SARM

Joint Analysis of SpectroAstrometry and Reverberation Mapping of 3C273

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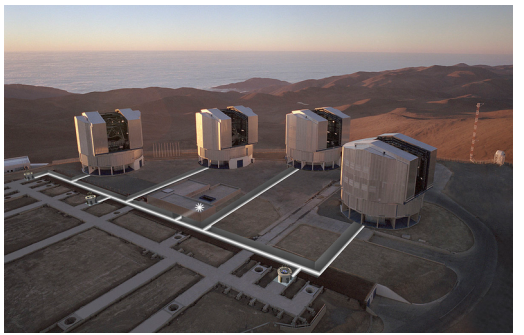


Outline

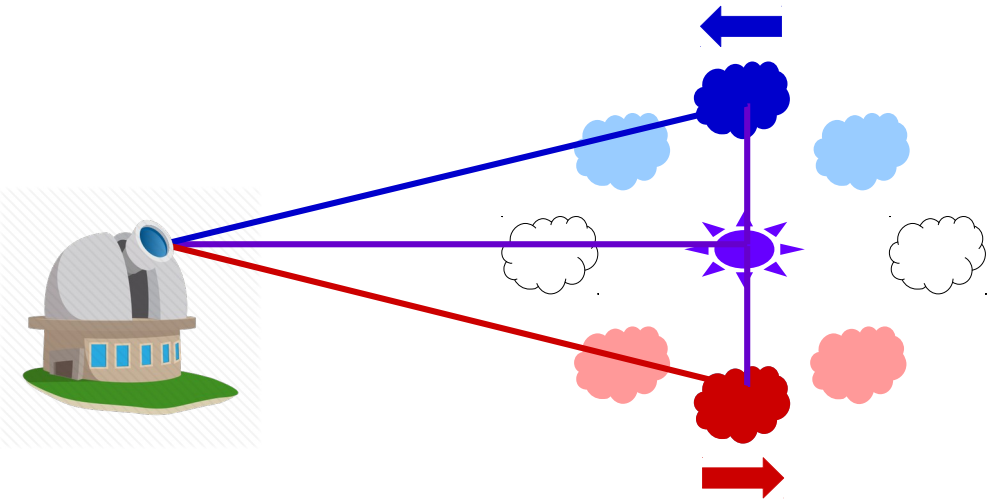
1. Joint analysis of SARM data
2. Application to 3C273
3. Future of SARM

What RM measures (Peterson's talk)

$$c\tau_{\rm lag} = r - \boldsymbol{r}\cdot\boldsymbol{n}_{\rm obs}$$

linear size of the BLR (ΔR)

structure along the line of sight



LOS velocities versus lags

velocity delay maps

black hole mass

What SA measures (Sturm's talk)

LOS velocities => angular displacements => optical path differences => differential phase

projection on to baseline

$$\phi_*(\lambda, \lambda_\mathrm{r}) = -2\pi \boldsymbol{B} \cdot [\boldsymbol{\epsilon}(\lambda) - \boldsymbol{\epsilon}(\lambda_\mathrm{r})]/\lambda$$

