高精度宇宙学距离阶梯：光干涉测量

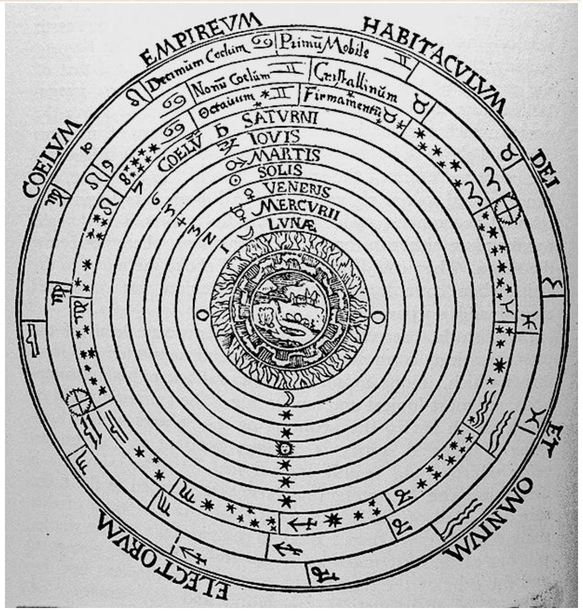
王建民

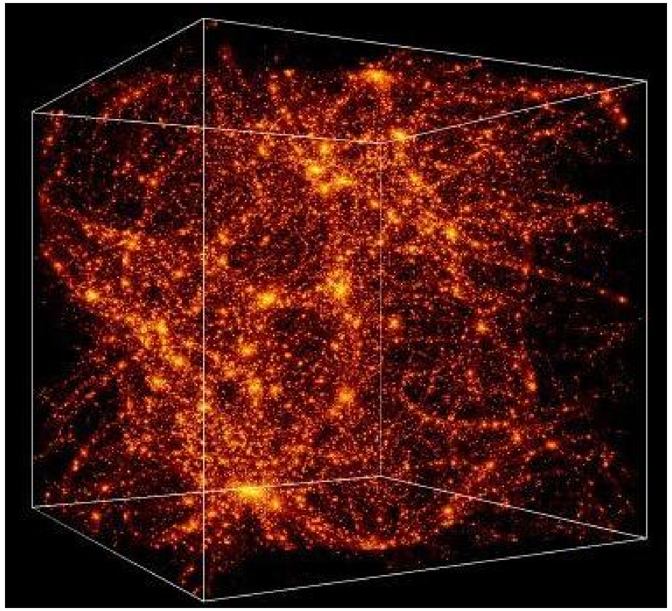
中国科学院高能物理研究所

25 June 2025, IHEP

Distance measurements hold the key

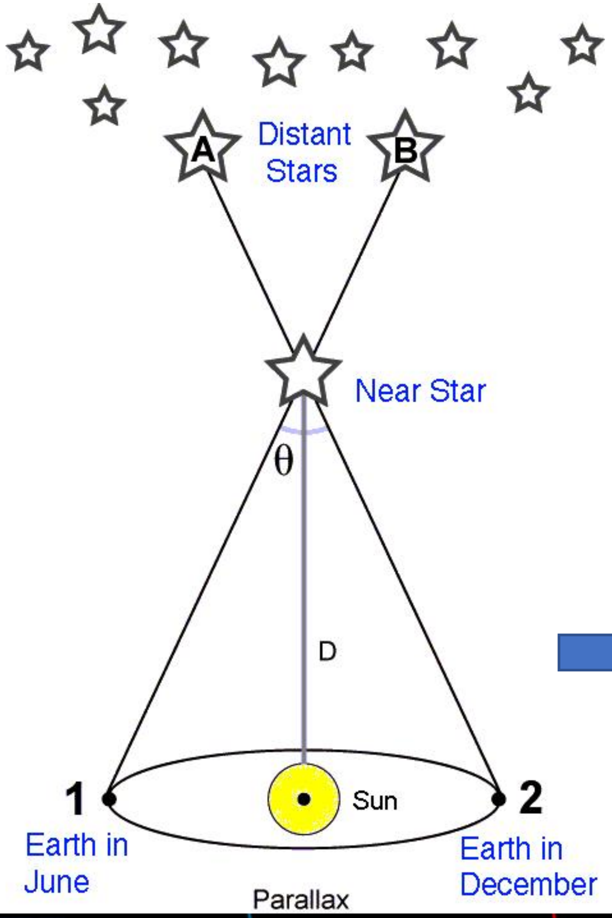
C. Ptolemy

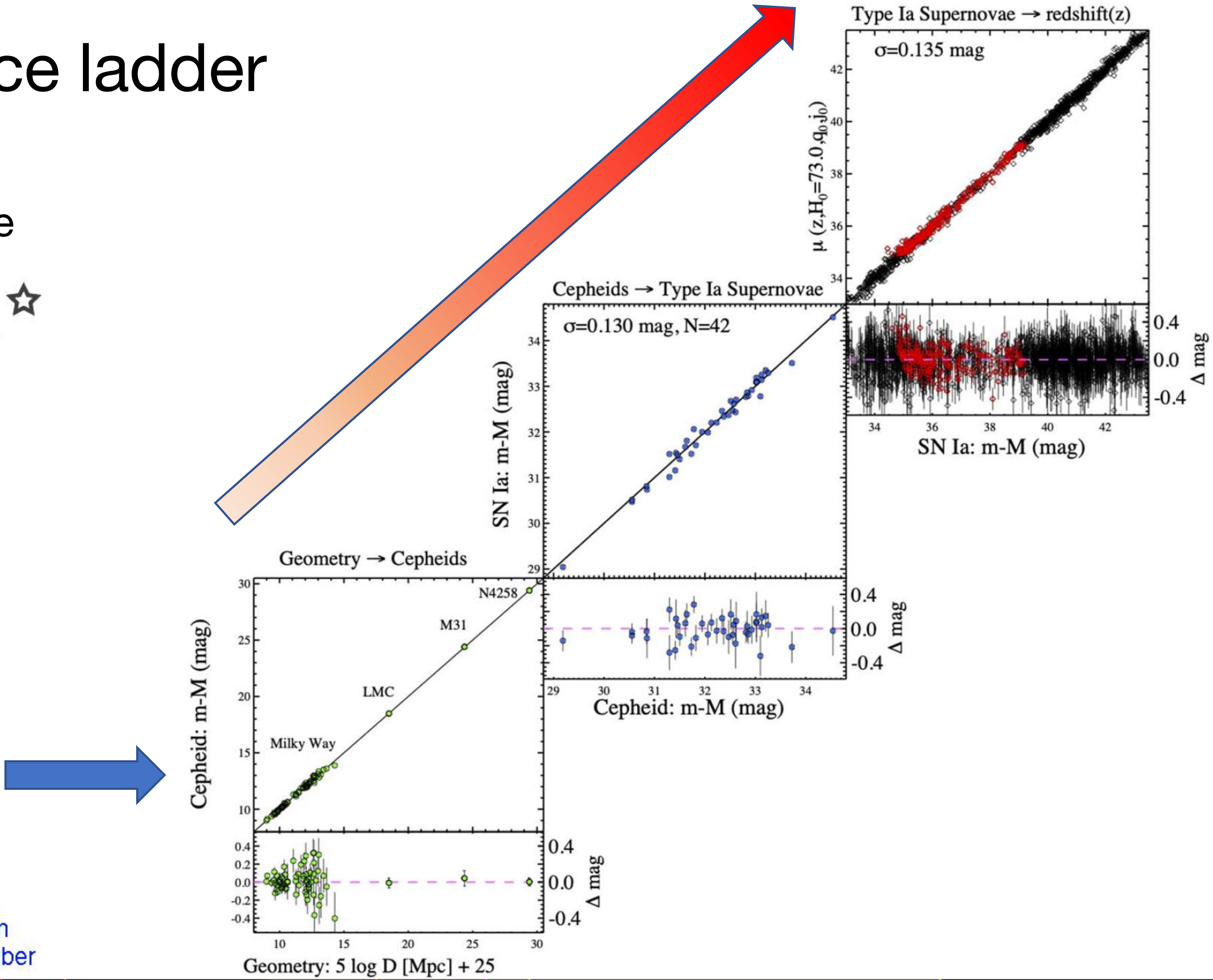


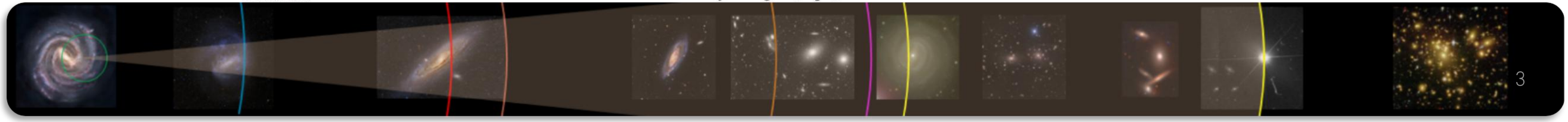


Cosmic distance ladder

geometric distance







2009年Gruber奖：HST哈勃常数测量

Publications of the Astronomical Society of Australia (2019), **36**, e001, 6 pages
doi:10.1017/pasa.2018.46

CAMBRIDGE UNIVERSITY PRESS

Research Paper

Galactic calibration of the tip of the red giant branch

Jeremy Mould[1], Gisella Clementini[2] and Gary Da Costa[3]

[1]Centre for Astrophysics & Supercomputing, Swinburne University, P.O. Box 218, Hawthorn, VIC 3122, Australia, [2]INAF—Osservatorio di Astrofisica e Scienza dello Spazio, 40129 Bologna, Italy and [3]Research School of Astronomy & Astrophysics, Australian National University, ACT 0200, Australia

Abstract

Indications from Gaia data release 2 are that the tip of the red giant branch (a population II standard candle related to the helium flash in low mass stars) is close to −4 in absolute *I* magnitude in the Cousins photometric system. Our sample is high-latitude southern stars from the thick disk and inner halo, and our result is consistent with longstanding findings from globular clusters, whose distances were calibrated with RR Lyrae stars. As the Gaia mission proceeds, there is every reason to think an accurate Galactic geometric calibration of tip of the red giant branch will be a significant outcome for the extragalactic distance scale.

