Active Galactic Nuclei with GRAVITY and GRAVITY+

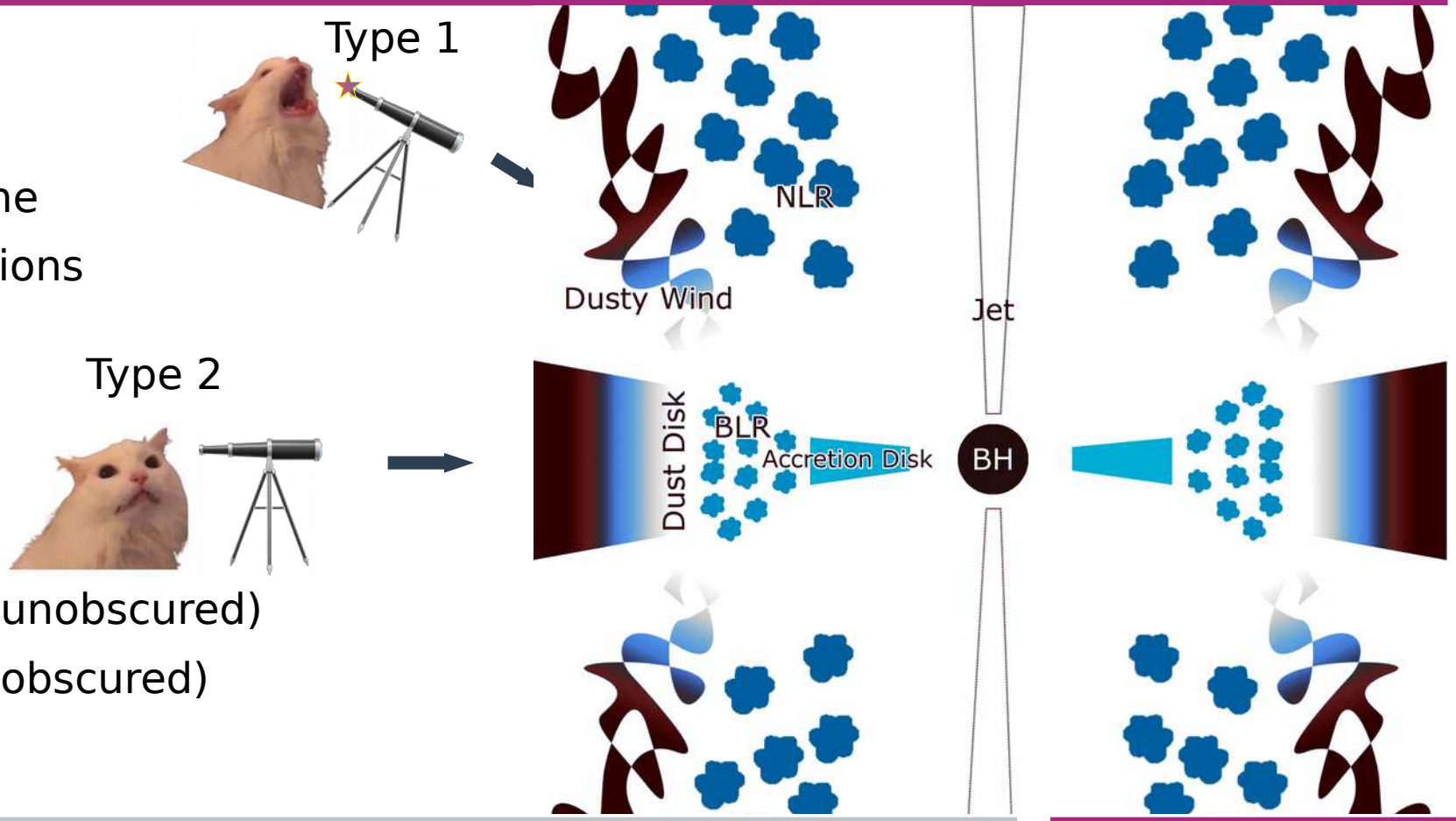
Taro Shimizu

James Leftley

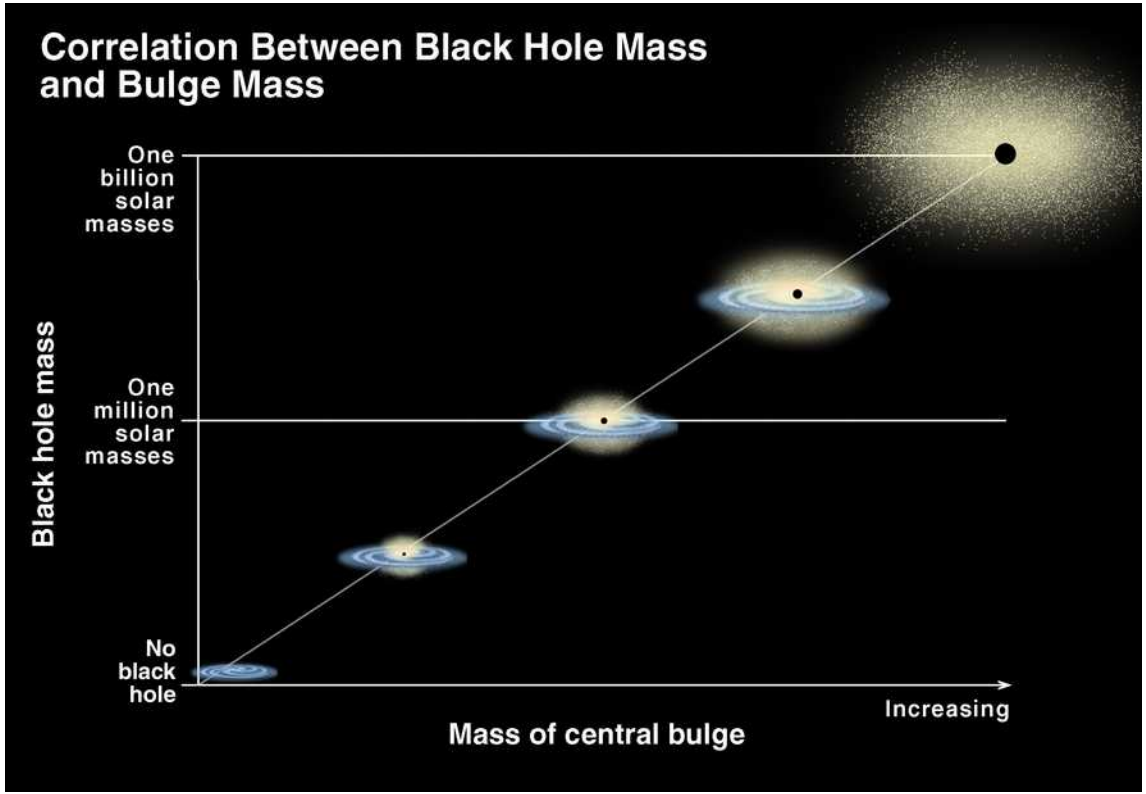
Sebastian Hoenig

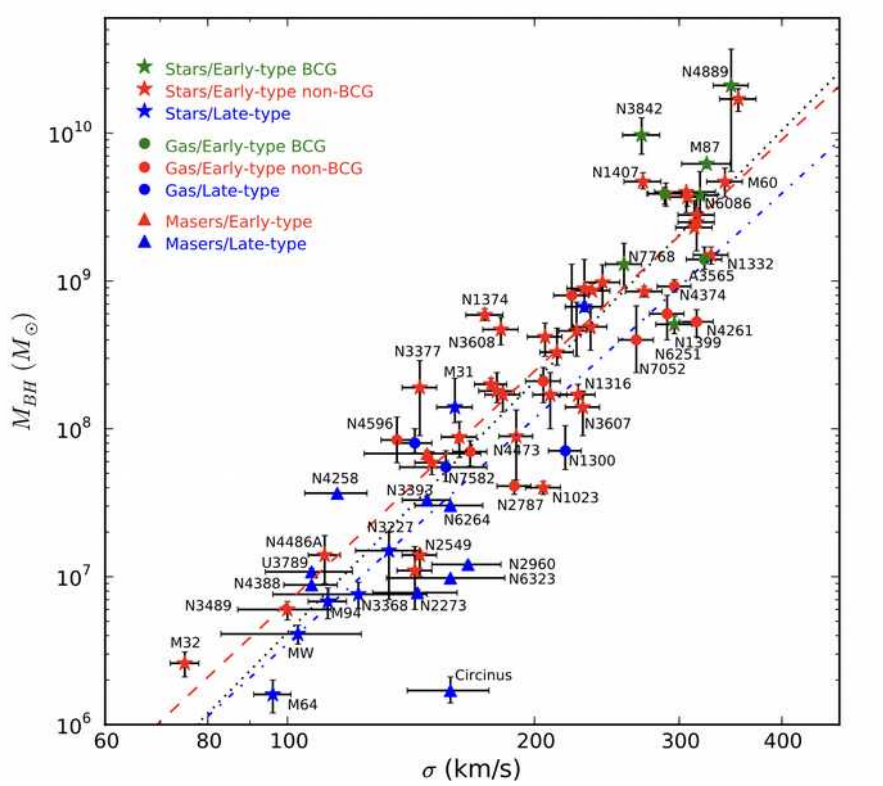
AGN overview

- Central engine
- Emission regions
  - BLR
  - NLR
- Type 1 AGN (unobscured)
- Type 2 AGN (obscured)



