Measuring AGN Geometric Distances Using Interferometry and Reverberation Mapping of Broad-line Regions

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（SARM Collaboration）

BRICS-AGAC Symposium 2026
Nov. 08 Hangzhou, China

Outline

I. Quasars: a new cosmic geometric distance probe

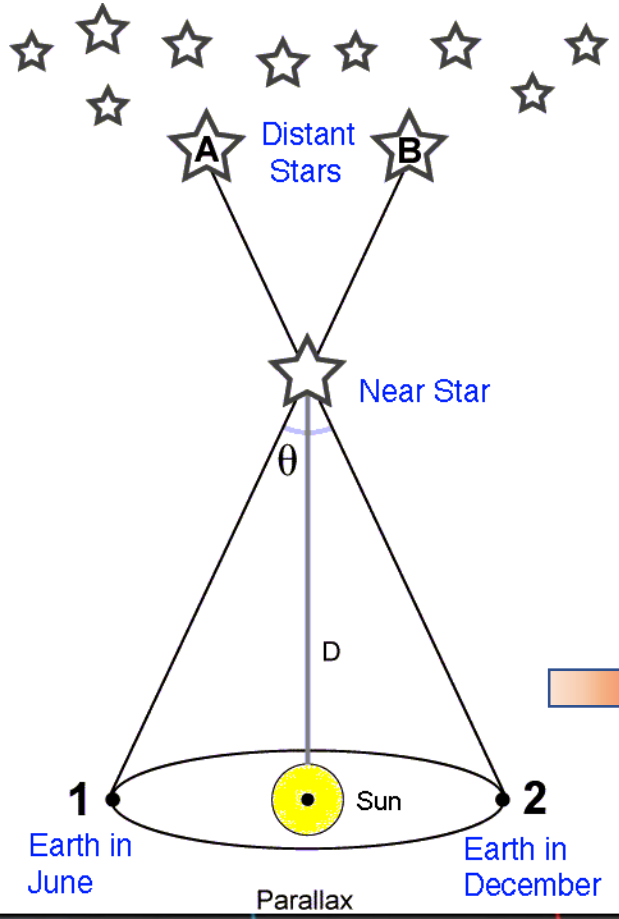
II. SARM: spectroastrometry + reverberation mapping

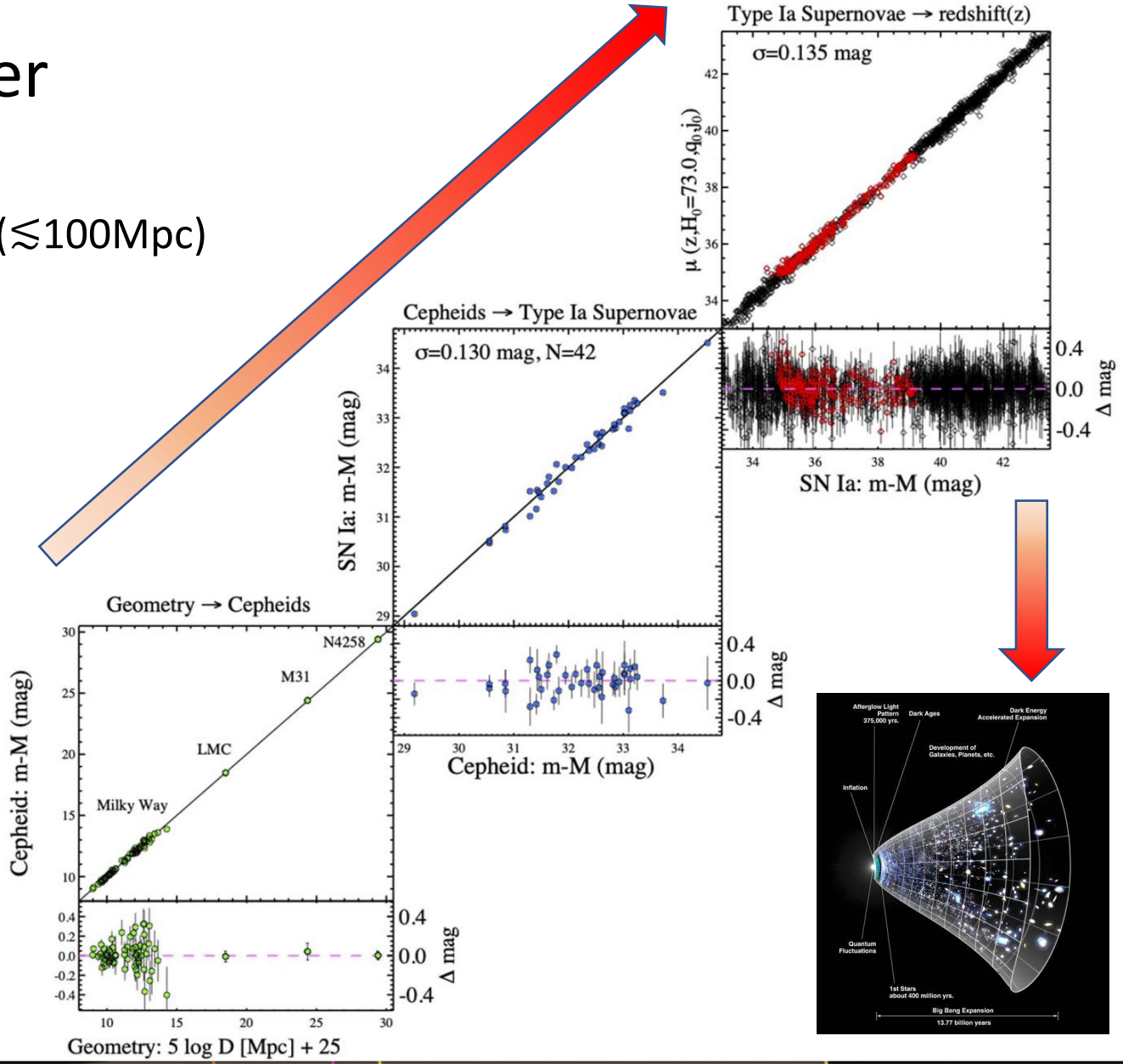
III. Applications to four GRAVITY-observed quasars

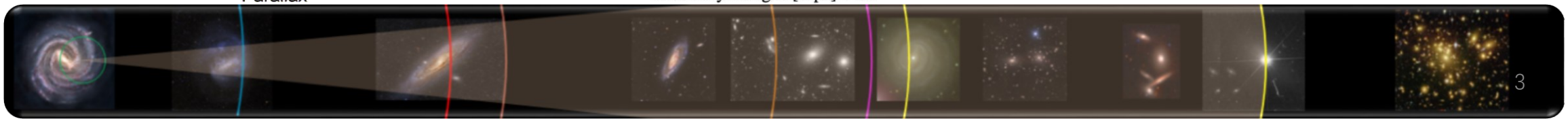
IV. Future perspectives for cosmology with interferometry

Cosmic distance ladder

geometric distance: parallax, megamaser (≲100Mpc)

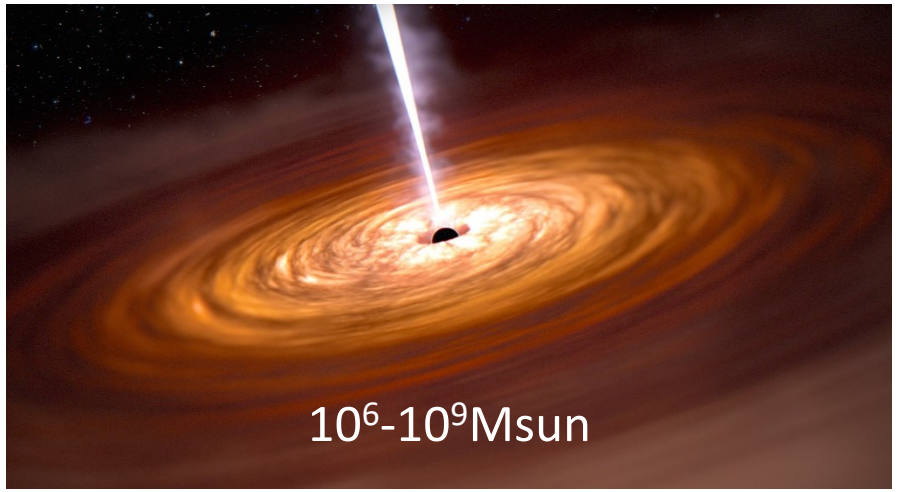


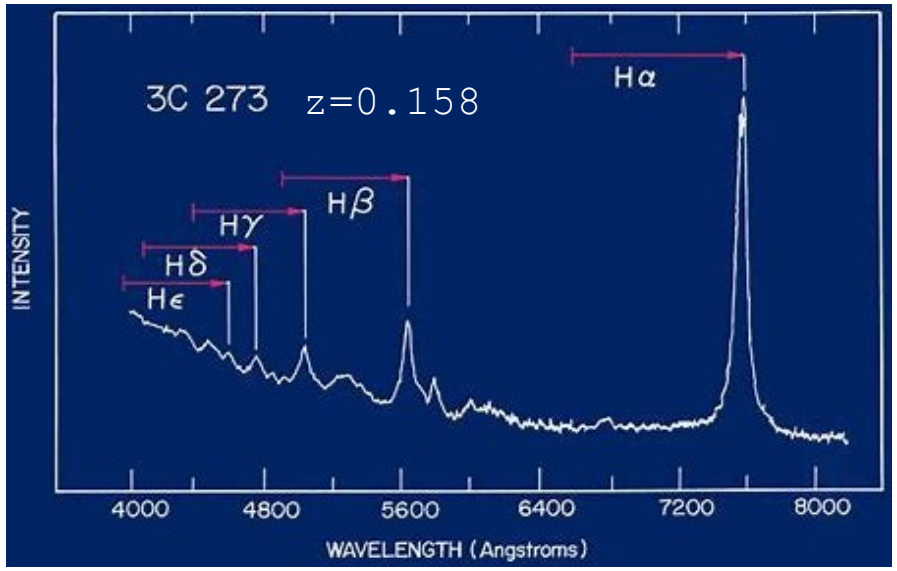


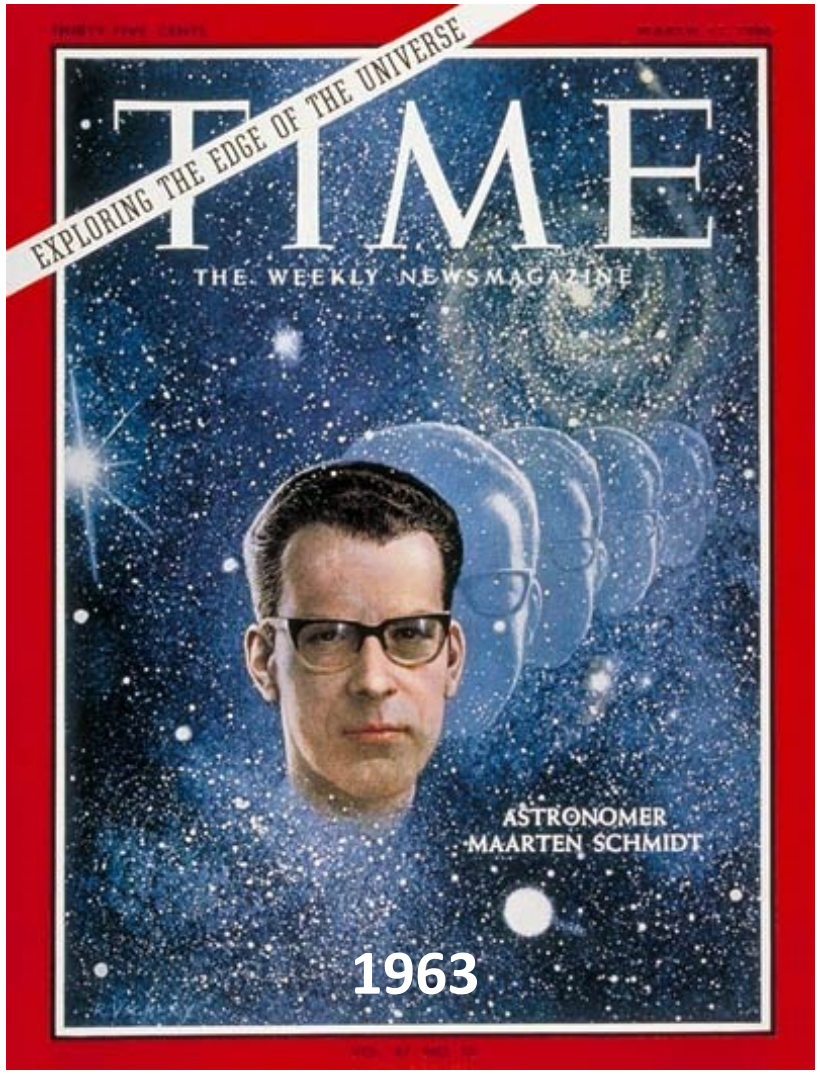


Quasars: accreting supermassive black holes

- First discovered in 1963 by M. Schmidt
- The most luminous, long-lived objects on the sky