Keywords: paralla

(Received 23 Augus

The goal of 1% accuracy in galaxy distances is now driven more by questions in fundamental physics than astronomy. A roadmap

1. Introduction

The goal of 1% accuracy in galaxy distances is now driven more by questions in fundamental physics than astronomy. A roadmap to reach this goal exists by means of observing and modelling cosmic microwave background anisotropies (Di Valentino et al. 2018). The astronomical distance ladder also has a path to reach this goal by calibrating the Cepheid period luminosity relation and the type Ia supernova standard candle. A second population

This means there is little to be gained by pursuing TRGB stars to great distances, where the relative errors are larger.

2.1. Database Query

We use as our input catalogue Data Release DR1.1 of the SkyMapper survey of the southern sky (Wolf et al. 2018) which incorpo 屏幕快照 crossmatch to Gaia DR2 catalogue and selected

Wendy L. Freedman

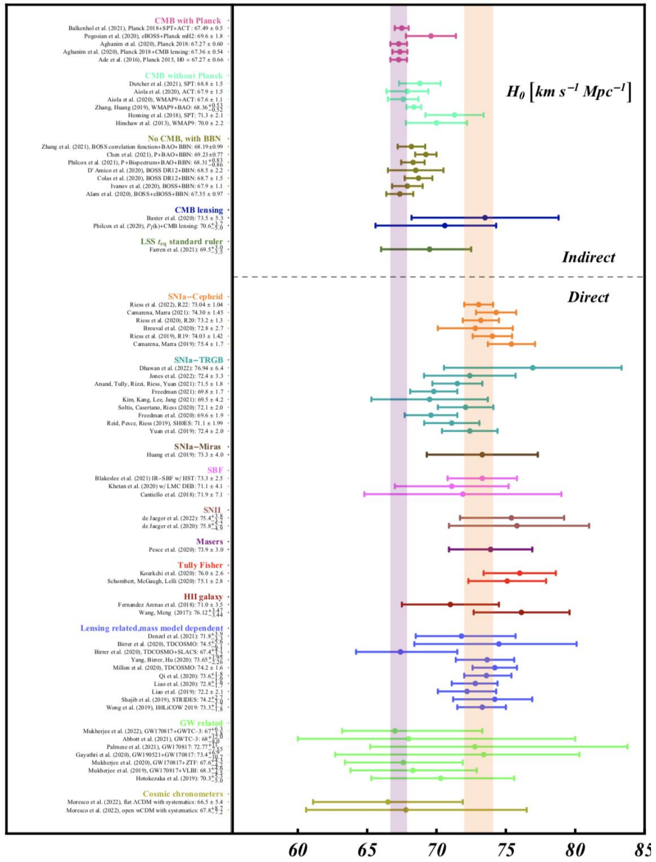
Robert C. Kennicutt

Jeremy Mould

H_0=50-100 km/s/Mpc →

72±8 km/s/Mpc

对星系距离精度好于1%的目标来自基础物理需求，而不是天文。

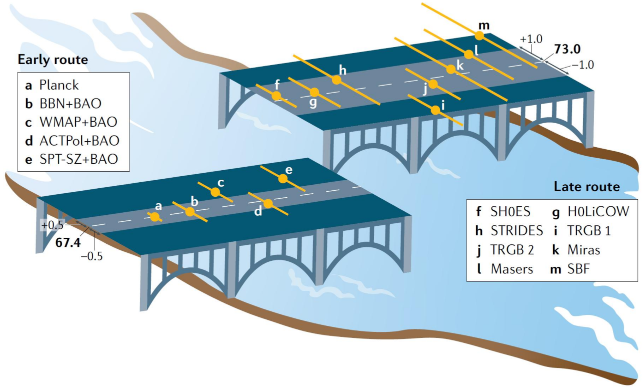


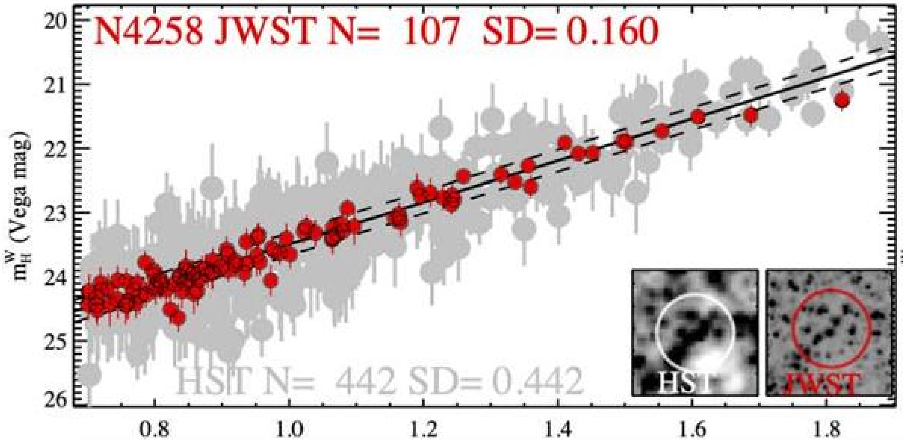
哈勃常数危机6σ

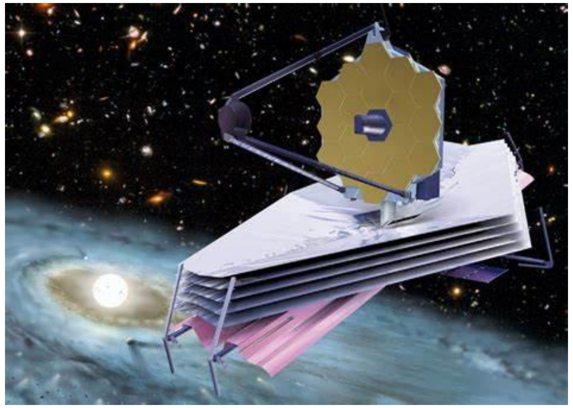
The Astrophysical Journal Letters, 962:L17 (13pp), 2024 February 10 https://doi.org/10.3847/2041-8213/ad1ddd

JWST Observations Reject Unrecognized Crowding of Cepheid Photometry as an Explanation for the Hubble Tension at 8σ Confidence

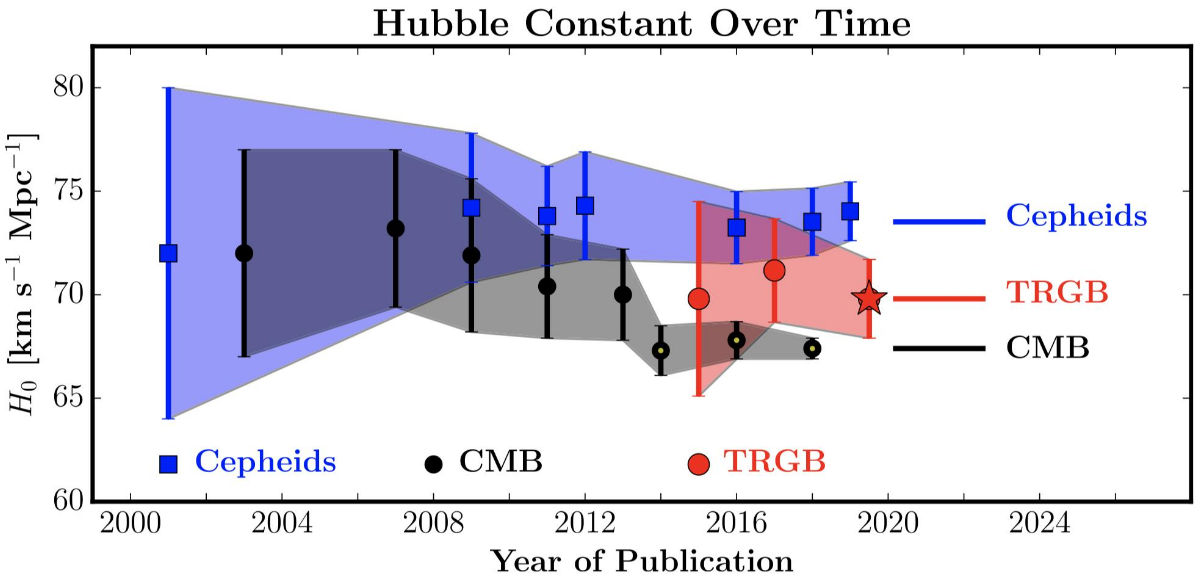
Adam G. Riess[1,2], Gagandeep S. Anand[1], Wenlong Yuan[2], Stefano Casertano[1], Andrew Dolphin[3], Lucas M. Macri[4], Louise Breuval[2], Dan Scolnic[5], Marshall Perrin[1], and Richard I. Anderson[6]