SMBH-galaxy local scaling relations indicate coevolution

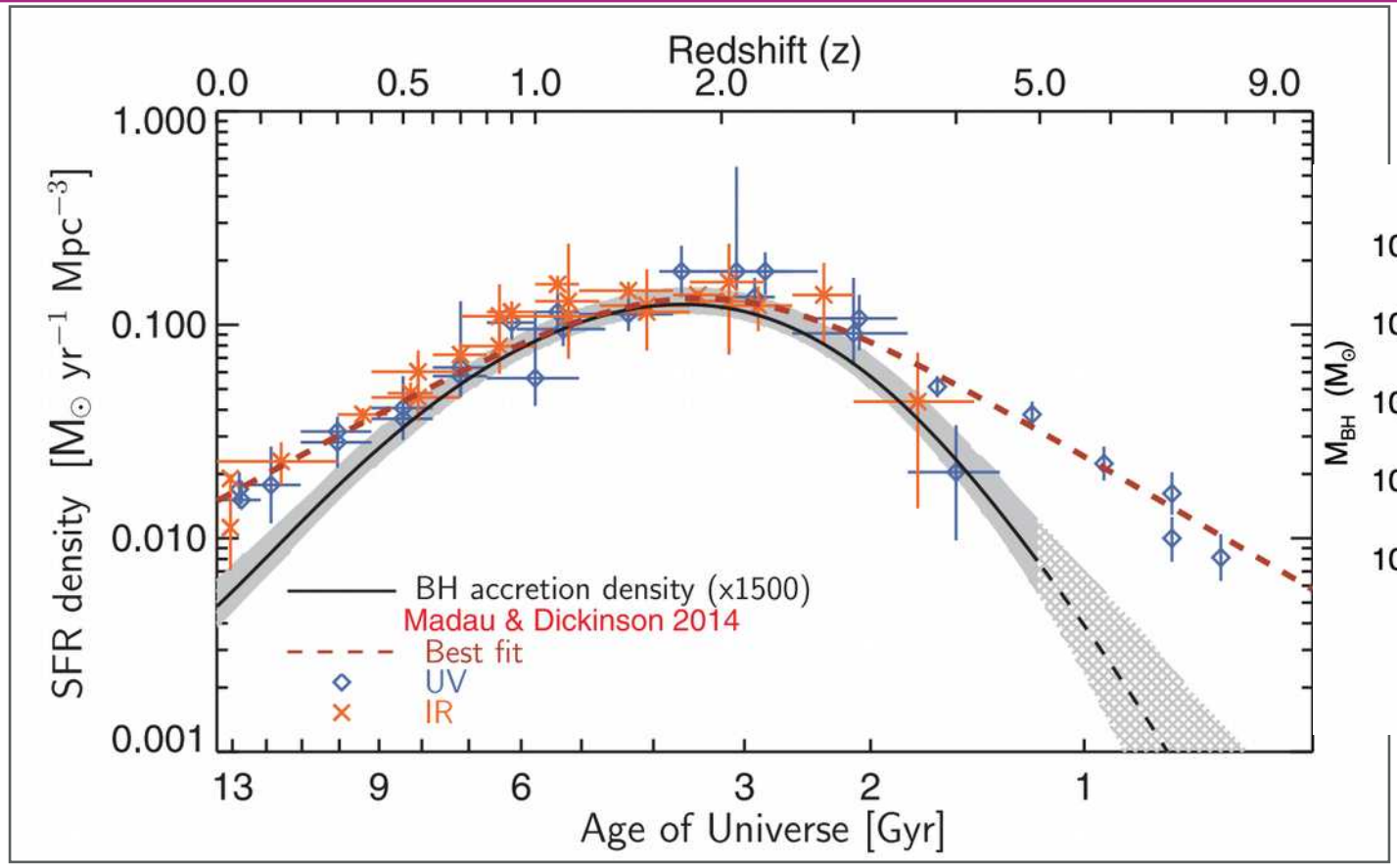


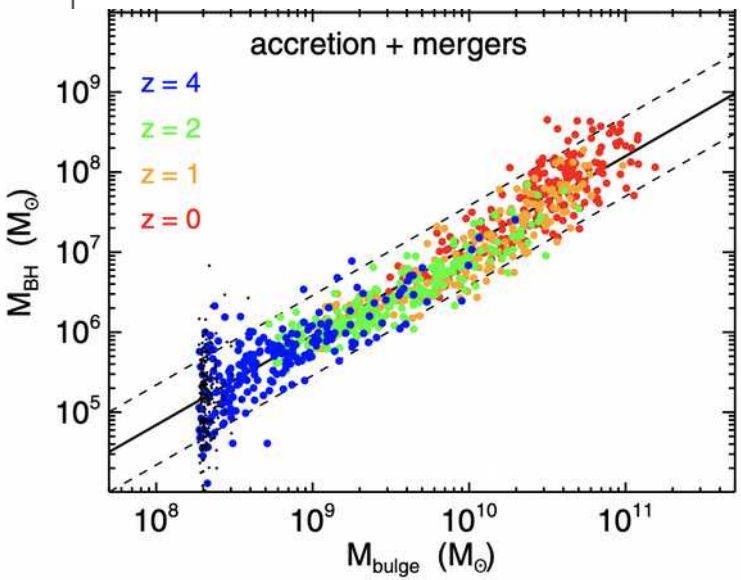


Credit: NASA/STSCI

McConnell & Ma 2013

Accretion and star formation histories broadly coincide





Broad Goals

1. What is the structure of AGN

- Dust and gas
- Inflows and outflows
- Evolution with accretion rate and mass

2. How do AGN influence the galaxy

- Feedback should exist but what transfers the energy
- How are the black hole and galaxy linked?

3. Black hole growth

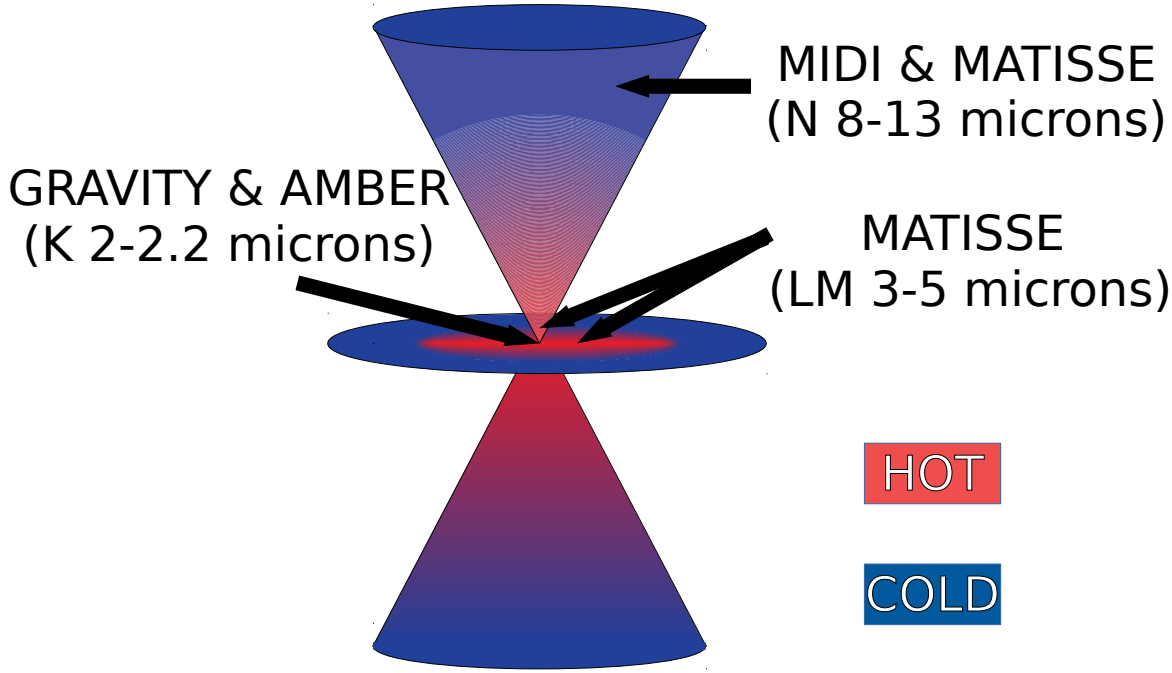
- How do black holes grow to local sizes?