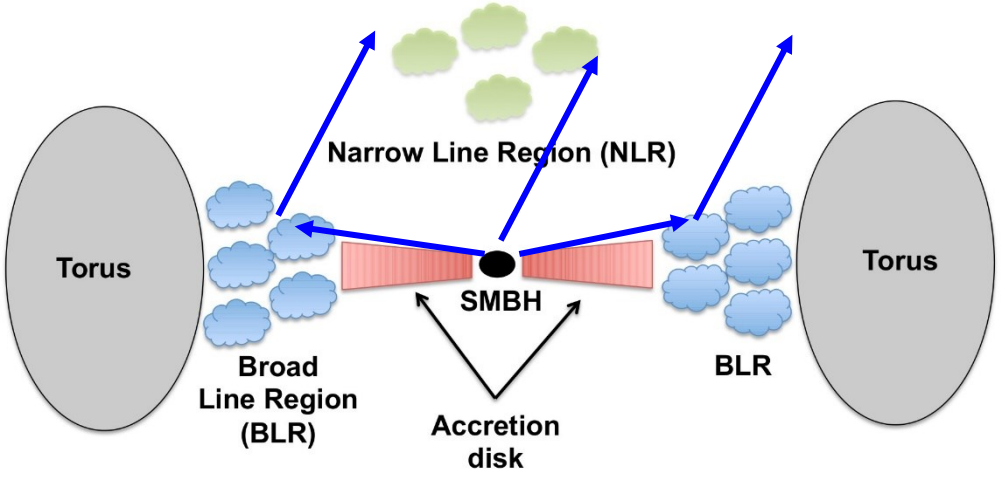


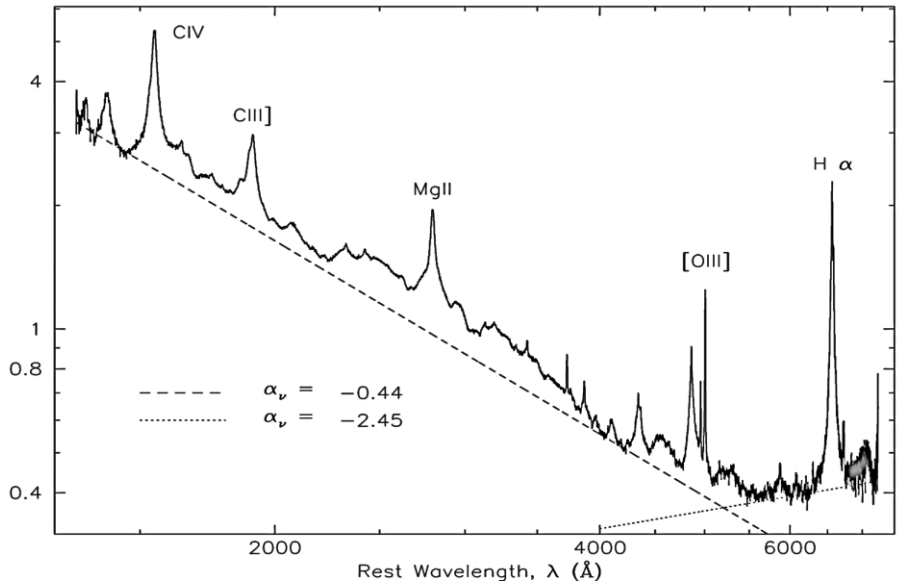






Quasars: accreting supermassive black holes





- Accretion disk： $\sim 10^3 R_g$
- Broad-line region： $\sim 10 - 100$light-day
- Torus： ~pc

at 1Gpc（z=0.35）

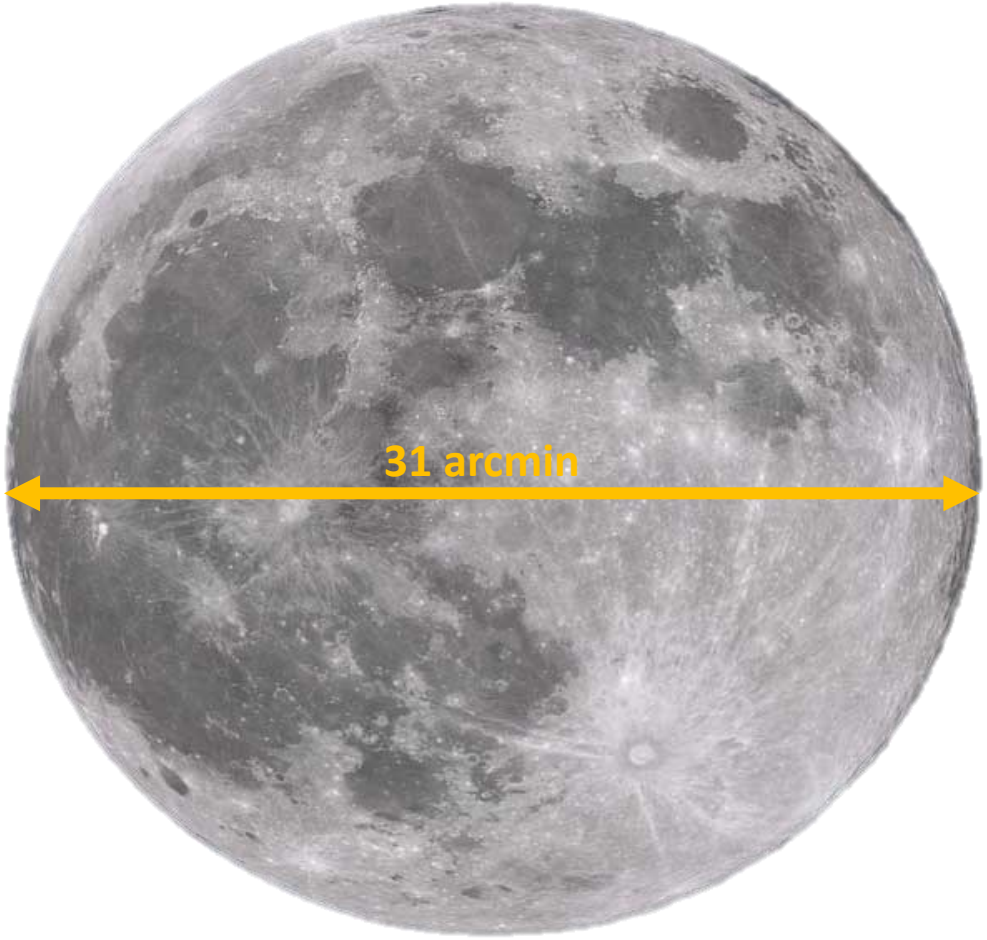
100light day— 20micro-arcsec

1pc—200micro-arcsec

JWST 6m： ~0.1arcsec@2μm

ELT 39m： ~10milli-arcsec@2μm

Quasars: accreting supermassive black holes



~micro-arcsec



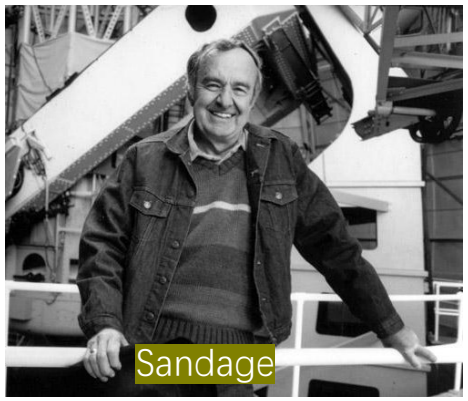
Quasar angular size: $>10^8$ times smaller!

a small stone (2cm) vs. the moon (1.7×10^8cm)

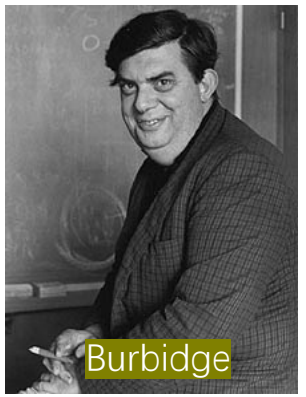
Quasars: accreting supermassive black holes

After 1963, an epic history of looking for quasars as a cosmic probe; most approaches ineffective

- Sandage (1965)
- Hoyle & Burbidge (1966)
- Longair (1967)
- Schmidt (1968)
- Weinberg (1972)
- Bahcall & Hills (1973)
- Baldwin (1977)
- Elvis & Karovska (2022)
- Watson+(2012)
- Wang+(2013)
- Yoshii+(2014)
- La Francis+(2014)
- Honig+(2015)
- Cao+(2017)
- Risaliti & Lusso(2019)