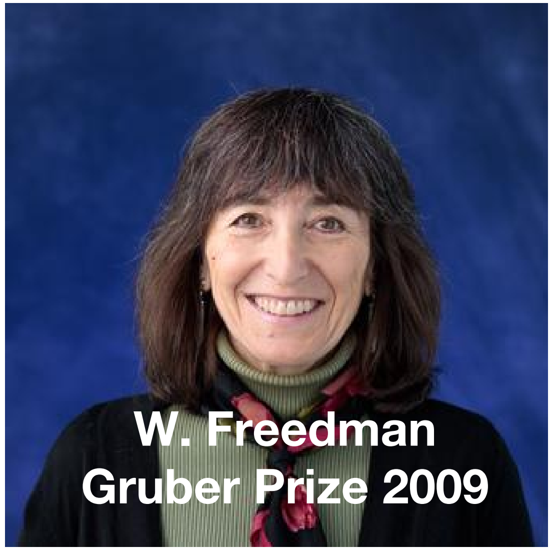


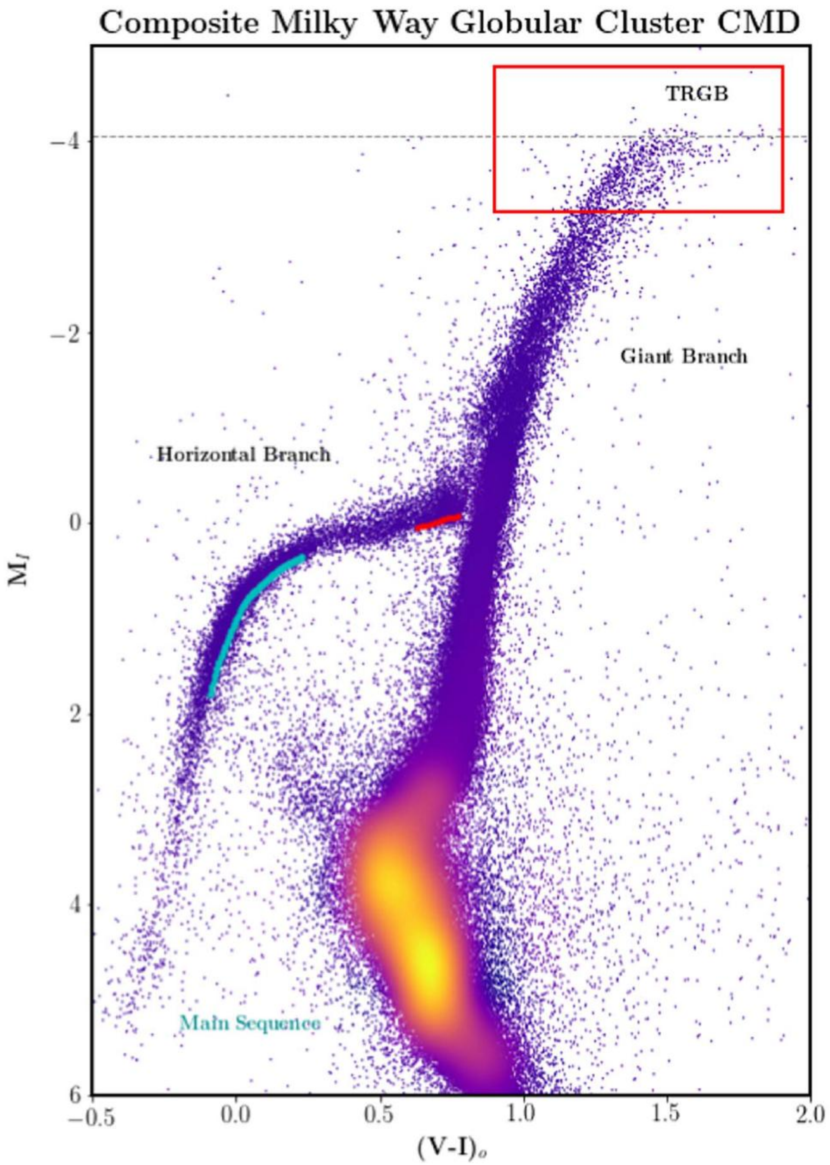




"Hubble tension" calls for new cosmic probes







高精度距离阶梯：是否可以构建？

类星体几何测距(SARM)

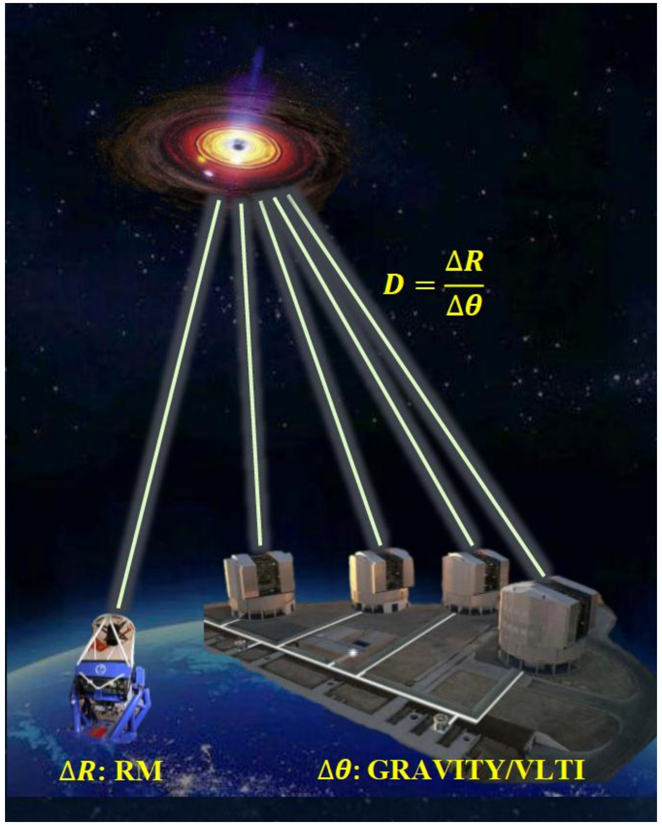
nature astronomy

LETTERS

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

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

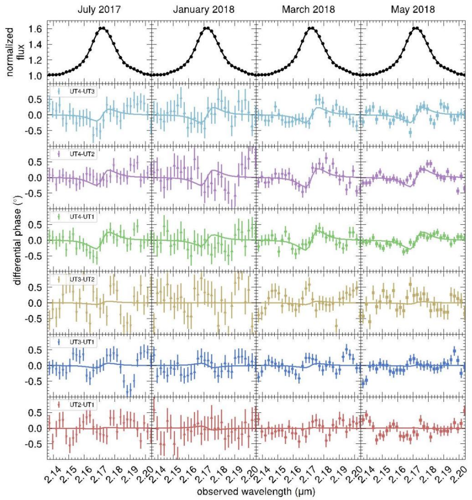
Jian-Min Wang[1,2,3]*, Yu-Yang Songsheng[1,4], Yan-Rong Li[1], Pu Du[1] and Zhi-Xiang Zhang[5]

