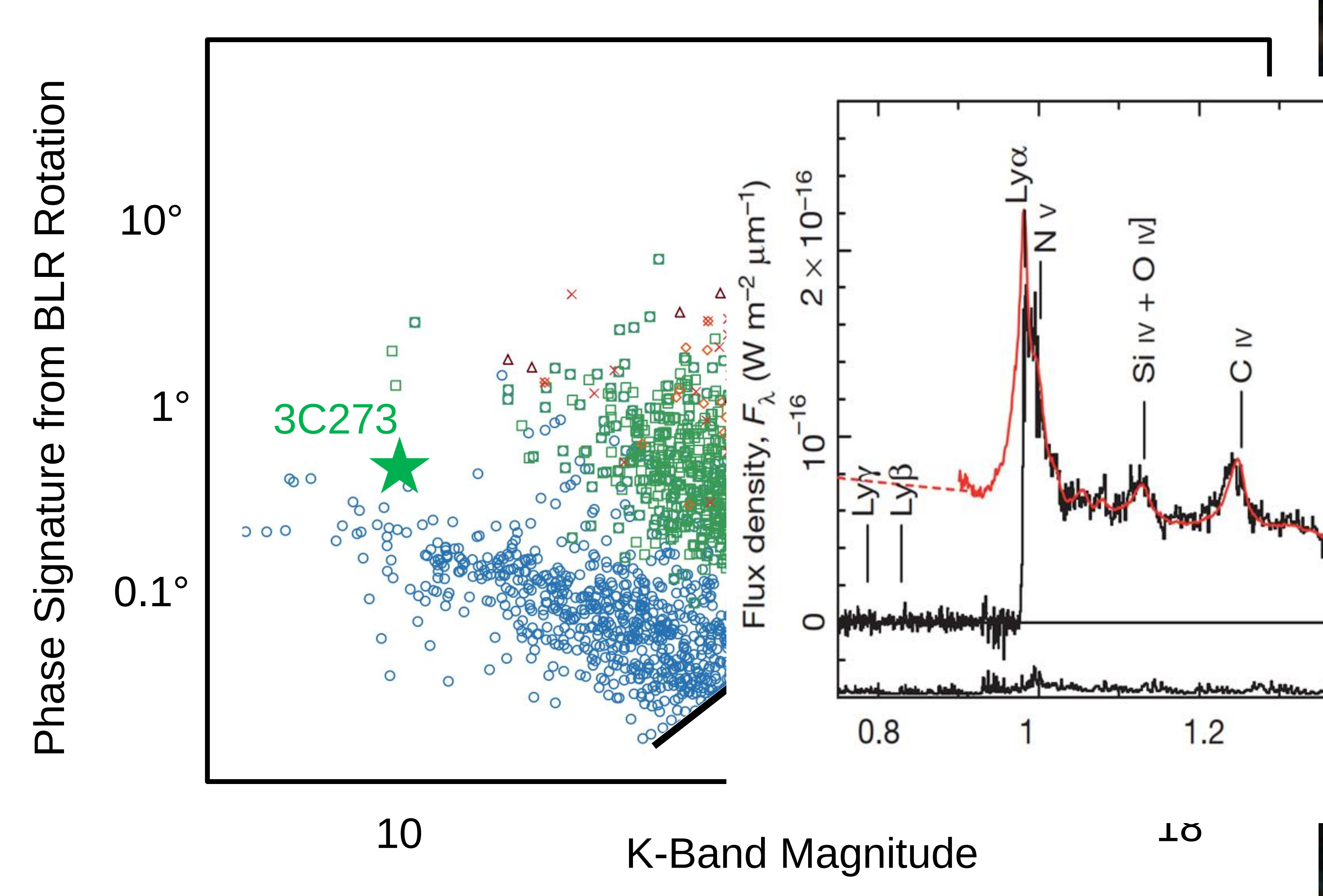
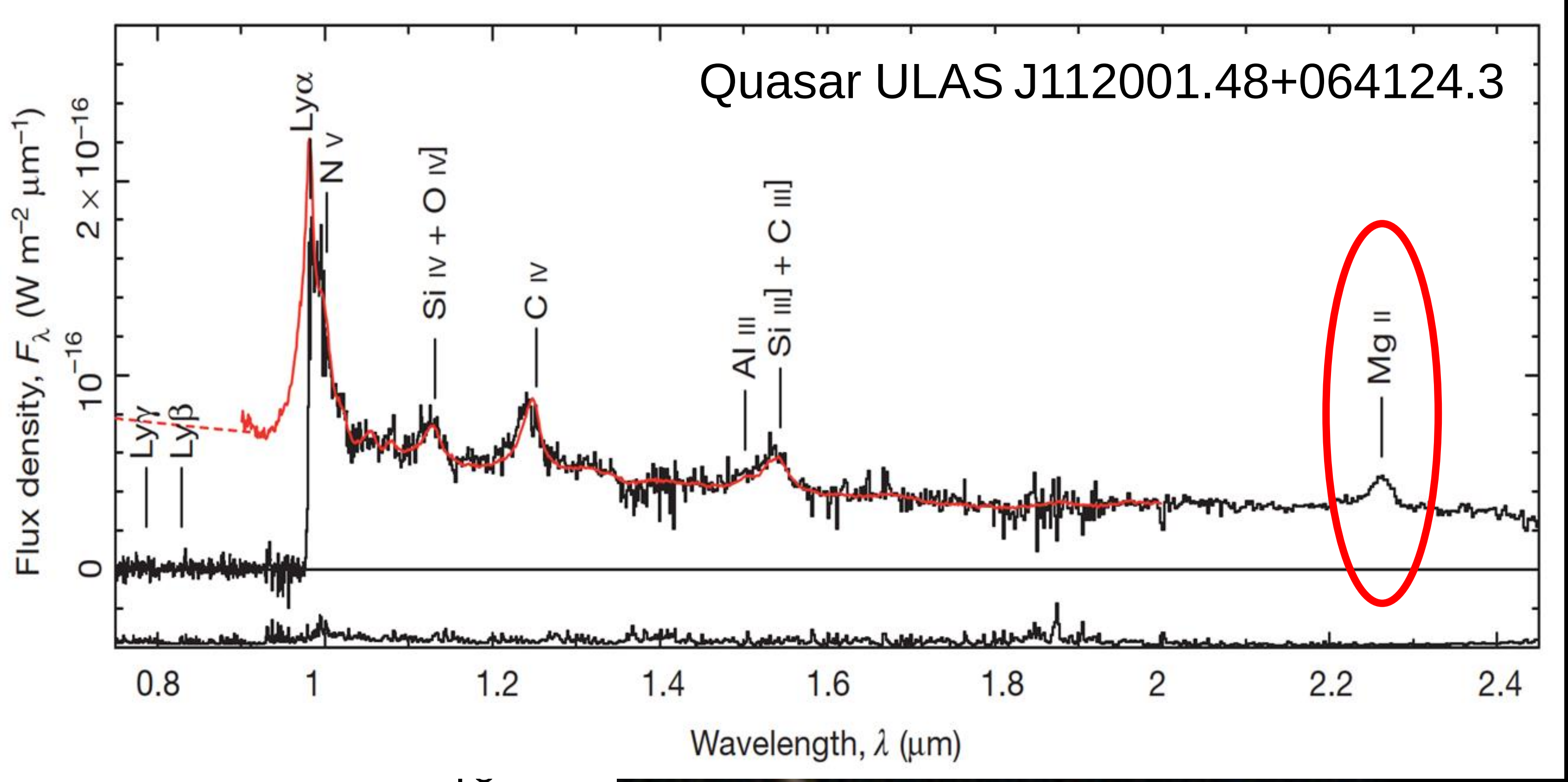