VLTI and AGN dust

MIDI showed polar dust extensions

AMBER found ring like sublimation regions in type-1

GRAVITY and MATISSE improved upon this



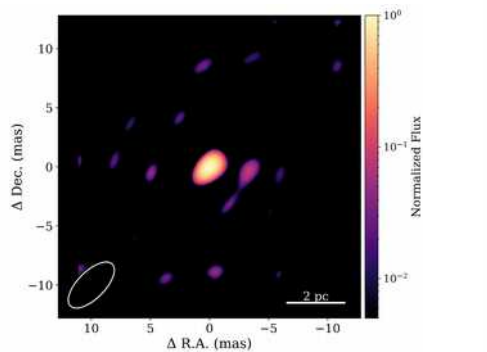
Dust – local AGN

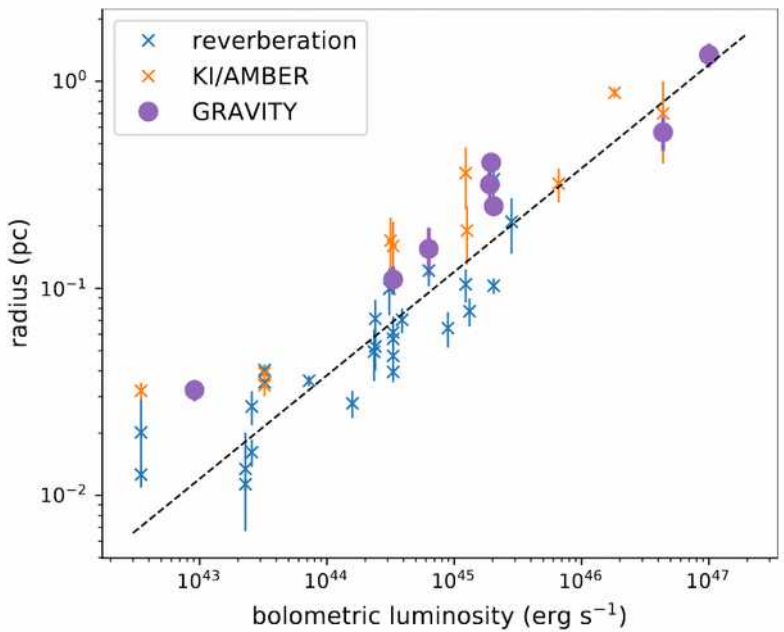
GRAVITY observe hottest dust

- Sublimation region in Sy1
- Clumpy in Sy2

Main results

- Images of local AGN
- Confirmed L-R relation
  - Possible deviation

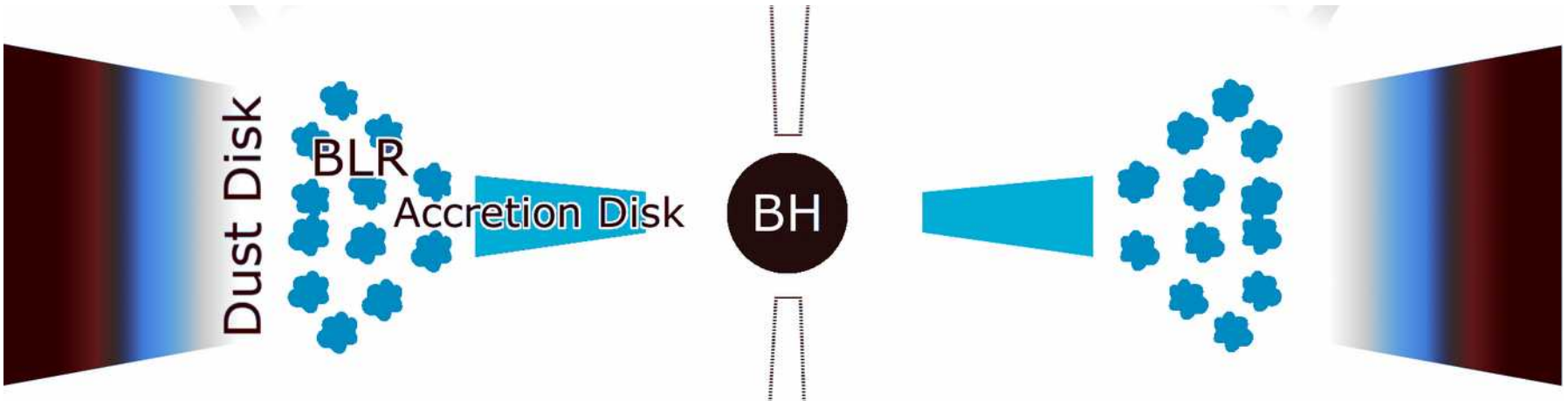




The BLR - simplified

The BLR is likely a complex system of inflow/disk and outflows

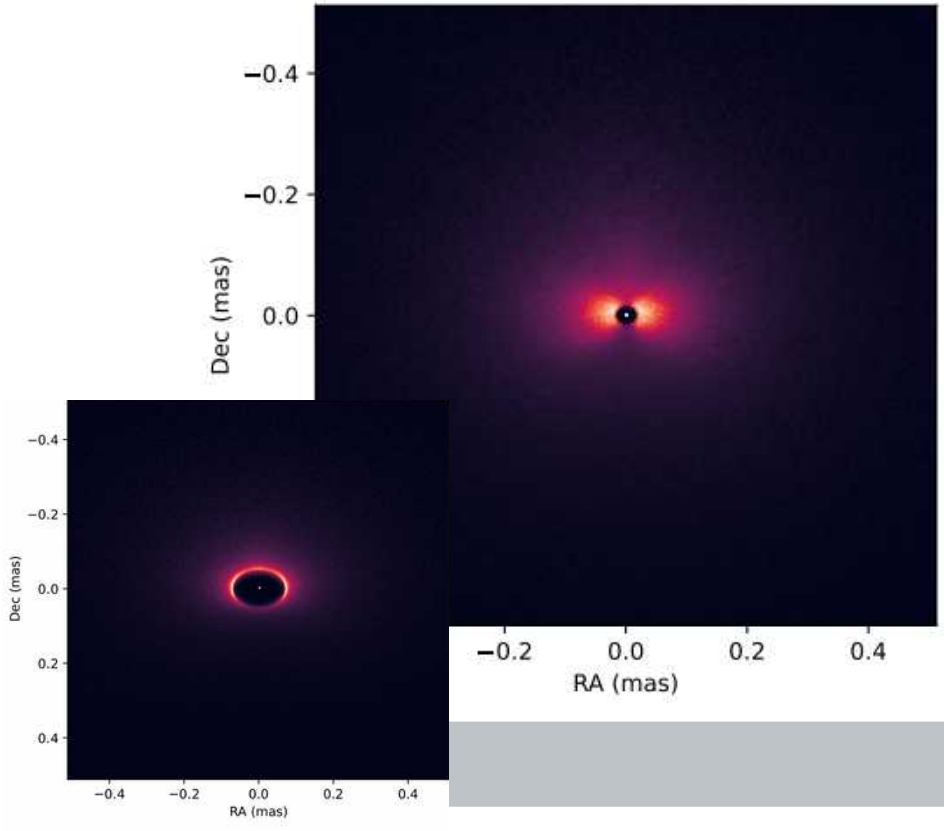
For simplicity we assume a disk dominates (for now)