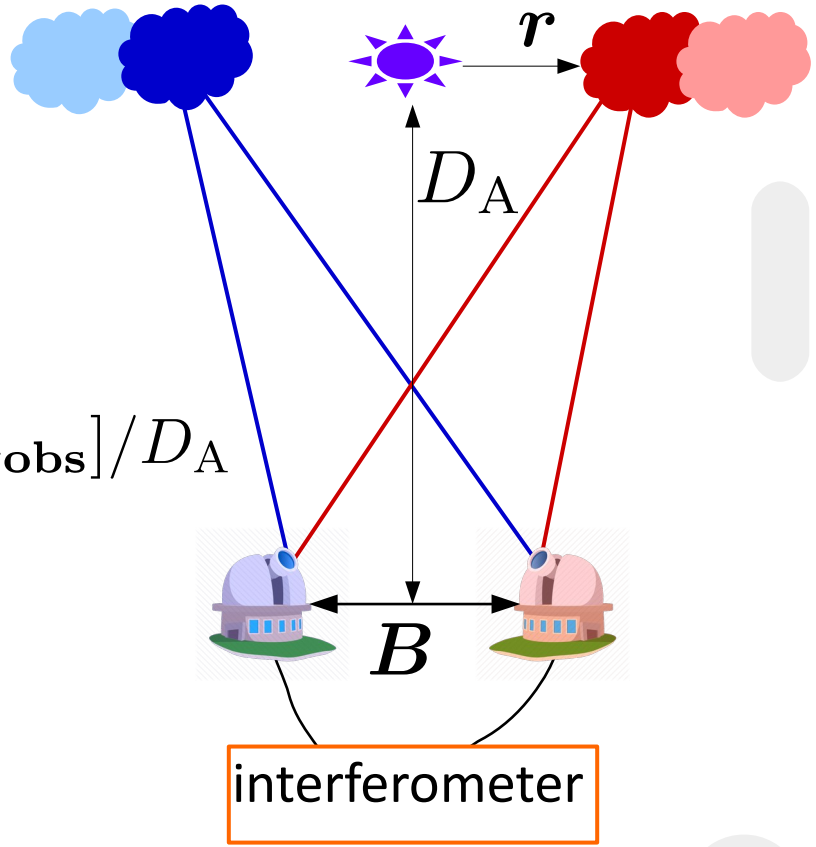
observed

$$\boldsymbol{\epsilon}(\lambda) = \bar{\boldsymbol{\alpha}}(\lambda) \sim [\boldsymbol{r} - (\boldsymbol{r} \cdot \boldsymbol{n}_\mathrm{obs})\boldsymbol{n}_\mathbf{obs}]/D_\mathrm{A}$$

angular size of the BLR (ΔΘ)