And Even z > 7



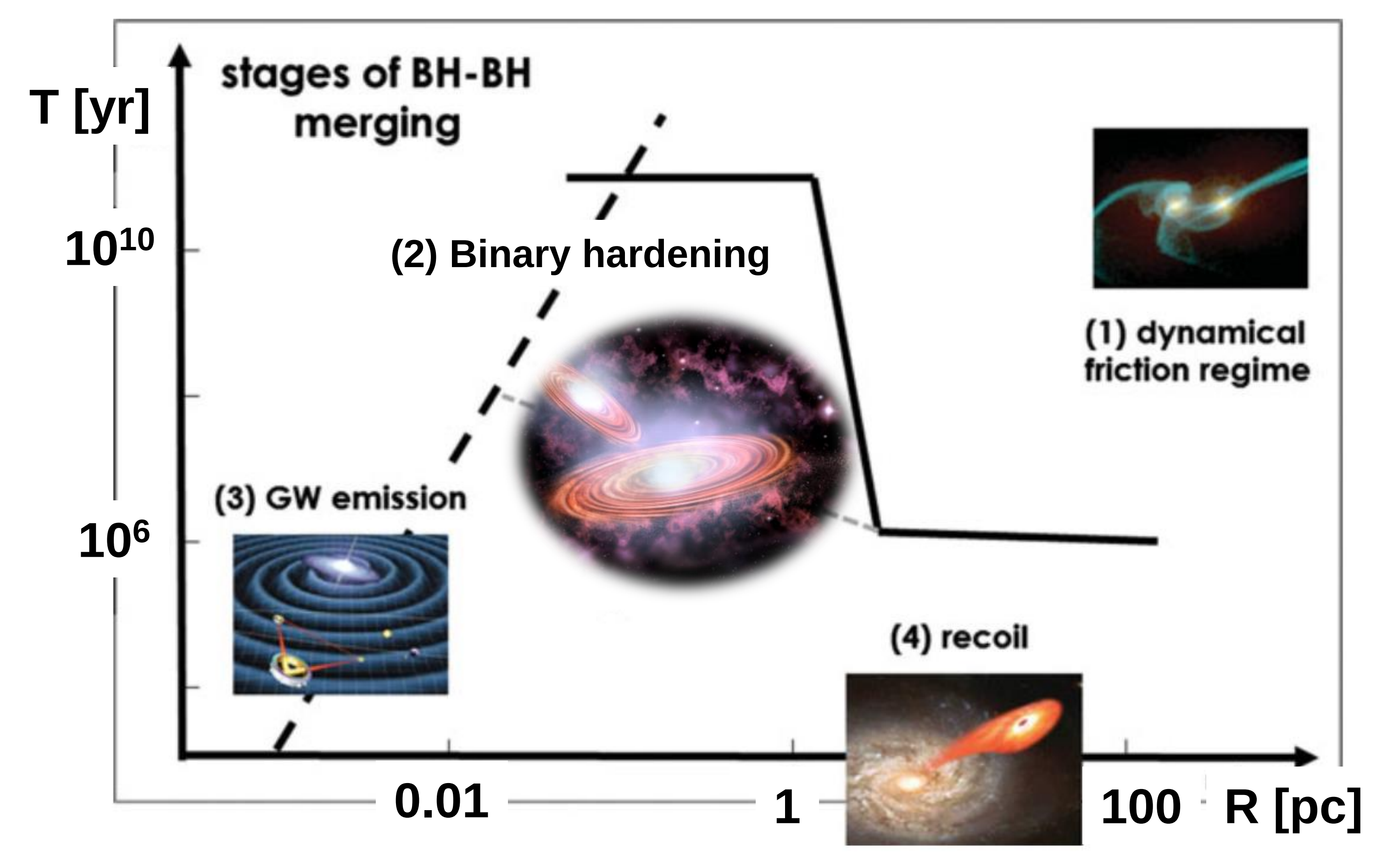
Mortlock+ 2011

Back of the envelope estimate

$R_{BLR} \approx 100$ μas, Signature ≈ 1.5 – 2.5°

K-Band ≈ 17.7 mag

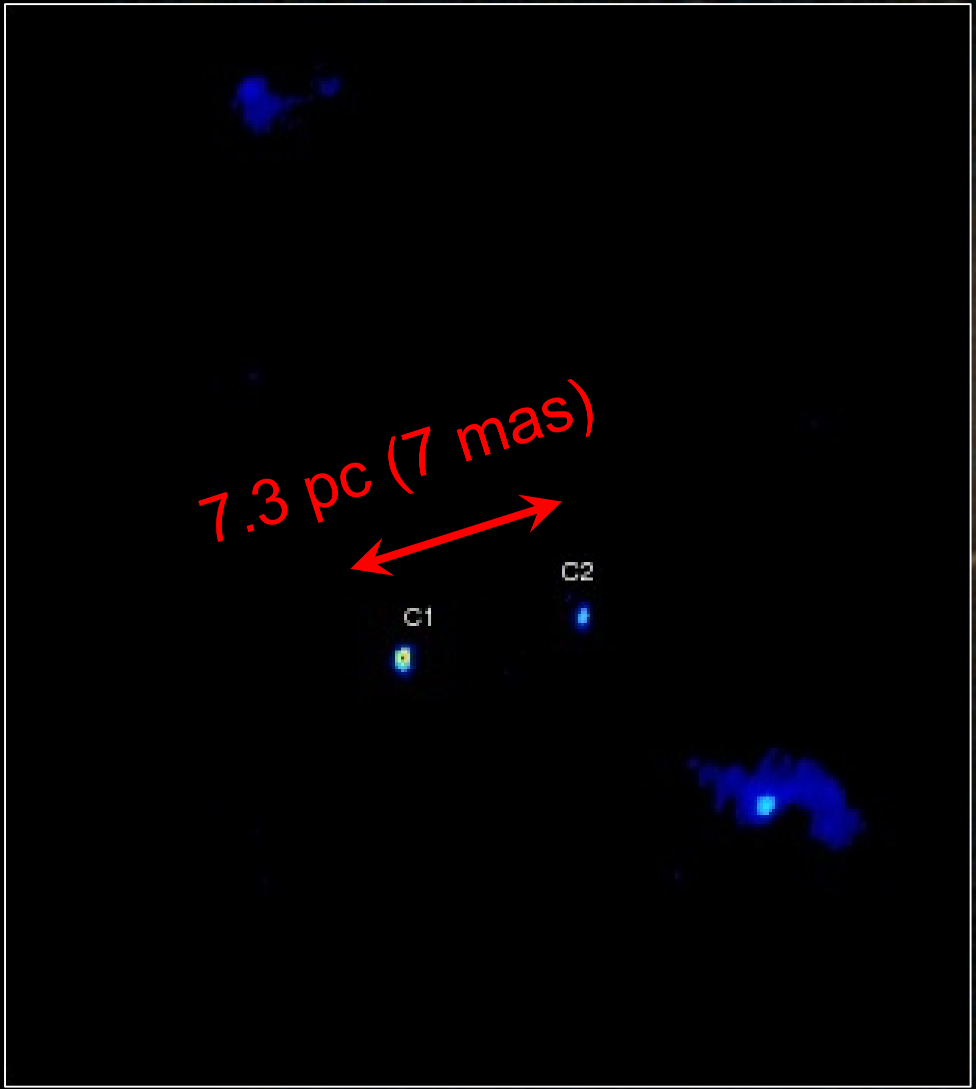
Supermassive Binary Black Holes – Final Parsec Problem