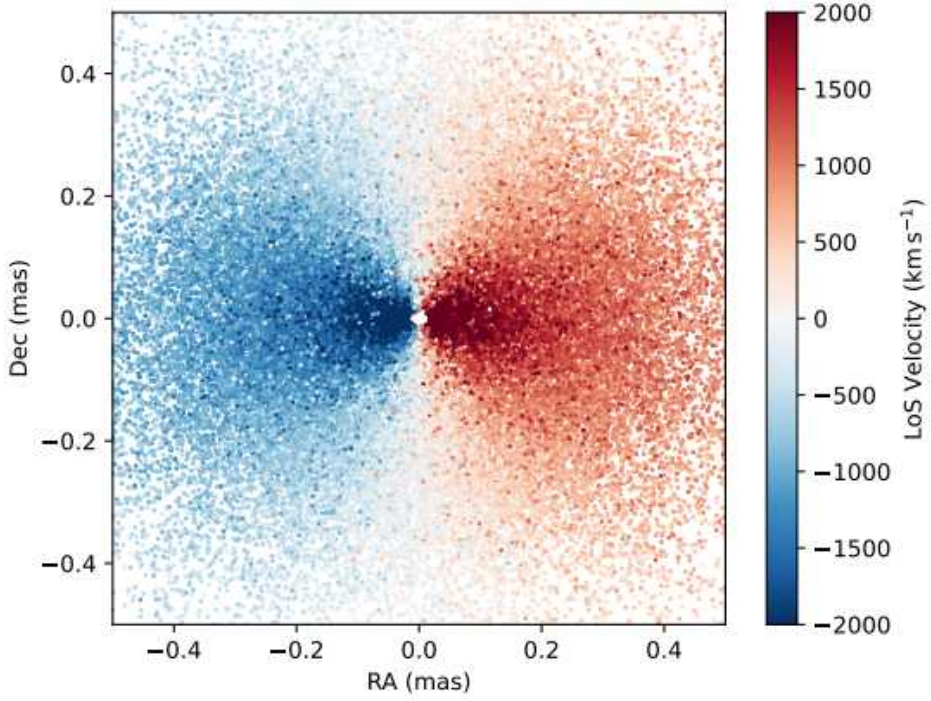


A BLR disk

A rotating thick disk of line emitting gas

Line offset by velocity





BLRs in galaxy evolution studies

Black hole masses

Difficult to determine in large samples

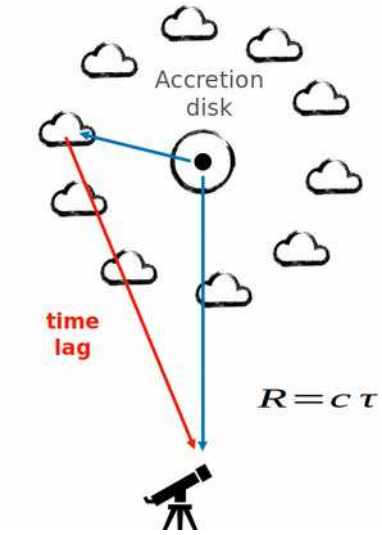
Needed for SMBH – galaxy evolution studies

Distances

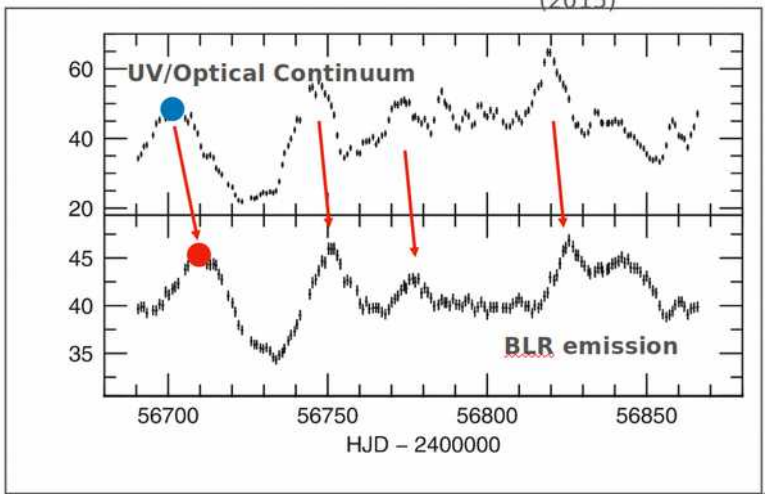
Independent from cosmic distance ladder

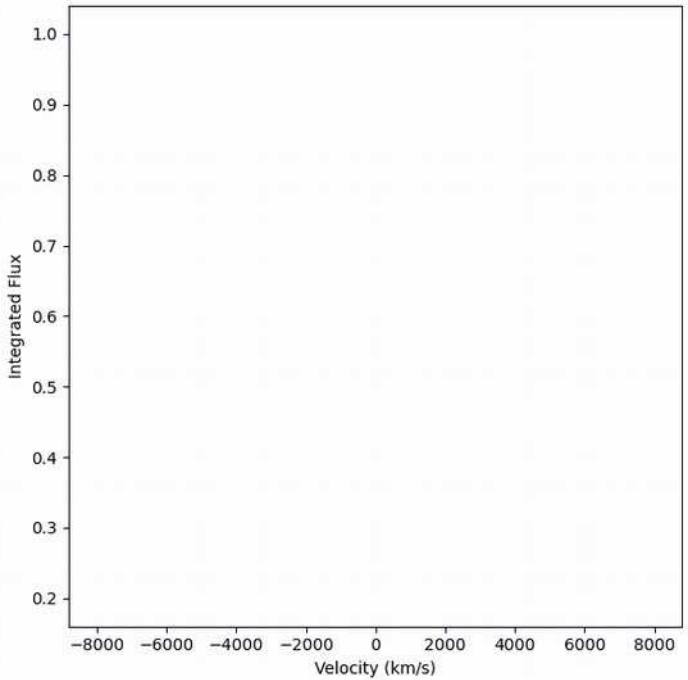
Useful for cosmology and Hubble tension

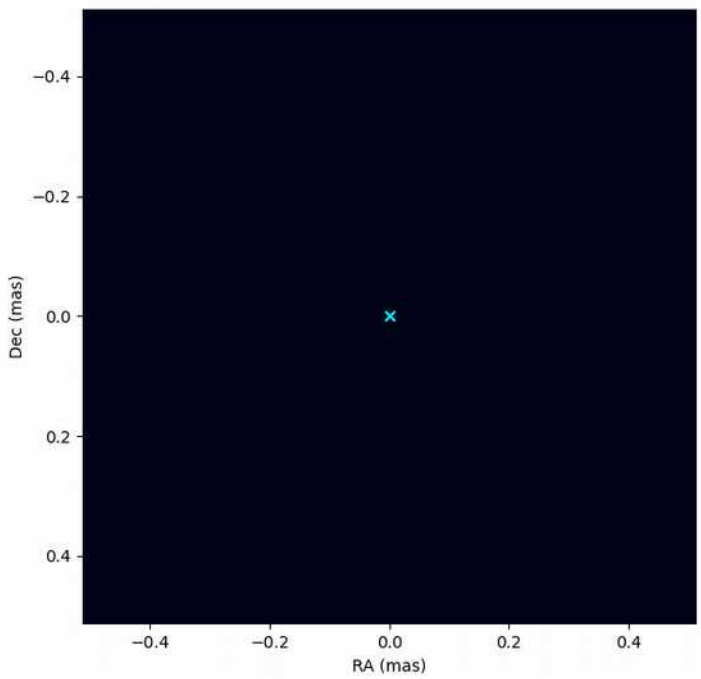
Requires reverberation mapping

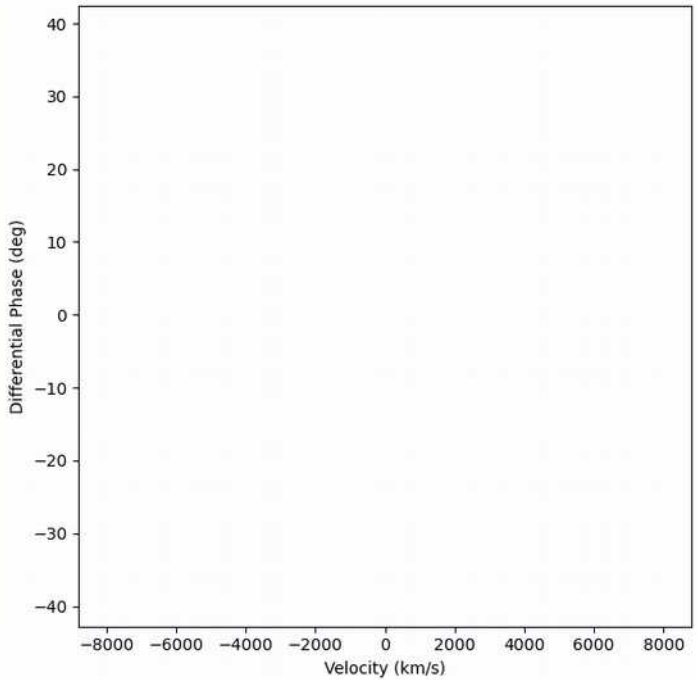


adapted from De Rosa et al. (2015)