structure ⊥ LOS

$10\mu\mathrm{as}$ resolution



Assuming $D_\mathrm{A} \rightarrow R_\mathrm{BLR}$ and $M_\bullet$

Aims: Combining supplementary data

- angular and linear size

$$D_{\mathrm{A}} = \frac{\Delta R}{\Delta \theta}$$

- along and perpendicular to the LOS

measuring distance and BH mass simultaneously and precisely

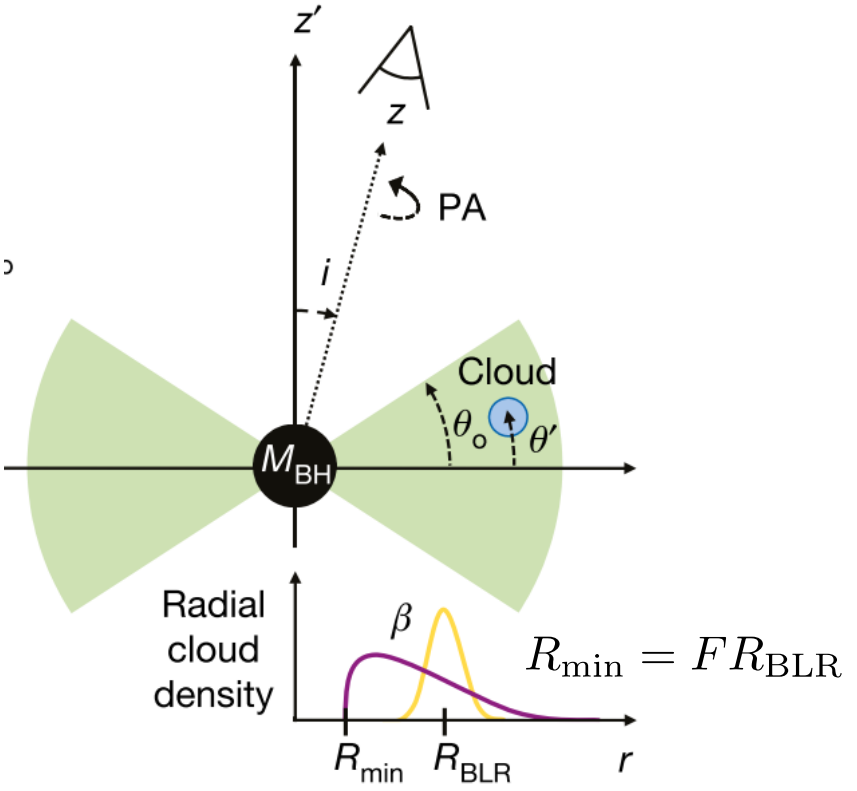
BLR model: geometry and kinematics

BLR Model

Parameters	GRAVITY	1D-RM
$\mathscr{F}$	√	√
β	√	√
$\theta_o(^\circ)$	√	√
$i_0(^\circ)$	√	√
PA$(^\circ)$	√	
$R_{\rm BLR}$(ltd)		√
$M_\bullet(10^8 M_\odot)$		
$D_{\rm A}$(Mpc)		
$\xi_{\rm BLR}$ (μas)	√	
η (10^{-2})	√	

$\xi_{\rm BLR} = R_{\rm BLR}/D_{\rm A}$

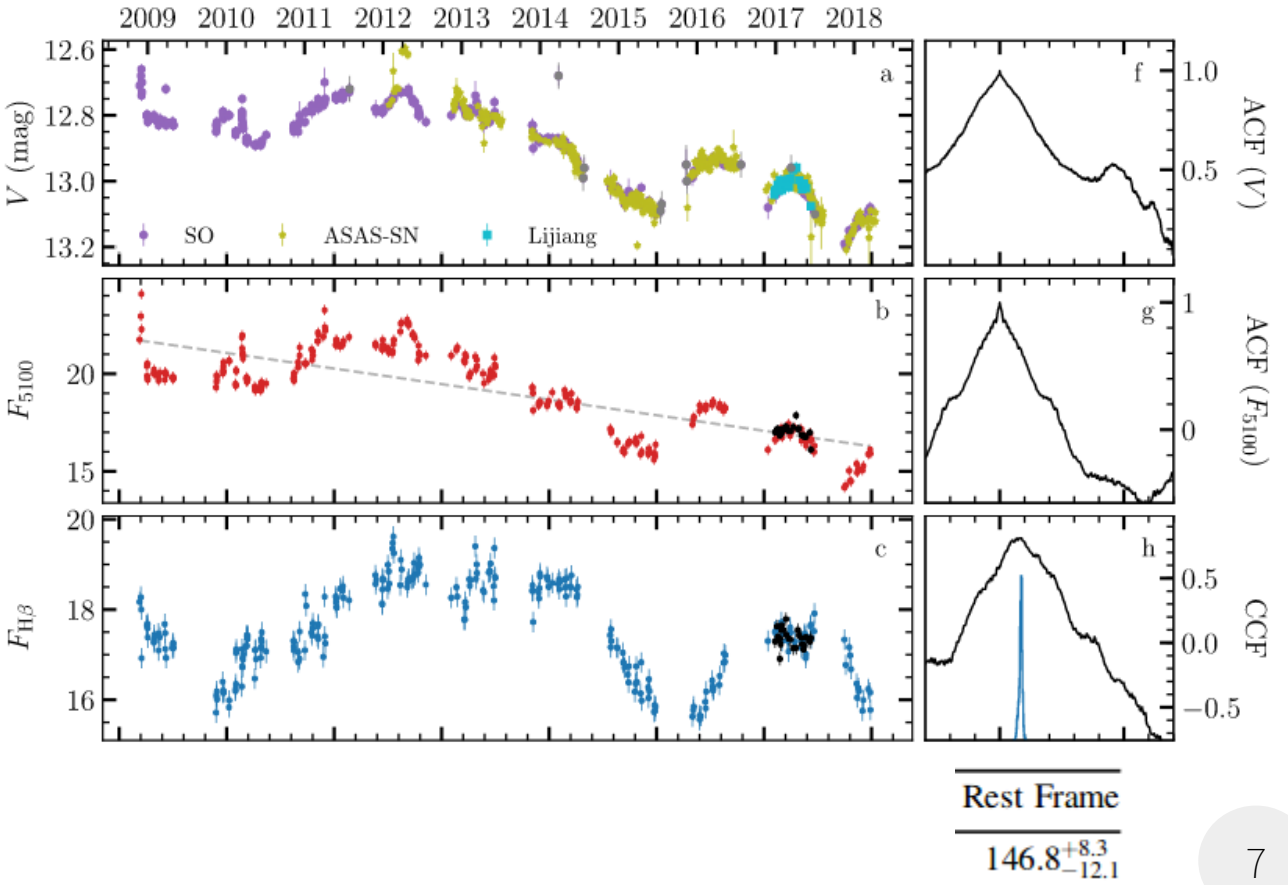
$\eta = (GM_\bullet/R_{\rm BLR})^{1/2} c^{-1}$