adapted from Komossa+ 16, going back to Begelman, Blandford, Rees 80

Supermassive Binary Black Holes – Final Parsec Problem

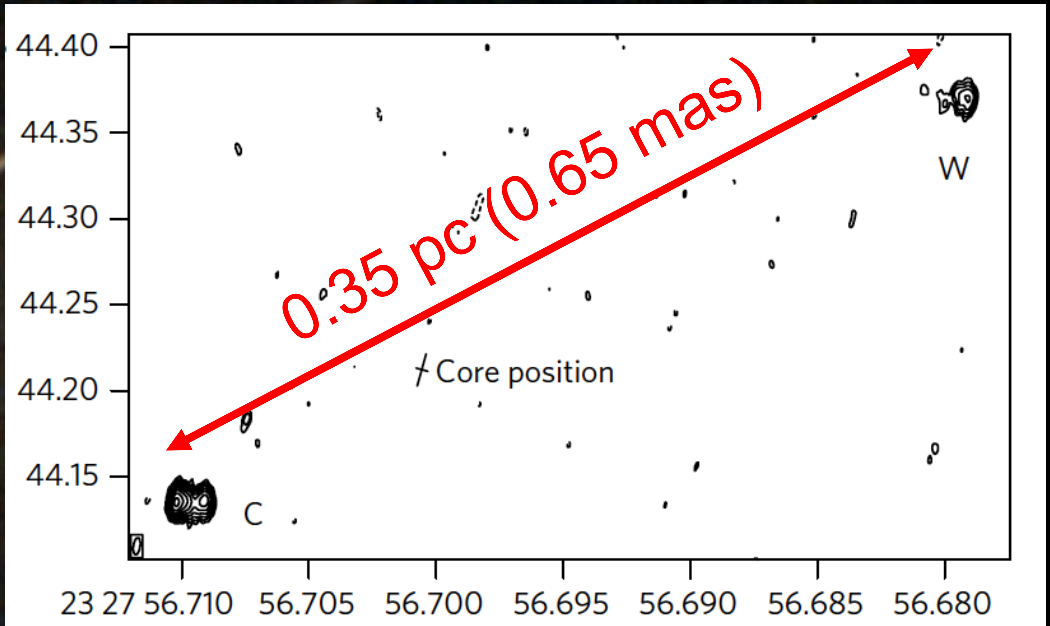
0402+379



Bansal+ 17, NRAO / AUI / NSF

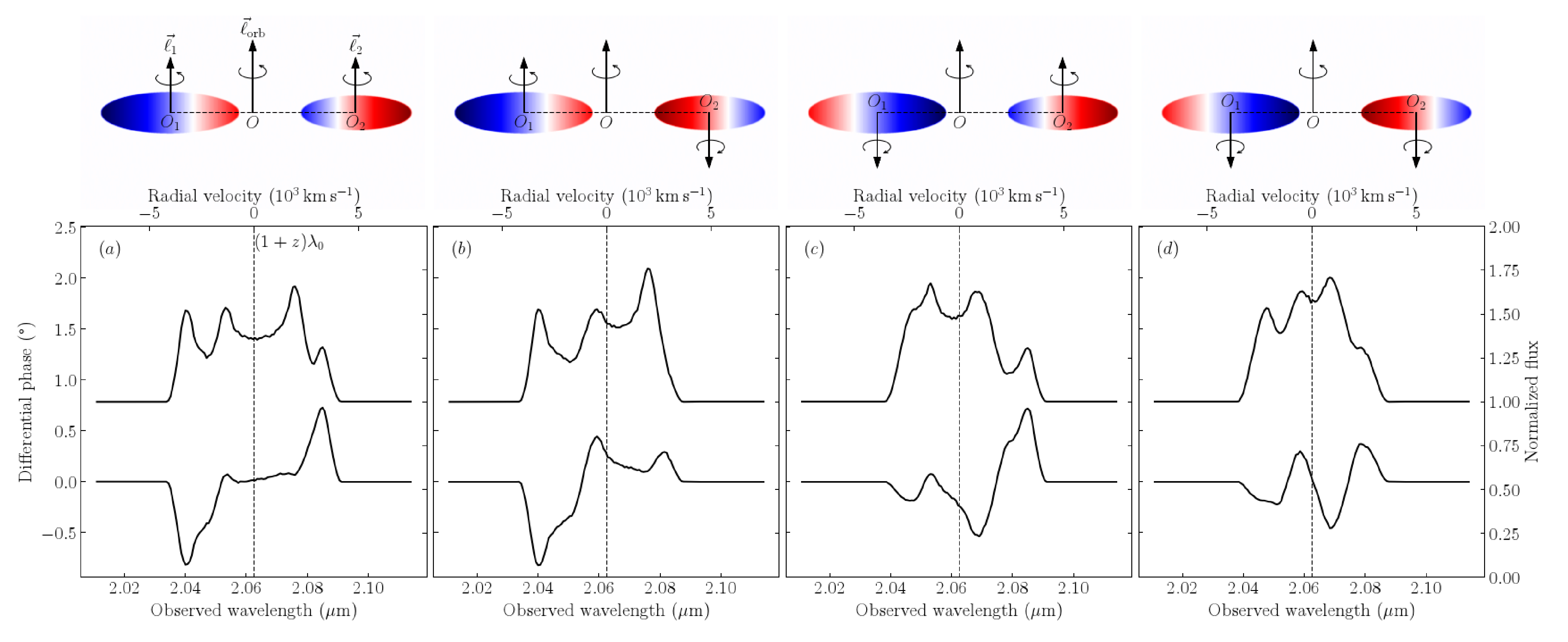
Credit: Marenfeld and NOAO / AURA / NSF

Mrk 533



Kharb+ 17

Supermassive Binary Black Holes – Final Parsec Problem



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

Towards Faint **All Sky** Milli Arcsecond Imaging

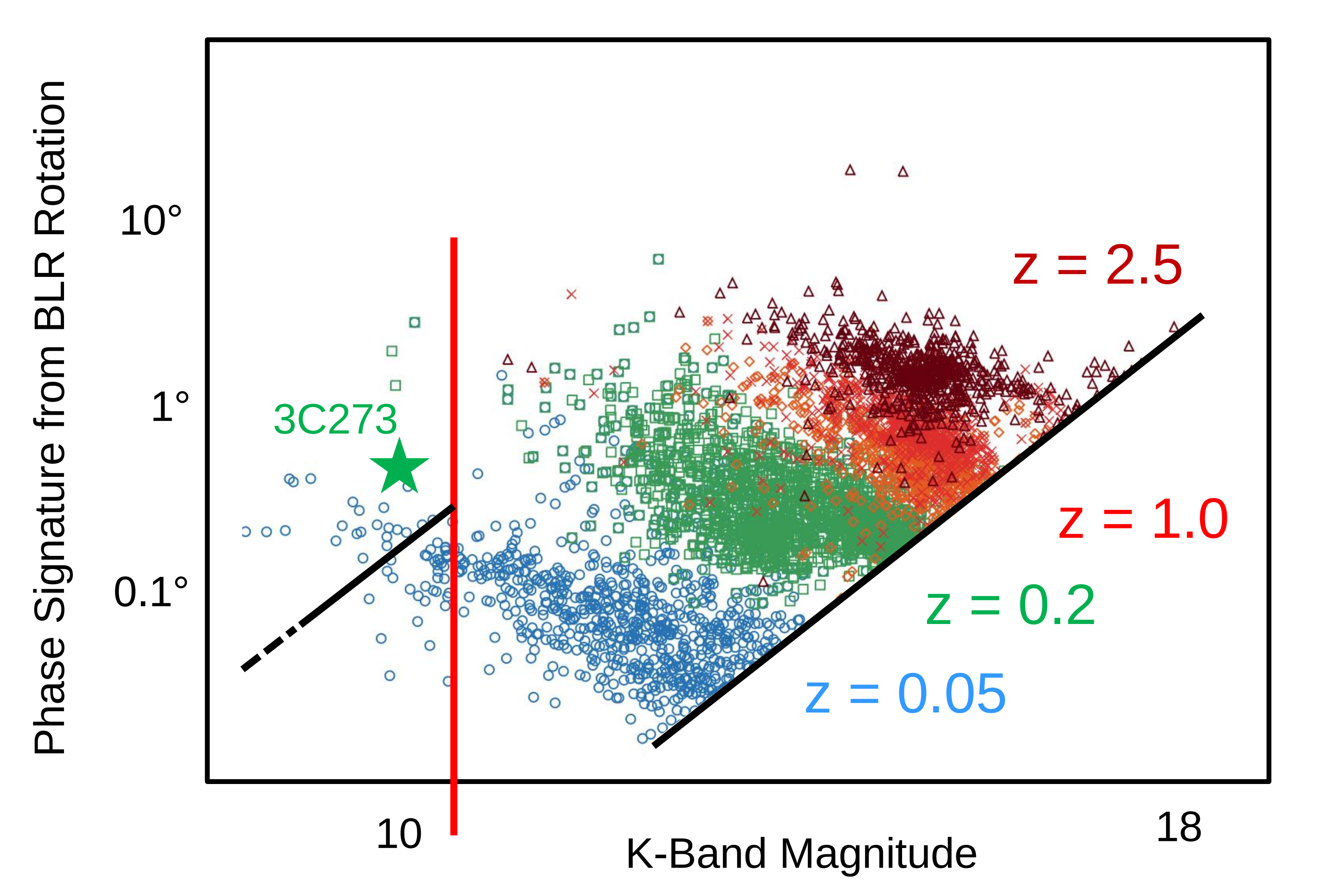
No Problem of Astrometric Signature

Off Axis Fringe Tracking

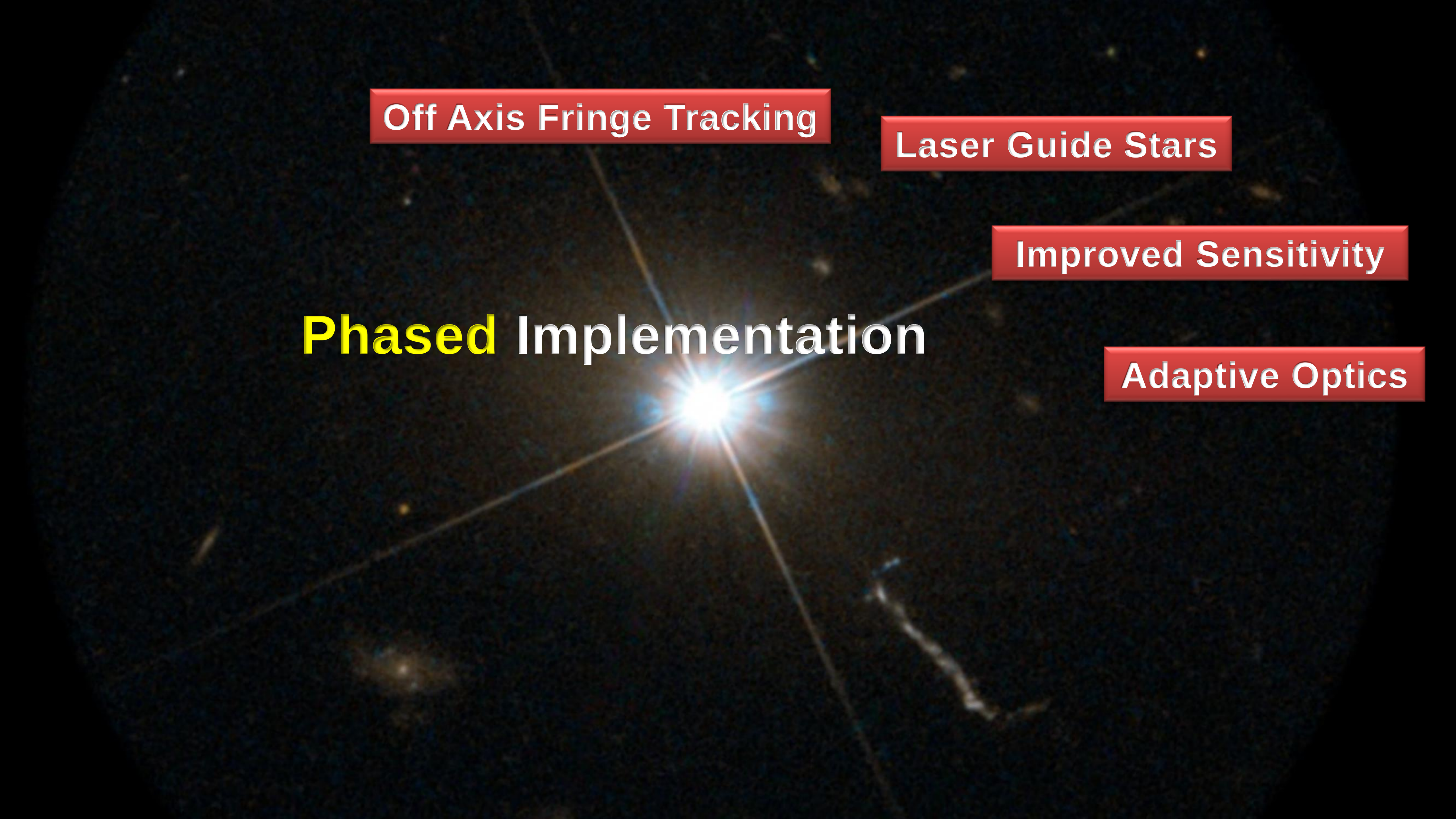
Laser Guide Stars

Improved Sensitivity