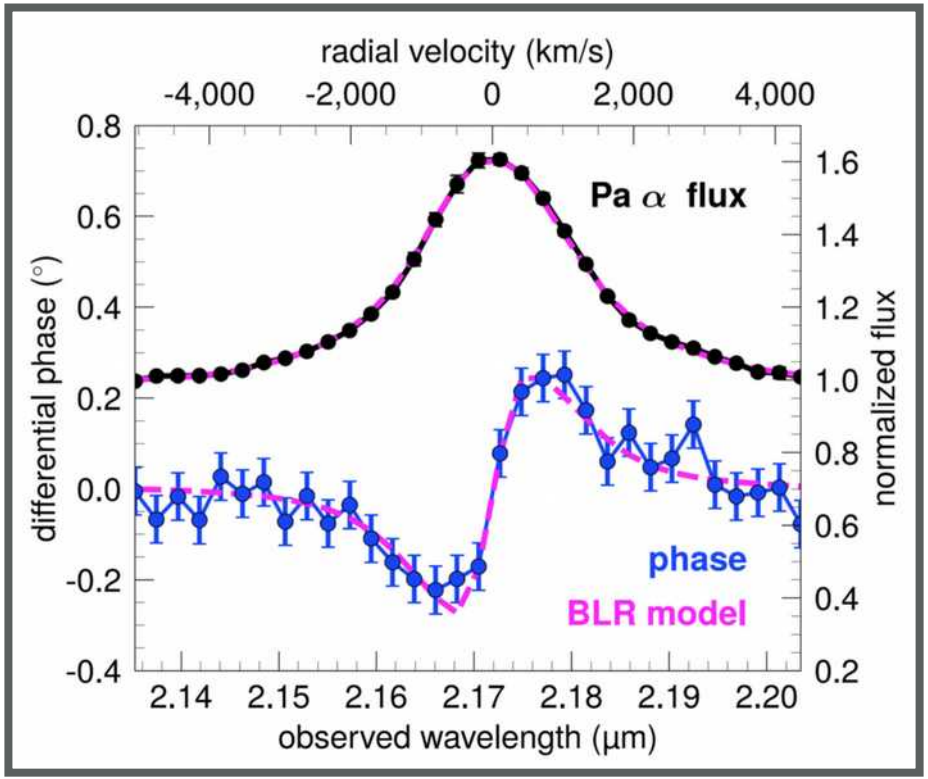


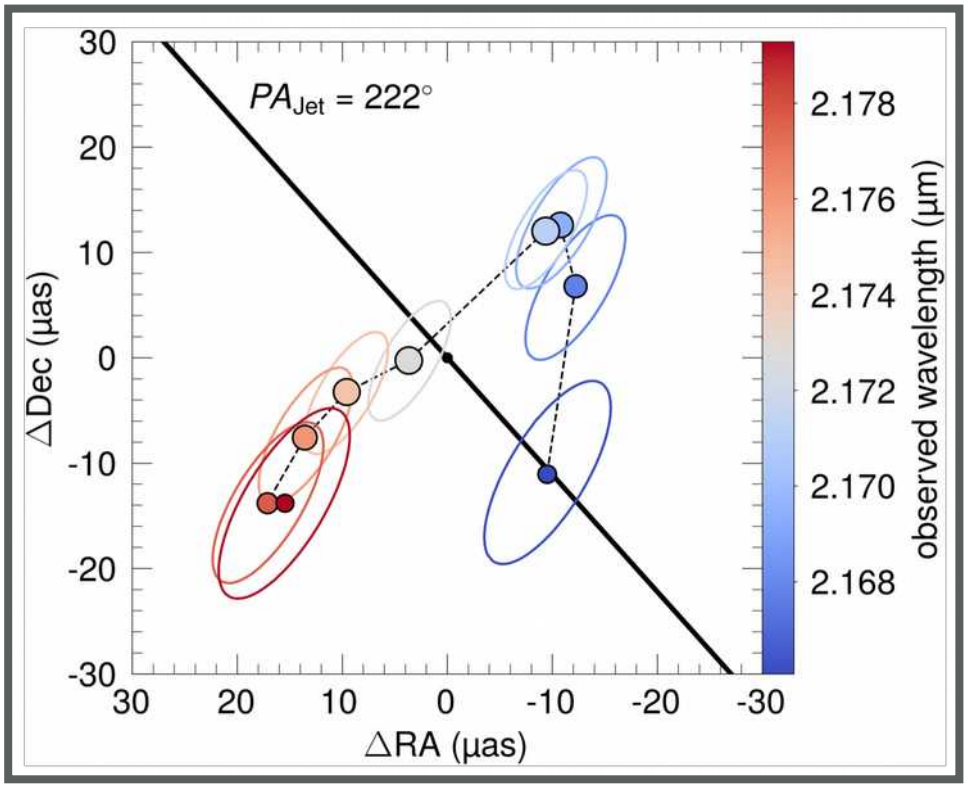

Integrated Flux
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
−8000 −6000 −4000 −2000 0 2000 4000 6000 8000
Velocity (km/s)


Dec (mas)
−0.4
−0.2
0.0
0.2
0.4
−0.4 −0.2 0.0 0.2 0.4
RA (mas)


Differential Phase (deg)
40
30
20
10
0
−10
−20
−30
−40
−8000 −6000 −4000 −2000 0 2000 4000 6000 8000
Velocity (km/s)

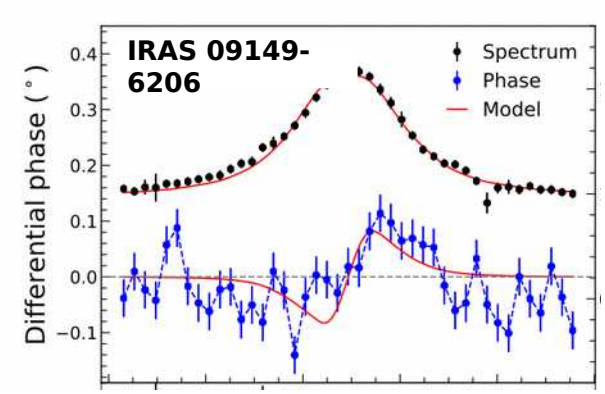
GRAVITY resolves the first BLR in 3C 273