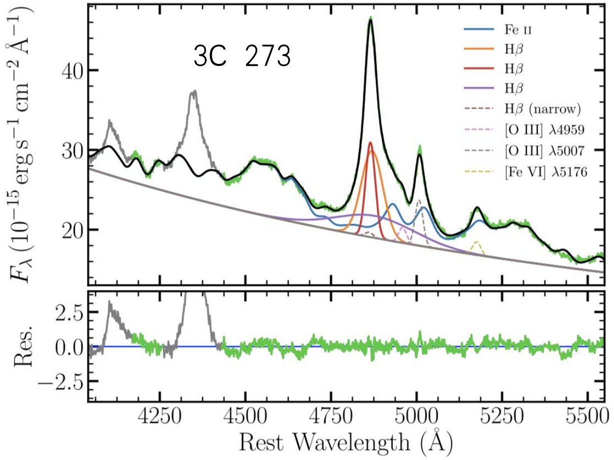


可以同时测量距离和黑洞质量 $d = \frac{\Delta R}{\Delta\theta}$; M_{BH}

纯几何测量

- 不依赖于消光
- 不依赖于标准化
- 阶梯校正（造父变星、超新星）
- 非大样本宇宙学统计（BAO）
- 系统误差检验

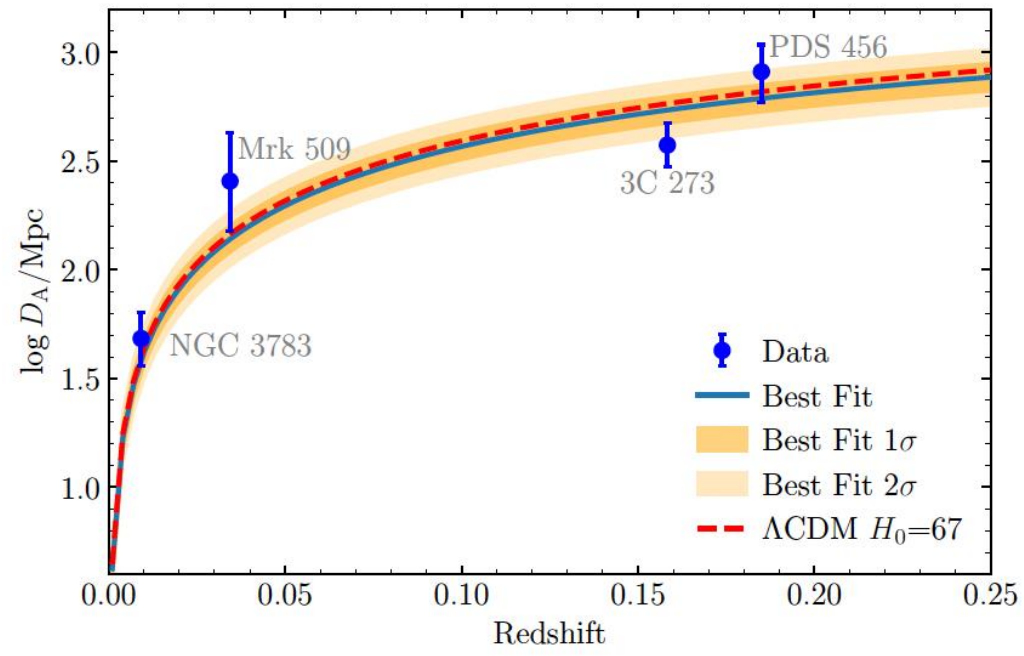


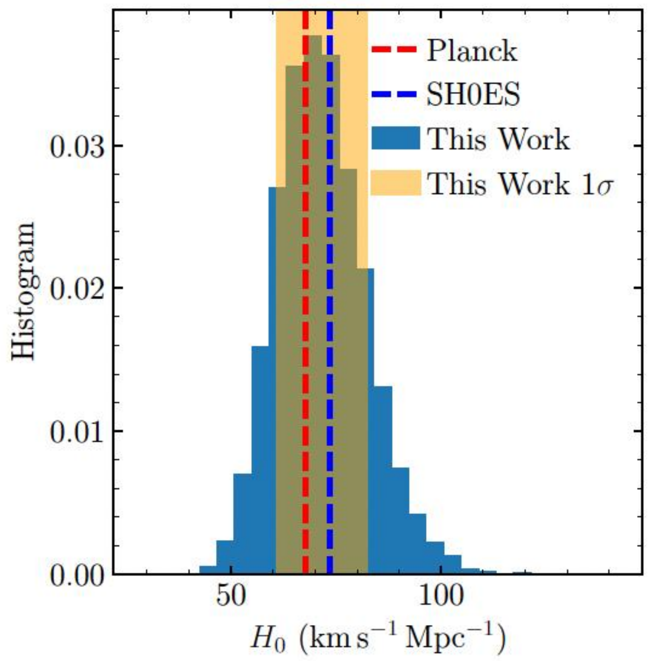


THE ASTROPHYSICAL JOURNAL, 00:000000 (18pp), 2025 Month Day

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

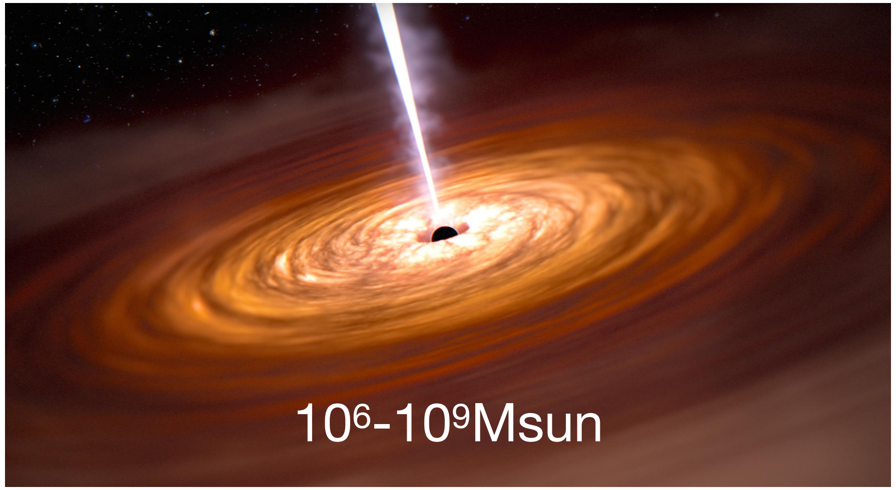
Yan-Rong Li[1], Jinyi Shangguan[2,3], Jian-Min Wang[1,4,5], Ric Davies[3], Daryl J. D. Santos[3], Frank Eisenhauer[3], Yu-Yang Songsheng[1], Hartmut Winkler[6], Jesús Aceituno[7,8], Hua-Rui Bai[1,9], Jin-Ming Bai[10], Michael S. Brotherton[11], Yixian Cao[3], Yong-Jie Chen[1,12], Pu Du[1], Feng-Na Fang[1,9], 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)

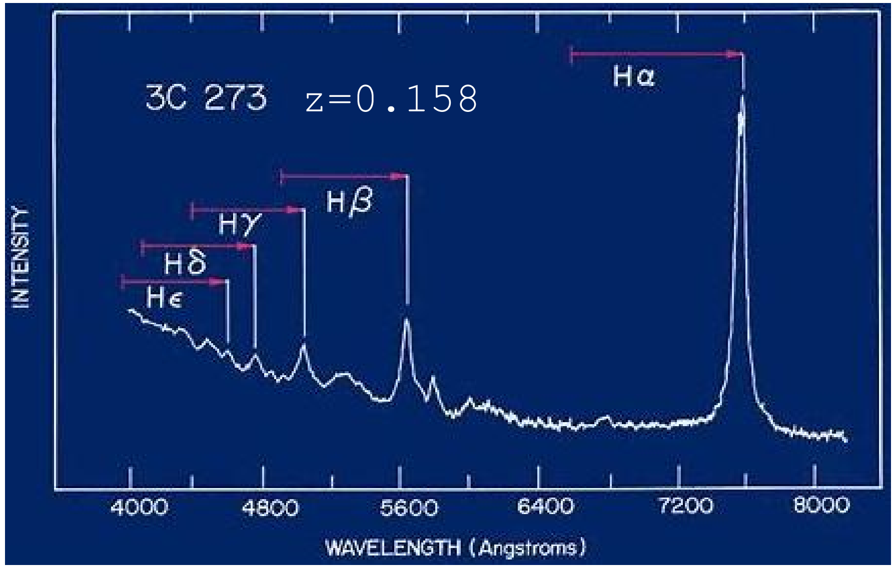


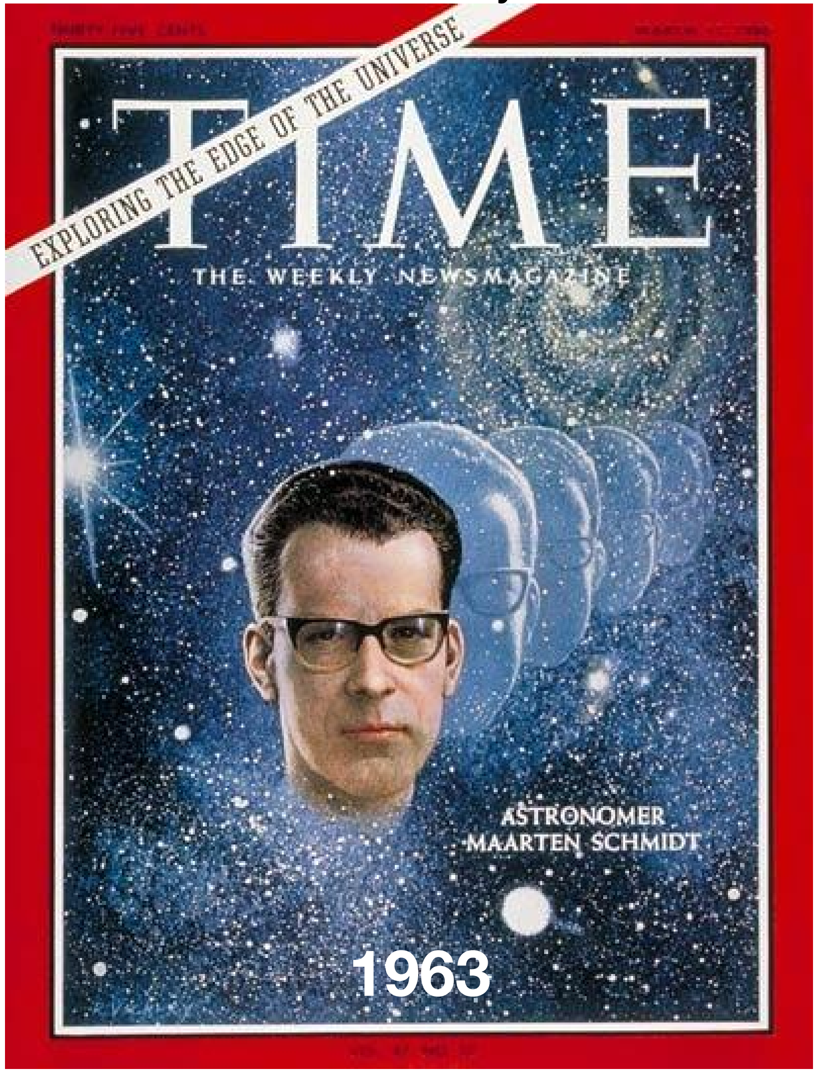


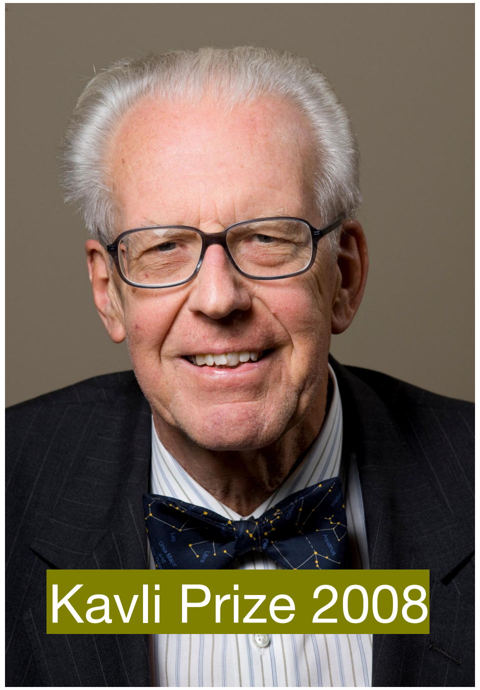
Quasars: accreting supermassive black holes