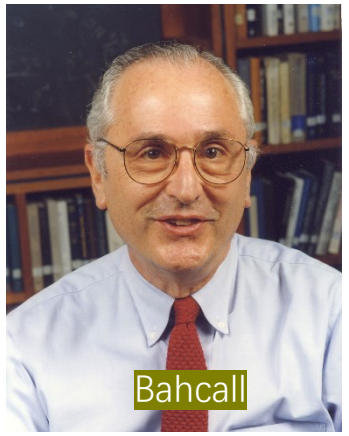


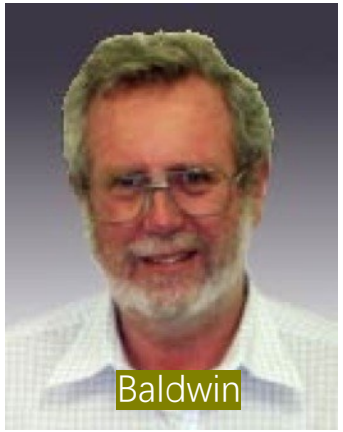




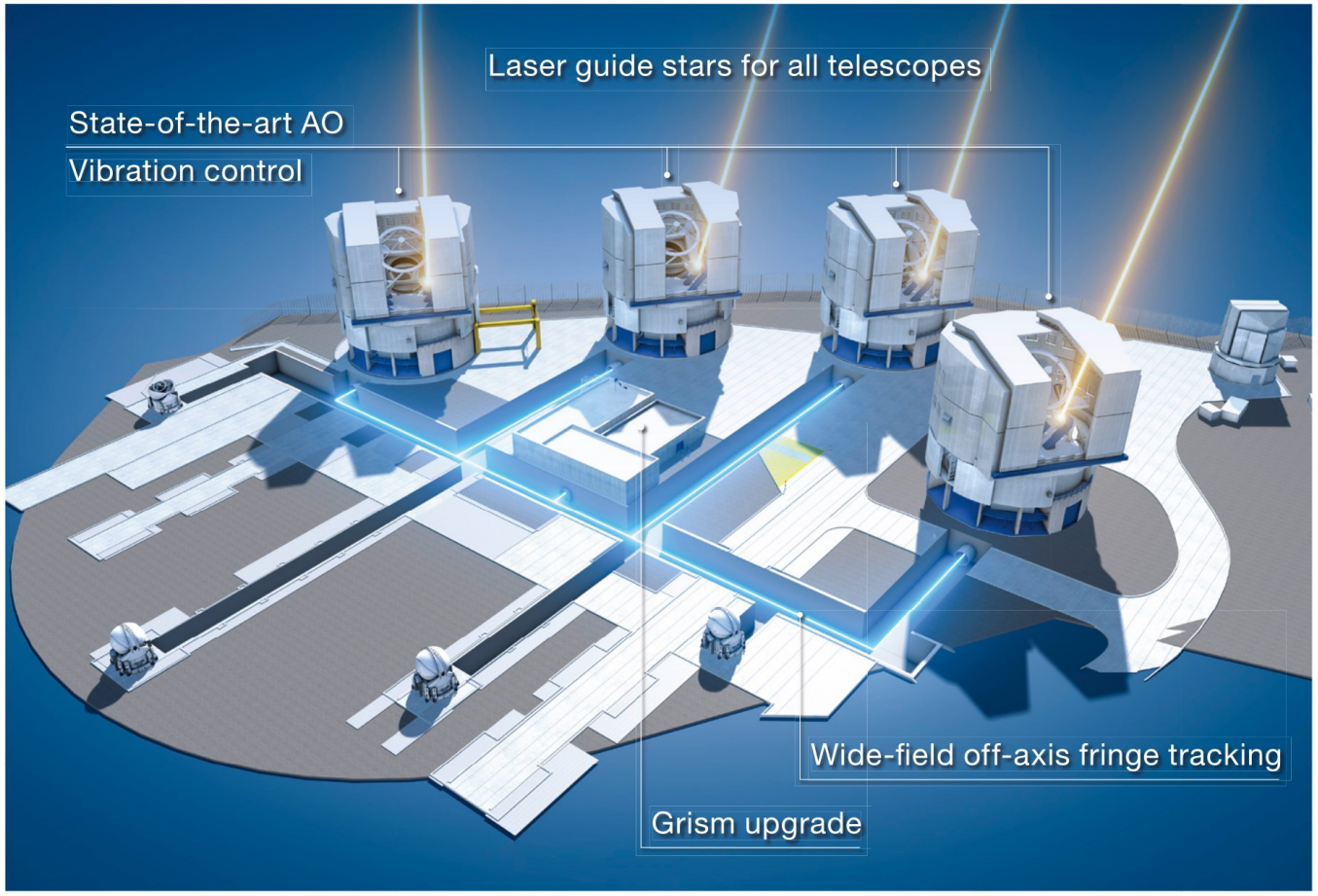


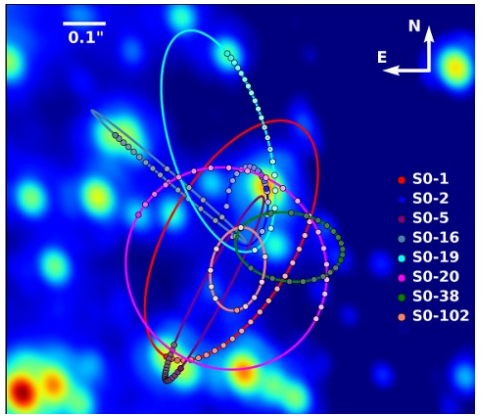


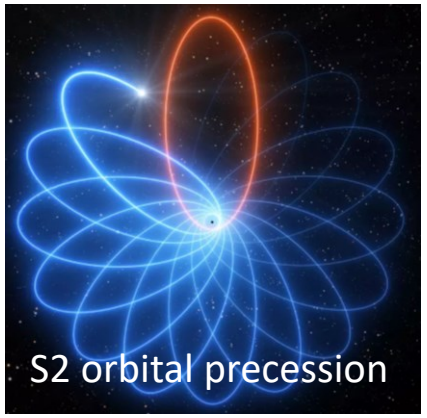




Breakthrough in 2017: infrared interferometry with VLTI









GRAVITY/VLTI, 4*8m, baseline ~100m

~10μas with spectroastrometry

Nobel physics prize in 2020

Breakthrough in 2017: infrared interferometry with VLTI

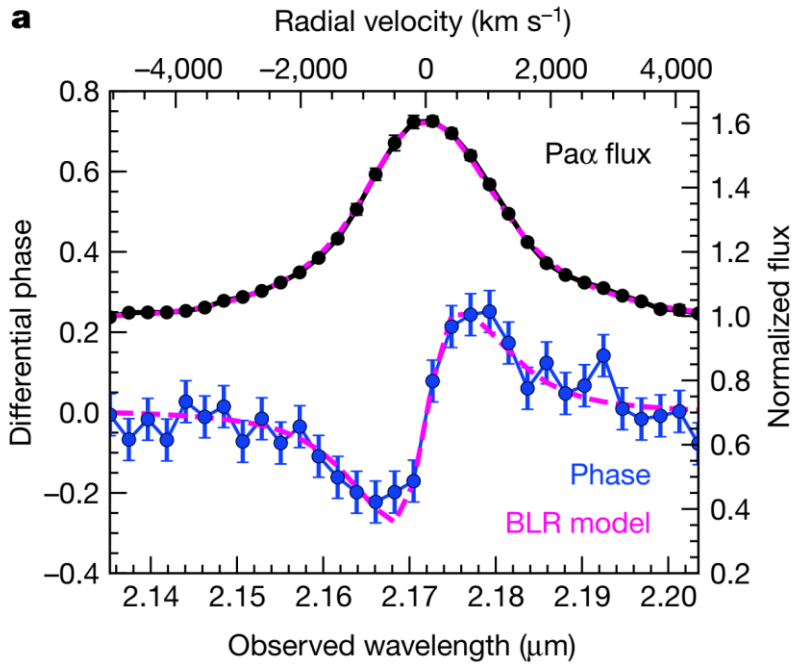
LETTER

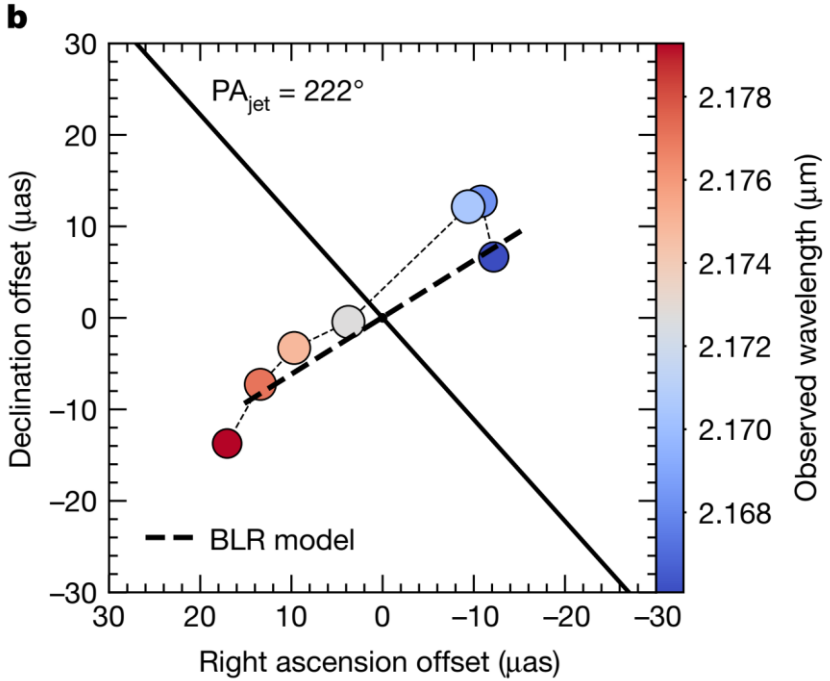
angular size: 46 μas, precision: 10 μas

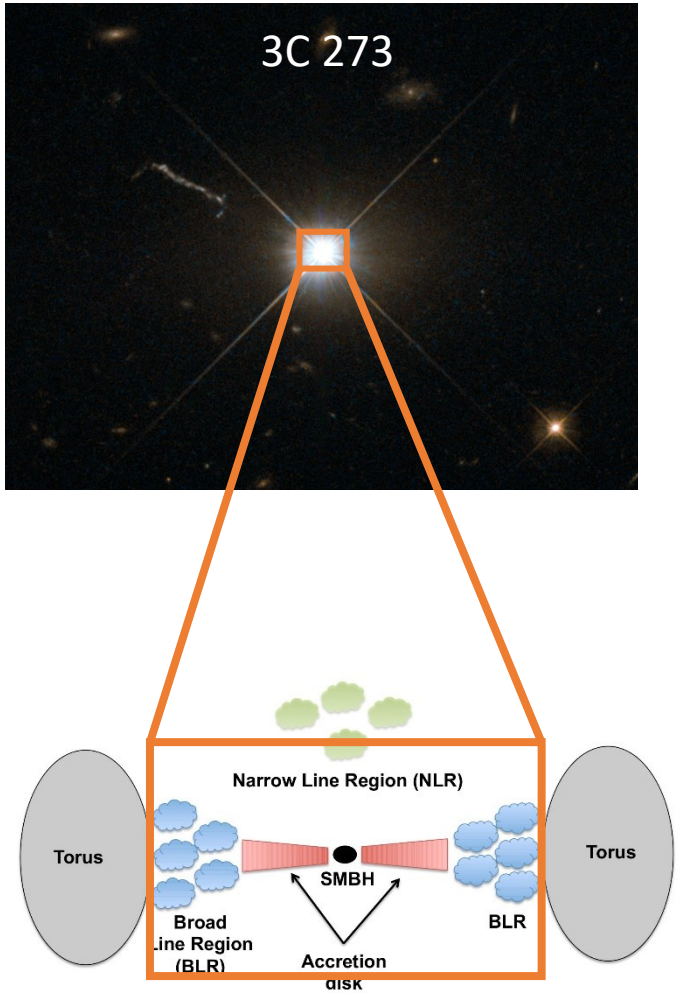
https://doi.org/10.1038/s41586-018-0731-9

Spatially resolved rotation of the broad-line region of a quasar at sub-parsec scale

GRAVITY Collaboration*

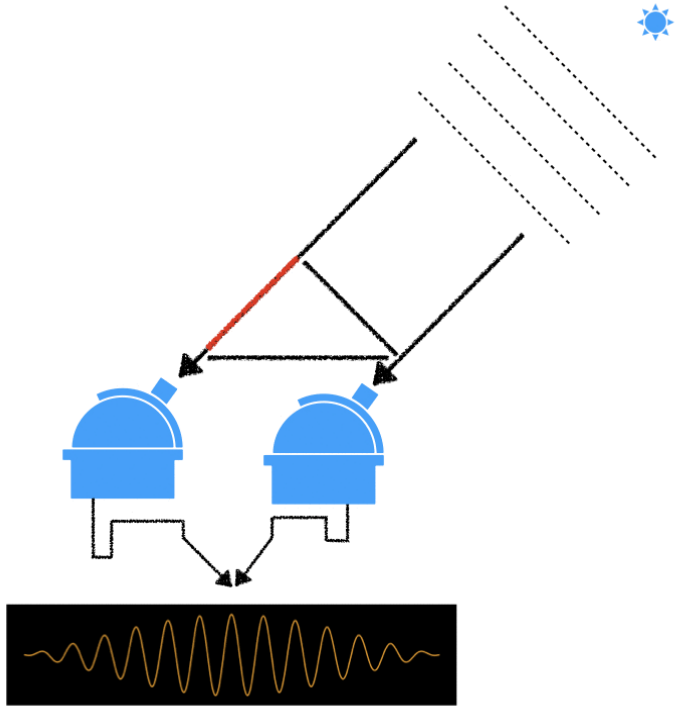




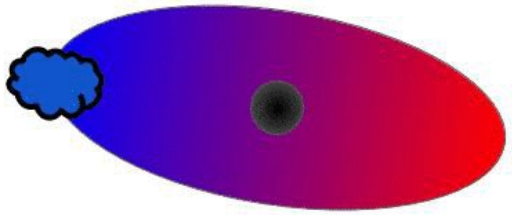


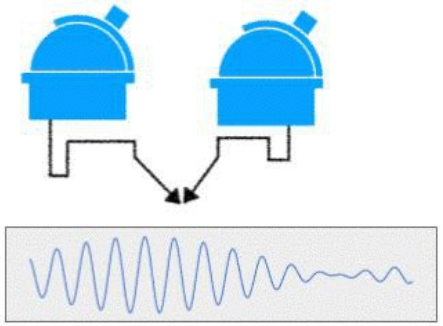
Breakthrough in 2017: infrared interferometry with VLTI

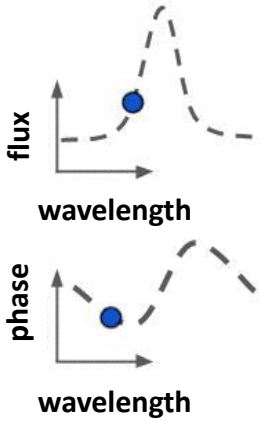
- Angular sizes from differential interferometric phases: super-high resolution