Adaptive Optics



Current Fringe Tracking and Sensitivity Limits



Phased Implementation

- Off Axis Fringe Tracking
- Laser Guide Stars
- Improved Sensitivity
- Adaptive Optics

Much Better Grisms and Revolution in IR Detectors

Germanium Grims with Antireflection Coating

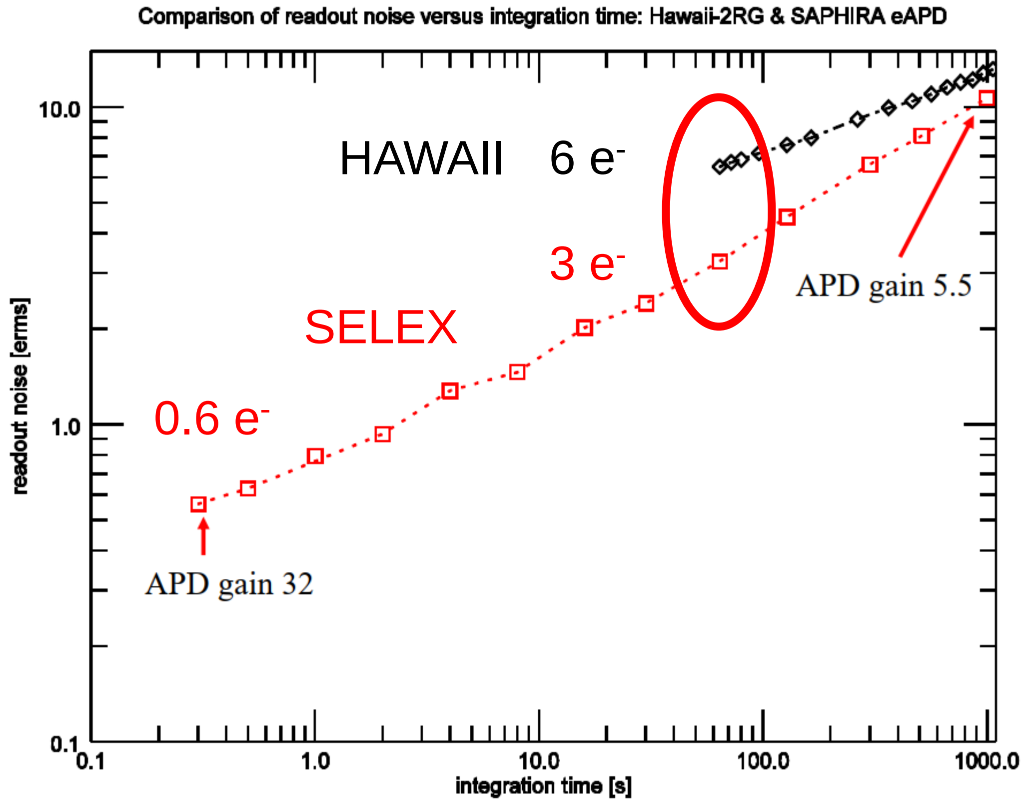
Canon Inc.

Factor 2-3 higher efficiency

Ongoing

Low Dark Current eAPD Detector

Improved Sensitivity



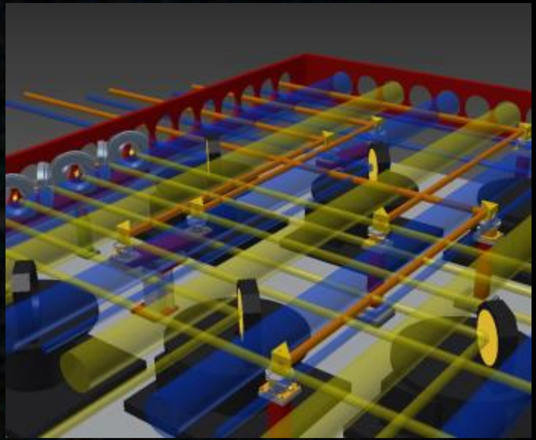
Factor 2 better noise than HAWAII detectors for long exposures

Finger, Baker, Eisenhauer+ 19

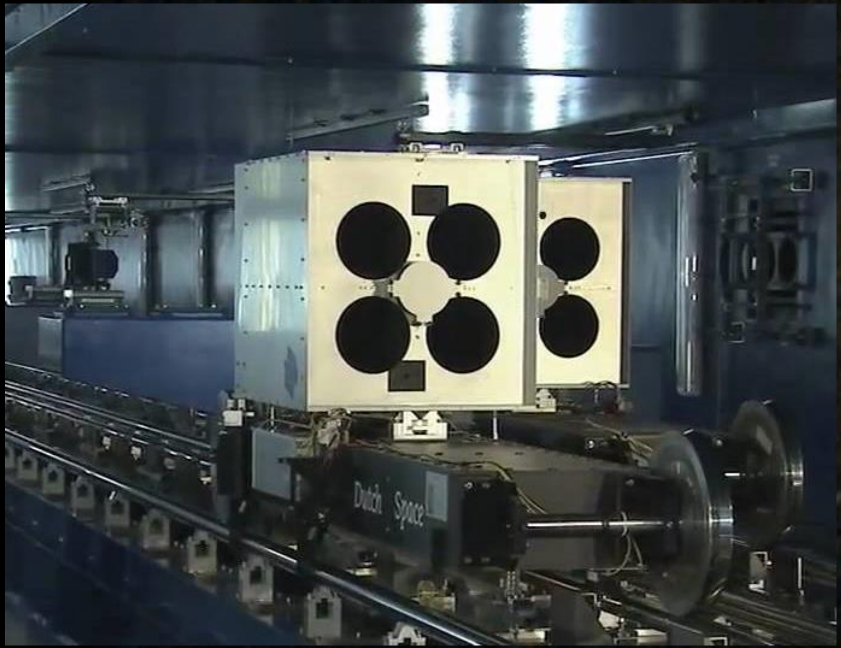
Taking Advantage of Fantastic Unexplored Infrastructure