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

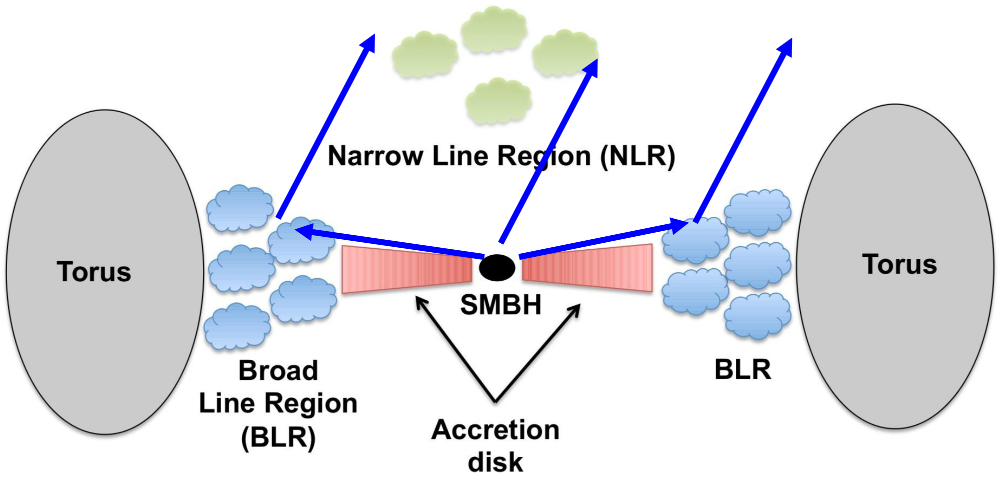


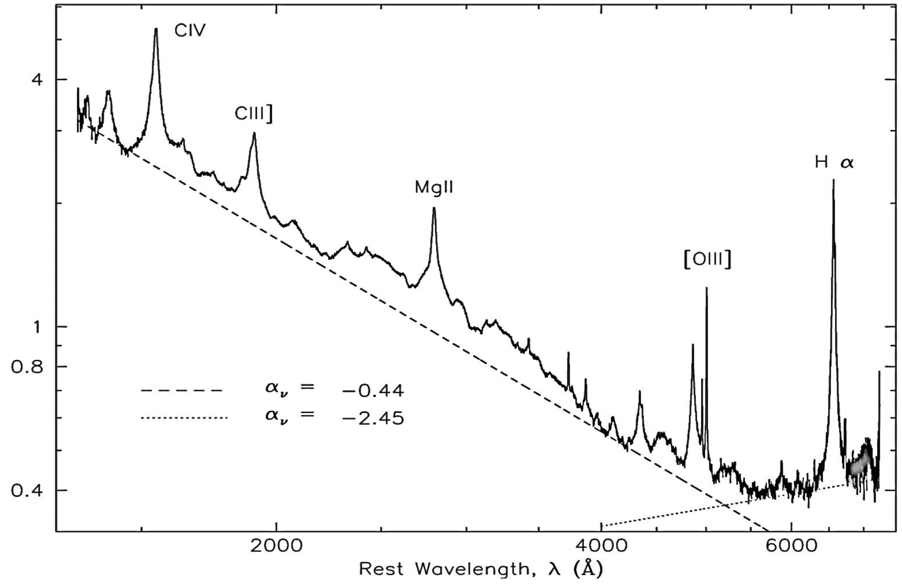






Quasars: accreting supermassive black holes





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

at 1Gpc （z=0.35）

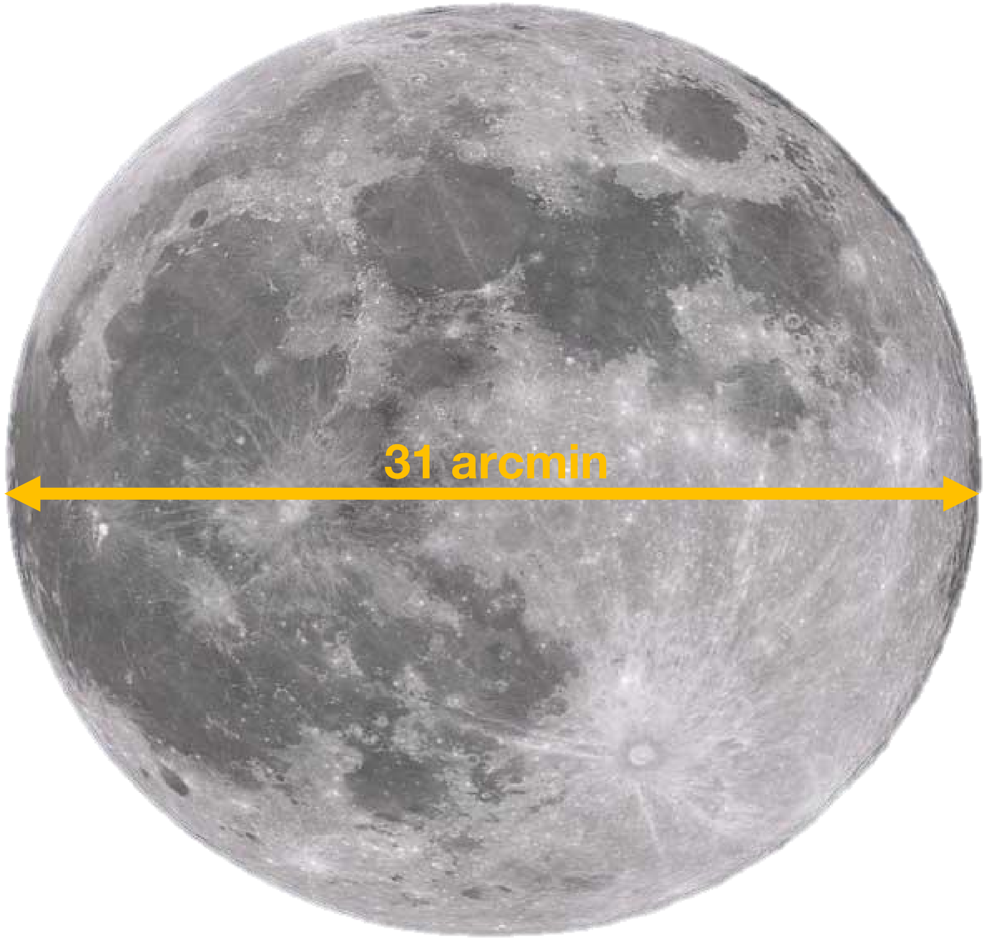
100light day—— 20micro-arcsec

1pc——200micro-arcsec

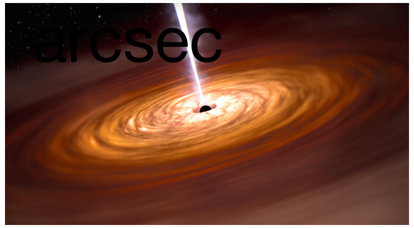
JWST 6m： ~0.1arcsec

ELT 39m： ~5milli-arcsec

Quasars: accreting supermassive black holes



~micro-arcsec



Quasar angular size: >10^8 times smaller!

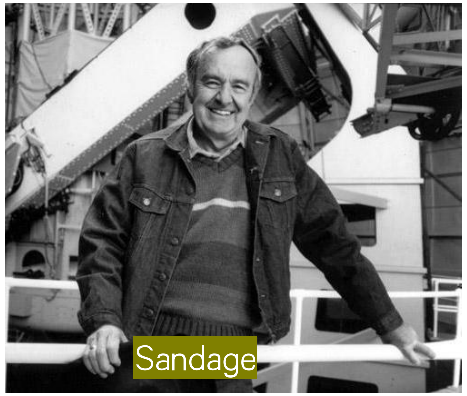
a small stone (2cm) vs. the moon

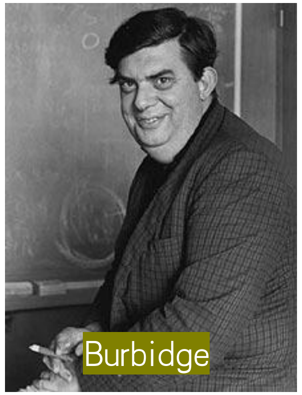
(1.7×10^8cm)