Gas clouds: orbital motion

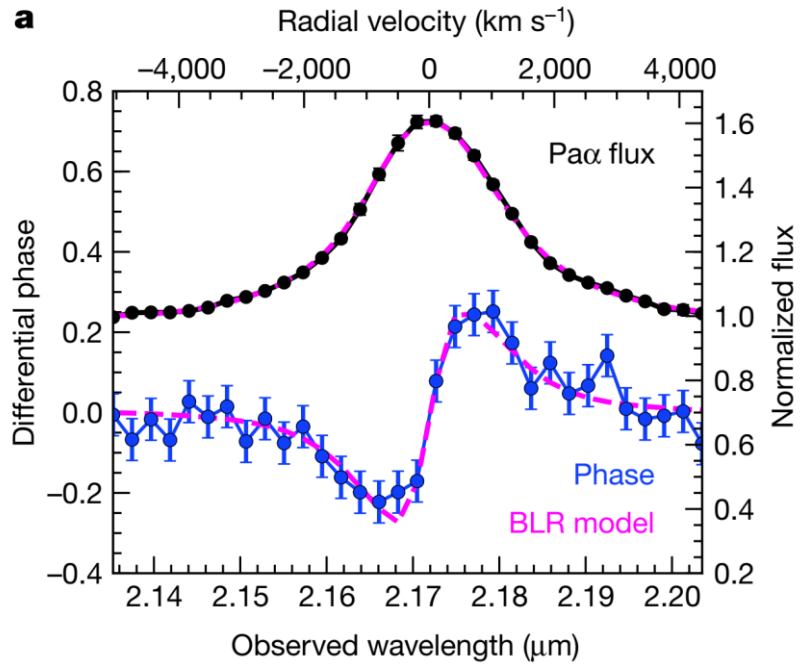






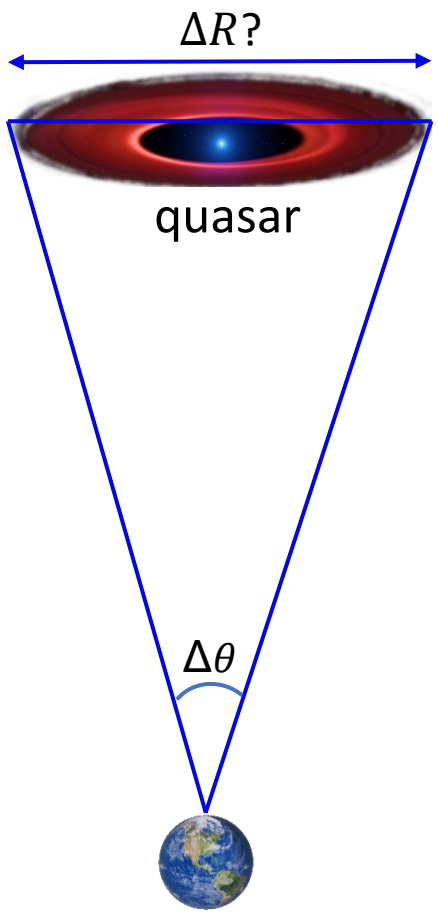
Resolution:

$$\sigma_s = \frac{\mathrm{FWHM_{PSF}}}{2.35\left(\frac{dN_{\mathrm{ph}}}{d\nu}\right)^{1/2}}$$



SARM approach: SpectroAstrometry + Reveberation Mapping

geometric distance:



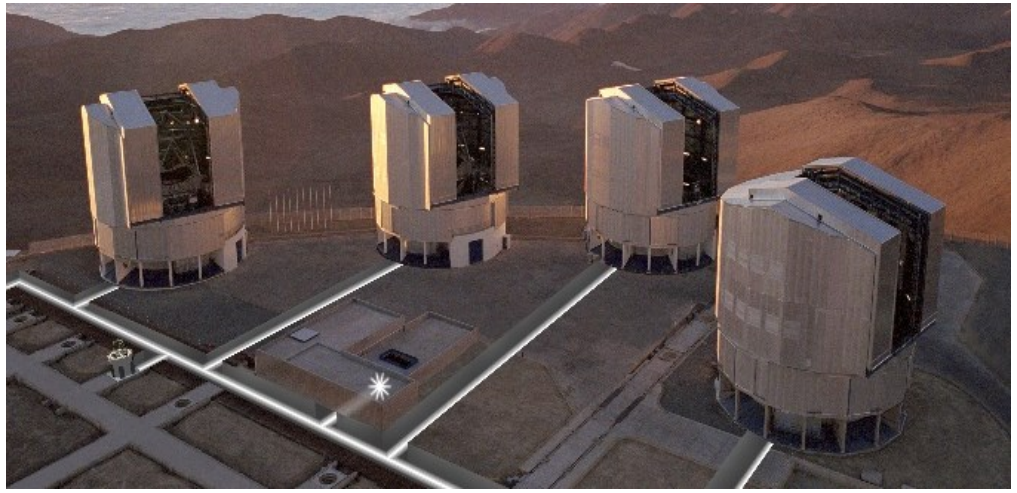
$$D = \frac{\Delta R}{\Delta \theta}$$

Reverberation Mapping with 2m telscopes

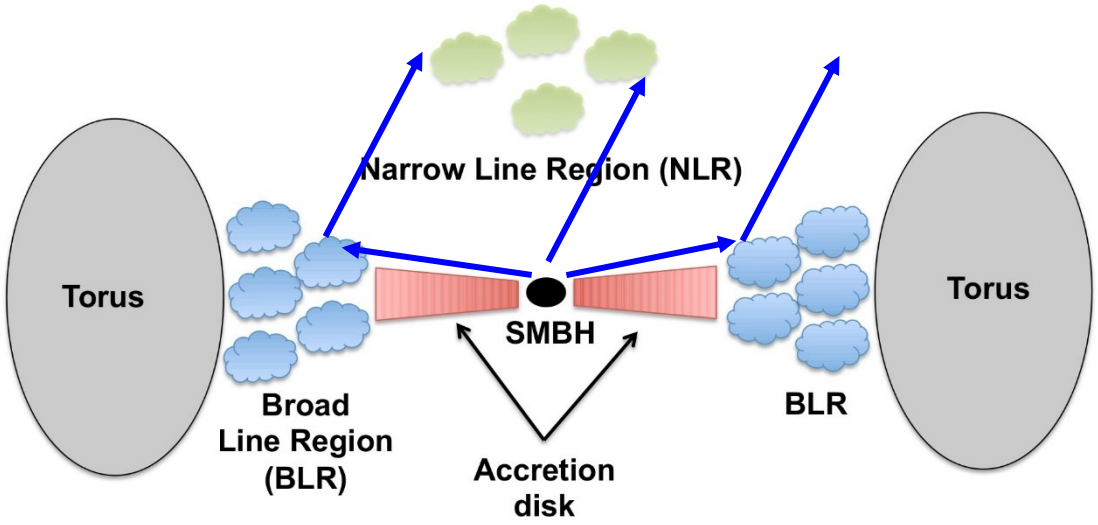


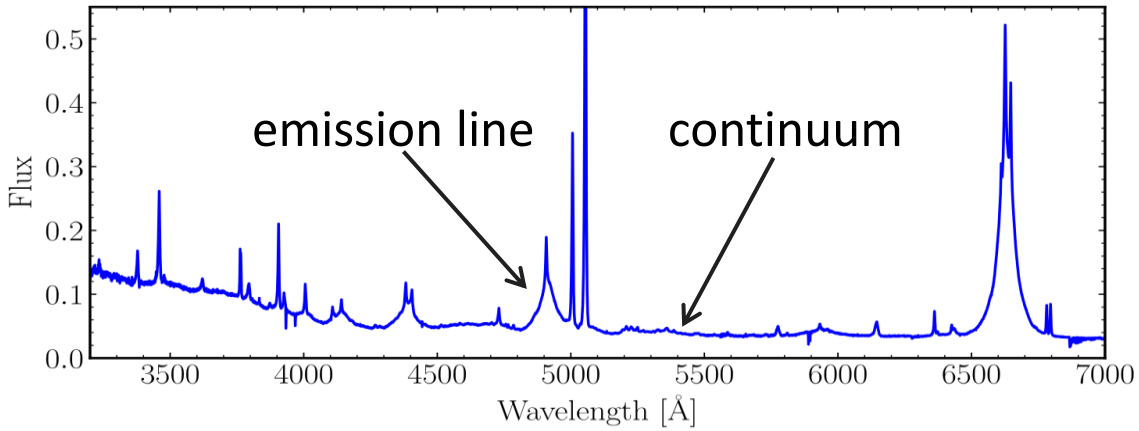


Spectroastrometry with interferometry



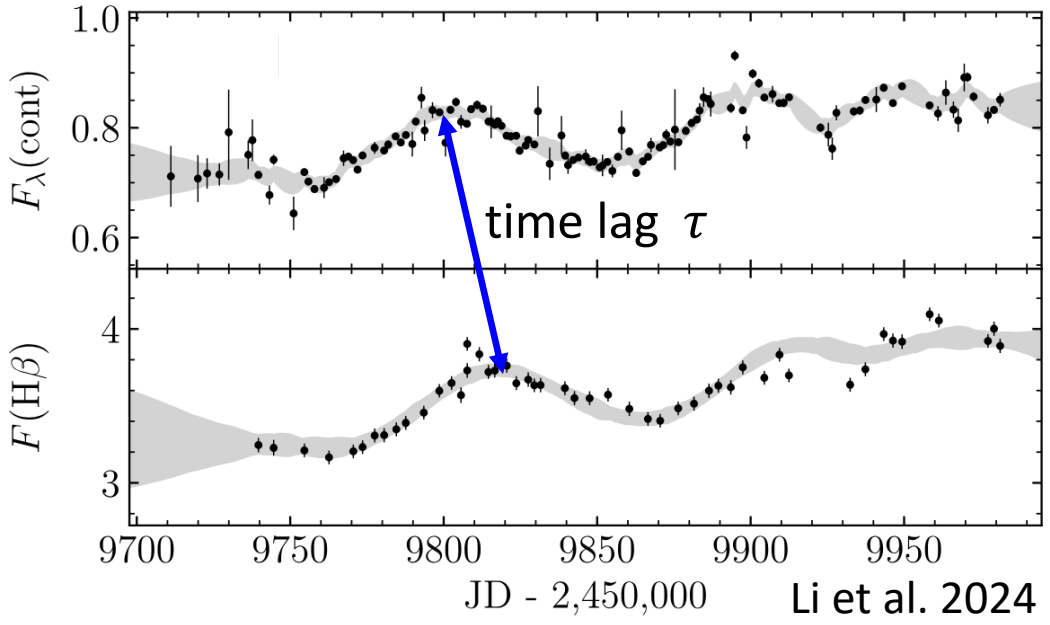
Reverberation mapping: linear sizes





BLR size: $\Delta R = c \times \tau$

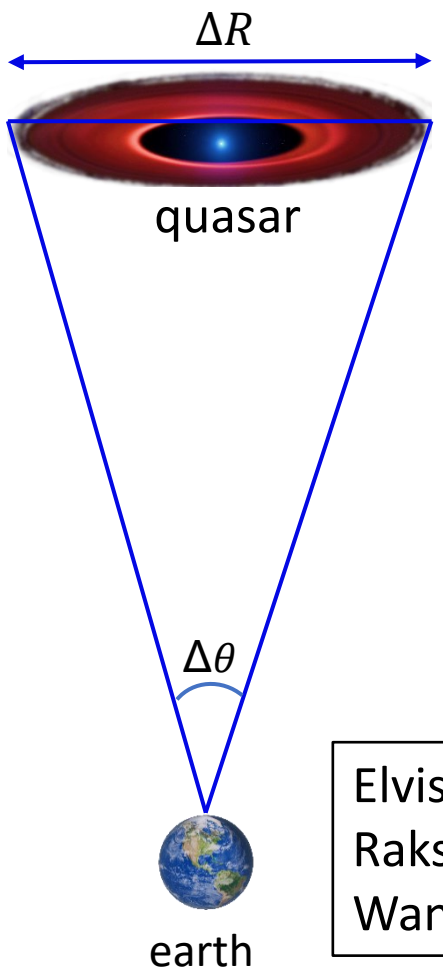
Light curves of continuum and emission line