Off Axis Fringe Tracking

First Test Possible already in 2019/20



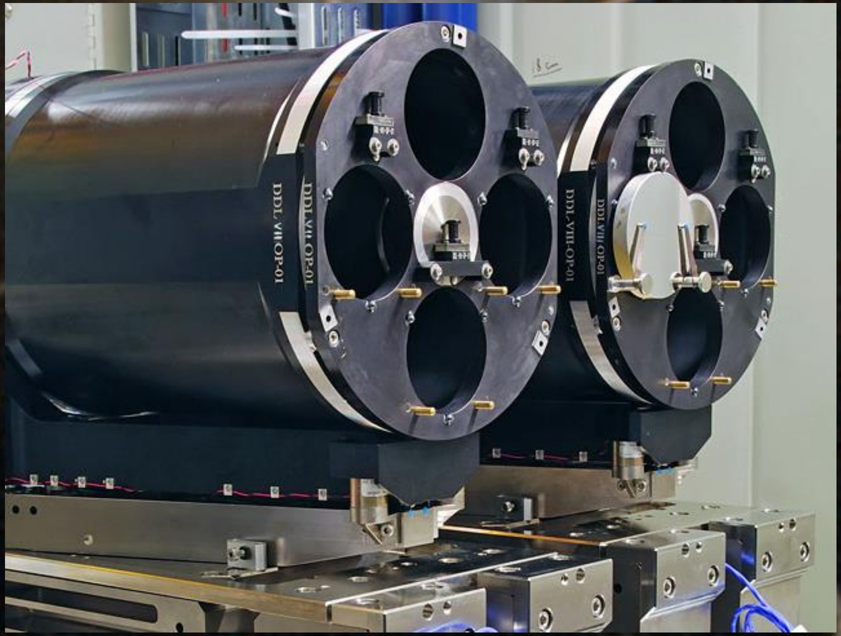
Dual Beam Main Delay Lines



Hogenhuis+ 03

Factor 2 more photons, no splitting of light

Differential Delay Lines



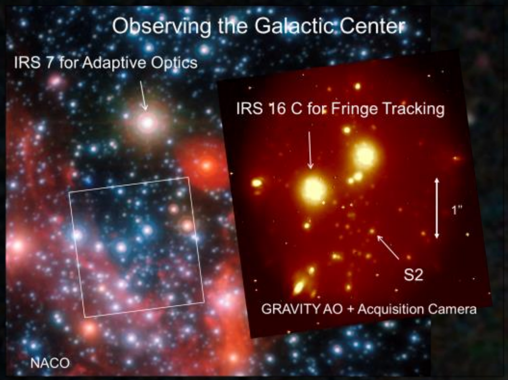
Pepe+ 08

Star Separators

Nijenhuis+ 08

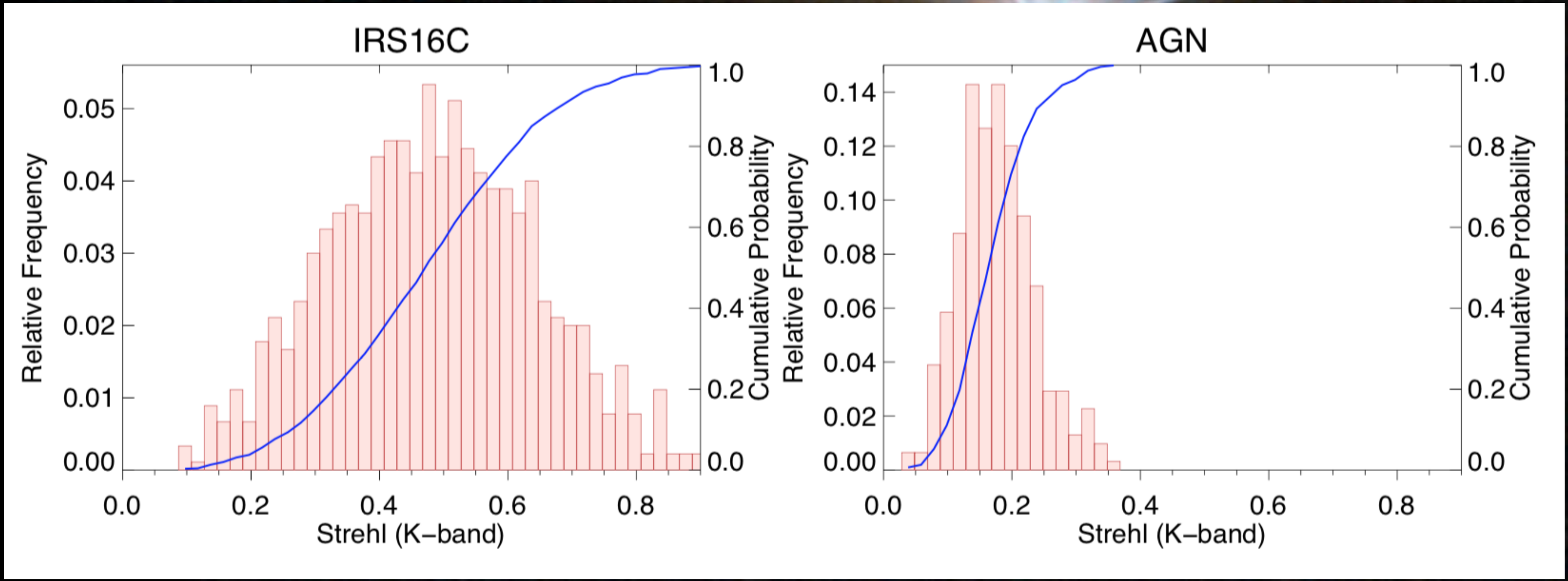
State of the Art Adaptive Optics

Galactic Center



Quasar

Phase A this year



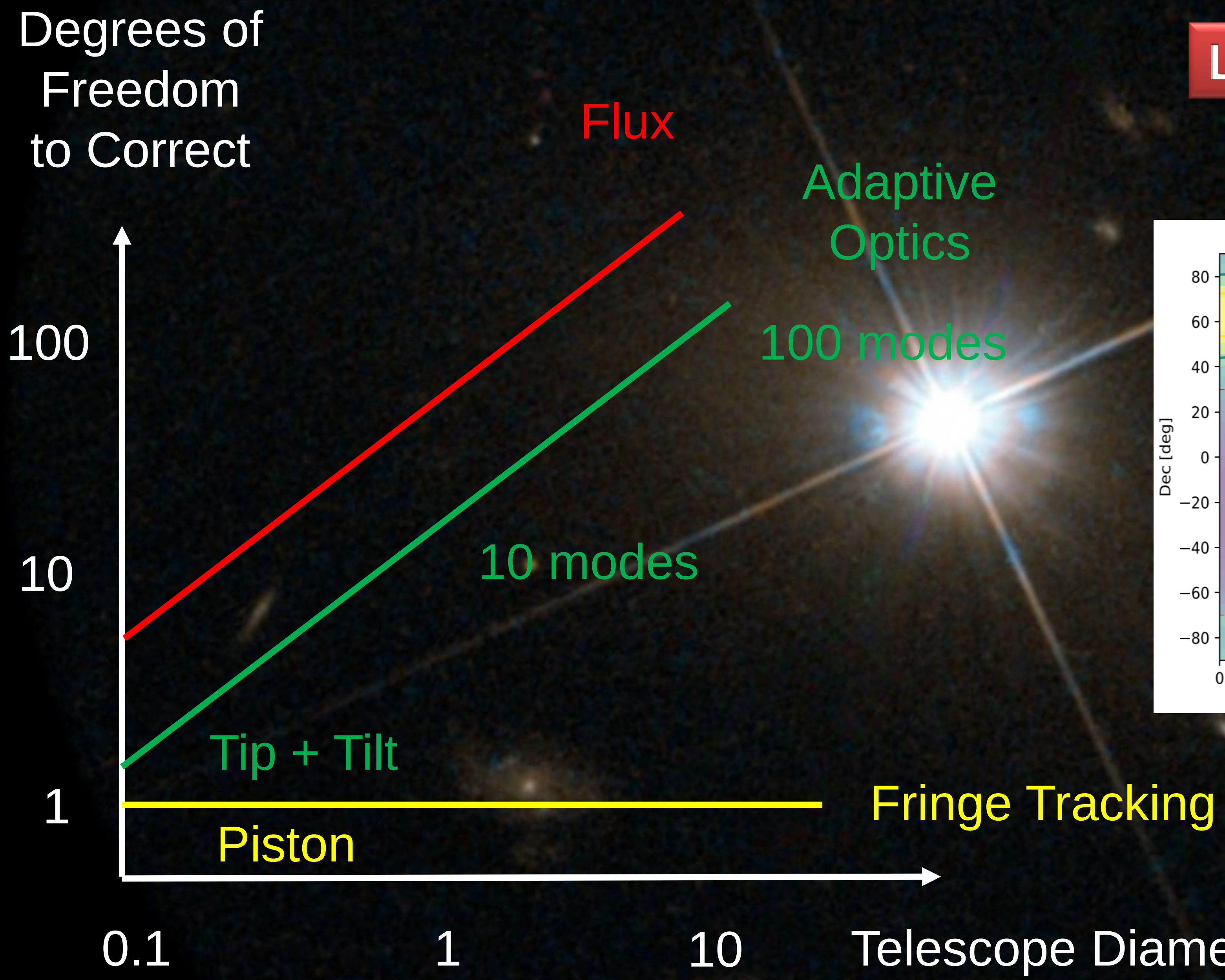
Strehl 55%

Strehl 15%

Adaptive Optics

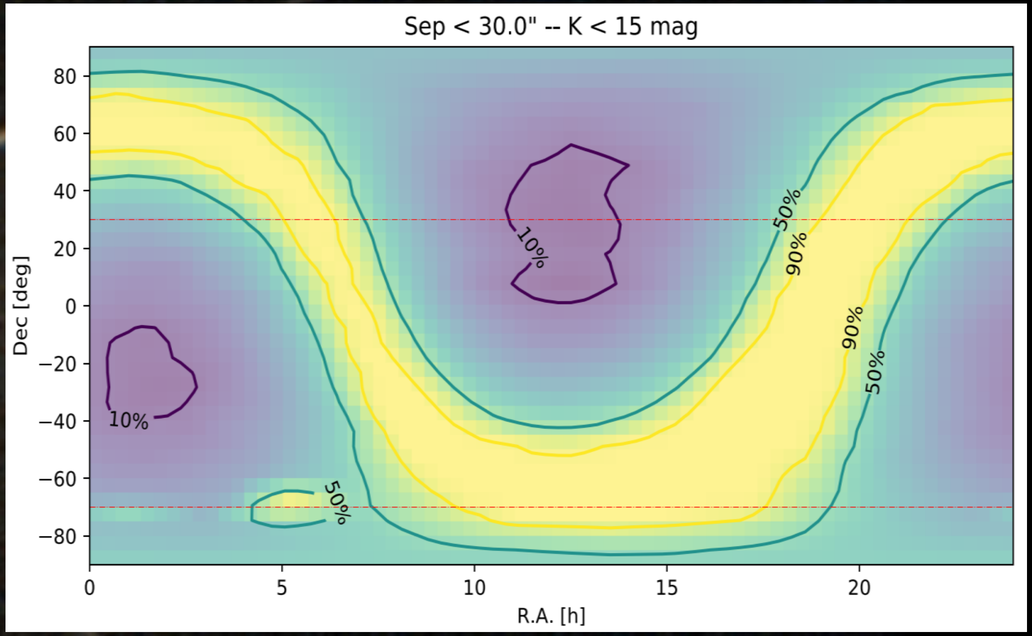
Factor 3 – 4 better injection together with laser guide star for faint target resulting in additional **Factor 2 – 3 better** Fringe Tracking

Laser Guide Stars are Key to Sky Coverage



Laser Guide Stars

