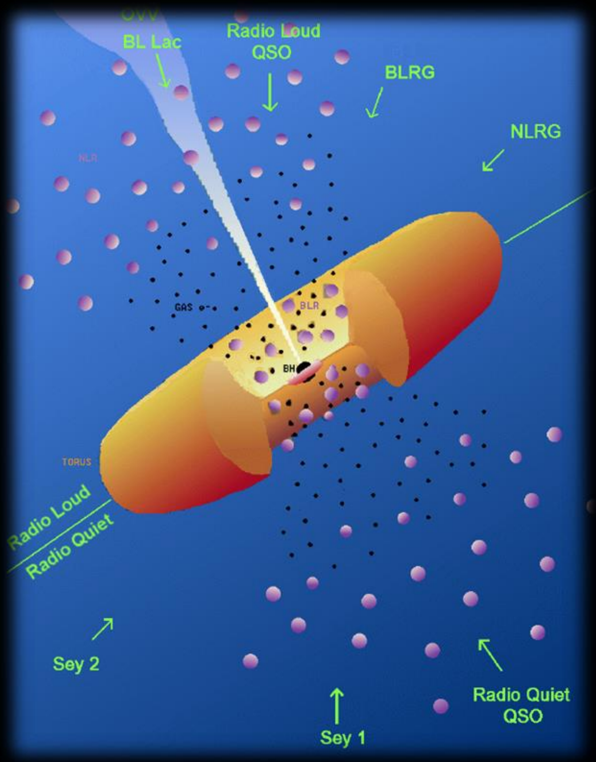
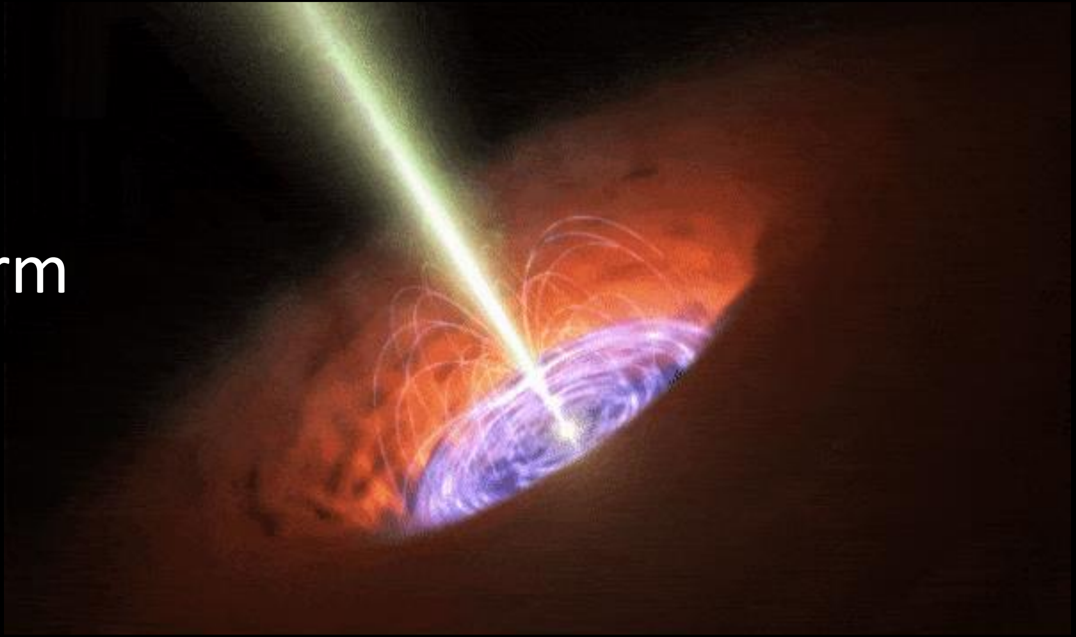
Resolving AGN central engines with GRAVITY - The BLR in the Quasar 3C 273





Eckhard Sturm

MPE

with **J. Dexter**, Y. Clenet, R. Davies, A. Eckart,
F. Eisenhauer, R. Genzel, D. Gratadour,
S. Hönig, M. Kishimoto, S. Lacour, D. Lutz, F. Millour,
H. Netzer, G. Perrin, B. Peterson, P.O. Petrucci,
O. Pfuhl, D. Rouan, **M. R. Stock**, I. Waisberg, J. Woillez,
and the GRAVITY collaboration

with

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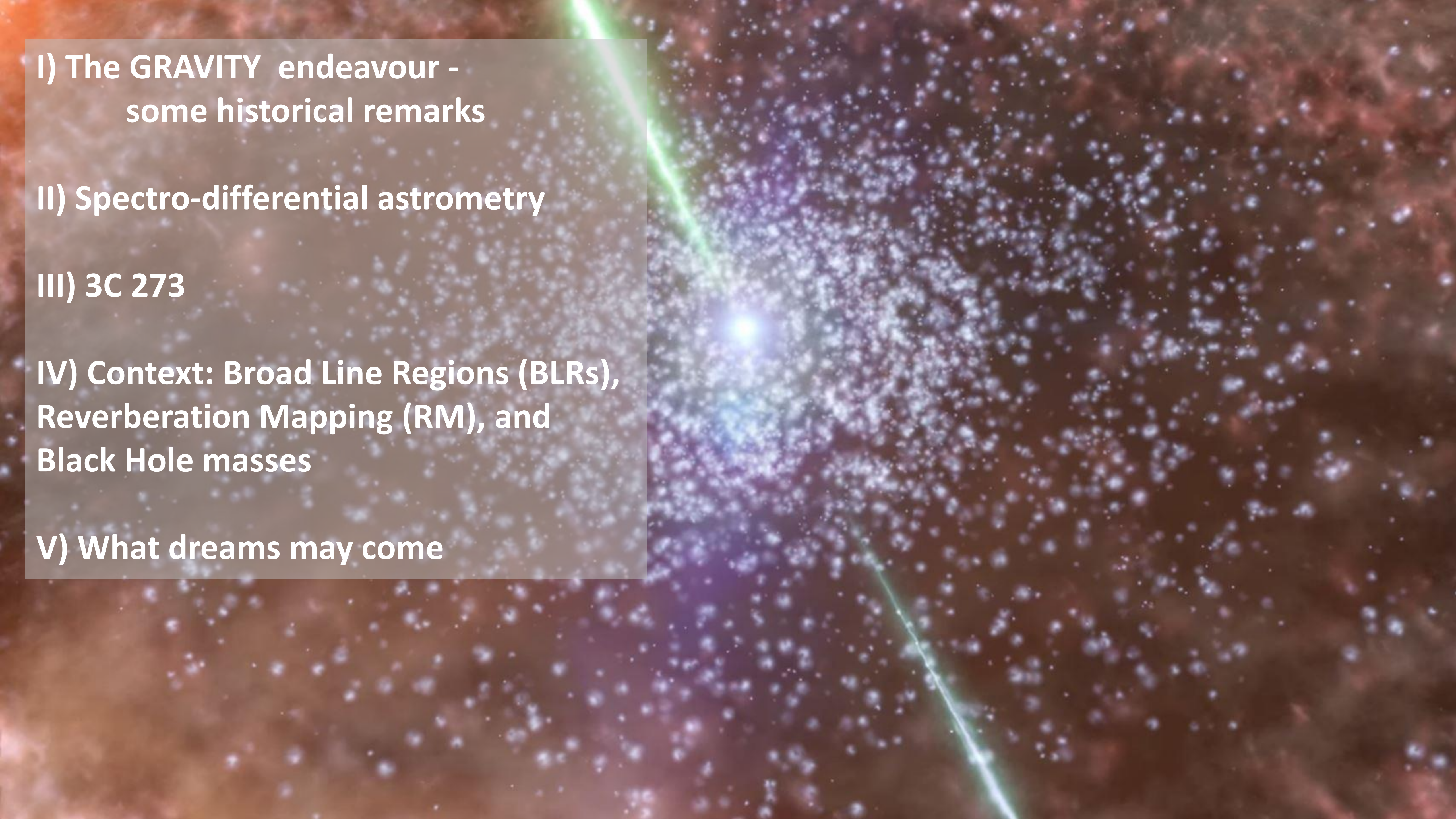
… the GRAVITY collaboration

Special thanks to Konrad Tristram and Leonard Burtscher



I) The GRAVITY endeavour -
some historical remarks

II) Spectro-differential astrometry

III) 3C 273

IV) Context: Broad Line Regions (BLRs), Reverberation Mapping (RM), and Black Hole masses

V) What dreams may come

The GRAVITY Family

GRAVITY Assembly and Integration on Paranal in July 2015

Milestones:

- project kick-off: 2005-2006
- Final Design Review: end 2011 – begin. 2012
- Installation on VLTI Jul.-Sept. 2015
- 1st AT light: October 2015
- 1st UT light : May 2016


INSTRUMENT GRAVITY BOX NO.: 16
ESO PARANAL OBSERVATORY
M.SCHOELLER/L.PALLANCA
DE-BY491523
HT
INSTRUMENT GRAVITY BOX NO.:
ESO PARANAL OBSERVATORY
M.SCHOELLER/L.PALLANCA
DE-BY491523
HT
9
83kg
INSTRUMENT GRAVITY BOX NO.: 9
ESO PARANAL OBSERVATORY
M.SCHOELLER/L.PALLANCA
DE-BY491523
HT


EXIT
GRAVITY
GRAVITY
GRAVITY
GRAVITY
GRAVITY


EXIT
GRAVITY Team
GRAVITY Team
GRAVITY Team
GRAVITY Team
GRAVITY Team
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GRAVITY Team




STÖHR



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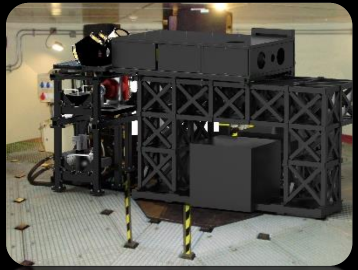
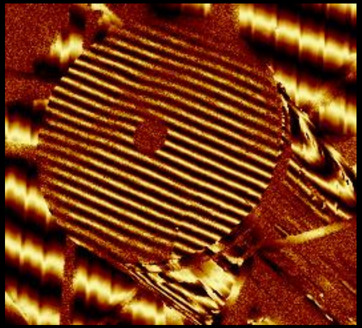
GRAVITY: all over the place in VLTI!