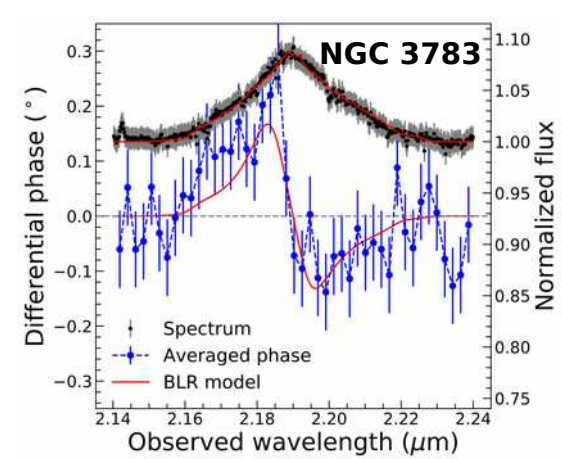


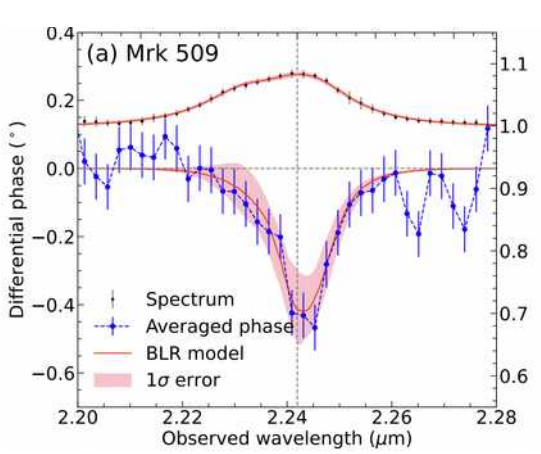


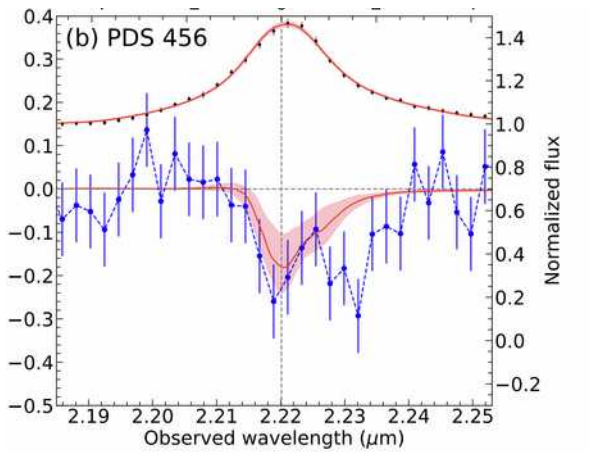
GRAVITY Collaboration 2018, Nature

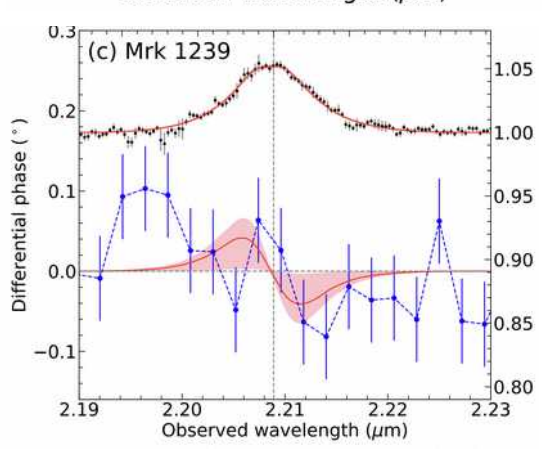
GRAVITY-AGN Large Programme: a sample of resolved BLRs

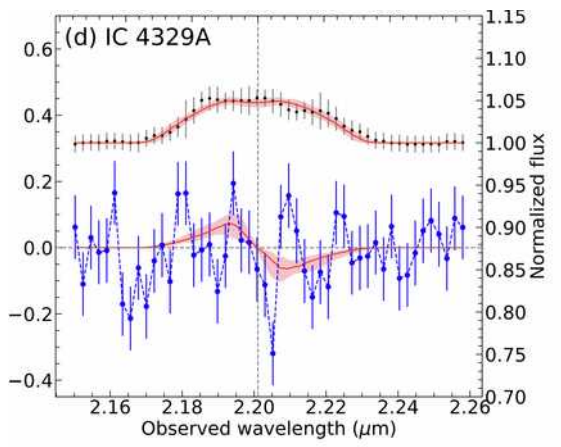












GRAVITY-AGN Radius-Luminosity Relation: a flatter slope?

Gradient of 0.37

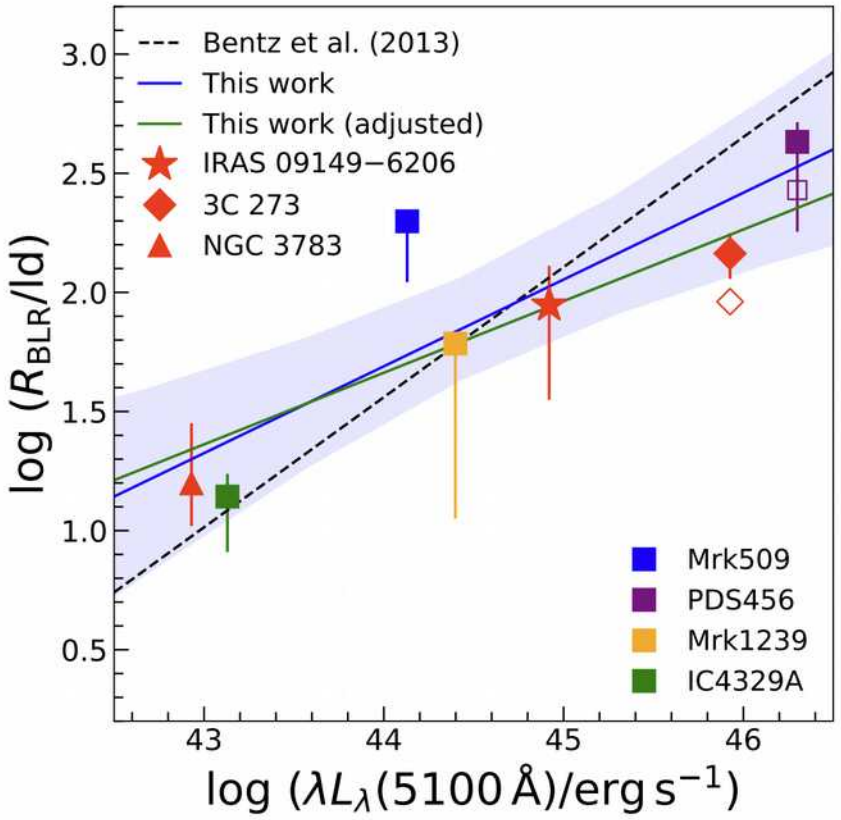
Compared to 0.53 from Bentz+2013

Two possibilities:

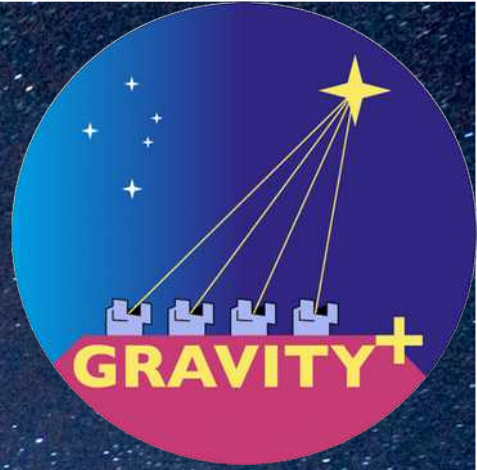
Smaller BLR in high Eddington AGN (Du+2018 Du & Wang 2019)