Phase A this year



Courtesy: Julien Woillez

Factor Hundred Improvement for 3C273 Like Observations

Off Axis FringeTracking

Laser Guide Stars

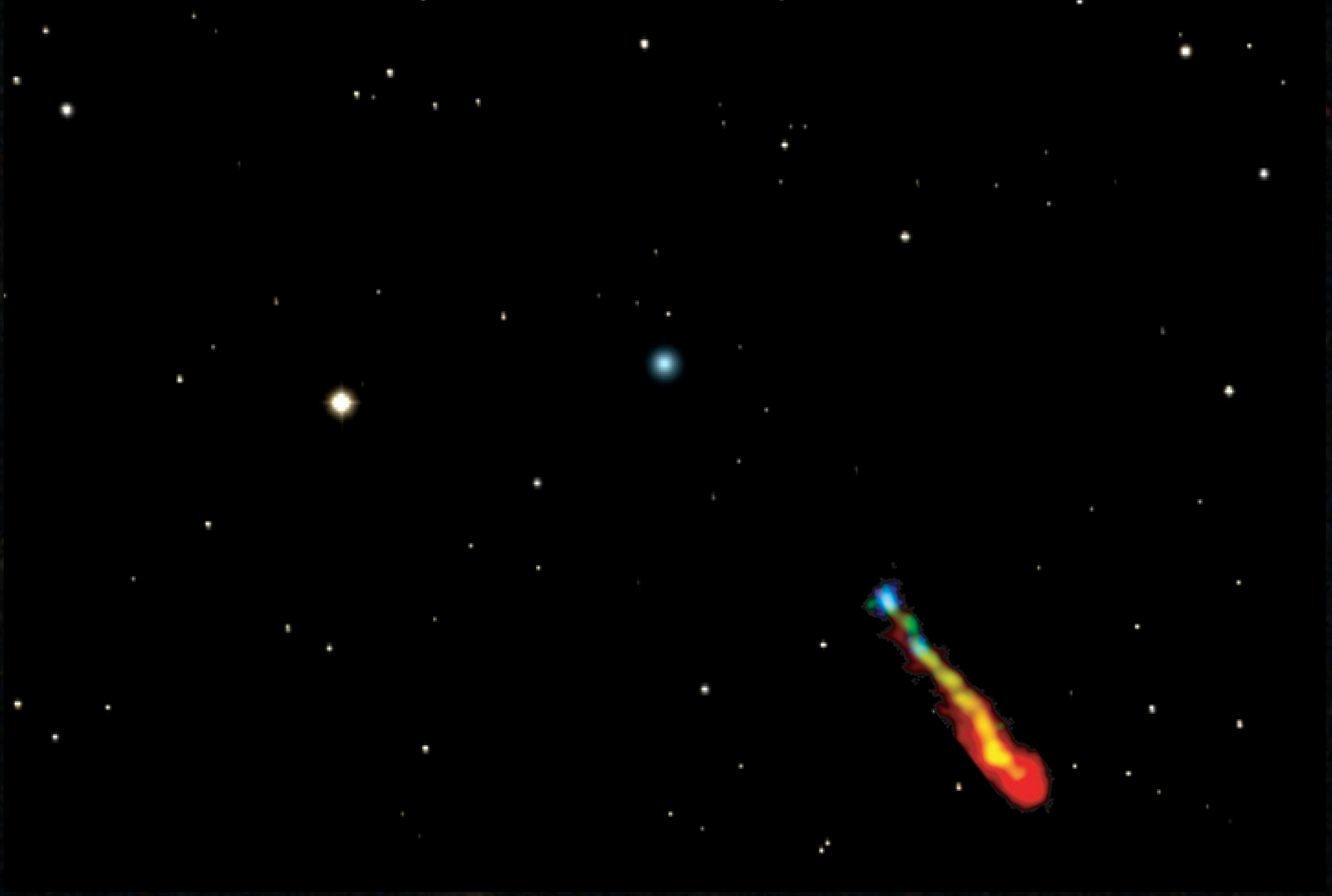
Improved Sensitivity

Adaptive Optics

Where	How much	Improvement
Adaptive Optics	Strehl from 15 to 55%	Factor 3.7
Fringe Tracking	550 to 150 nm RMS, corresponding to Visibility 35 to 90%	Factor 2.6
Instrument Throughput	Grism efficiency from 25/50 to 70/90 %, rsp. for R4000/500	Factor 2.3
Low Noise Detector, reduced metrology stray light	Readnoise 6 to 3 e- Background 1 to 0.1 e^-/s (60 s exposure)	Factor 2.5
Off-axis operation	No light splitting	Factor 2
Total		**Factor >100 or 5 mag**

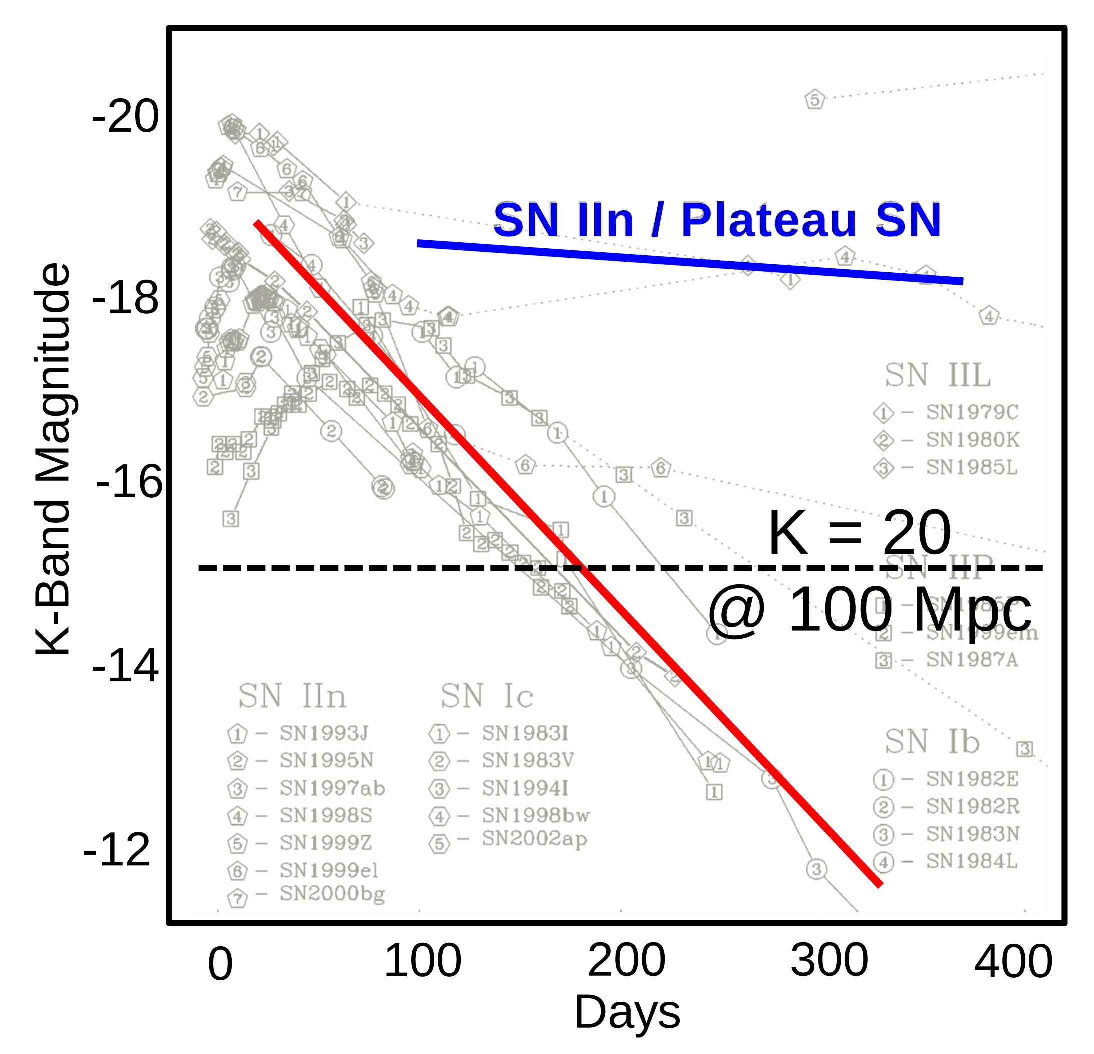
What Else – Supernovae as Example for Time Domain Astronomy