In addition to the beam combiner:

- 4 infrared adaptive optics (CIAO)



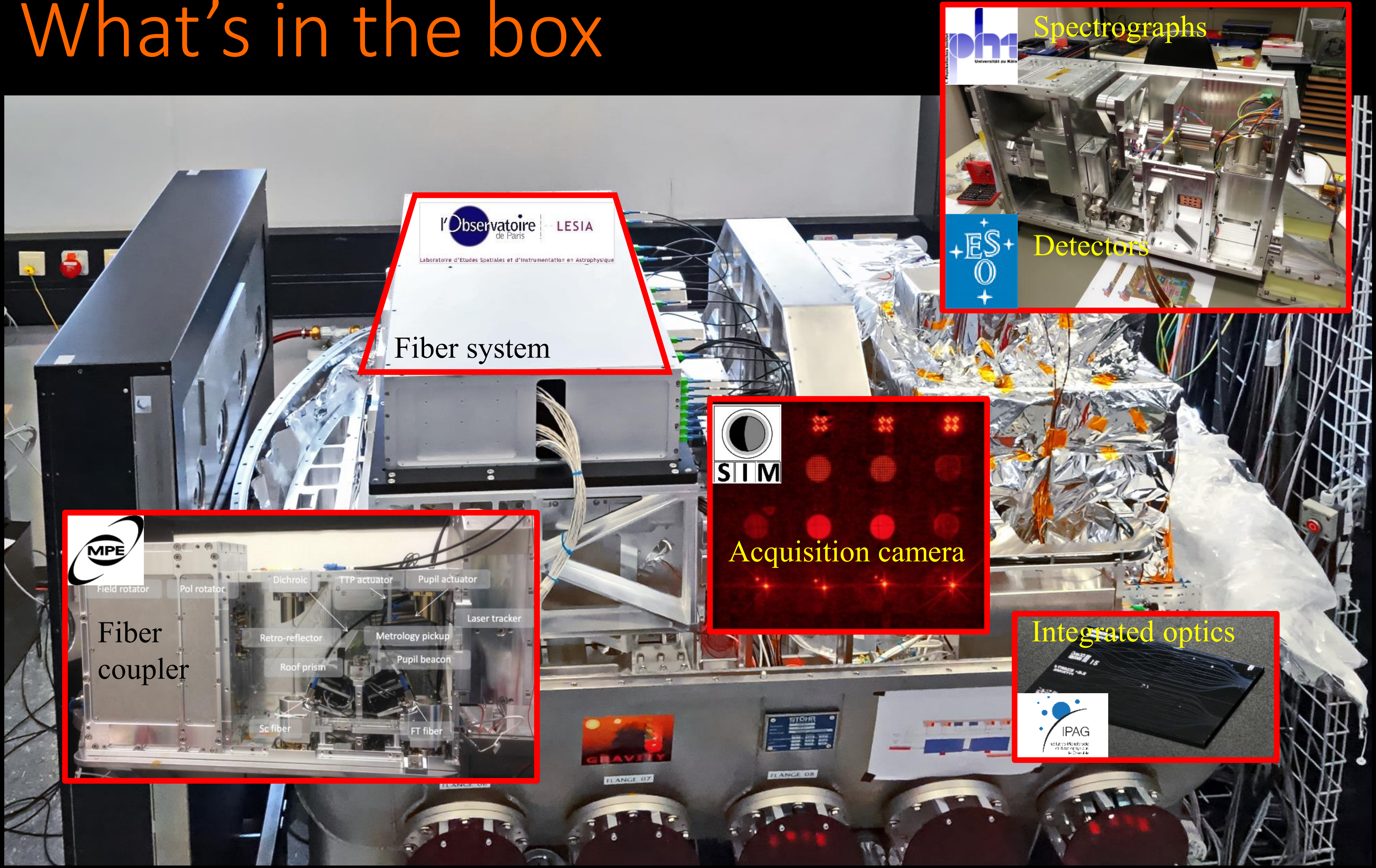
- Metrology sensors (UTs and ATs) for high precision astrometry and phase reference imaging