Li et al. 2024

SARM approach: SpectroAstrometry + Reveberation Mapping

geometric distance:



$$D = \frac{\Delta R}{\Delta \theta}$$

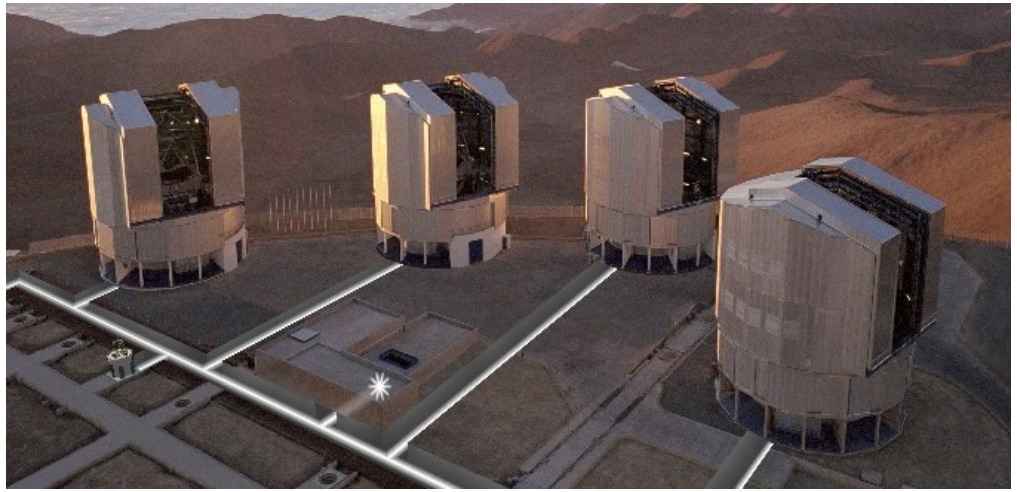
Elvis & Karovska 2002
Rakshit, Petrov et al. 2015
Wang et al. 2020

Reverberation Mapping with 2m telscopes





Spectroastrometry with GRAVITY



SARM: SpectroAstrometry+Reverberation Mapping

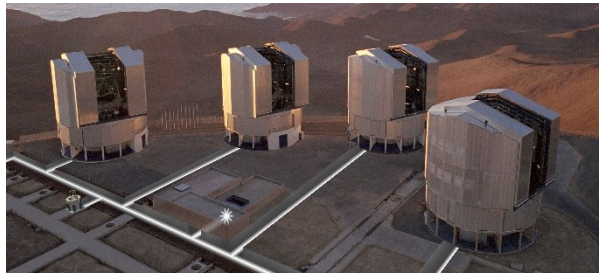
reverberation mapping



2m telescopes

Flux(1D) Profile(2D)

spectro-astrometry



Interferometry

Single-epoch Time-domain (TD)

$$\begin{bmatrix} F_{\rm BLR}(v,\,t) \\ \boldsymbol{M}_{\rm BLR}(v,\,t) \end{bmatrix} = \begin{bmatrix} \Psi(v,\,t) \\ \boldsymbol{\Pi}(v,\,t) \end{bmatrix} \otimes F_{\rm c}(t),$$

- 1D SARM：single SA + 1D RM (Wang et al. 2020)
- 2D SARM：single SA + 2D RM (Li, Wang et al. 2022)
- TD SARM：TD SA + 2D RM (Li & Wang 2023)

The Astrophysical Journal, 979:126 (13pp), 2025 February 1 https://doi.org/10.3847/1538-4357/ad9fee
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Radial-dependent Responsivity of Broad-line Regions in Active Galactic Nuclei: Observational Consequences for Reverberation Mapping and Black Hole Mass Measurements

Yan-Rong Li[1] and Jian-Min Wang[1,2,3]

The Astrophysical Journal, 943:36 (21pp), 2023 January 20 https://doi.org/10.3847/1538-4357/aca66d
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Spectroastrometric Reverberation Mapping of Broad-line Regions

Yan-Rong Li[1] and Jian-Min Wang[1,2,3]

The Astrophysical Journal, 927:58 (21pp), 2022 March 1 https://doi.org/10.3847/1538-4357/ac4bcb
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Spectroastrometry and Reverberation Mapping: The Mass and Geometric Distance of the Supermassive Black Hole in the Quasar 3C 273

Yan-Rong Li[1], Jian-Min Wang[1,2,3], Yu-Yang Songsheng[1], Zhi-Xiang Zhang[4], Pu Du[1], Chen Hu[1], and Ming Xiao[1]

nature astronomy LETTERS https://doi.org/10.1038/s41550-019-0979-5

A parallax distance to 3C 273 through spectroastrometry and reverberation mapping

Jian-Min Wang[1,2,3*], Yu-Yang Songsheng[1,4], Yan-Rong Li[1], Pu Du[1] and Zhi-Xiang Zhang[5]

First application: 3C 273

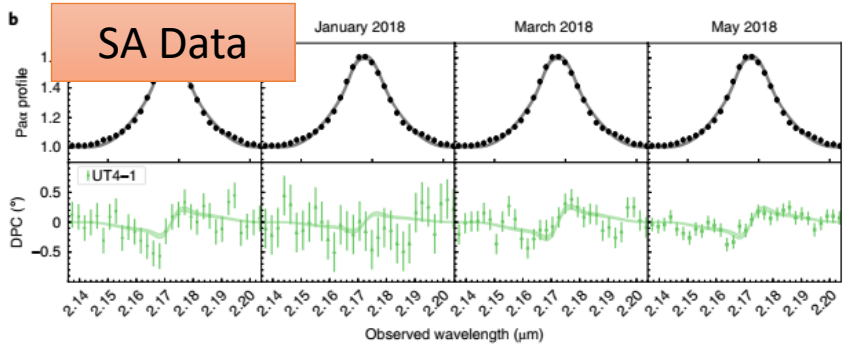
nature astronomy (Wang et al. 2020) LETTERS https://doi.org/10.1038/s41550-019-0979-5

D_A (Mpc) = $551.47^{+96.02}_{-78.75}$ precision: ~16%

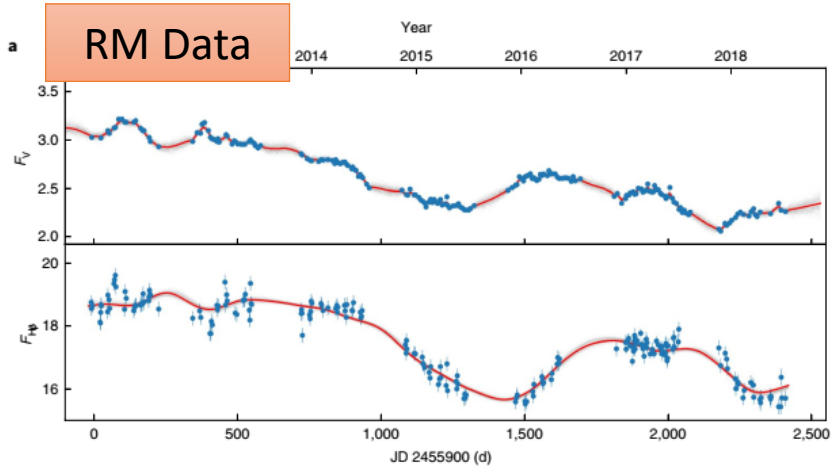
A parallax distance to 3C 273 through spectroastrometry and reverberation mapping

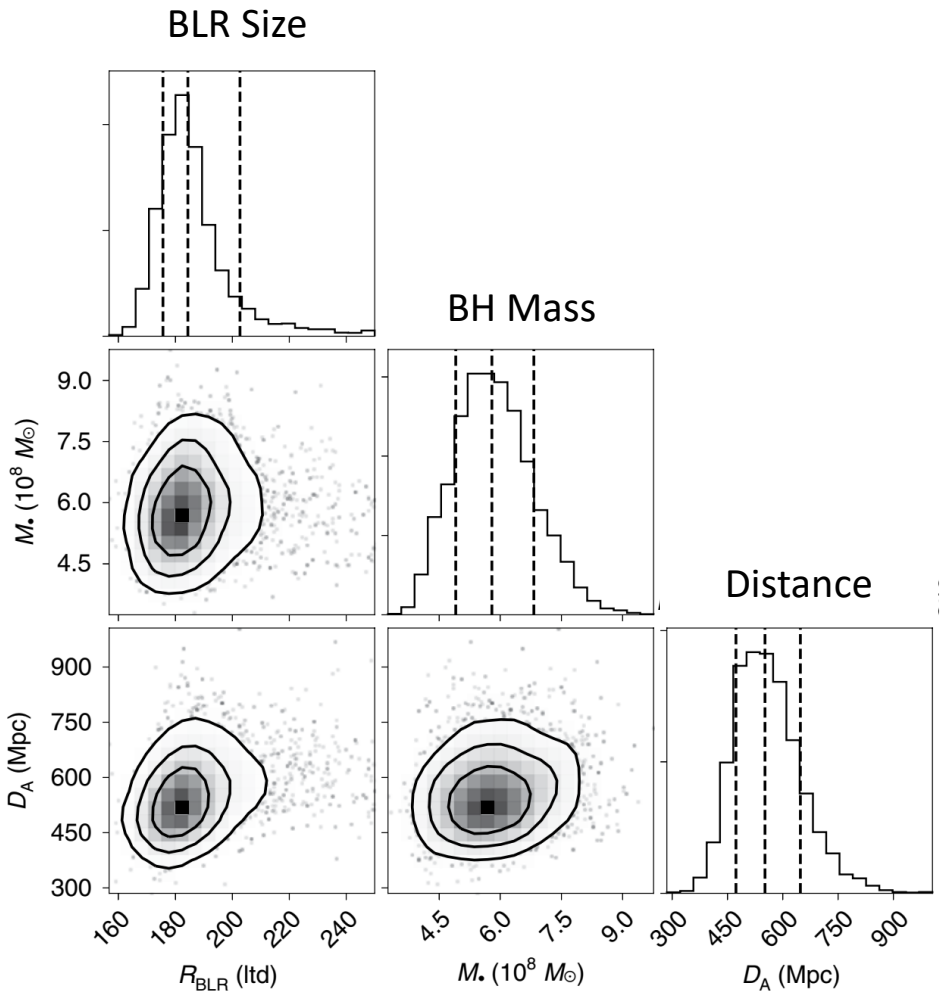
Jian-Min Wang[1,2,3*], Yu-Yang Songsheng[1,4], Yan-Rong Li[1], Pu Du[1] and Zhi-Xiang Zhang[5]

SA Data



RM Data





Second application: NGC 3783

A&A 654, A85 (2021)
https://doi.org/10.1051/0004-6361/202141426
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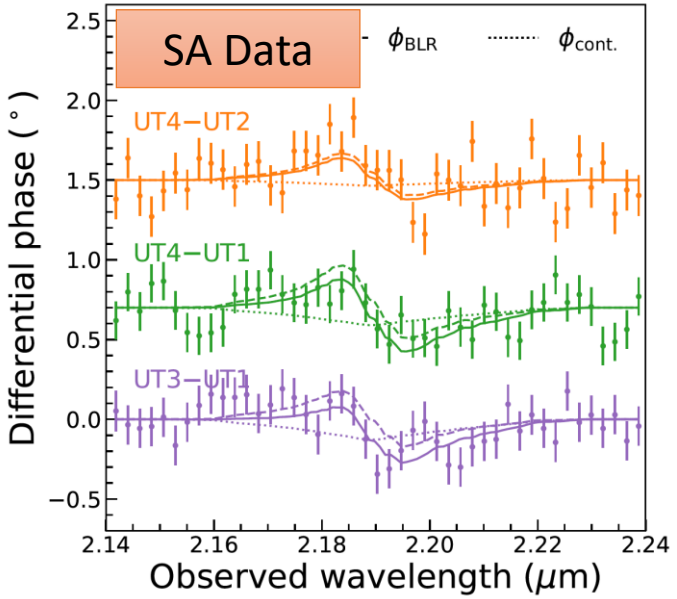
Astronomy & Astrophysics