Quasars: accreting supermassive black holes

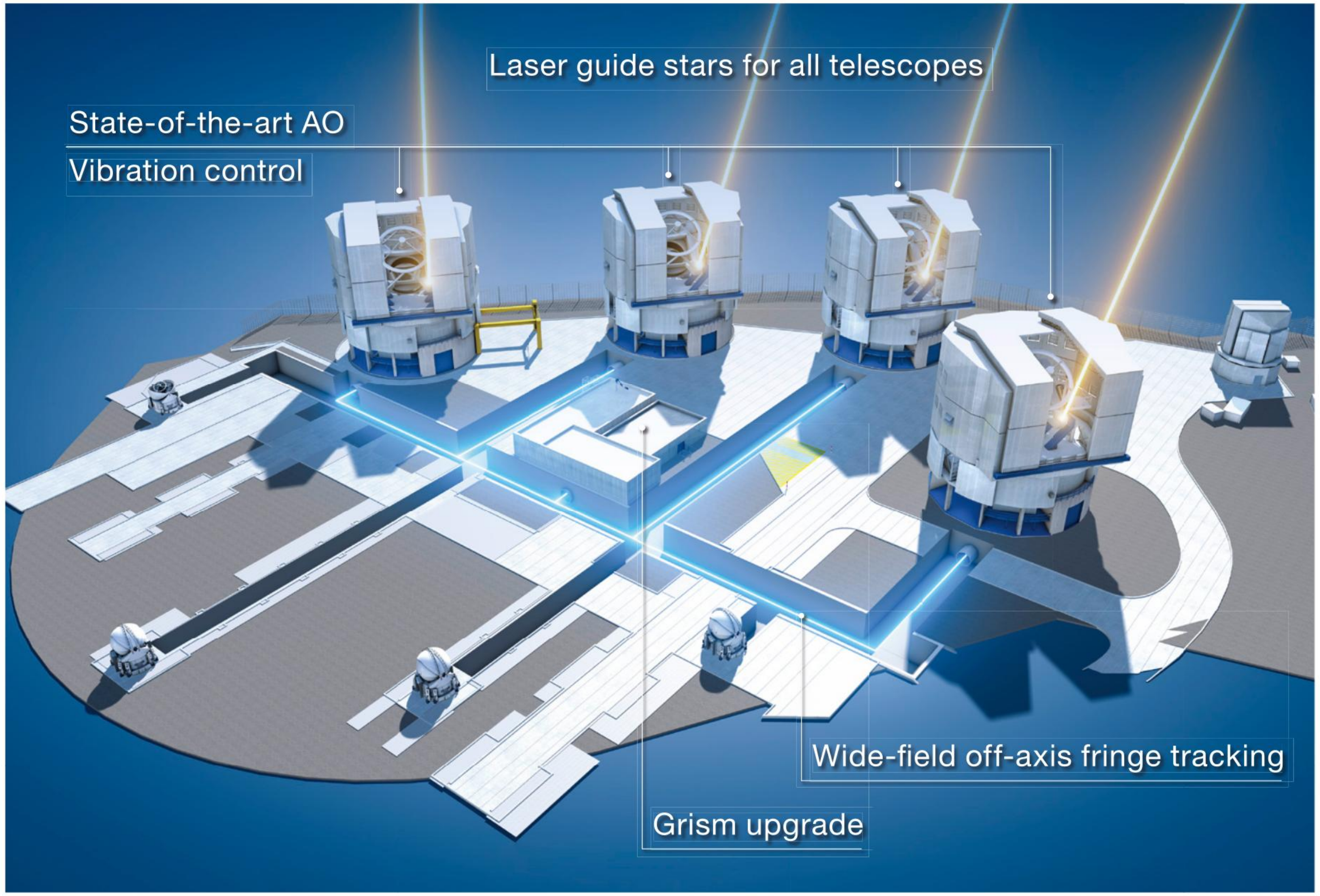
After 1963, an epic history of looking for quasars as a cosmic probe; most approaches ineffective

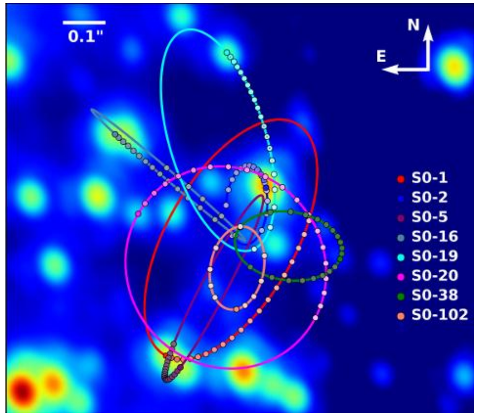
- Sandage (1965)
- Hoyle & Burbidge (1966)
- Longair (1967)
- Schmidt (1968)
- Weinberg (1972)
- Bahcall & Hills (1973)
- Baldwin (1977)
- Elvis & Karovska (2022)
- Watson+(2012)
- Wang+(2013)
- Yoshii+(2014)
- La Francis+(2014)
- Honig+(2015)
- Cao+(2017)
- Risaliti & Lusso(2019)

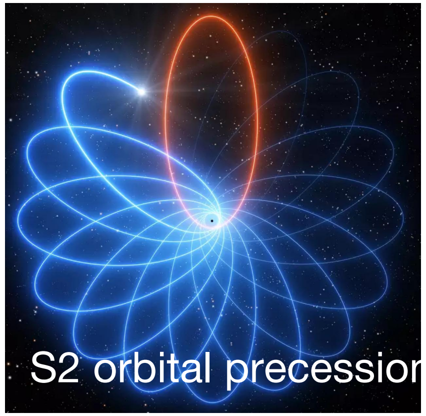




Breakthrough in 2017: infrared interferometry with VLTI







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

~10μas with spectroastrometry

Nobel physics prize in 2020

Breakthrough in 2017: infrared interferometry with VLTI

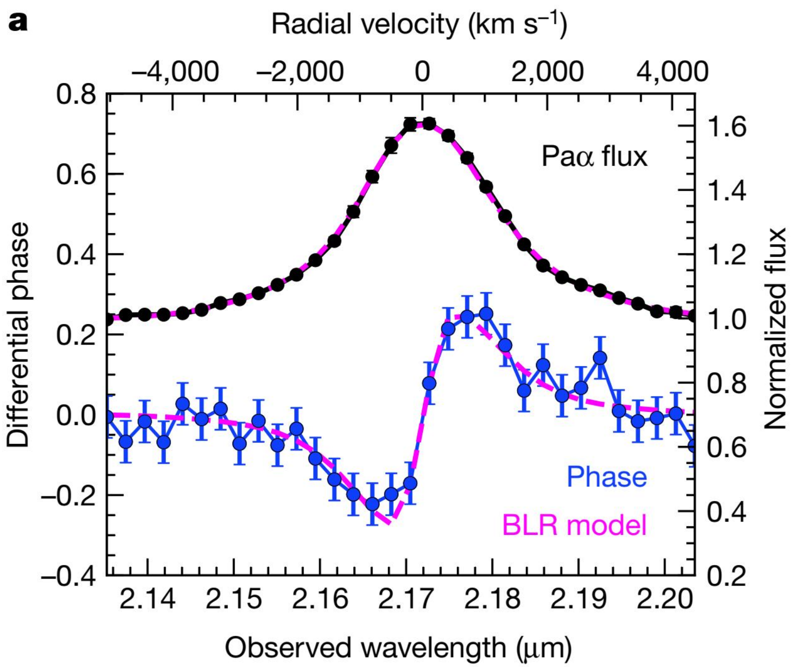
angular size: 46 µas, precision: 10 µas

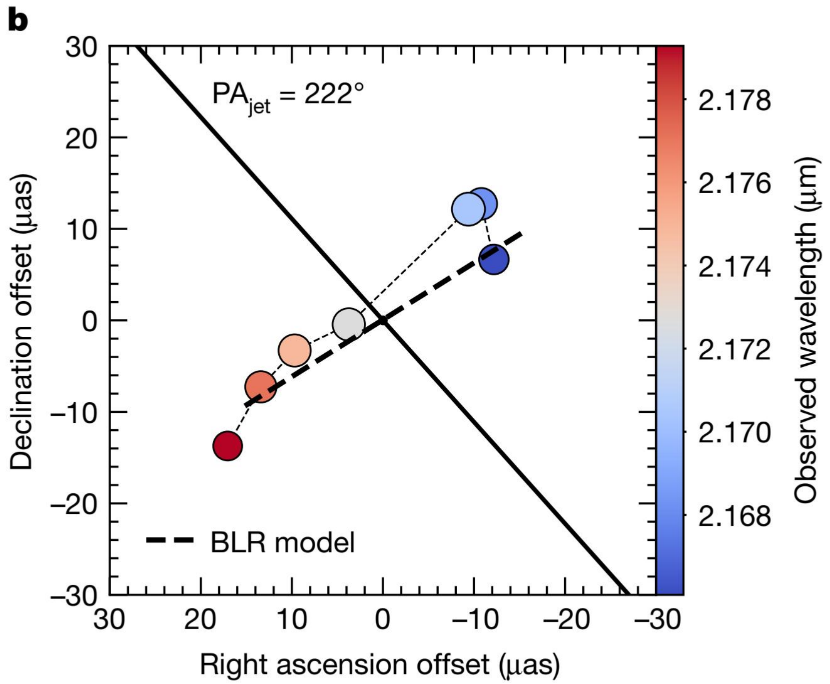
LETTER

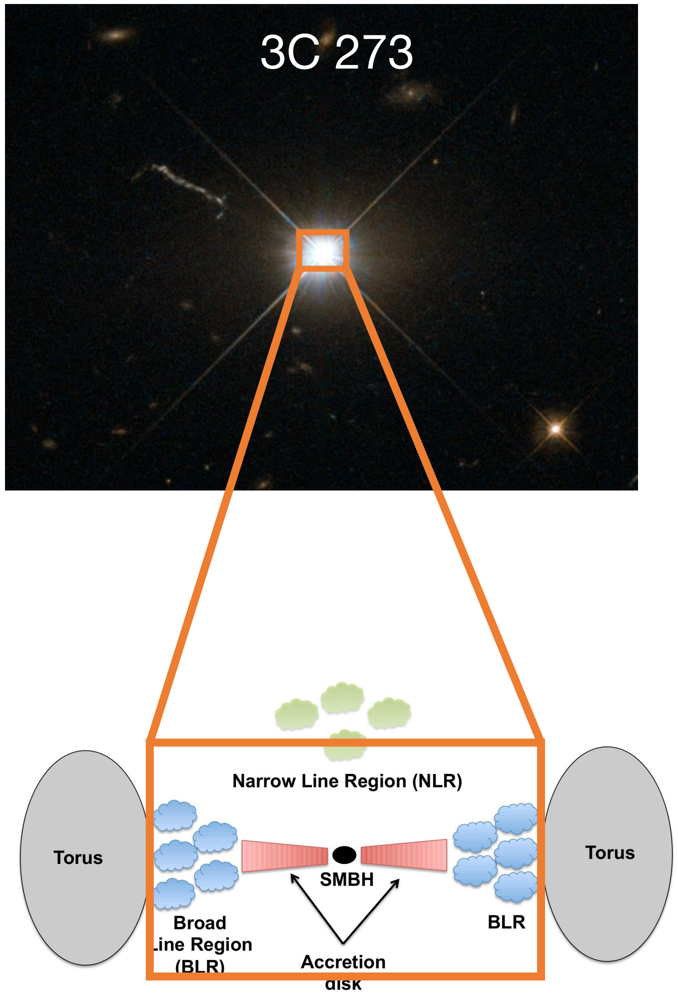
https://doi.org/10.1038/s41586-018-0731-9