Asymmetry, Jets, Element- and Dust Formation



Supernovae

- Asymmetry, Jets, Element- and Dust Formation



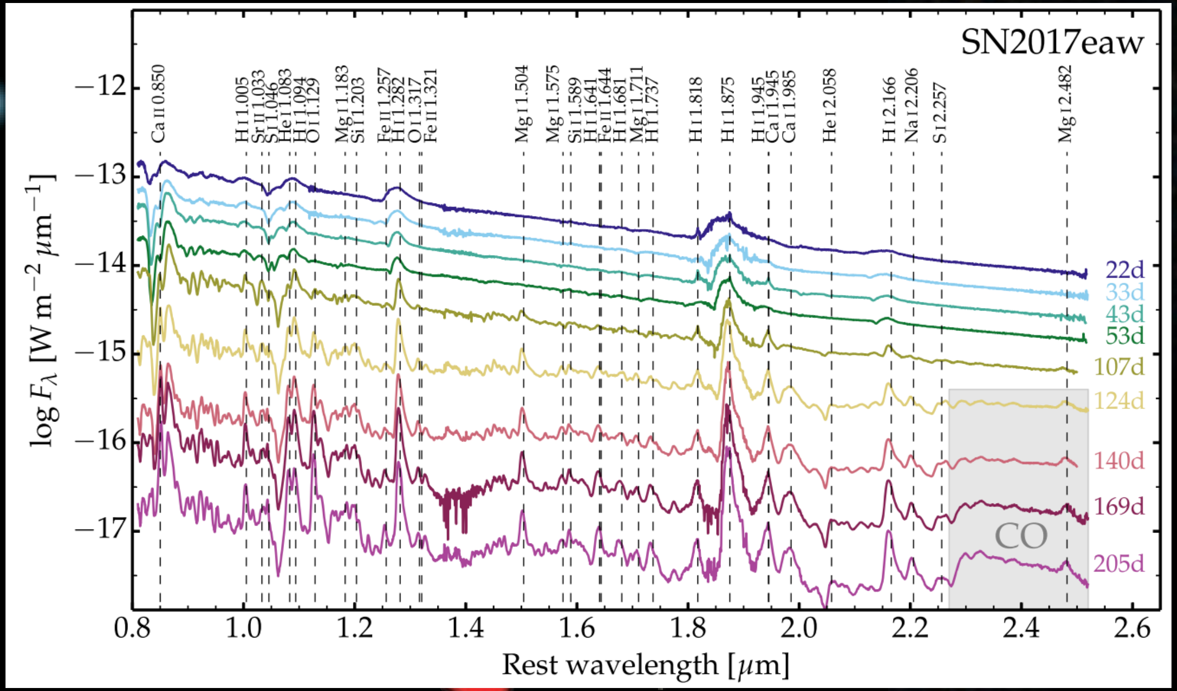
Adapted from Mannucci+ 03

SN IIn / Plateau SN

Circumstellar material ionized by UV

v = 300000 km/s

1.5 mas @ 18 mag @ 100 Mpc @ 1yr

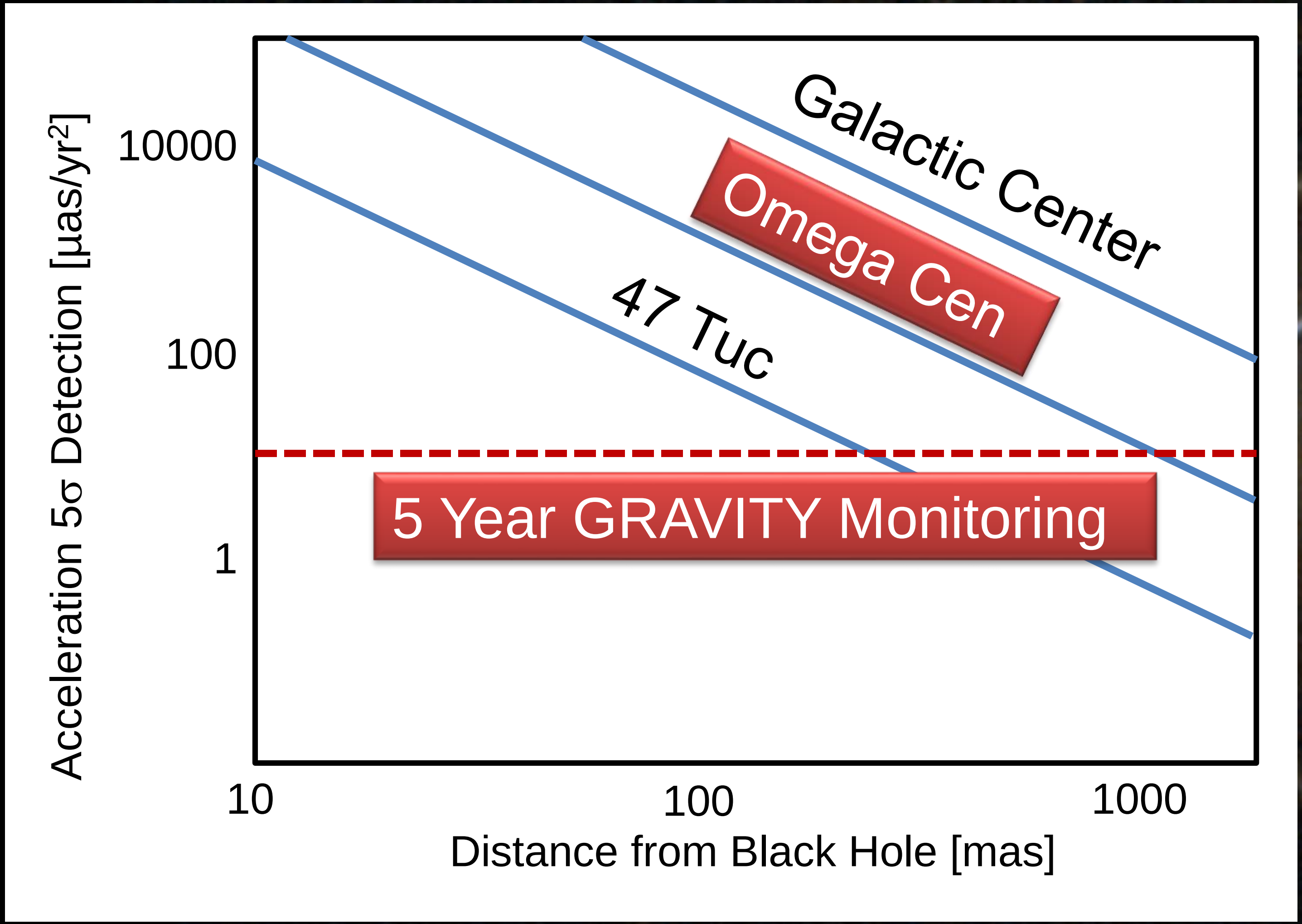


Rho+ 18

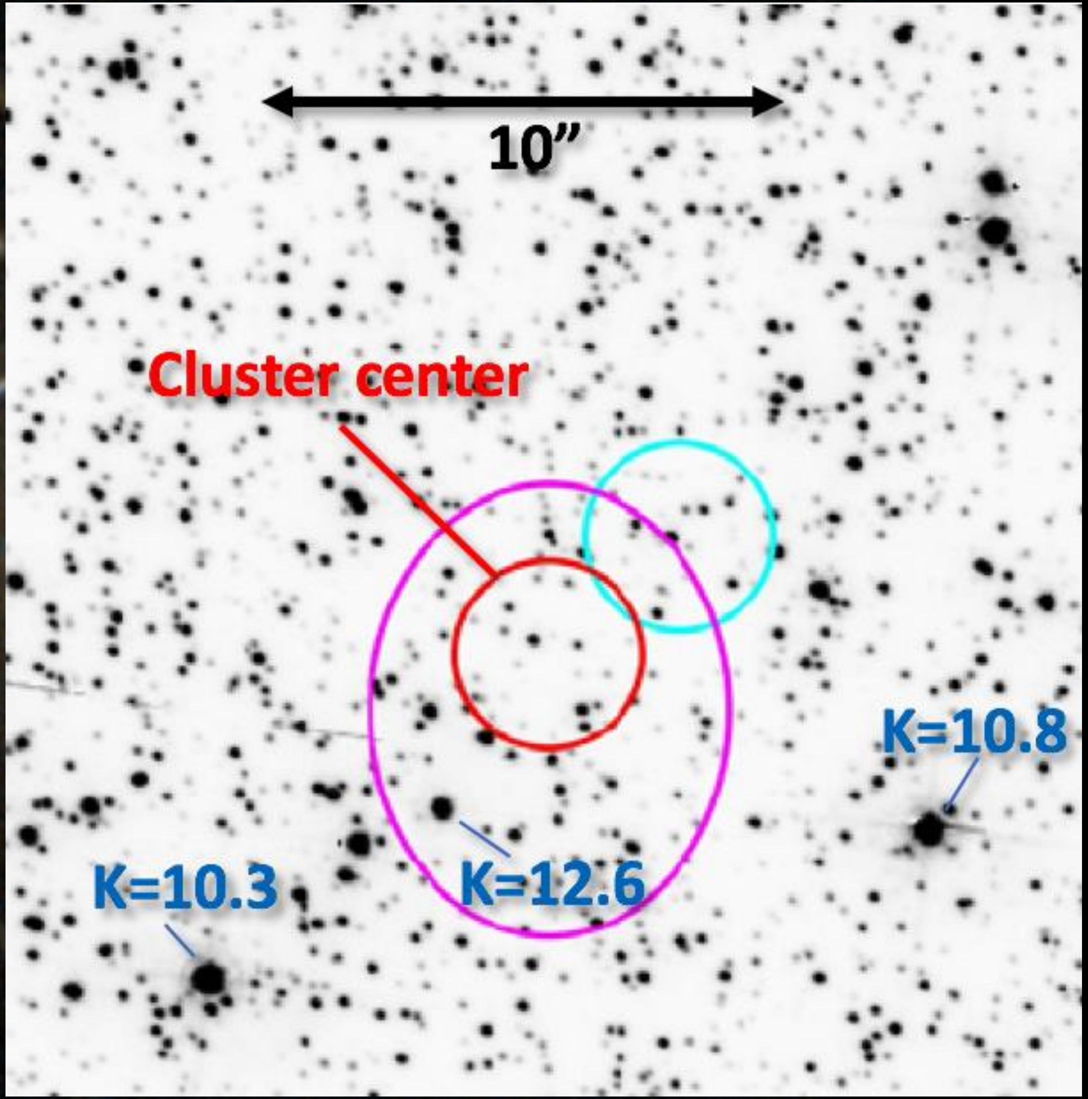
Exploding Shell v ≈ 10000 – 15000 km/s

What Else – Intermediate Mass Black Holes

as Example for Astrometry



Omega Cen



Anderson+ 10

What Else – Planet Formation

Talks by Michael Ireland and Frantz Martinache

What Else – Exoplanet Detection and Characterization

Talks by Sylvestre Lacour and Denis Defrère

What Else – Starformation

Talk by Stefan Kraus

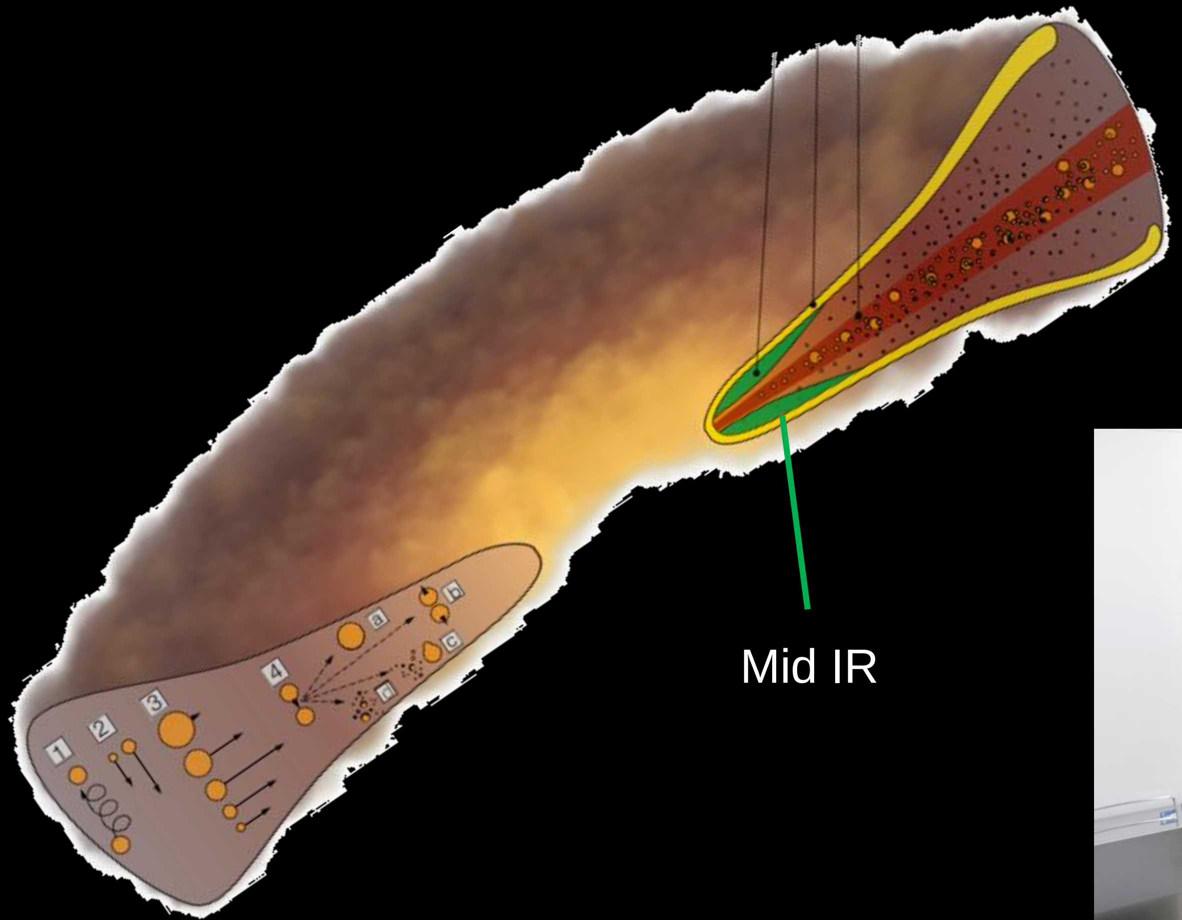
What Else – Serving MATISSE

Talk by Roman Petrov

and Gerd Weigelt

And New Instruments

Talk by Florentin Millour



Merand 18, adapted from Testi 14

Lopez+ 14

Phased Implementation

Phase	Description	Hardware Cost	Comment
1	Upgrade with 2x higher throughput grisms	250 k€	- cost covered by GRAVITY consortium - October 2019
	Re-activations of PRIMA DDL a… STS off-axis fringe tracking with… GRAVITY		- First observations of z=2 Quasars - Characterization of outer scale of atmospheric turbulence for off-axis fringe tracking
	Optimization of UT vibrations a… Fringe Tracking anti-vibration control		- Residual fringe tracking residuals on UTs currently 3x larger than with ATs, corresponding to a sensitivity loss of 1-2 mag
2	Adaptive optics upgrade with higher order deformable mirror and Pyramid wave-front sensor for all four UTs	6000 k€	- substantially improved limiting magnitude for faint-object on-axis operation - …d peak performance for high contrast …ets) … deformable DM and 750 k€ per new …ensing)
3	Laser Guide Stars for UT1,2,3	6000 k€	…F lasers - Assuming 1 M€ per launch telescope, and 1 M€ per laser
4	Specialized Instrument		e.g. nulling-interferometer, next generation fringe tracker
		Total ≈ 13 M€	

MPE Funding Guaranteed

Applied for MPG Central Funding

The Very Large Telescope in 2030