SED change at high luminosity

Converting to bolometric luminosity does recover alpha=0.5 relation

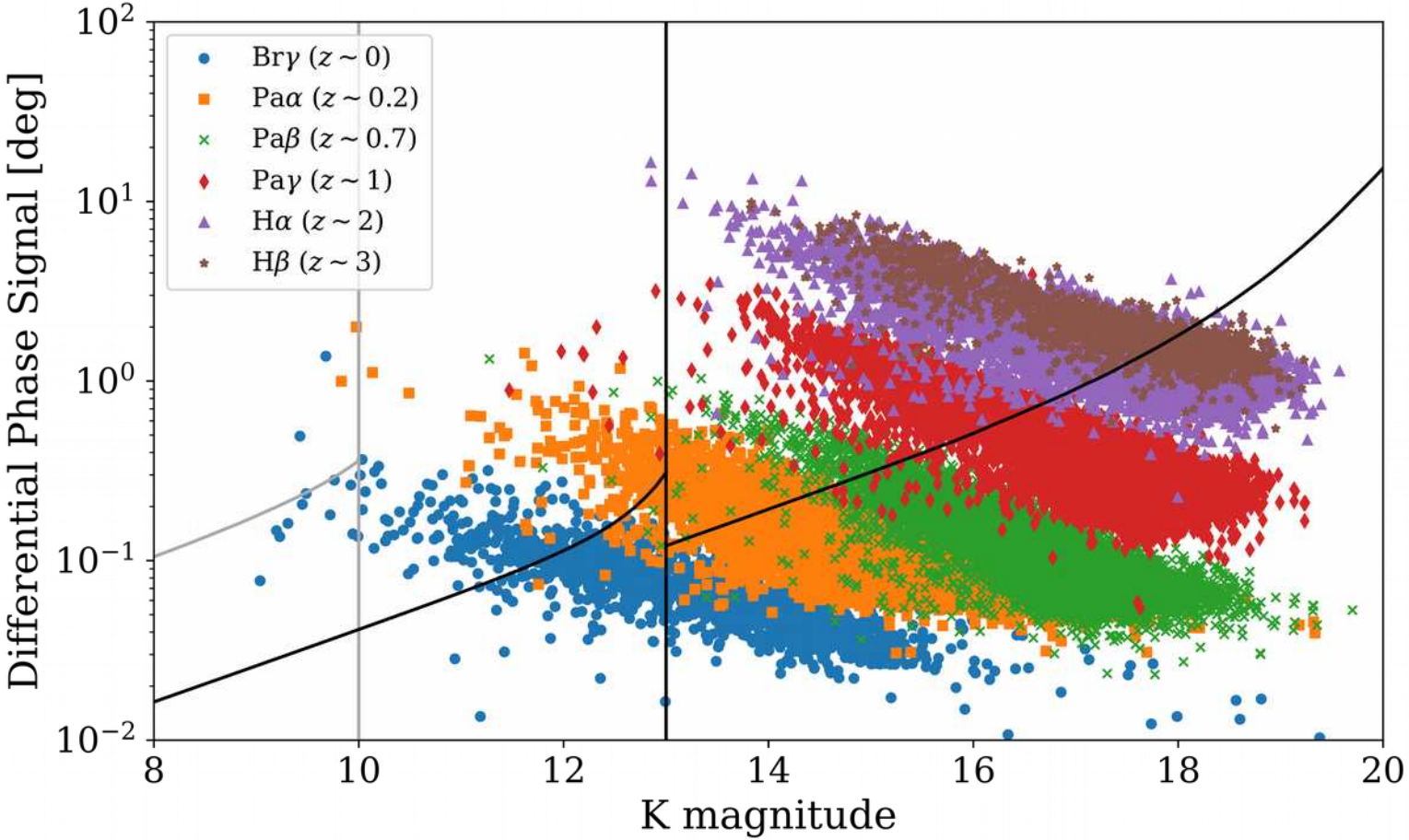


From GRAVITY to GRAVITY+



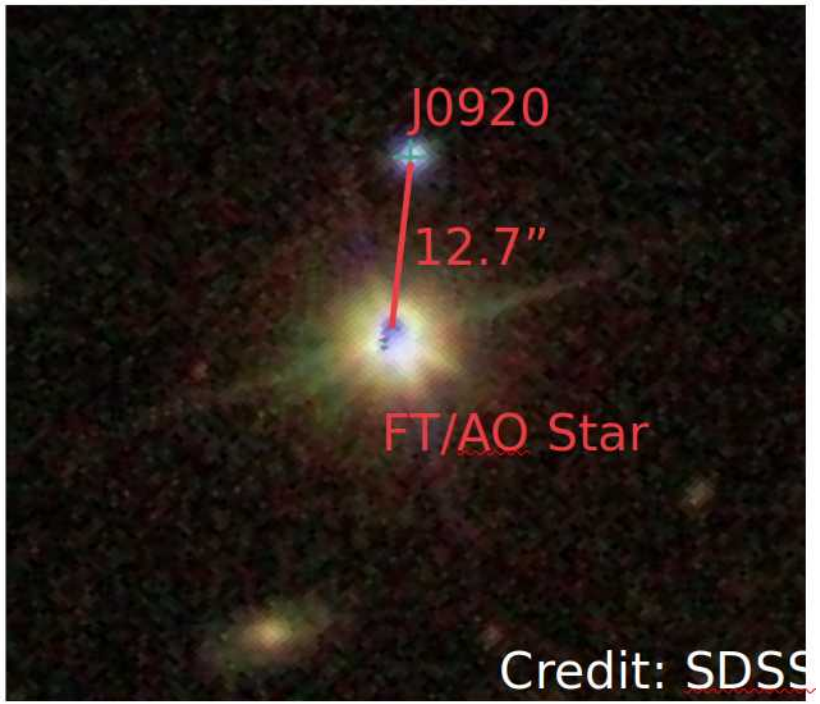
- Wide Angle Off-axis Fringe Tracking — Now
- Improved Vibration Control — Now
- State of the Art Adaptive Optics — In progress
- Laser Guide Stars for all UTs - 2026

Many more targets



High z BLR

SDSS J092034.17+065718.0 (J0920): A prime first target

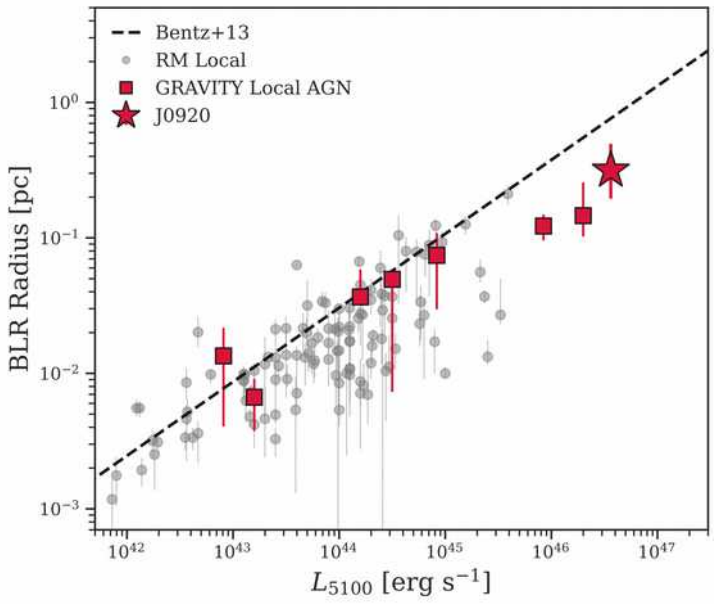


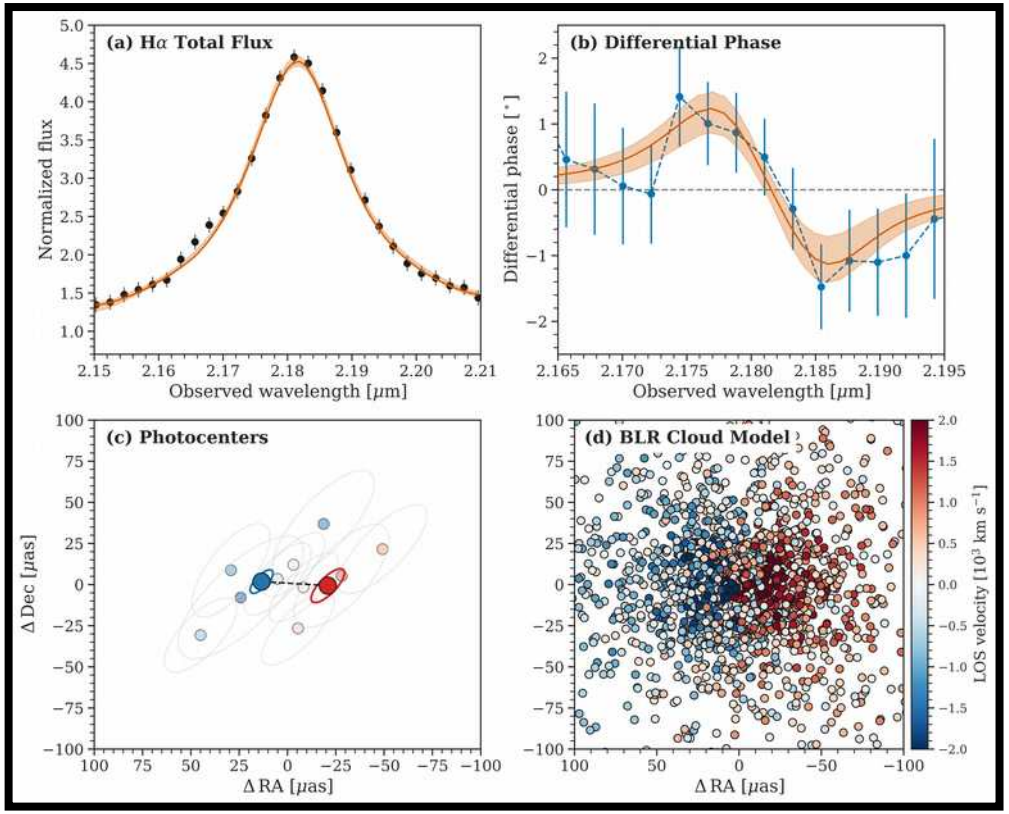
- Selected from *Milliquas* Catalog
- Very bright quasar: K = 15, $L_{Bol} \sim 10^{47}$ erg/s
- z = 2.3 —> H in K-band
- Bright star (K ~ 10) nearby to quasar (12.7”)
- Observed with GRAVITY+ for 3.6 hrs