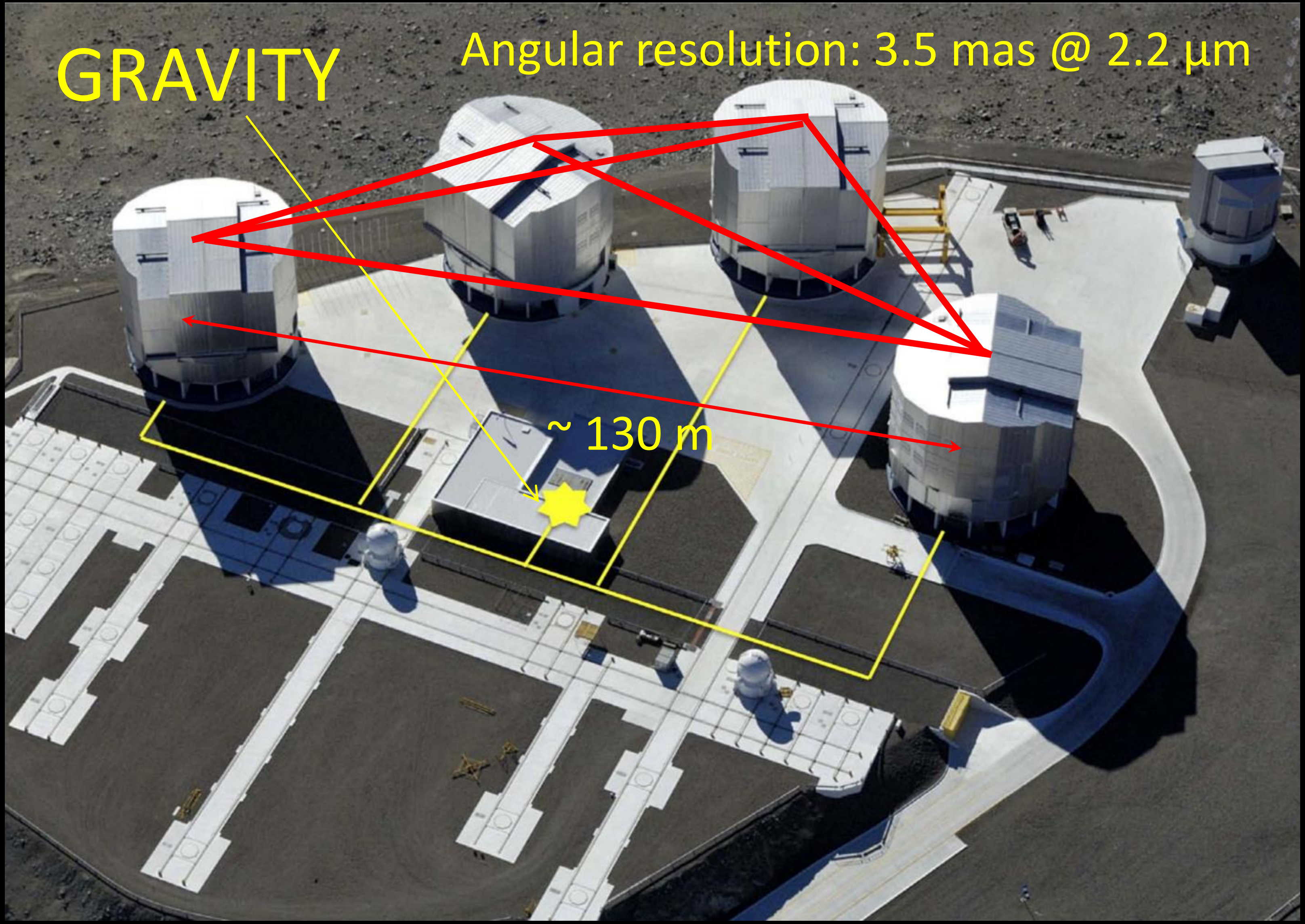
Beam combiner

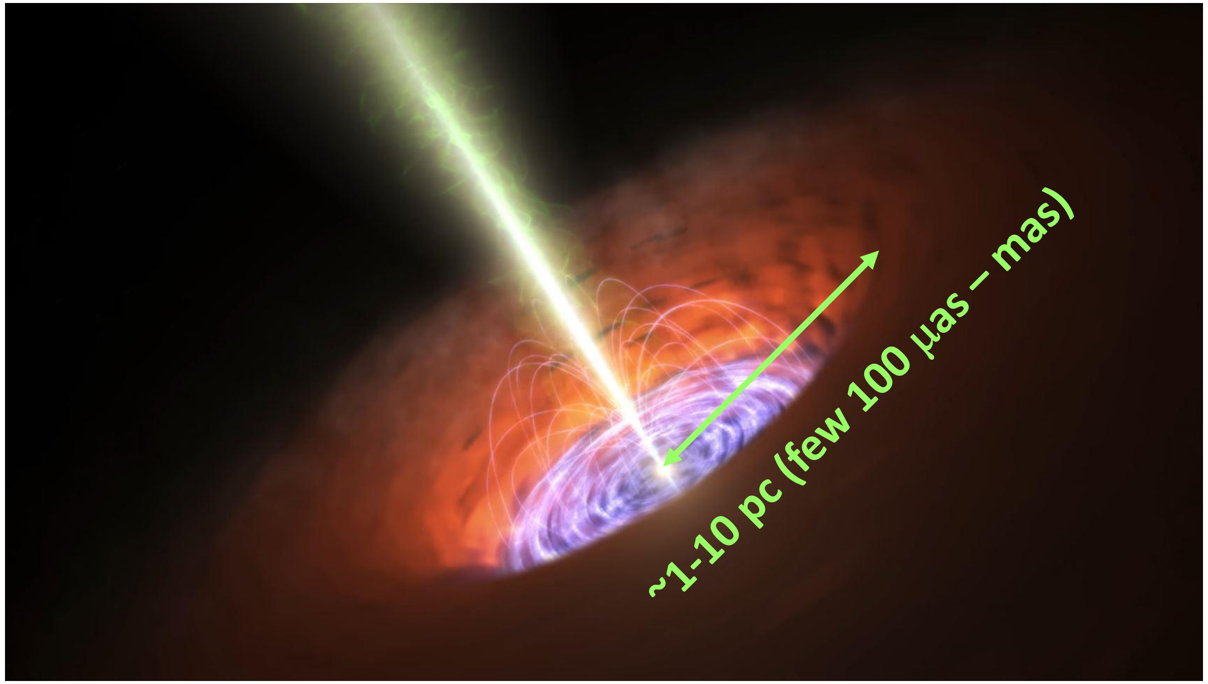
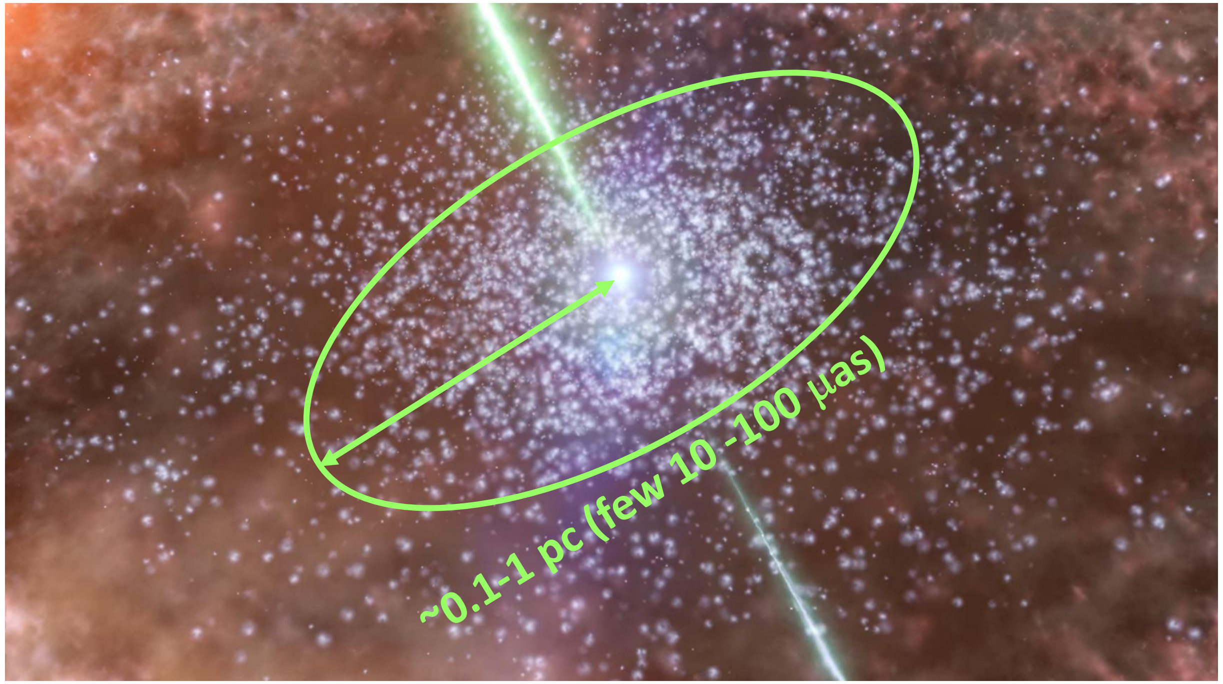
Eisenhauer+ 05,11

What's in the box



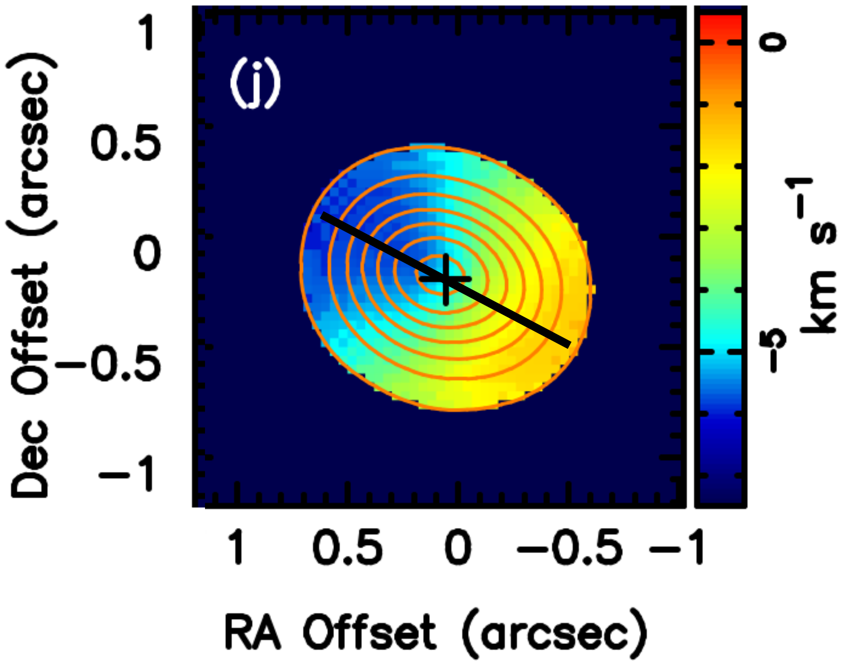
II) Spectro-differential astrometry with the near-IR interferometer GRAVITY



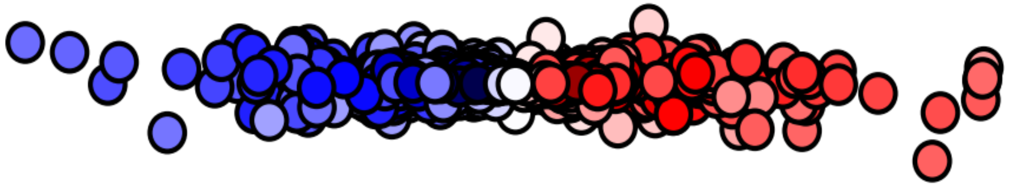

~1-10 pc (few 100 μas – mas)

~0.1-1 pc (few 10 -100 μas)

Reminder: Signatures of (Kepler) rotation

Velocity Map

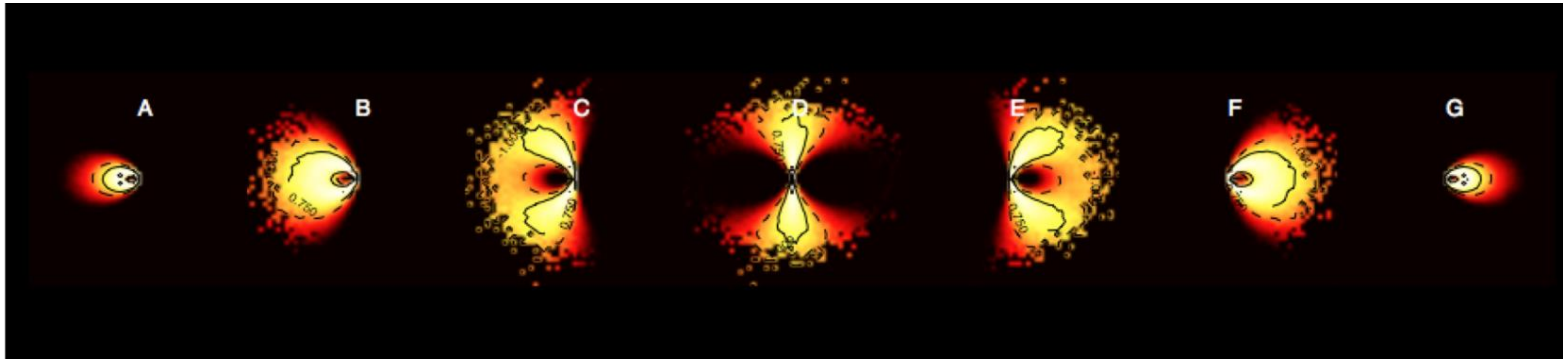


→ Velocity gradient

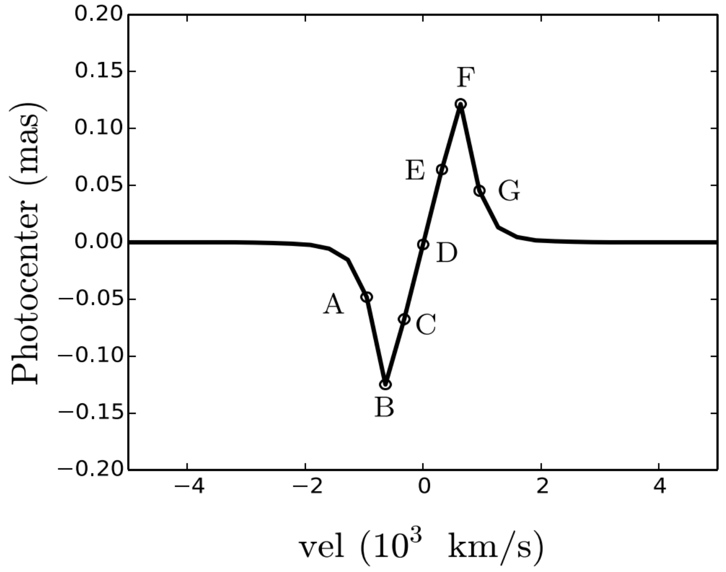


Channel Map

(Line intensity map for different channels/velocities)