GRAVITY Collaboration, 2018

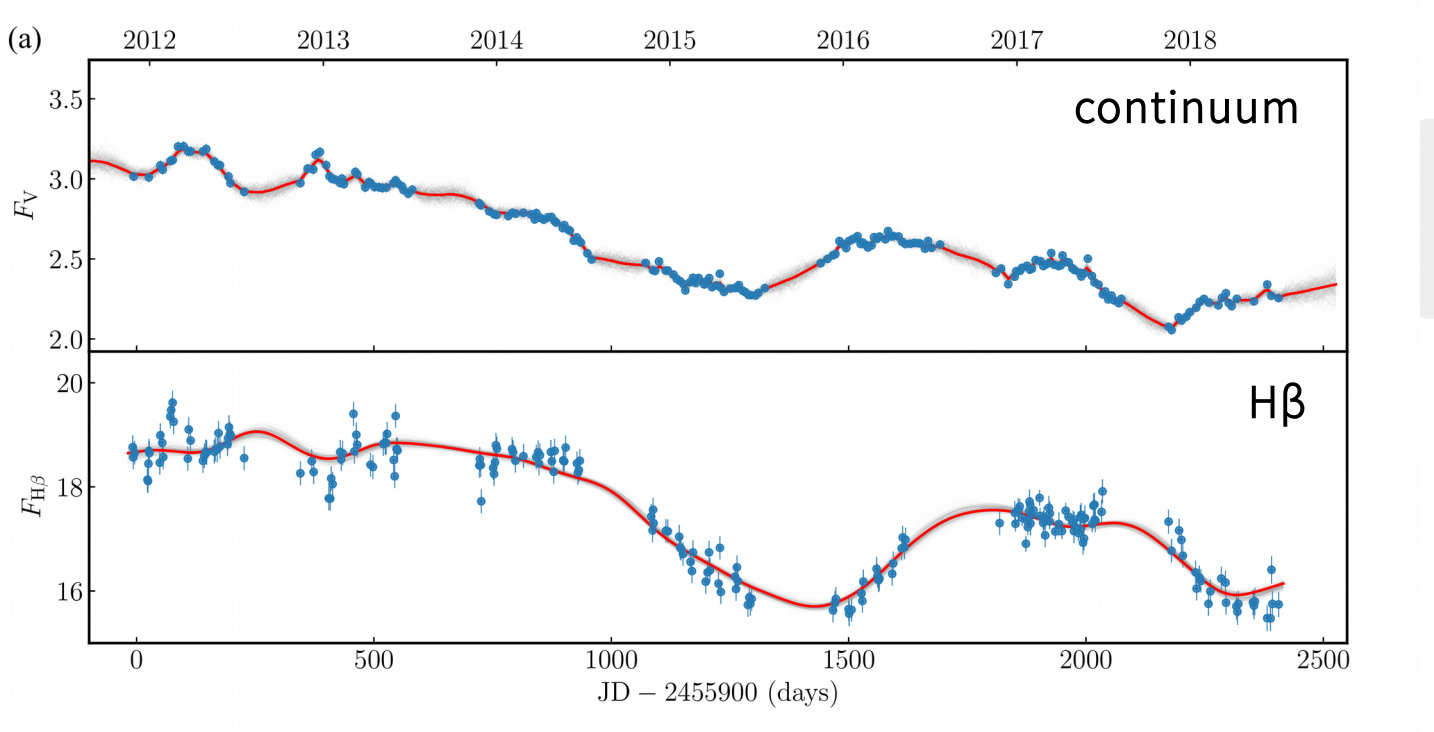
RM of 3C273 (Zhang+ 2019)

- 10yr RM
- Bok 2.3m + Lijiang 2.4m
- Long-term trending (jet contaminations: Li+2019: arXiv:1909.4451)