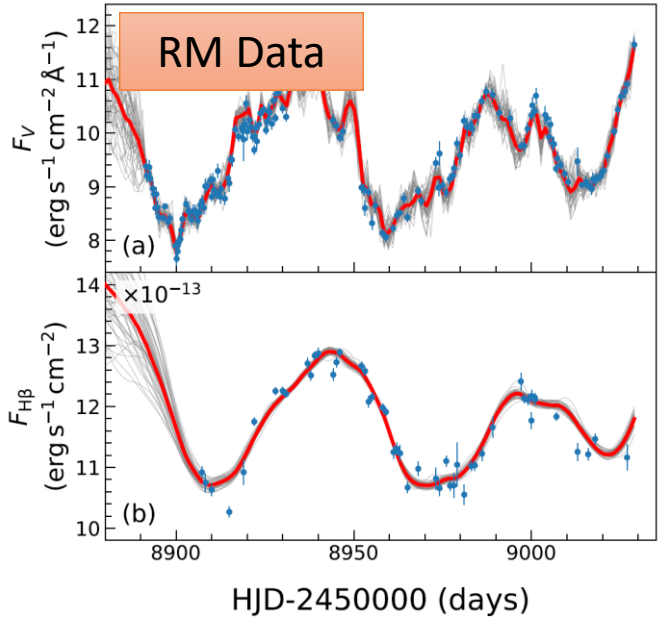
A geometric distance to the supermassive black Hole of NGC 3783

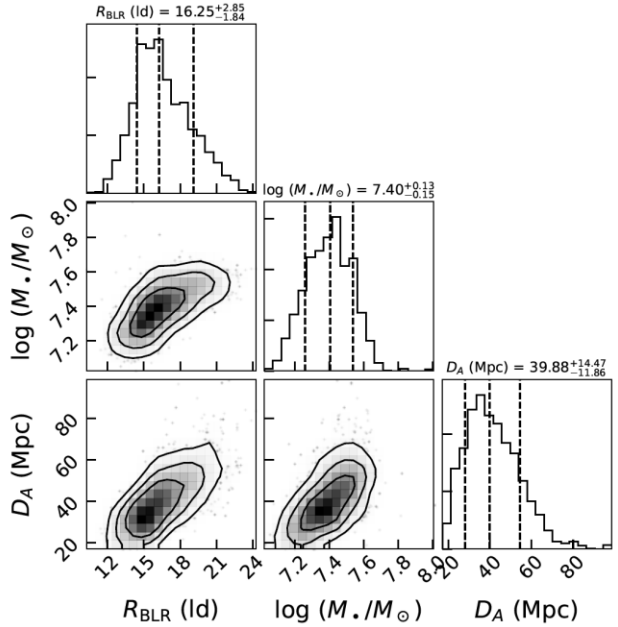
GRAVITY Collaboration:* A. Amorim[15,17], M. Bauböck[1], M. C. Bentz[23], W. Brandner[18], M. Bolzer[1], Y. Clénet[2], R. Davies[1], P. T. de Zeeuw[1,13], J. Dexter[20,1], A. Drescher[1,22], A. Eckart[3,14], F. Eisenhauer[1], N. M. Förster Schreiber[1], P. J. V. Garcia[11,16,17], R. Genzel[1,4], S. Gillessen[1], D. Gratadour[2,21], S. Hönig[5], D. Kaltenbrunner[1], M. Kishimoto[6], S. Lacour[2,12], D. Lutz[1], F. Millour[7], H. Netzer[8], C. A. Onken[21], T. Ott[1], T. Paumard[2], K. Perraut[9], G. Perrin[2], P. O. Petrucci[9], O. Pfuhl[12], M. A. Prieto[19], D. Rouan[2], J. Shangguan[1], T. Shimizu[1], J. Stadler[1], A. Sternberg[8,10], O. Straub[1], C. Straubmeier[3], R. Street[24], E. Sturm[1], L. J. Tacconi[1], K. R. W. Tristram[11], P. Vermot[2], S. von Fellenberg[1], F. Widmann[1], and J. Woillez[12]