→ Photocentre displacement perpendicular to the rotation axis



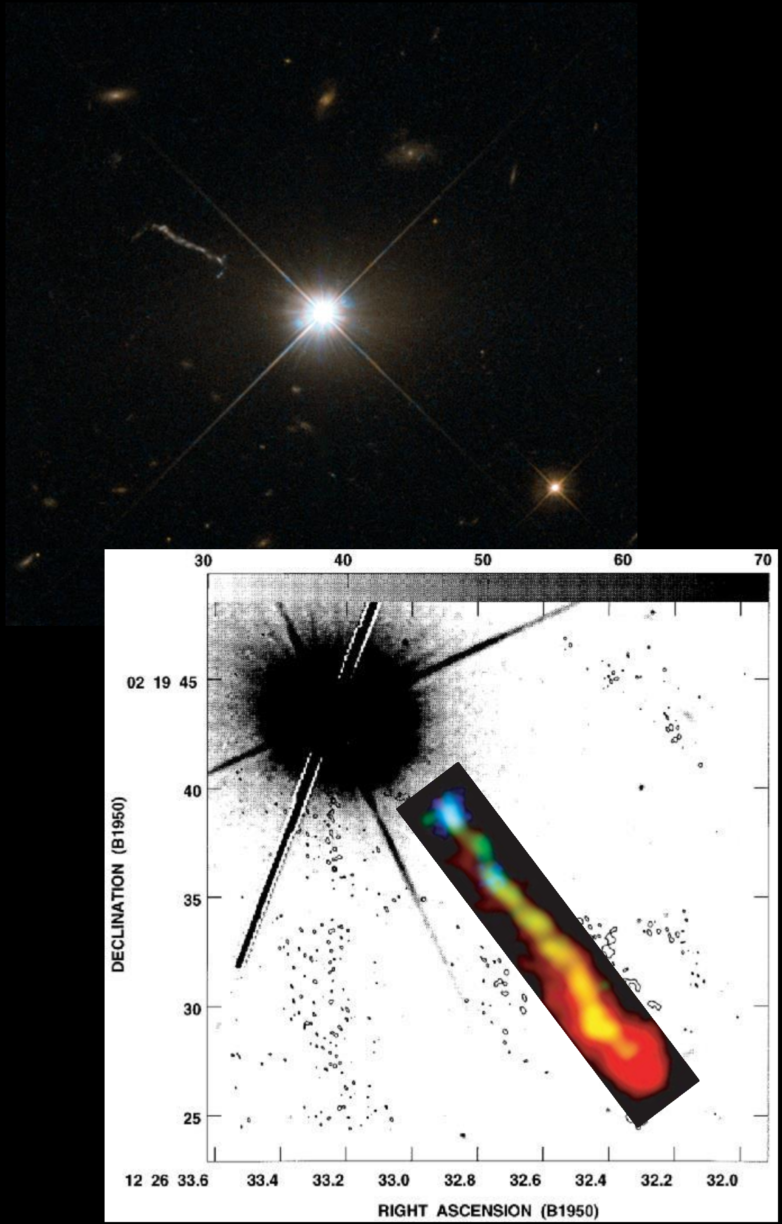
Model-independent photocenter map

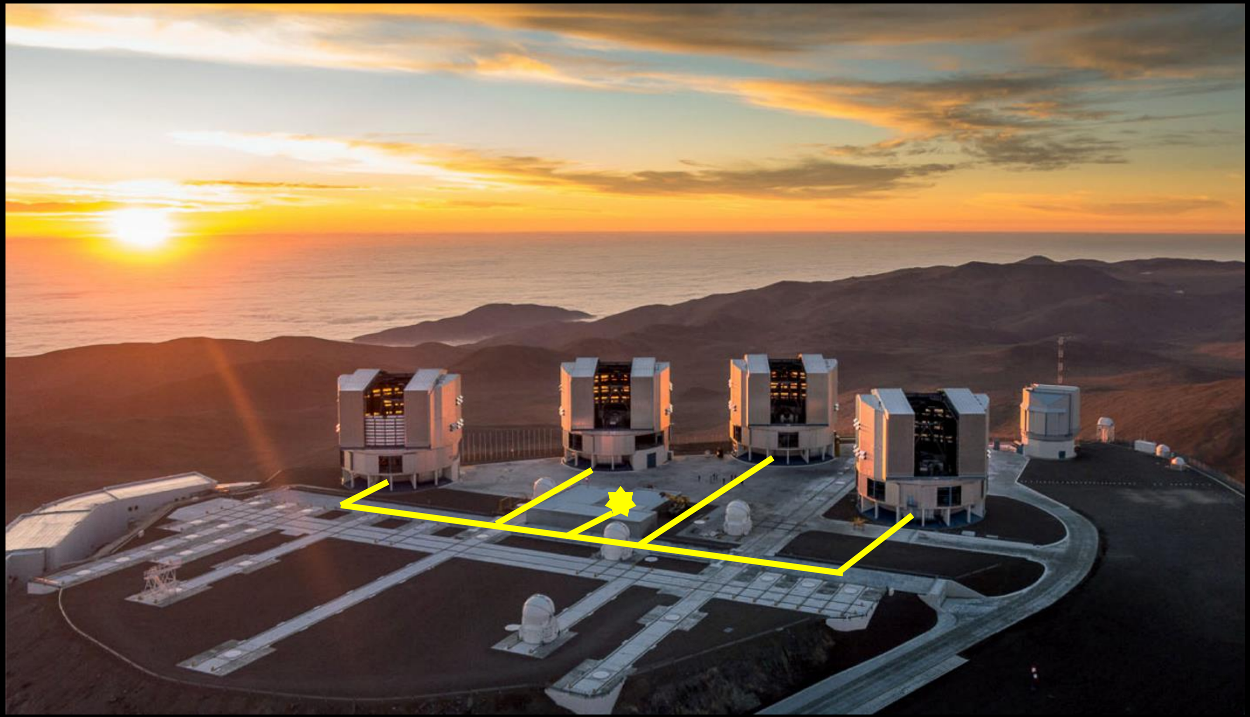
$$\underbrace{\Delta\phi(\lambda)}_{\text{phase}} = -2\pi \underbrace{\frac{r(\lambda)}{1+r(\lambda)}}_{\text{line strength}} \left[\underbrace{\vec{u}(\lambda)}_{\text{baseline}} \cdot \underbrace{\vec{\epsilon}(\lambda)}_{\text{photocenter}} \right]$$

- From measured phases, fit for 2D photocenter on sky at each wavelength

Beckers (1982); Christy, Wellnitz & Currie (1983), Aime+ (1988), Petrov+ (1991), Bailey (1998)

III) 3C 273 with GRAVITY



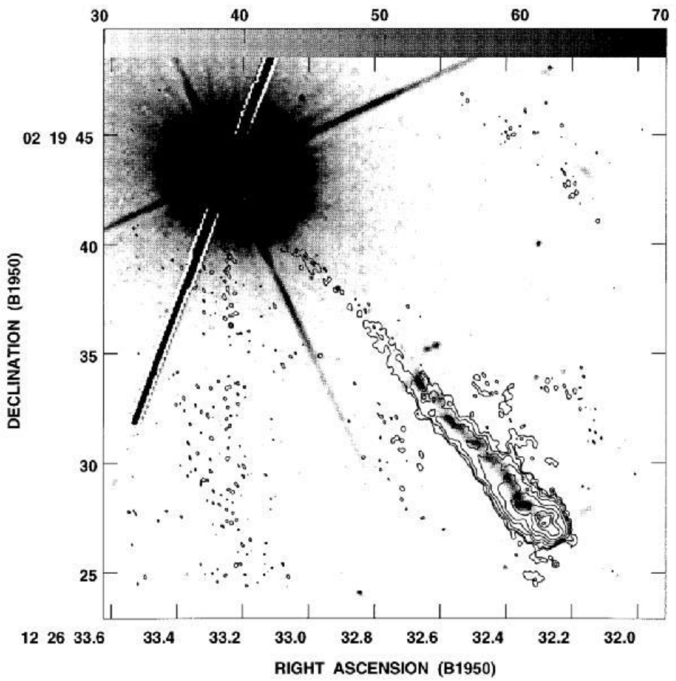


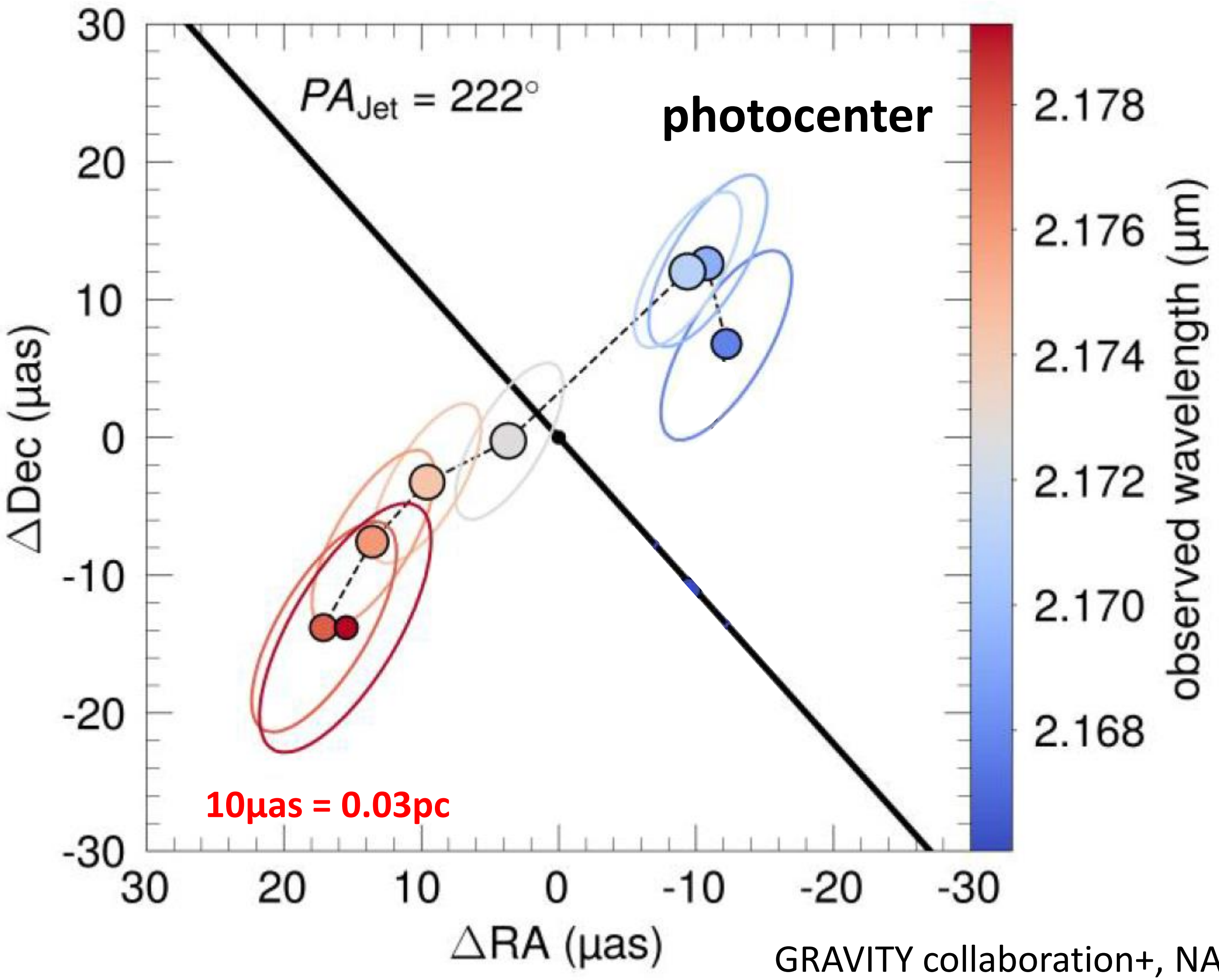
- Bright quasar, $L \sim L_{Edd}$
- Radio loud: known position angle on sky