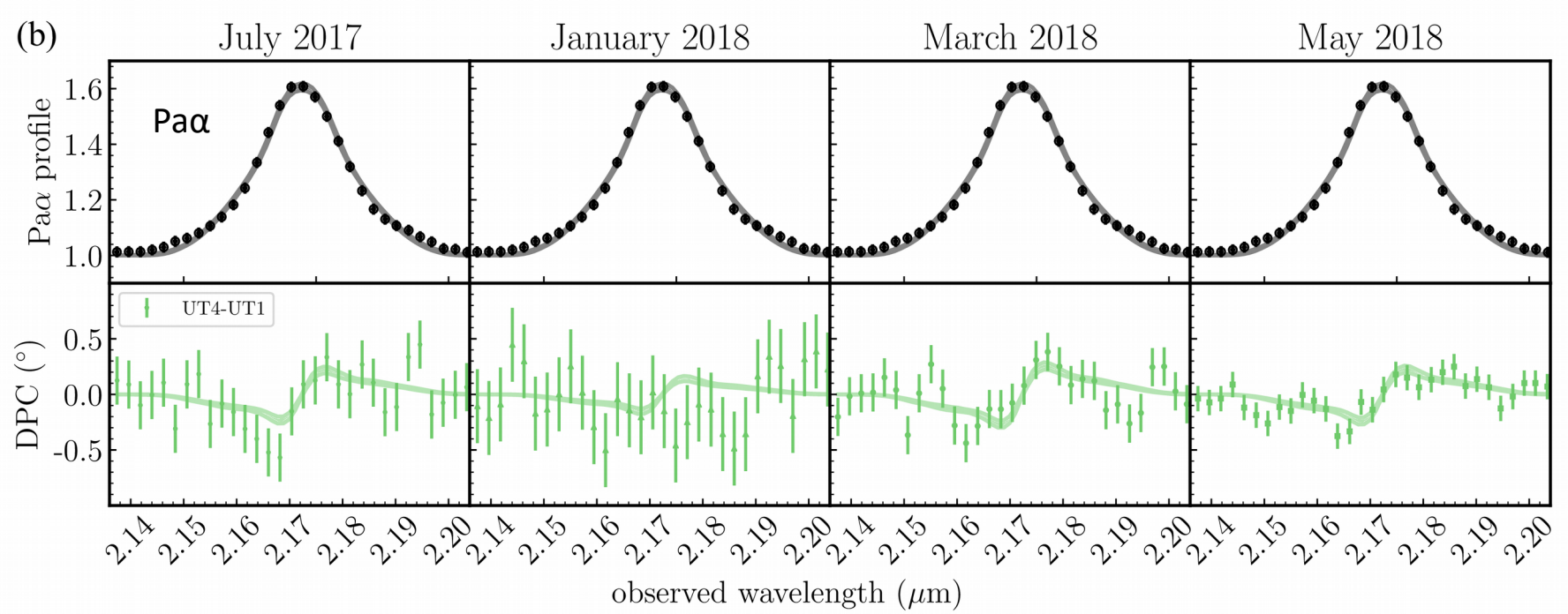


Joint fitting: RM

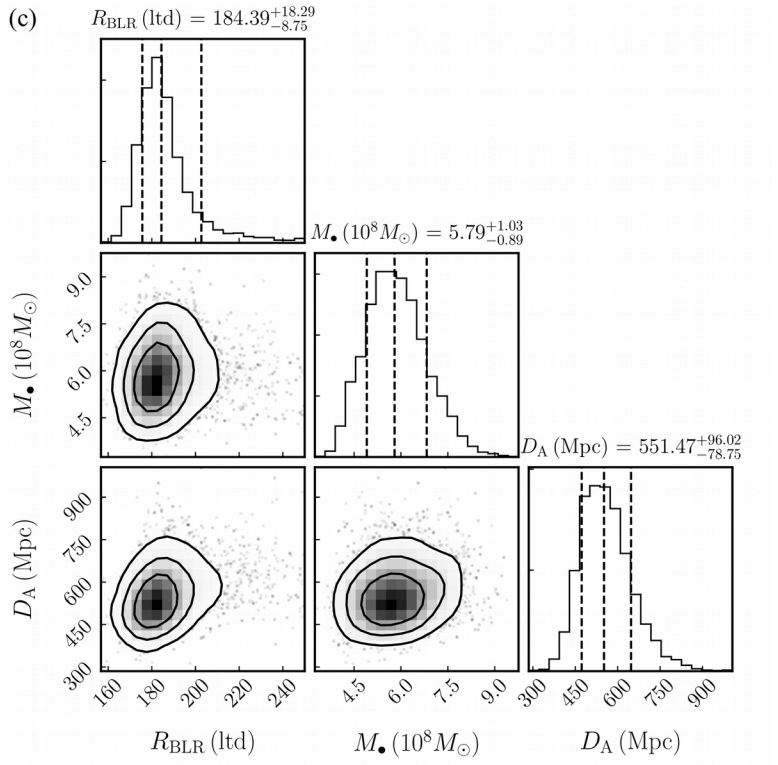
- using 7yr data
- damped random walk model
- detrending included