D_A (Mpc) = $39.88^{+14.47}_{-11.86}$

precision: ~30%

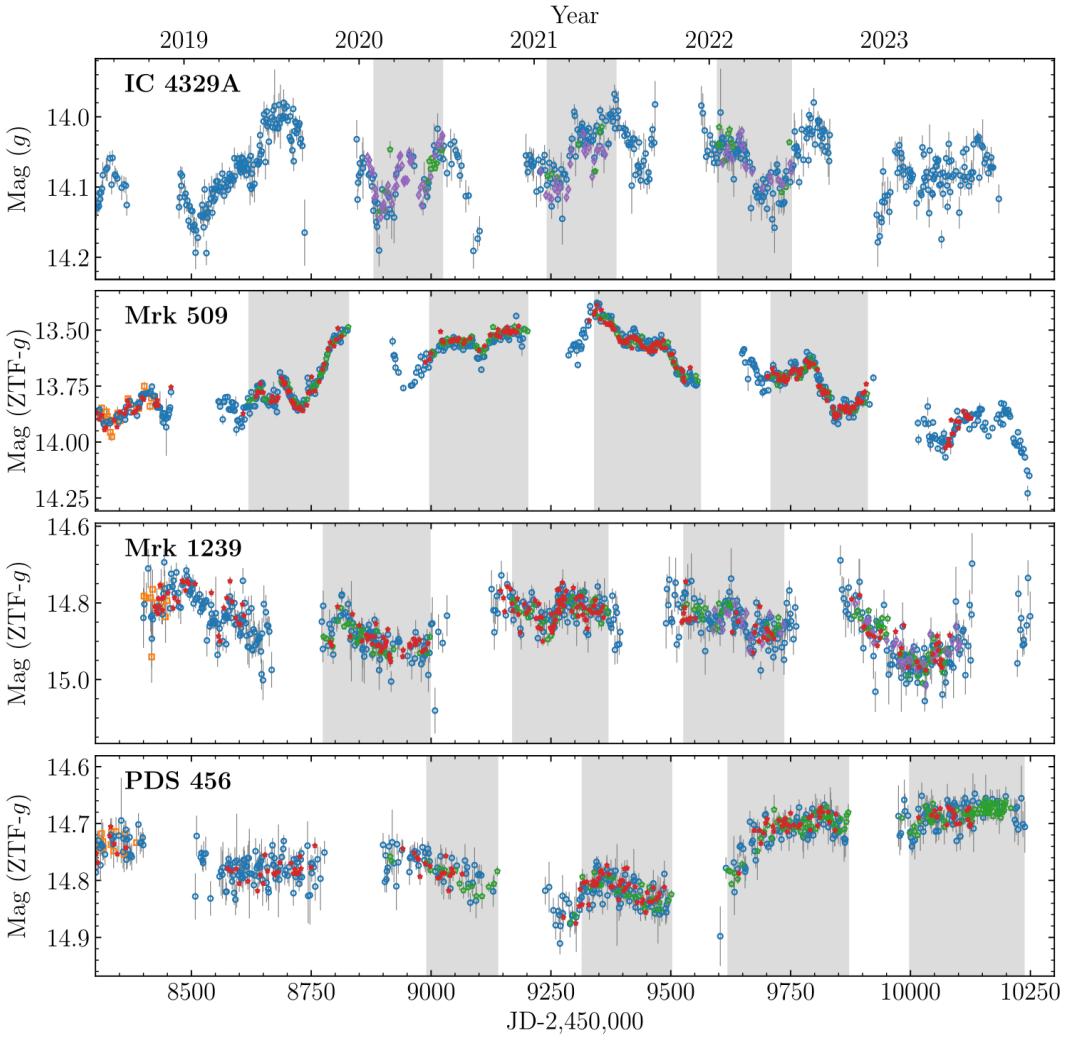




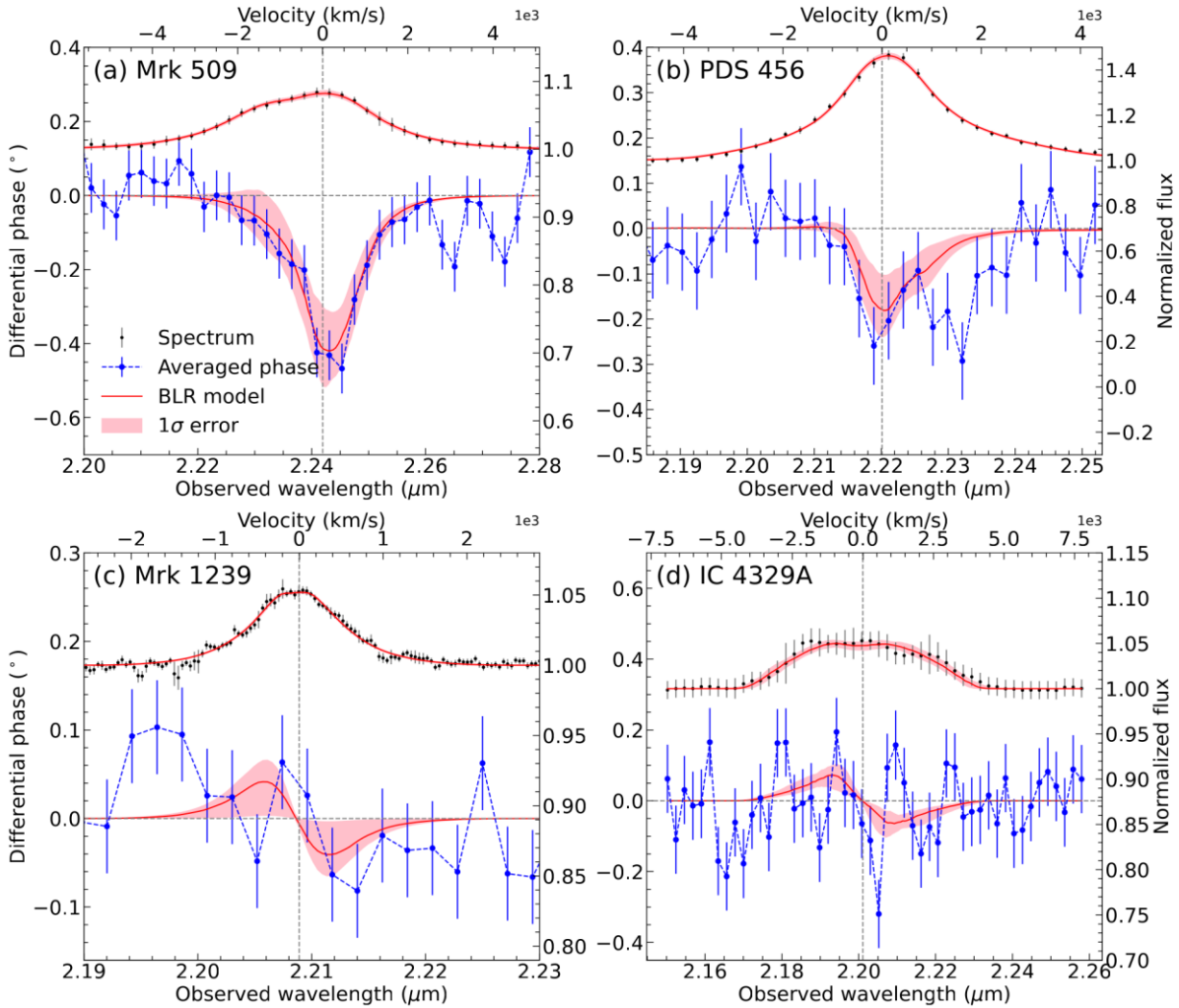


Latest progress: four quasars

- SARM analysis on four quasars in collaboration with GRAVITY team



Li et al. 2024



GRAVITY Collaboration et al. 2024

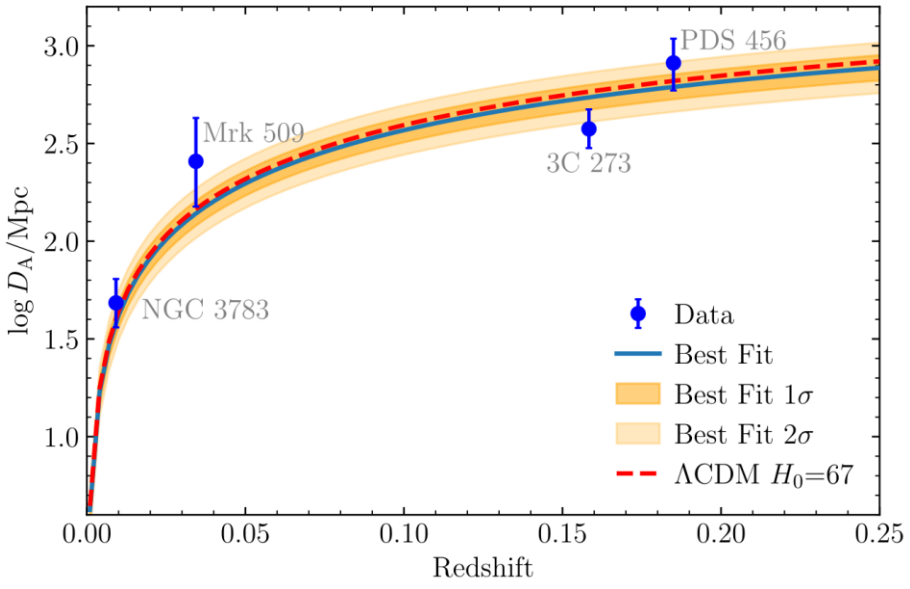
Latest progress: four quasars

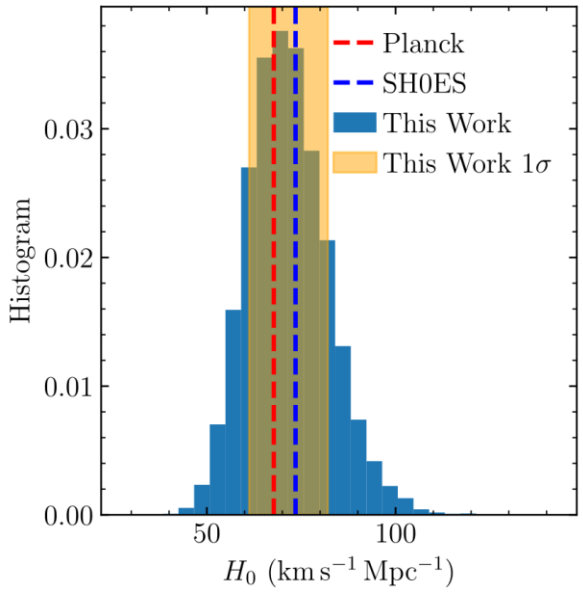
$H_0 = 69_{-10}^{+12}$ km s^{-1} Mpc^{-1} Precision: 15% (sys. err. <7%)

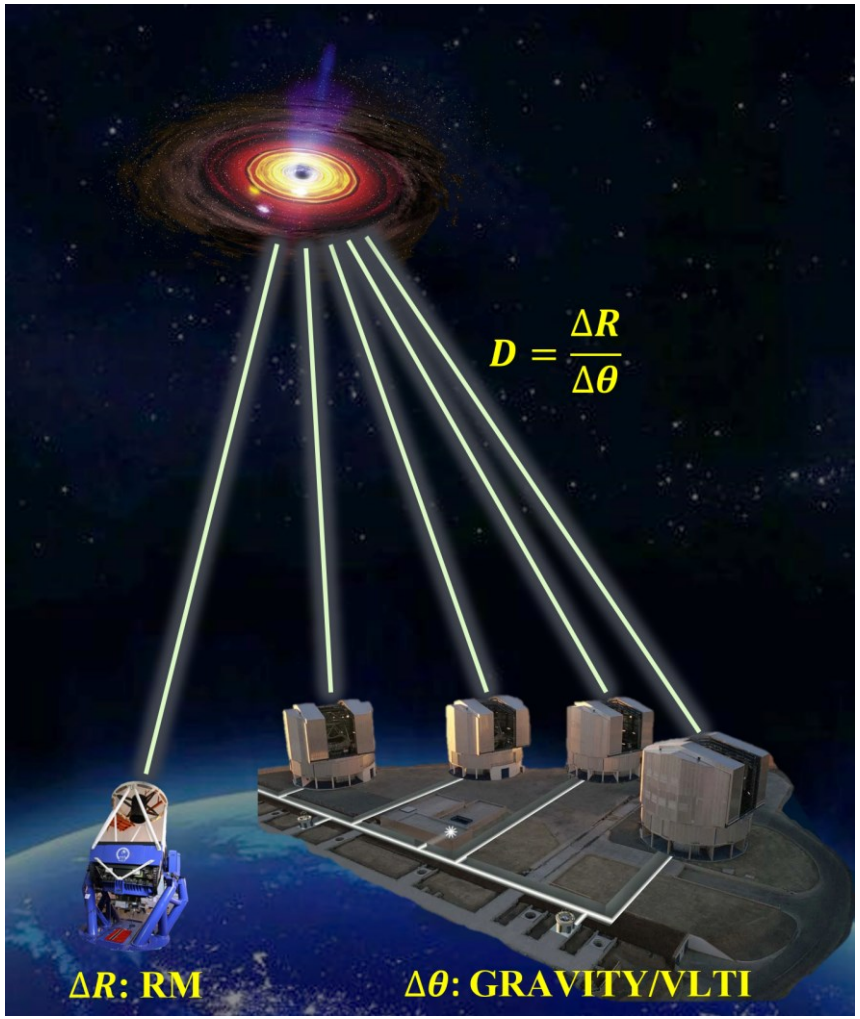
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Spectroastrometry and Reverberation Mapping of Active Galactic Nuclei. II. Measuring Geometric Distances and Black Hole Masses of Four Nearby Quasars

Yan-Rong Li[1], Jinyi Shangguan[2,3], Jian-Min Wang[1,4,5], Ric Davies[3], Daryl J. D. Santos[3], Frank Eisenhauer[3], Yu-Yang Songsheng[1], Hartmut Winkler[6], Jesús Aceituno[7,8], Hua-Rui Bai[1,9], Jin-Ming Bai[10], Michael S. Brotherton[11], Yixian Cao[3], Yong-Jie Chen[1,12], Pu Du[1], Feng-Na Fang[1,9], Jia-Qi Feng[1,9], Helmut Feuchtgruber[3], Natascha M. Förster Schreiber[3], Yi-Xin Fu[1,9], Reinhard Genzel[3], Stefan Gillessen[3], Luis C. Ho[2,13], Chen Hu[1], Jun-Rong Liu[1], Dieter Lutz[3], Thomas Ott[3], Romain G. Petrov[14], Sebastian Rabien[3], Taro Shimizu[3], Eckhard Sturm[3], Linda J. Tacconi[3], Yi-Lin Wang[1,9], Zhu-Heng Yao[5], Shuo Zhai[5], Hao Zhang[1,9], Yi-Peng Zhao[1,9], and Yu Zhao[1,9]
(SARM Collaboration)



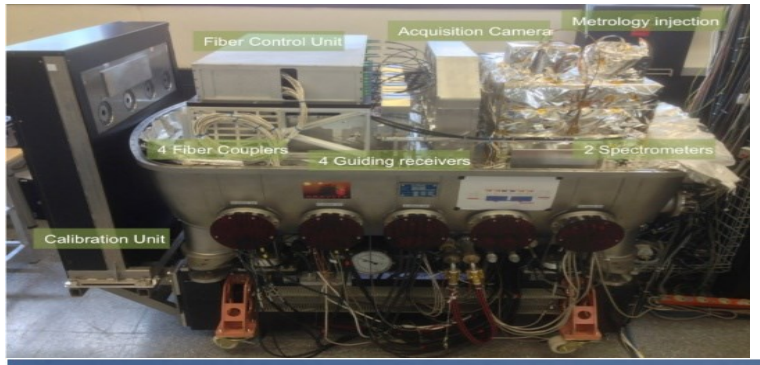




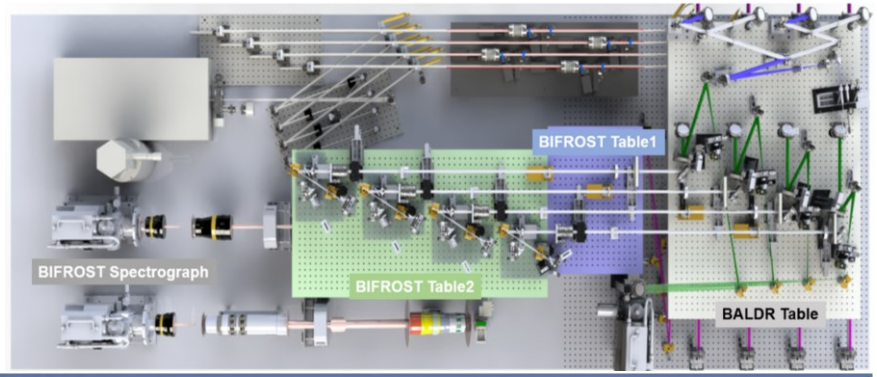
Future Perspectives

- ~50 quasars ⟹ Hubble constant precision ~2% (15% per quasar)

GRAVITY+: ***K*** band (2.0-2.4μm)



BIFROST: ***J, H*** band (1.0-1.8μm)