Hubble Space Telescope images and radio (Merlin) images
Jester+2006 (Chandra)

III) 3C 273 with GRAVITY

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





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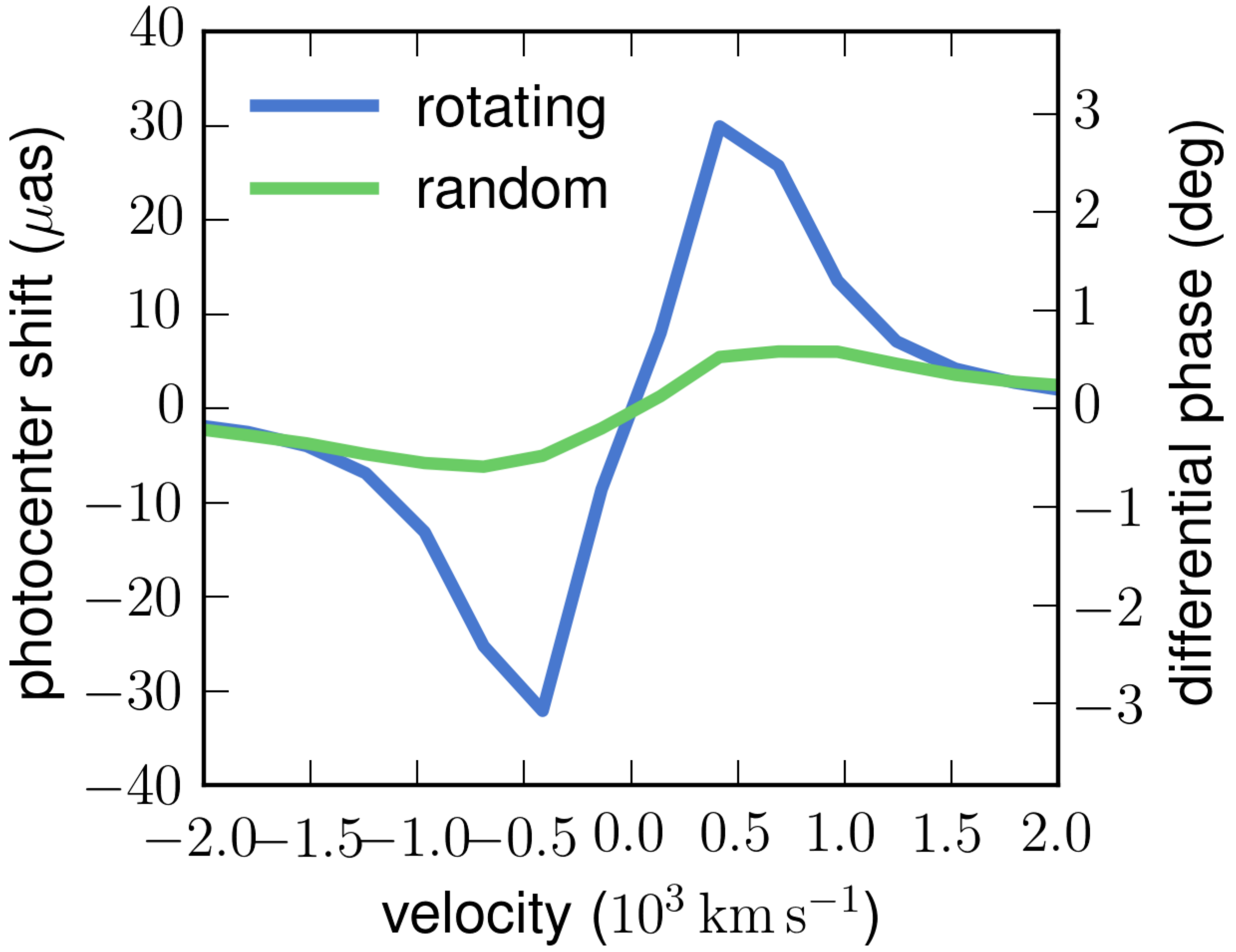
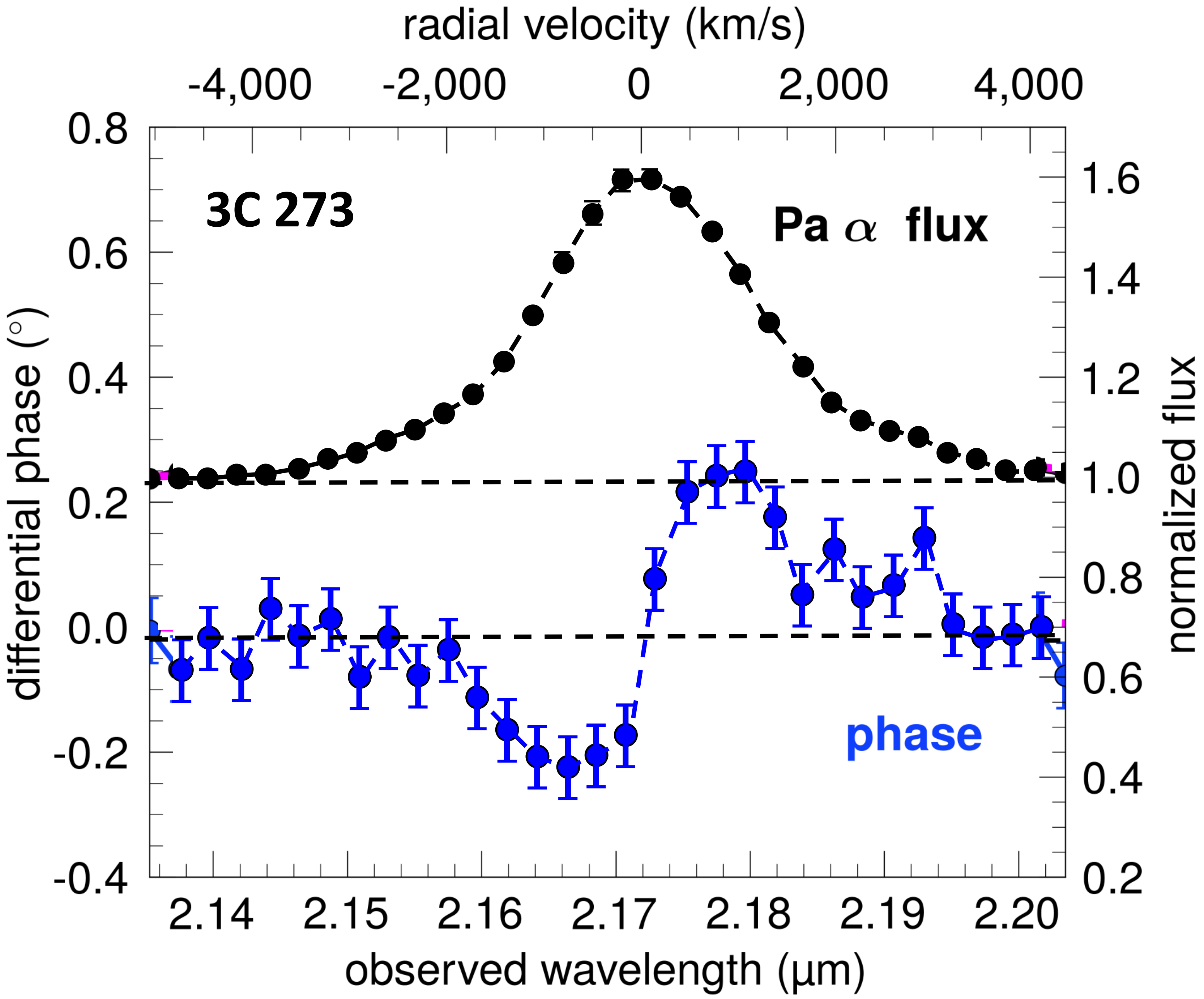
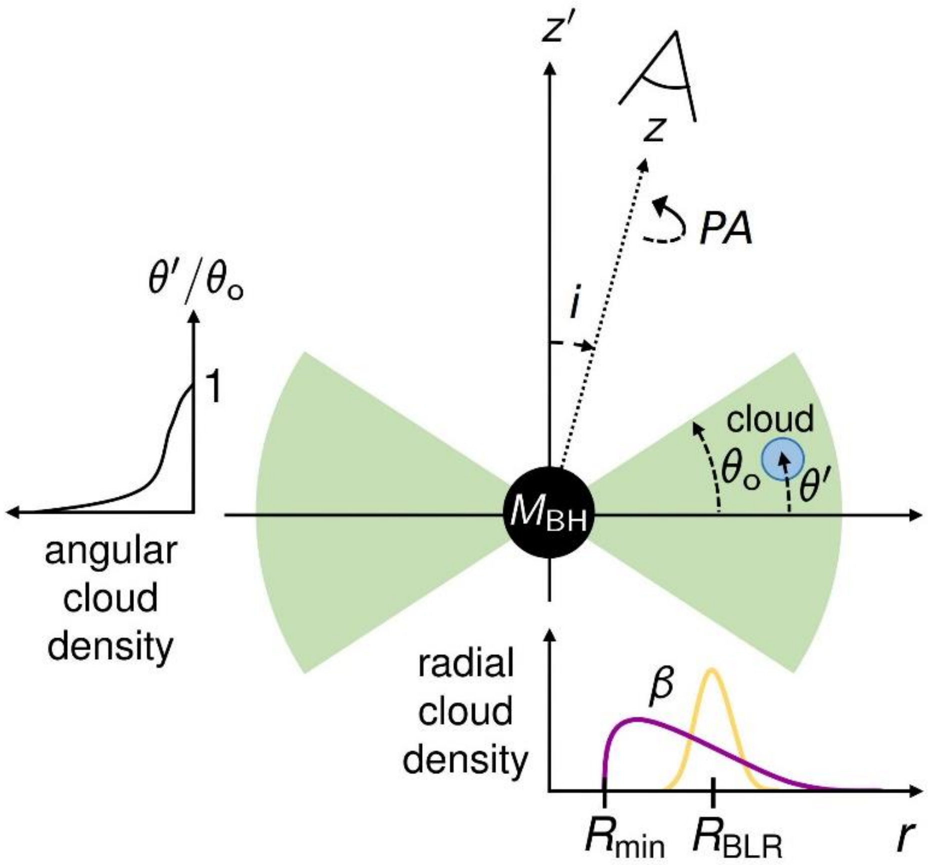
- a spatial velocity gradient (i.e. different photocenter positions) corresponds to wavelength-dependent phase shifts.