Joint fitting: GRAVITY



Results



Parameters	GRAVITY	Joint analysis
$i_0(^\circ)$	12 ± 2	$8.41^{+0.99}_{-0.91}$
$R_{\rm BLR}$(ltd)	146 ± 32	$184.17^{+16.77}_{-8.57}$
$M_\bullet(10^8 M_\odot)$	2.6 ± 1.1	$5.78^{+1.11}_{-0.88}$
$D_{\rm A}$(Mpc)	550 (assumed)	$551.50^{+97.31}_{-78.71}$
$\xi_{\rm BLR}$ (μas)	46 ± 10	$59.70^{+8.72}_{-10.31}$

1.645σ

1σ

Remarkable results

- distance: direct measurement

$$D_{\rm A} = 551.5^{+97.3}_{-78.7}\,{\rm Mpc}$$

$$\Omega_{\rm M} = 0.315, \Omega_\Lambda = 0.685$$

$$H_0 = 71.5^{+12.7}_{-10.2}\,{\rm km\,s^{-1}\,Mpc^{-1}}$$

  - **relative error is 16%**
  - **without extinction and ladder calibration**

- BH mass: precise

$$M_\bullet = (2.6 \pm 0.67) \times 10^8 M_\odot (26\%)$$

$$M_\bullet = 5.78^{+1.11}_{-0.88} \times 10^8 M_\odot (17\%)$$

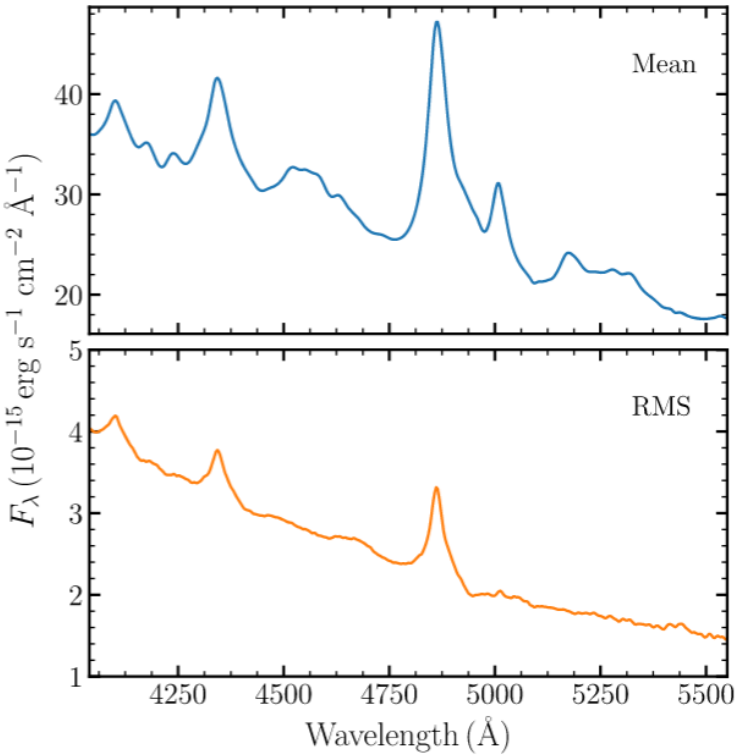
higher than the virial measurement by one order