J0920 is offset from the local R-L relation

BLR size factor of ~2.5 smaller than R-L relation

BLR size follows previous trend of flattening at high-L and/or high L/LEdd



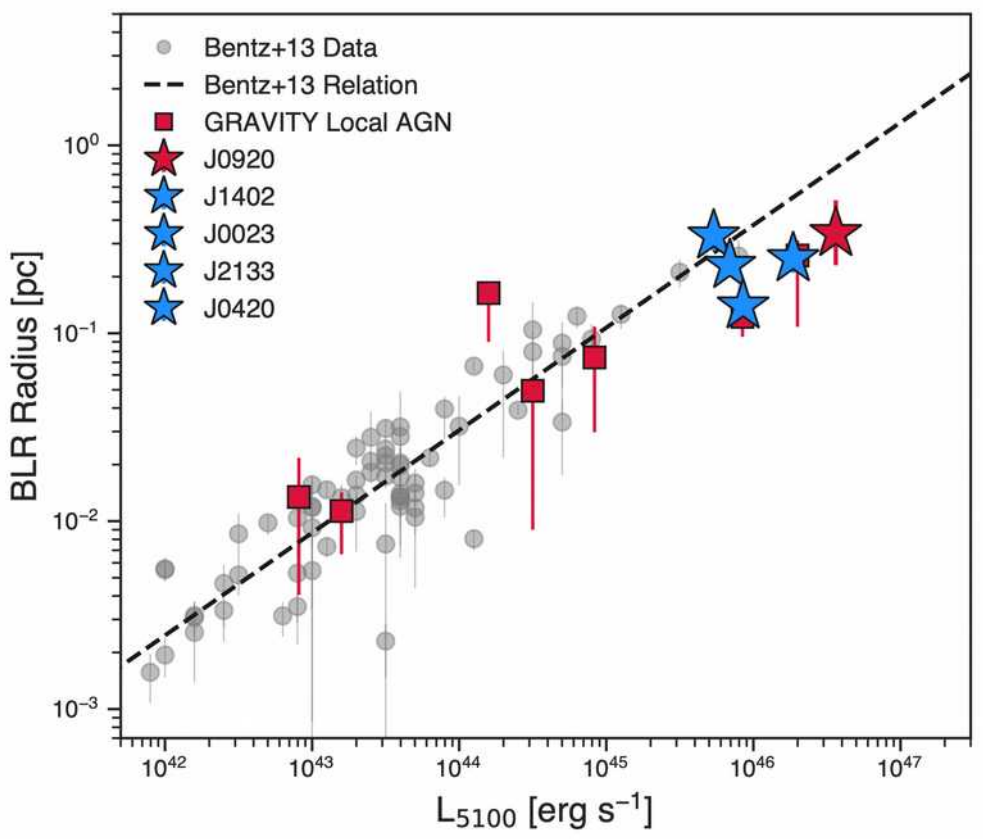


More targets

Preliminary

Several targets observed

BLR detected



Future possibilities – non exhaustive

Local fainter or redder targets

- Obscured AGN
- Low power AGN

Accretion disks

- In extreme cases

Binary super massive black holes

- Sub-pc galaxy merger remanents

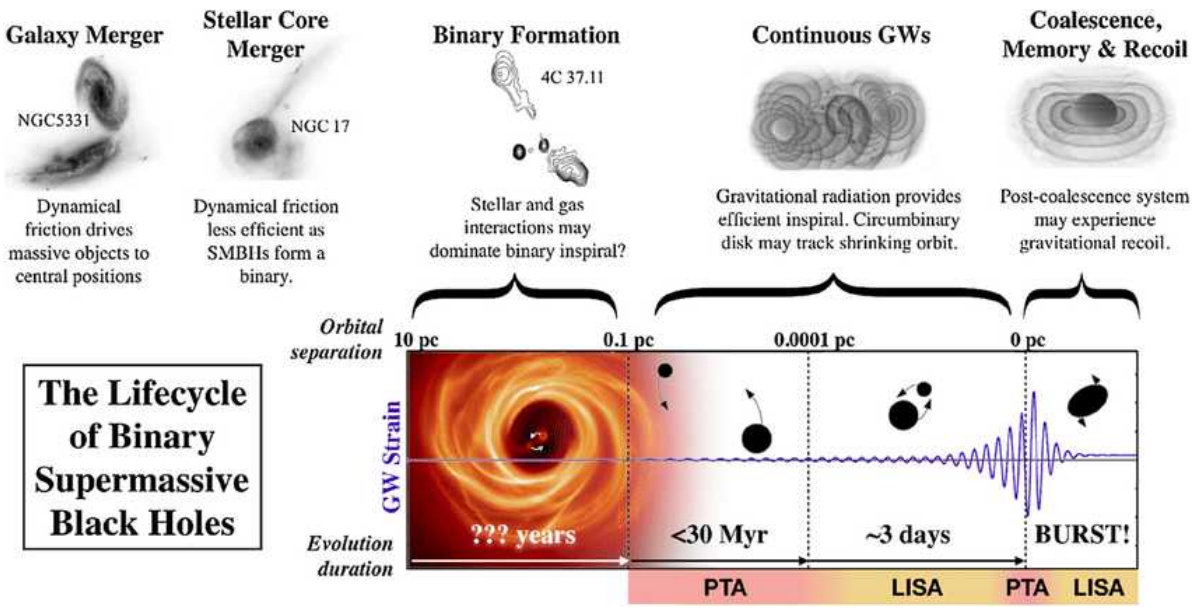
Polarisation

Dual SMBH

Late stage merger remnants

AGN feeding can be triggered by mergers (e.g. Gao+2020)

Dual AGN detection methods are separation dependent



All Sky	→	AO/Spectral	→	???	→	Gravitational waves
Kpc	→	pcs	→	sub-pc	→	ld
GAIA/LSST	→	ERIS	→	VLTI	→	LISA/PTA

Burke-Spolaor+2019

MATISSE in this context

MATISSE can provide complimentary science

Inclination degeneracy introduces error in SMBH mass

Locally GRAVITY can observe sublimation region

Prior information for system inclination from dust

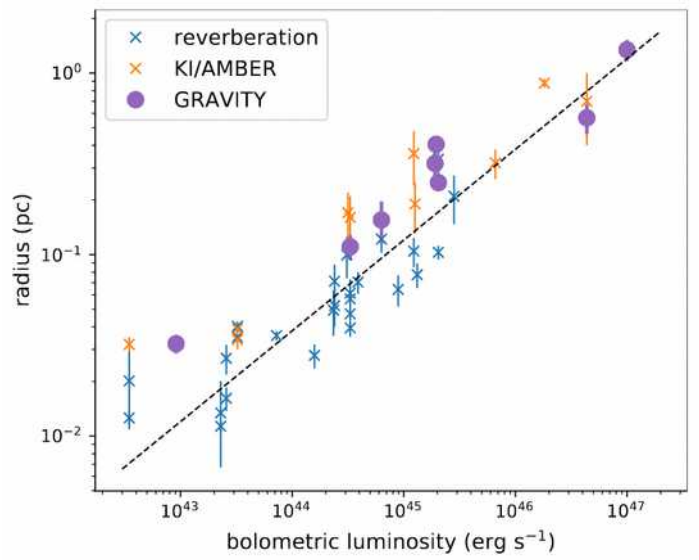
At high z, sublimation region is in LM (0.5<z<~2)

Line BLR size comparisons?

e.g. Hbeta vs PaAlpha/BrGamma

Radius-luminosity relationship at high z/ extreme AGN?

GRAVITY+MATISSE Polarisation



Summary

GRAVITY is a powerful tool to study AGN dust and gas

- It has imaged the dust some targets and confirmed the AMBER/Keck offset R-L relation
- It has resolved the BLR in several AGN and directly measured SMBH mass
- GRAVITY measured BLRs are starting to show a flatter than usual R-L relation, possible related to changes in the SED or smaller sizes for high Eddington ratio

GRAVITY+ has extended resolved BLR studies out to cosmic noon, allowing for the first time direct black hole mass measurements at high-z.

- The measured black hole mass of J0920 reveals an undermassive, super Eddington SMBH undergoing a rapid transition to a massive elliptical galaxy.
- We are now building a high precision sample of z=2 quasars to test SMBH-galaxy coevolution

GRAVITY could be used to begin investigating sub-pc dual SMBHs for LISA