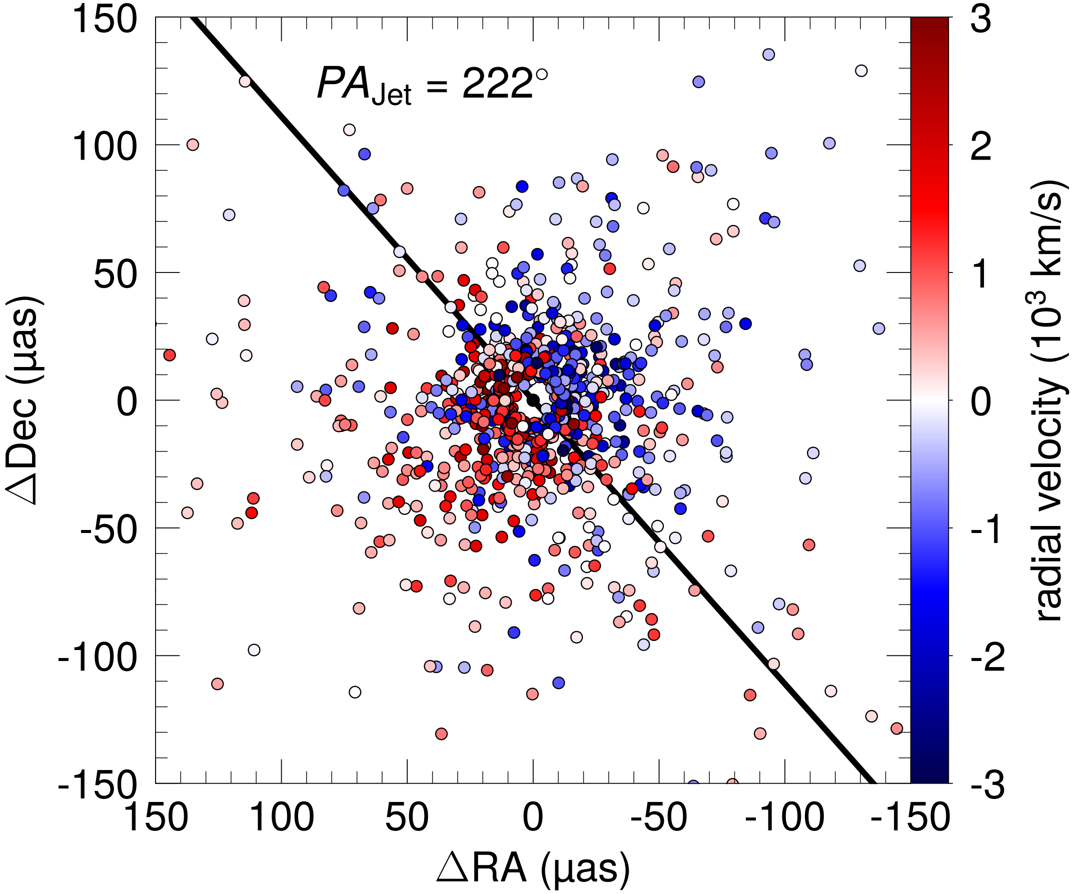



radial velocity (km/s)
-4,000
-2,000
0
2,000
4,000
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
differential phase (°)
3C 273
Pa α flux
phase
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
normalized flux
2.14
2.15
2.16
2.17
2.18
2.19
2.20
observed wavelength (µm)

A rotating, thick disk BLR model

- Kinematic "cloud" model fit to line profile, phases
  (R. Stock et al.; following Pancoast+ 2014, Rakshit+ 2015)





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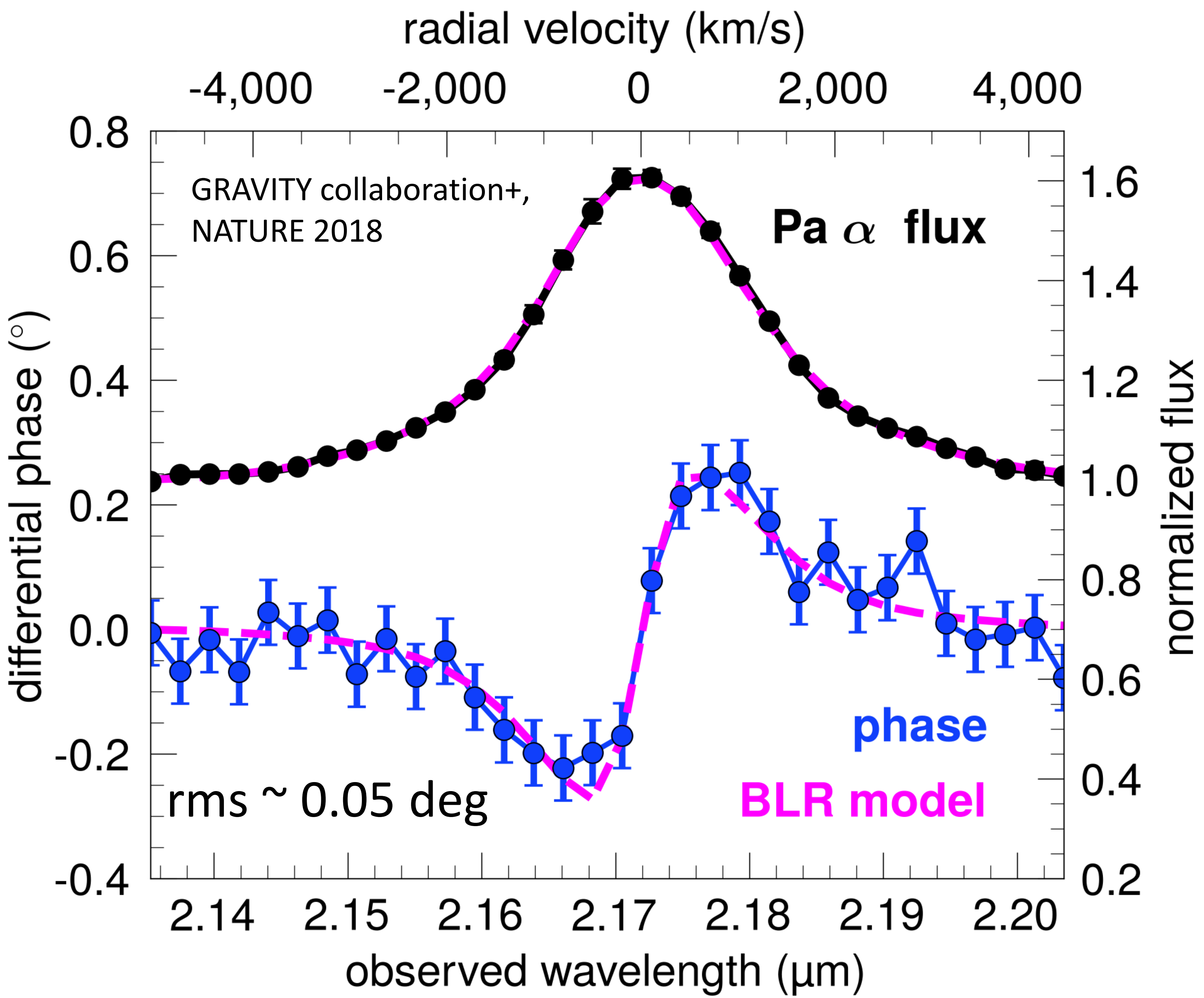
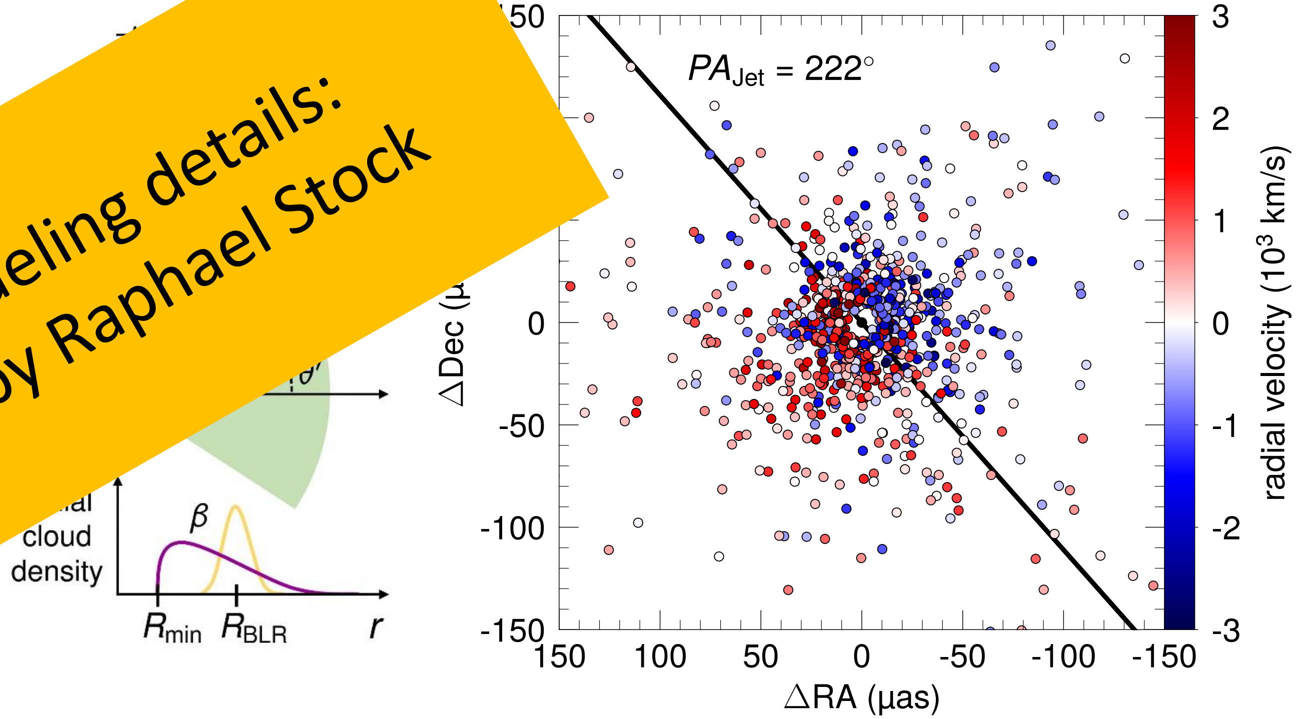


radial velocity (km/s)
-4,000
-2,000
0
2,000
4,000
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
differential phase (°)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
normalized flux
GRAVITY collaboration+,
NATURE 2018
Pa α flux
phase
BLR model
rms ~ 0.05 deg
2.14
2.15
2.16
2.17
2.18
2.19
2.20
observed wavelength (μm)