Systematic errors

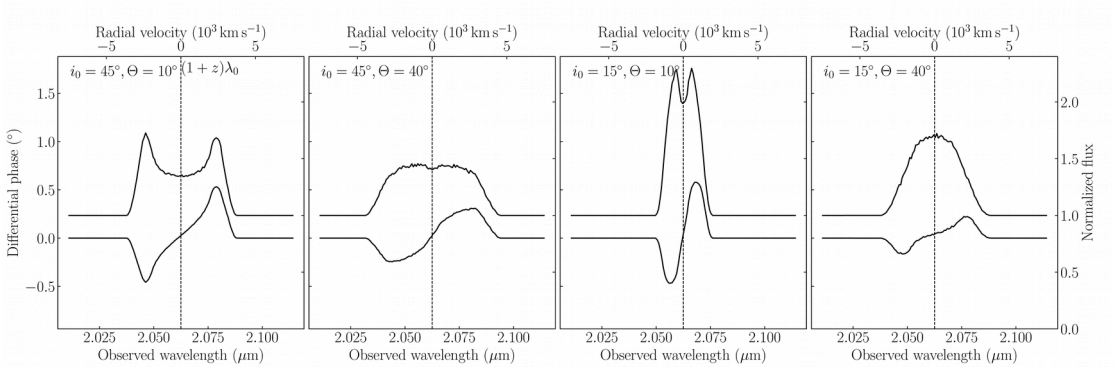
1. Pa and Hβ: different BLR size?
2. RM: variable part; SA: entire BLR
3. non-disk geometry, radial motion
4. disordered rotation
5. change of BLR during RM campaign

Improvements

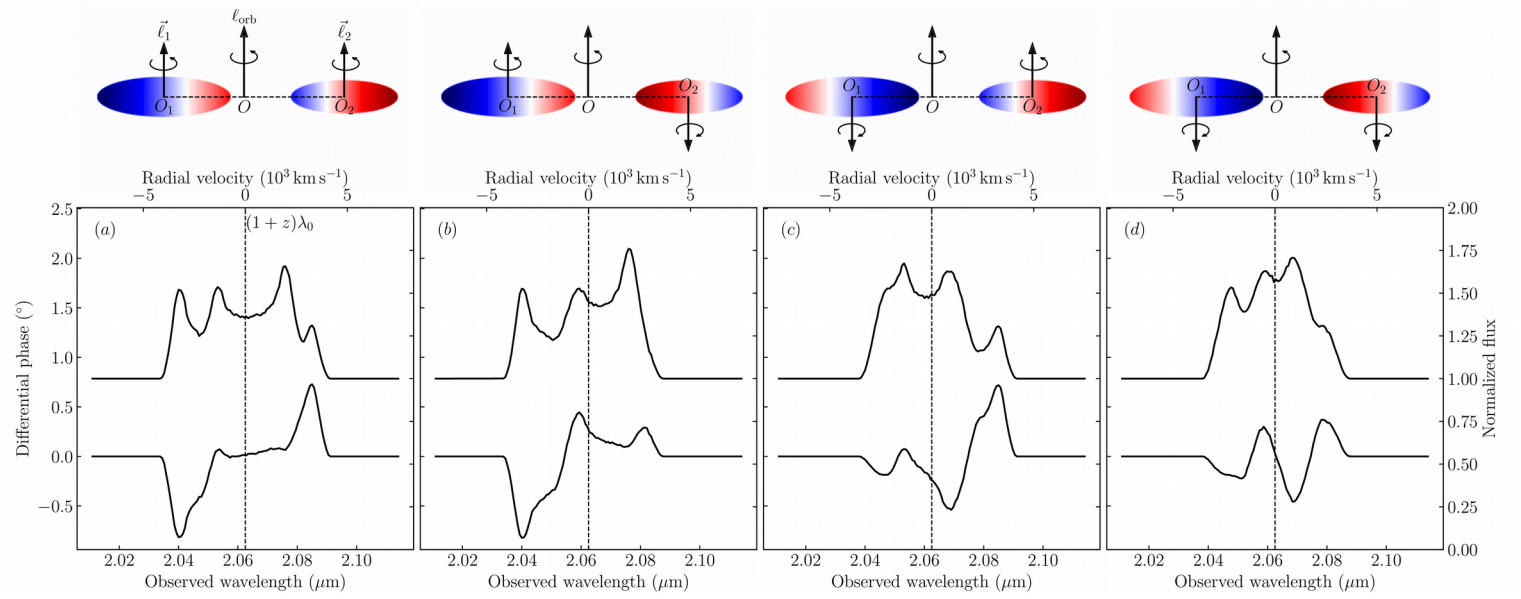
- mapping Paα (reduce E1)
- rms versus mean spectra (E2)
- 2D RM (E1, E3)
- polarization observation (E4)
- scheduling strategy (E5)