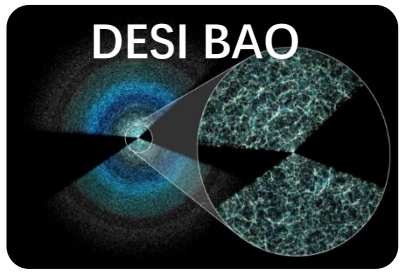


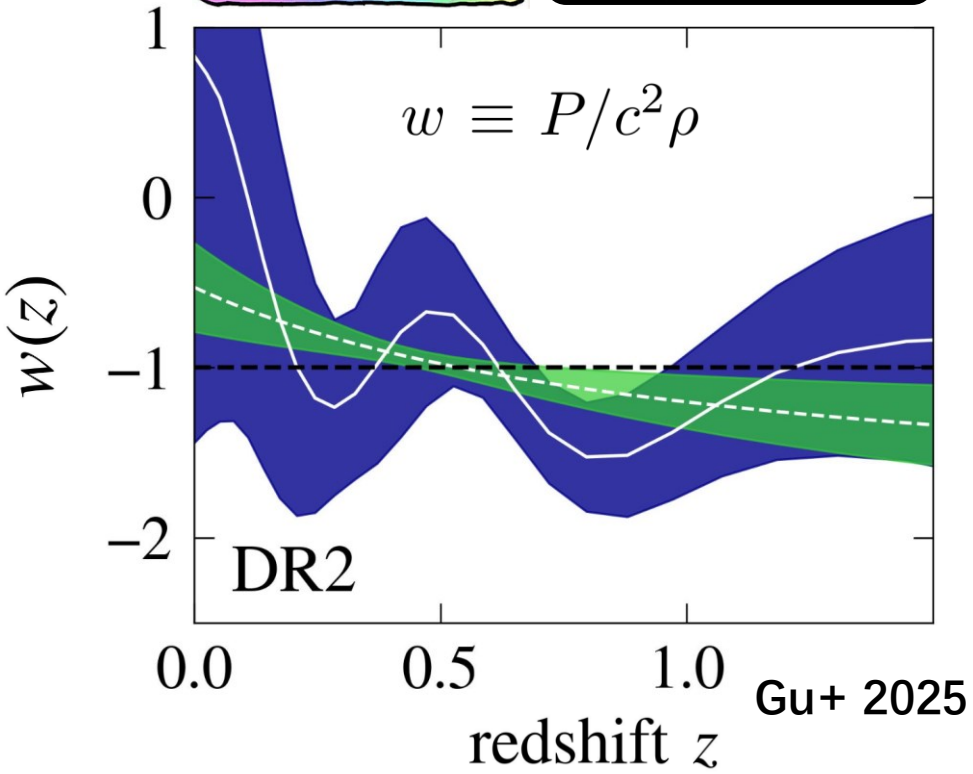


Future Perspectives

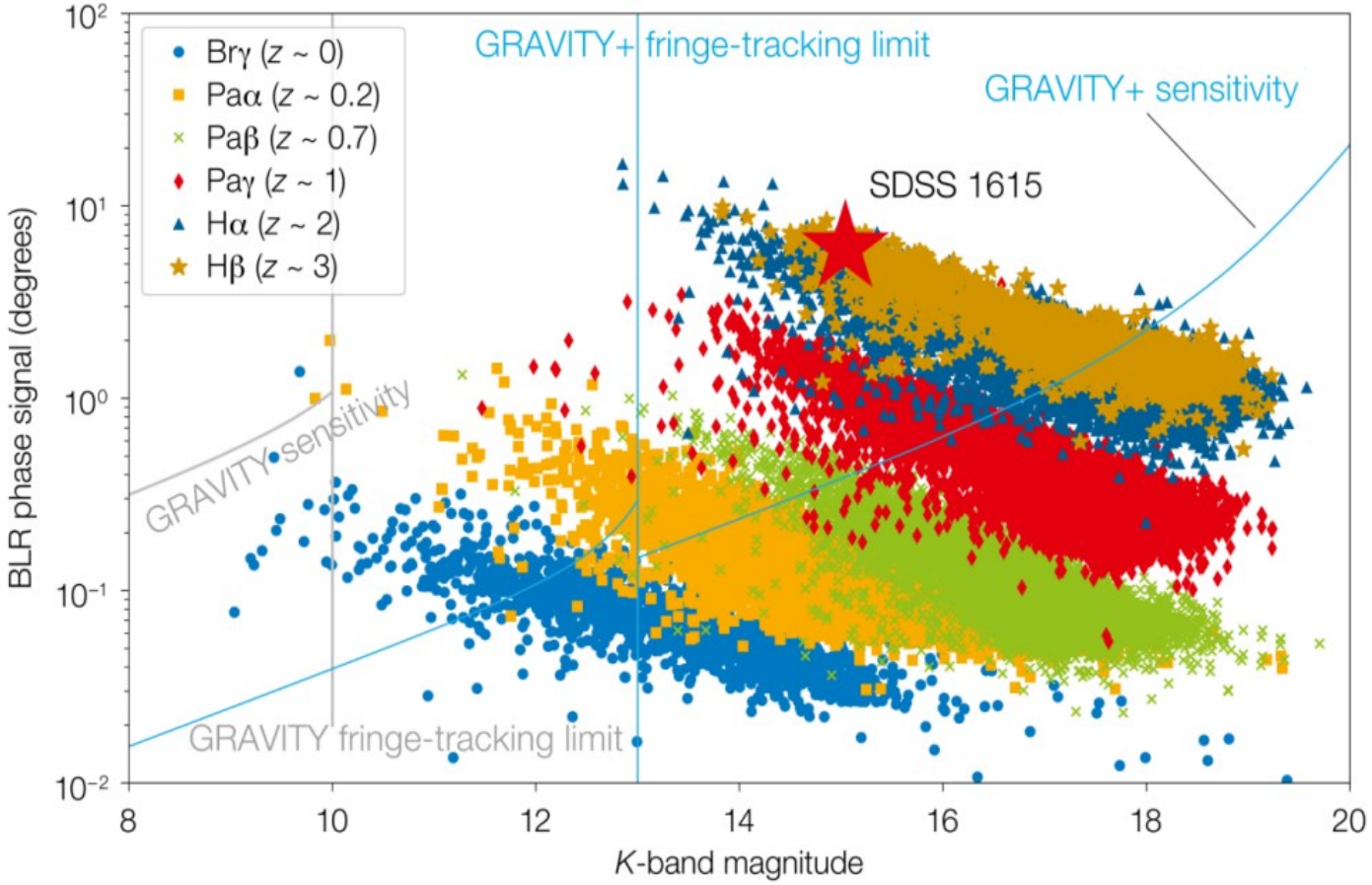
- z~0.5 quasar sample: constrain dynamical dark energy







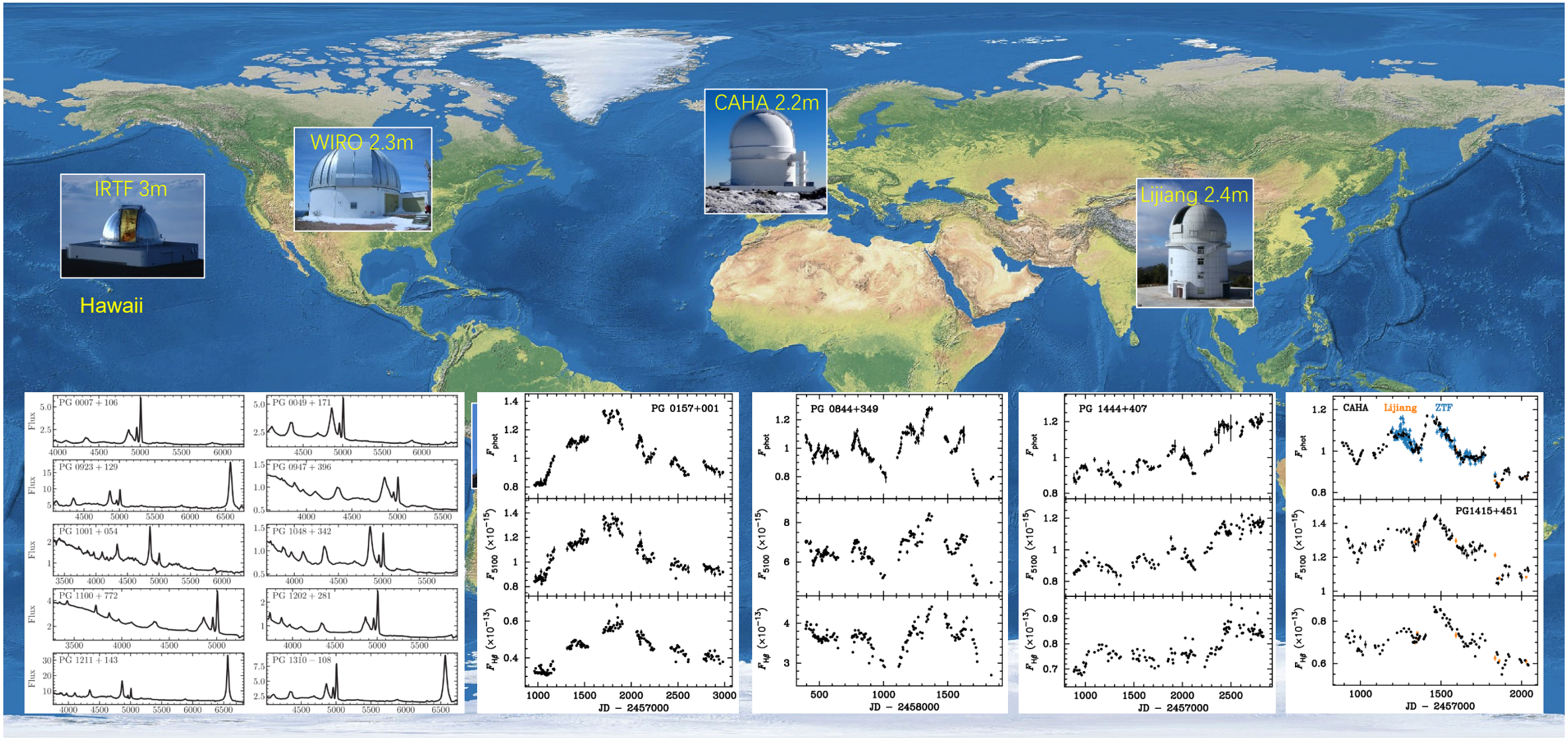
Gu+ 2025



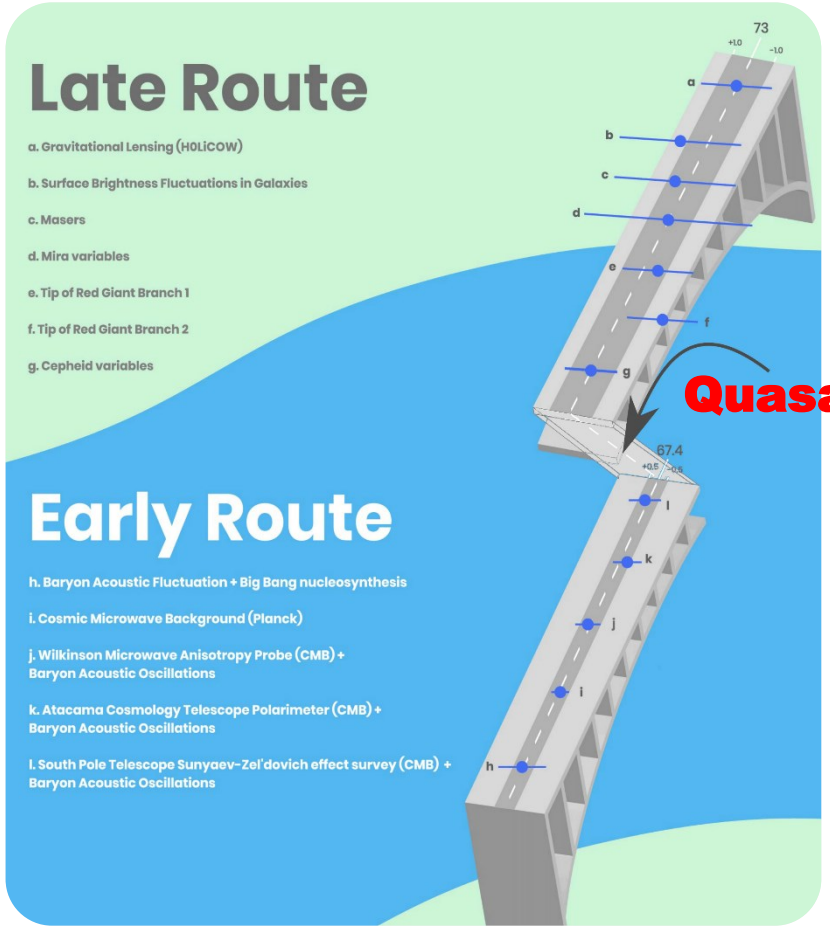
GRAVITY+ Collaboraton+ 2022

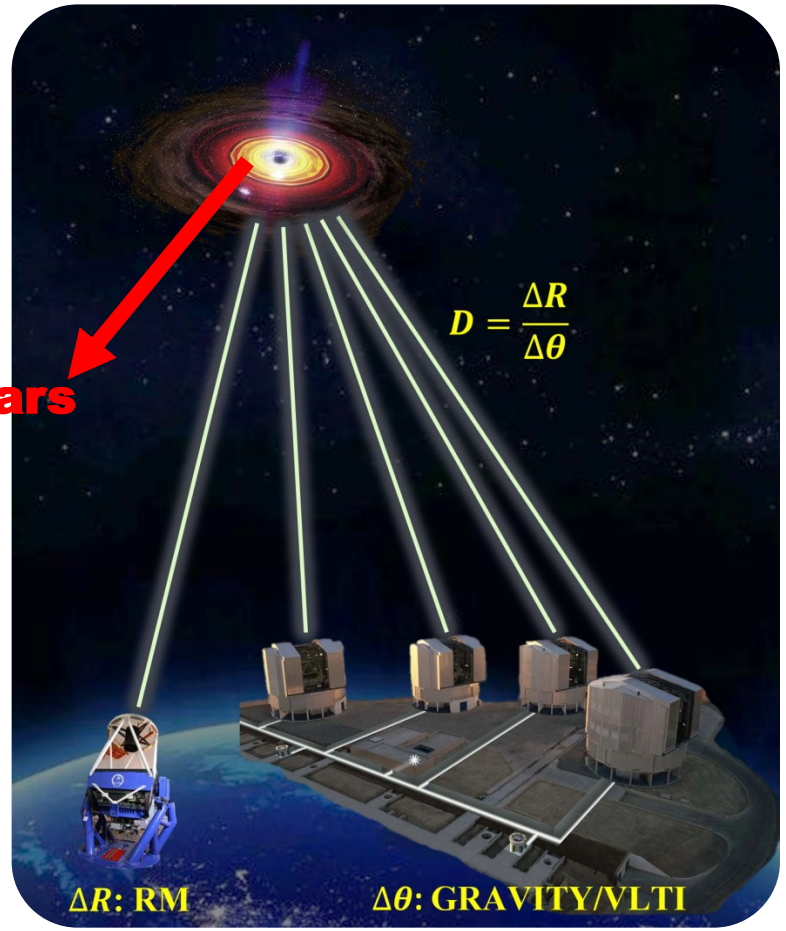
Quasar spectral monitoring campaign

- 2-3m class telescope network
- since 2012
- more than 150 quasars



Quasar as a geometric probe for cosmology





(Wang et al. 2020)

nature astronomy
LETTERS
https://doi.org/10.1038/s41550-019-0979-5

A parallax distance to 3C 273 through spectroastrometry and reverberation mapping

Jian-Min Wang[1,2,3*], Yu-Yang Songsheng[1,4], Yan-Rong Li[1], Pu Du[1] and Zhi-Xiang Zhang[5]

(Li & Wang 2023)

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Spectroastrometric Reverberation Mapping of Broad-line Regions

Yan-Rong Li[1] and Jian-Min Wang[1,2,3]

(Li et al. 2025)

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(SARM Collaboration)

Thank you for listening!