3C 273 - A rotating, thick disk BLR viewed face-on

- Kinematic "cloud" model fit to line profile, phases (R. Stock)
- i = 12+/-2, PA=210+/-10 deg (aligned w/ jet in 2D)

→ Modeling details: Talk by Raphael Stock



- R_{BLR} = 46 +/- 10 µas * 150+/-40 lt-d
- M_{BH} = 2-4x10^8 M_{sun}

* 10 µas = 0.03pc

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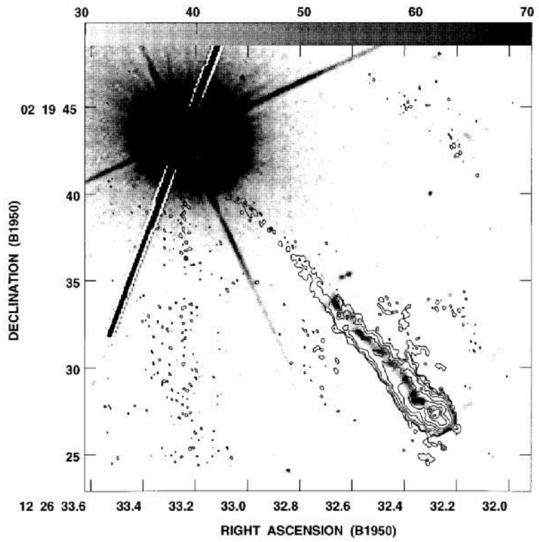
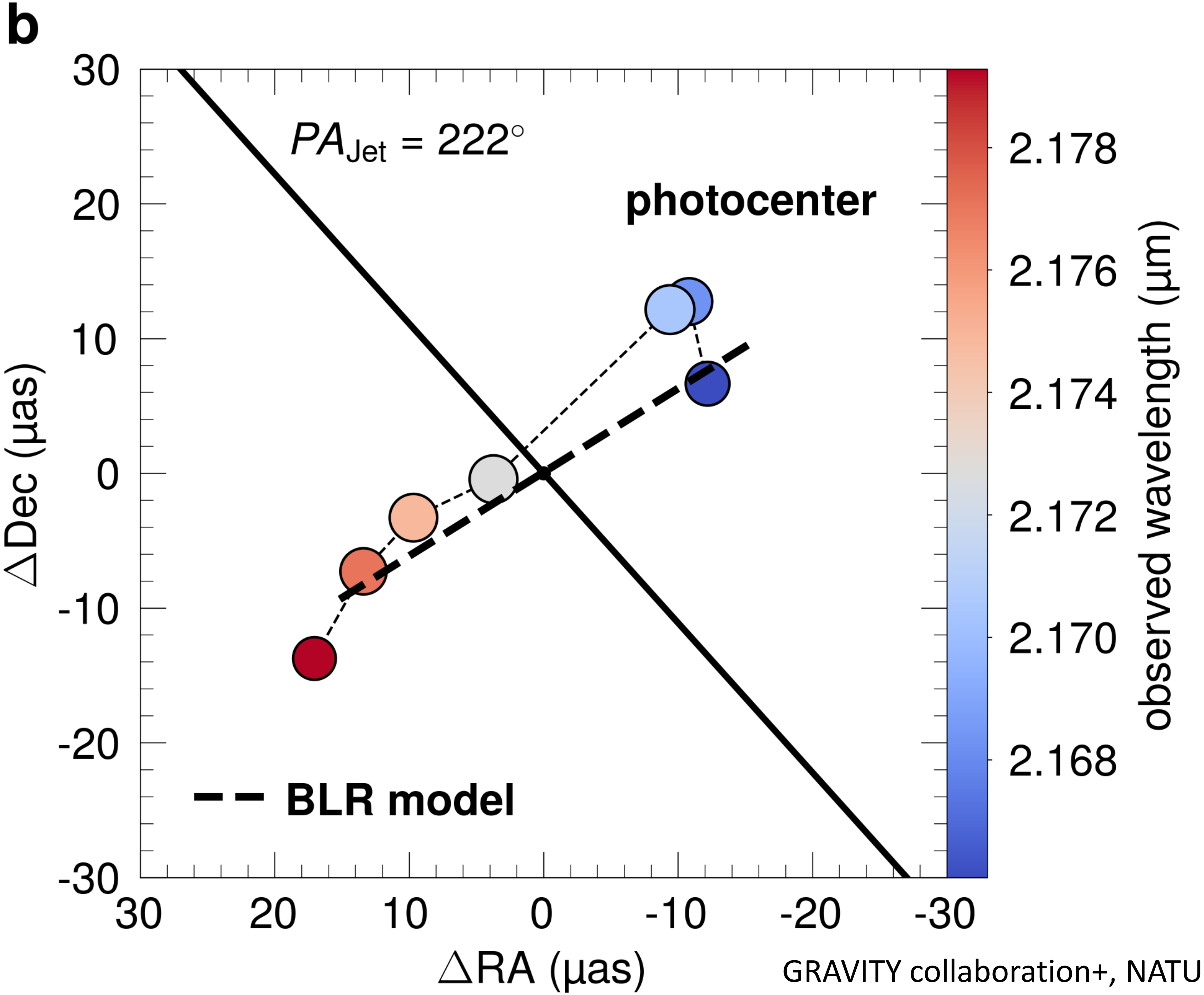
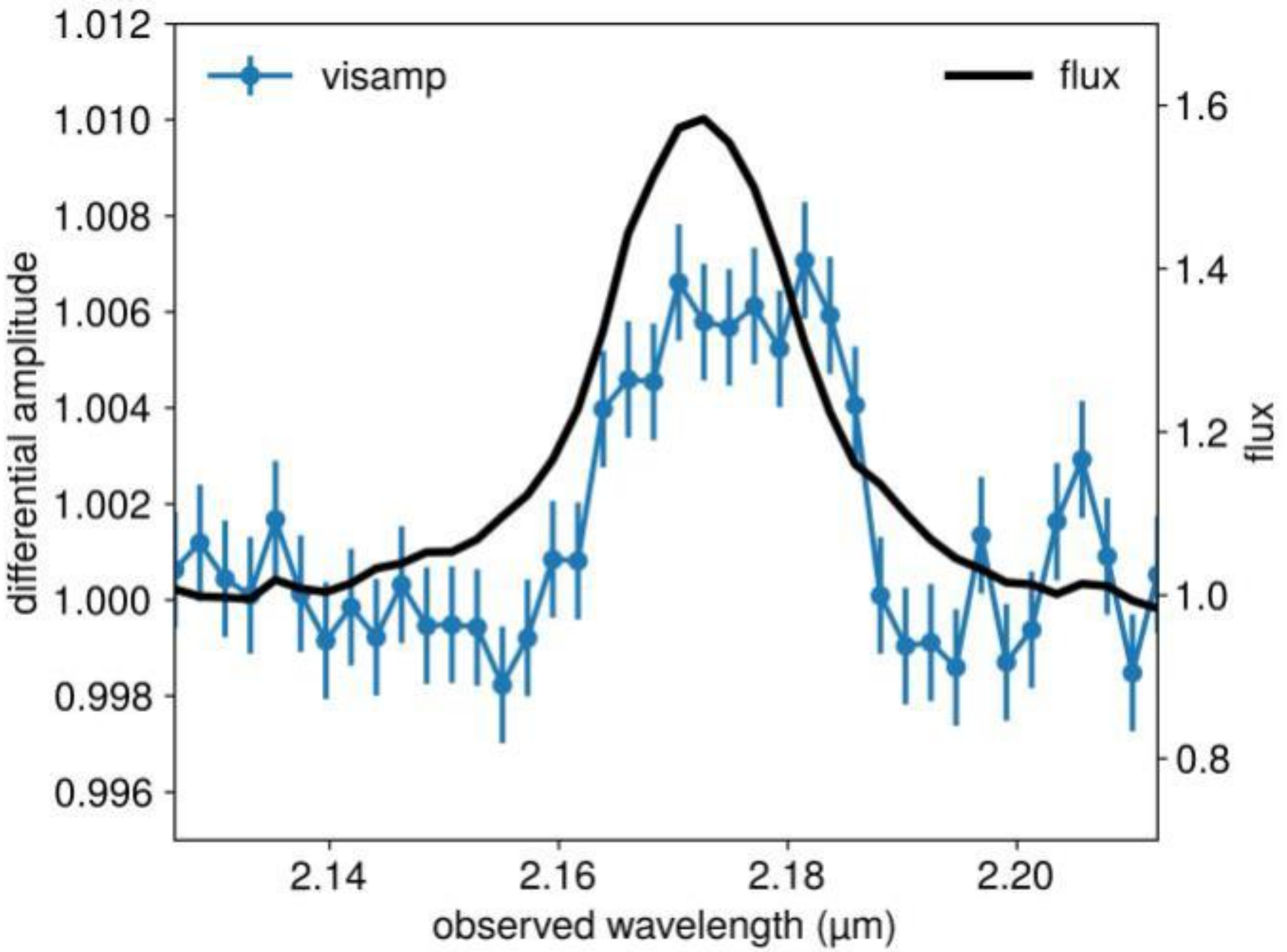




GRAVITY collaboration+, NATURE 2018

Independent check of compact BLR size:

3C 273 differential visibility amplitude (blue) averaged over all epochs and between the two longest (UT4-1, UT3-1) baselines.
The amplitude increases at the spectral line (black), demonstrating that the broad line region must be much smaller in size than the hot dust continuum (R ~ 150 µas).