GRAVITY: Close binaries of SMBHs



Songsheng+ 2019

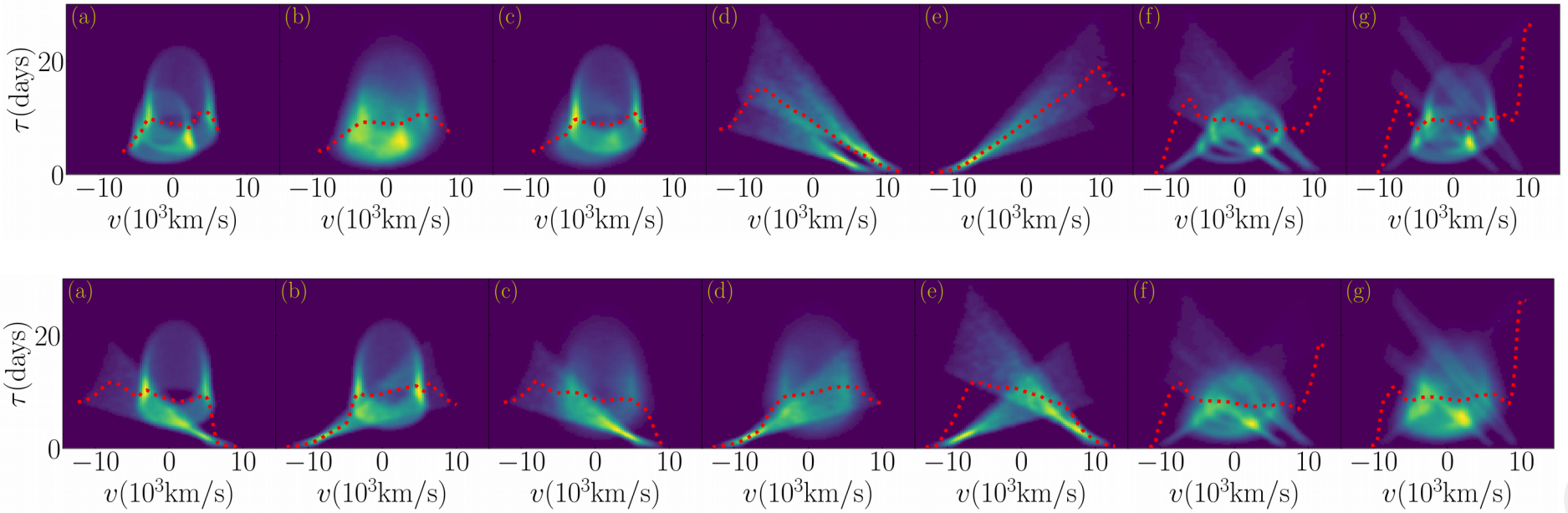


High spatial resolution

Binary-SARM analysis

RM:complex gas dynamics

Wang+ 2018, Songsheng+ 2019
Kovacevic+ 2019



Future SARM

- Targets for GRAVITY: K bright Type I AGNs
- Aims at:
  - H0 at 2% precision with 50 targets
  - close binaries of SMBHs
  - formation of the BLR
  - super-Eddington accretion process

Conclusion

- SARM: BH mass and distances
- Application to 3C273:
  - $D_{\rm A} = 551.5^{+97.3}_{-78.7}\,{\rm Mpc}\,(16\%)$
  - $M_\bullet = 5.78^{+1.11}_{-0.88} \times 10^8 M_\odot\,(17\%)$
- Future SARM: expected for BH mass, cosmology, binary BH