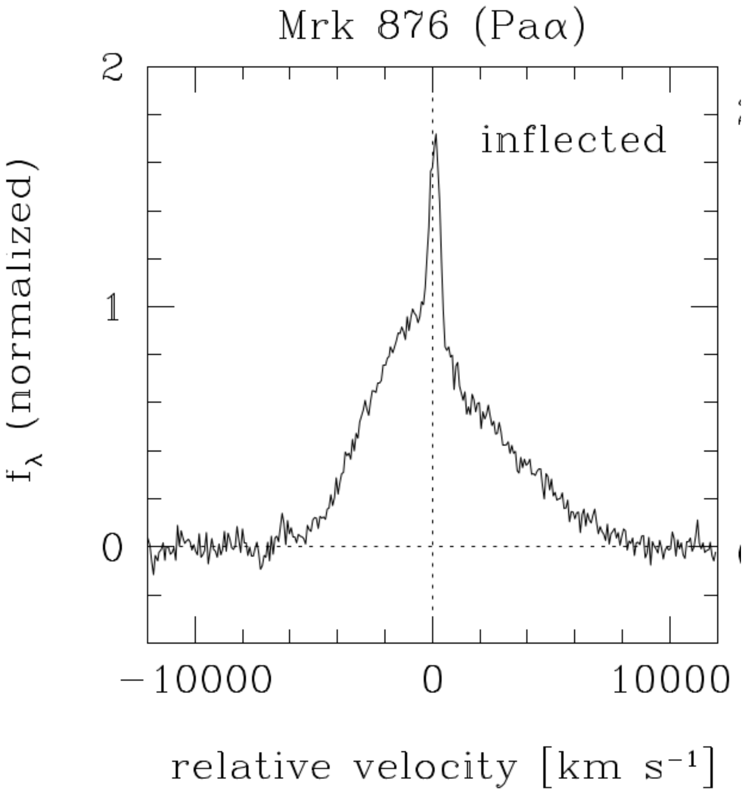
Notepad - I

- The kinematics of the BLR of 3C 273 is dominated by rotation
- R_{BLR} = 46 +/- 10 μas* (or 150+/-40 light days, or 0.13pc)
- $M_{BH} = 2\text{-}4 \times 10^8\ M_{sun}$

* 10 μas = 0.03pc at the distance of 3C 273

IV) Context: Broad Line Regions (BLRs), Reverberation Mapping (RM), and Black Hole masses

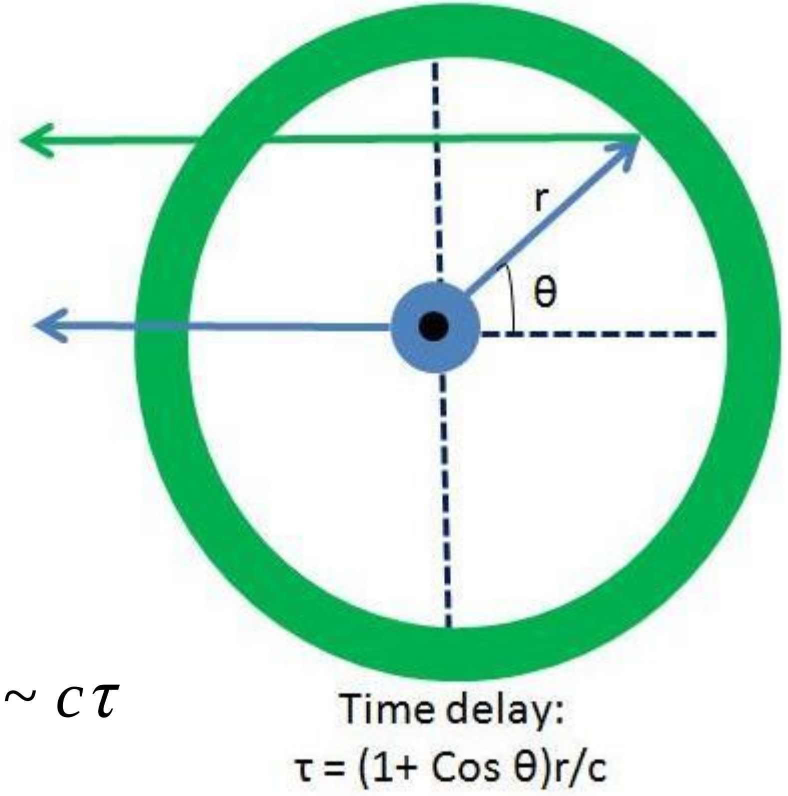
Broad Line Regions, Reverberation Mapping (RM), and Black Hole masses



$$GM_* = f\, R_{BLR}(\Delta v)^2$$

Spectroscopy: $\Delta v \sim FWHM$

Reverberation mapping: $R_{BLR} \sim c\,\tau$



Broad Line Regions, Reverberation Mapping (RM), and Black Hole masses

- This requires monitoring over long periods of time (often many years), which is laborious and time consuming.

- RM observations have established a BLR radius – AGN luminosity relation (and hence a mass – luminosity relation) as powerful diagnostic tool

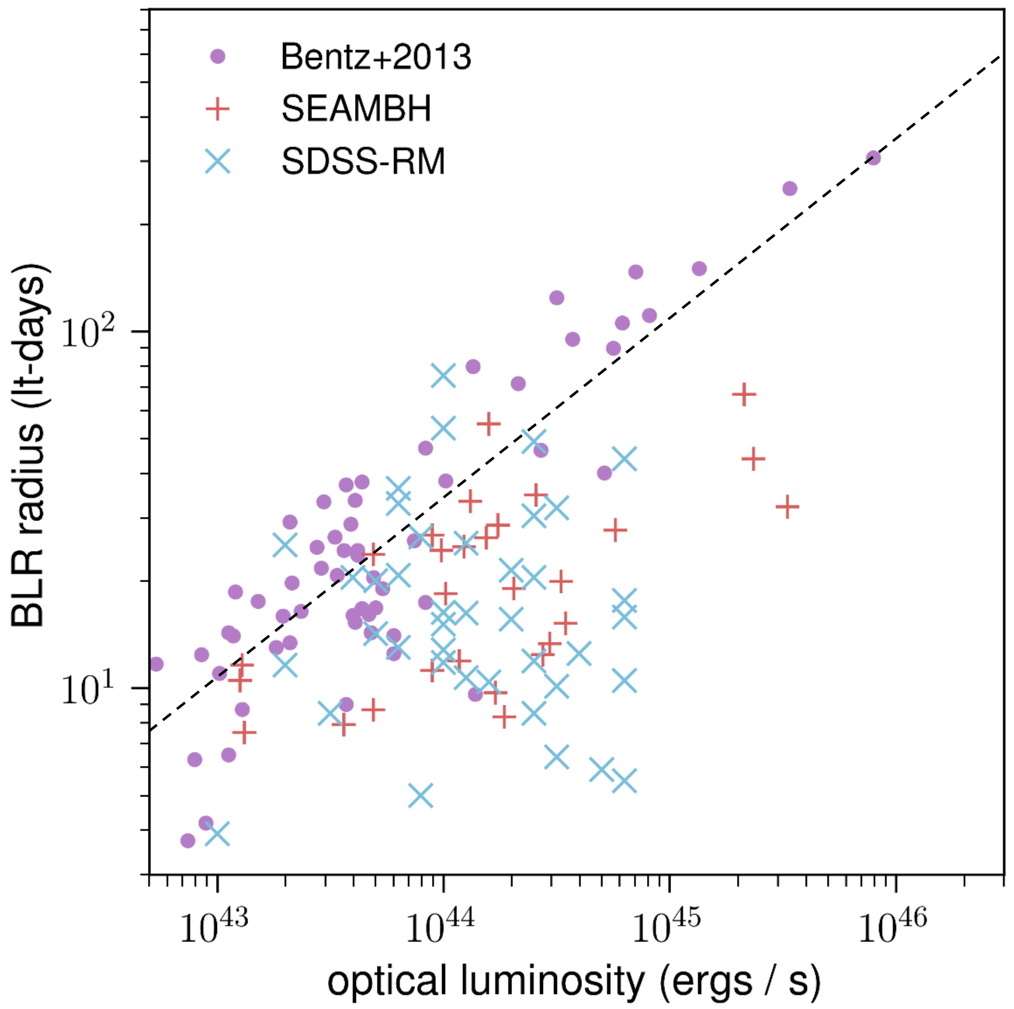
$$R_{BLR} = bL^{\alpha}$$

Broad Line Regions, Reverberation Mapping (RM), and Black Hole masses

$$R_{BLR} \sim L^{\alpha}$$

$\alpha \sim 0.5$

e.g. Bentz+2013



(Almost) all BH masses to date are measured like this !!
This is the only available method for measuring black hole mass in large surveys and out to high redshift

→ key role in our understanding of black hole growth over cosmic time.

Broad Line Regions, Reverberation Mapping (RM), and Black Hole masses

Comparison GRAVITY vs. RM for 3C273

- R_{BLR} = 46 +/- 10 μas
  150+/-40 lt-d RM: < 100 - 380
- $M_{BH} = 2\text{-}4 \times 10^8\ M_{sun}$ RM: $3\text{-}8 \times 10^8$
- BLR rotation dominated

Notepad - II

- BLR kinematics and structure as well as M_{BH} are consistent with RM results (for this one object); i.e. these findings support the use of virial relations to measure quasar masses.

Summary

- spectro-differential astrometry with the near-infrared interferometer GRAVITY on the VLTI reaches a precision of 10 μas (=0.03pc at D=550 Mpc for 3C273)
- The BLR in 3C273 is dominated by ordered rotation
- BLR kinematics and structure as well as M_{BH} are consistent with RM results (for this one object); i.e. these findings support the use of virial relations to measure quasar masses.
- Potentially a new, independent tool to understand BLR physics and to improve AGN black hole mass determinations.
- Potentially a new, powerful tool for measuring torus size and structure, etc.