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

GRAVITY Collaboration*





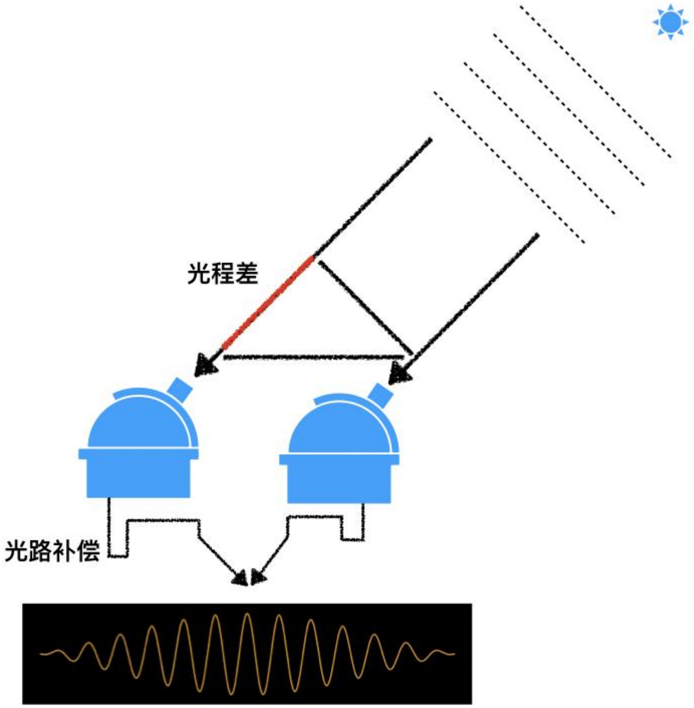


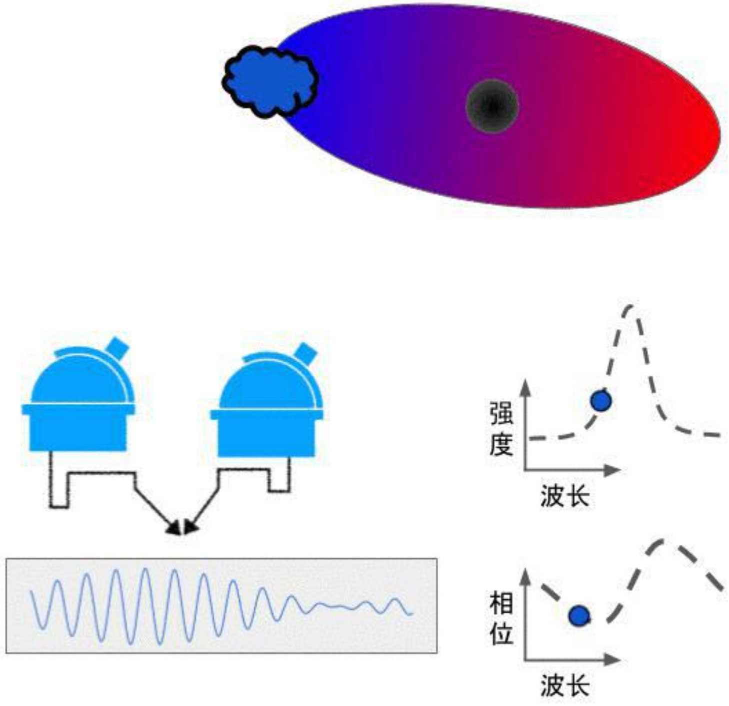
Breakthrough in 2017: infrared interferometry with VLTI

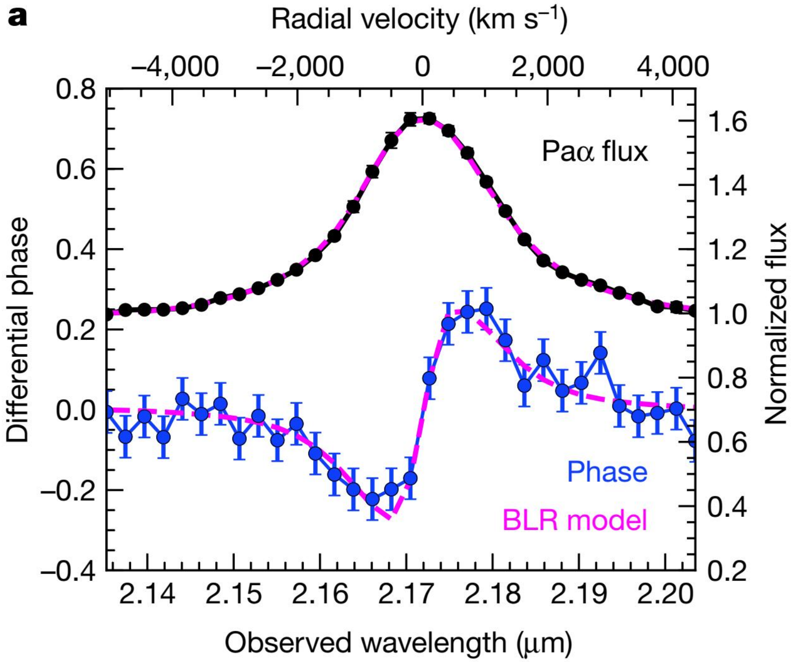
- Spectroastrometry with interferometry: angular size

Resolution:

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

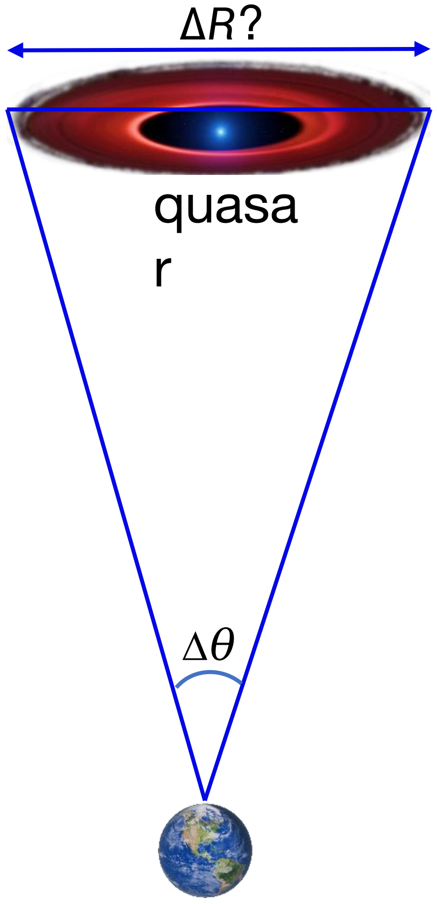






SARM approach: SpectroAstrometry + Reveberation Mapping

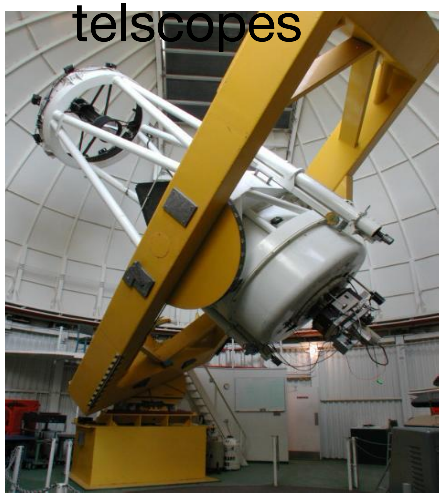
geometric distance:



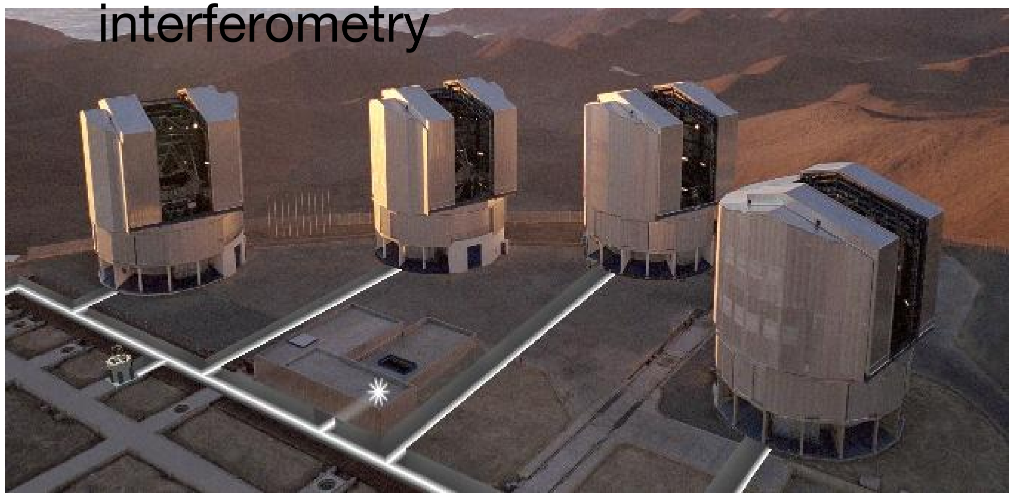
earth

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

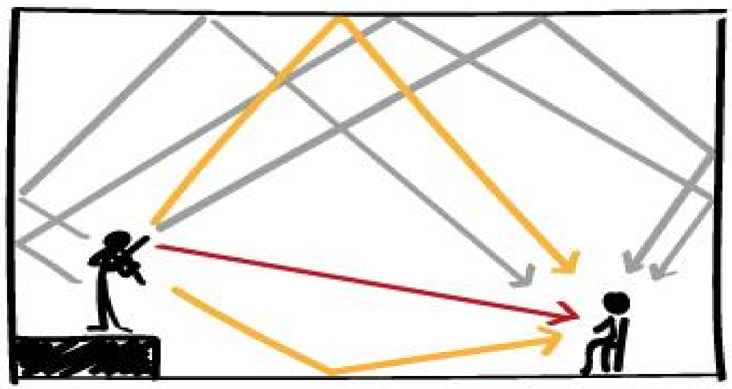
Reverberation Mapping with 2m telscopes

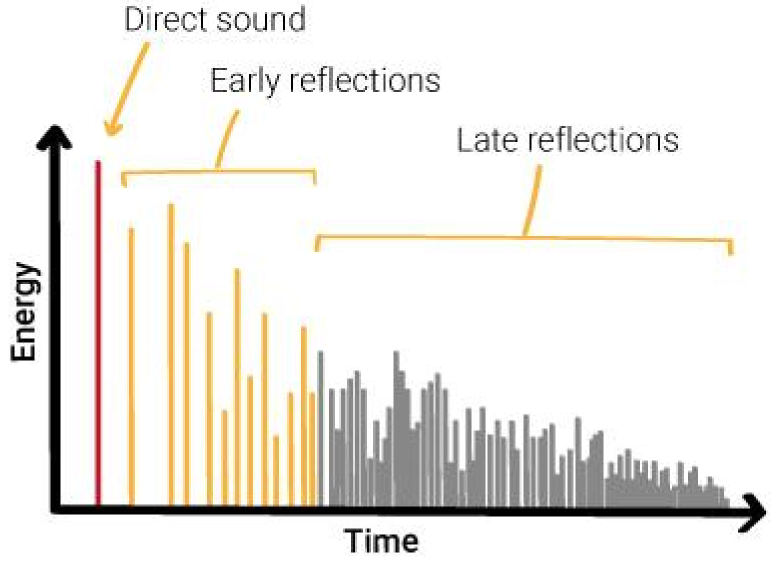


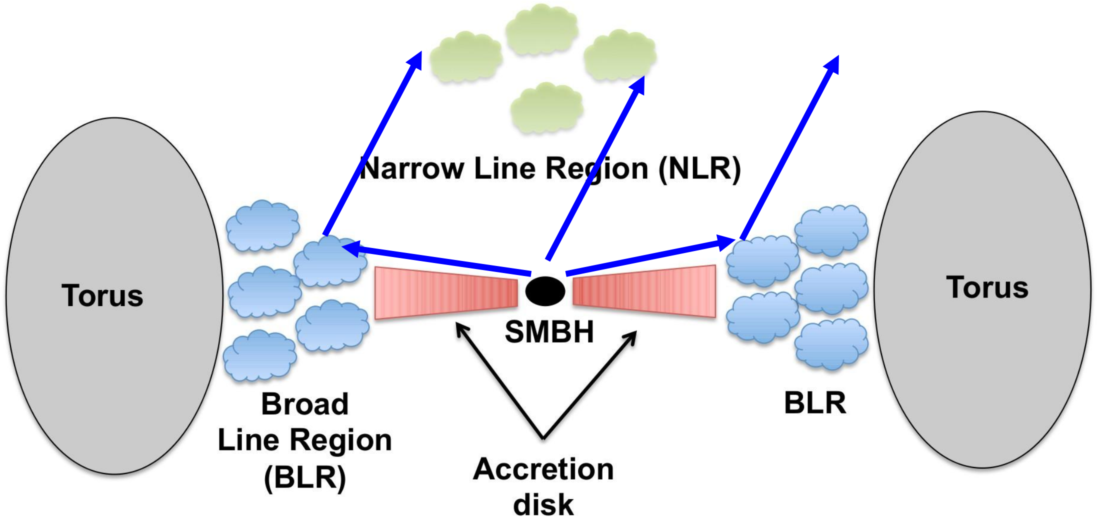
Spectroastrometry with interferometry

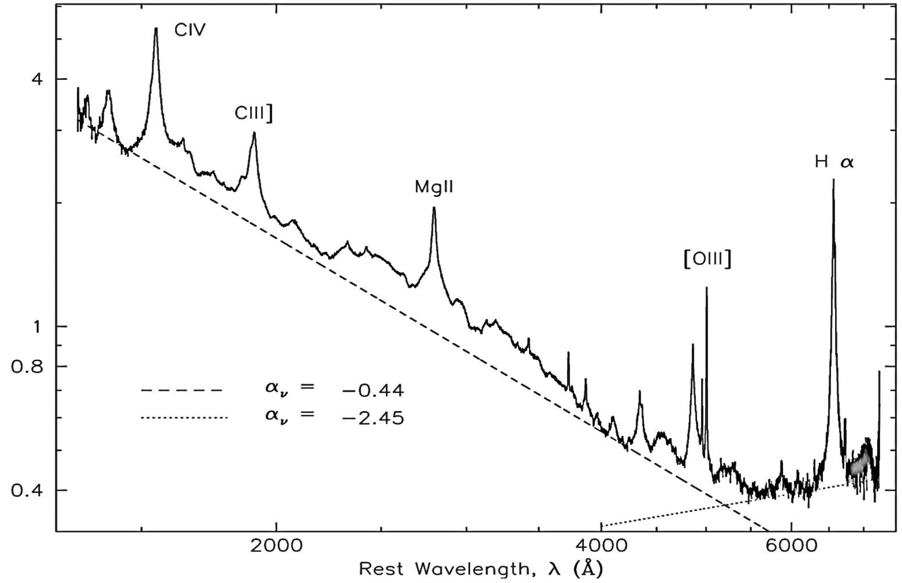


Reverberation Mapping





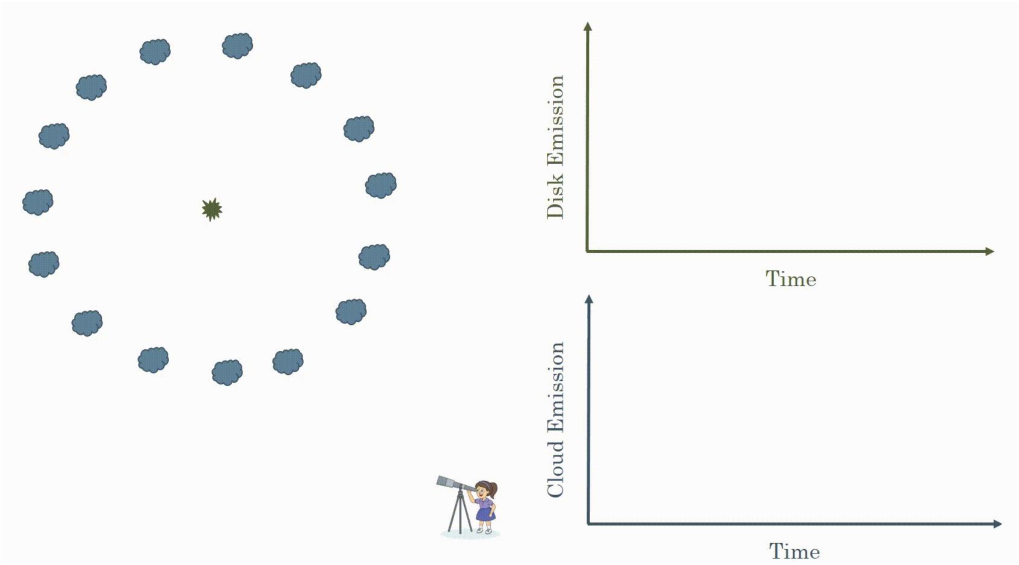


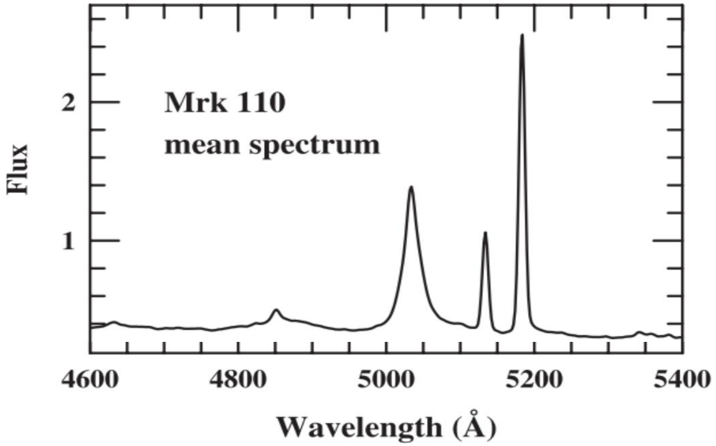


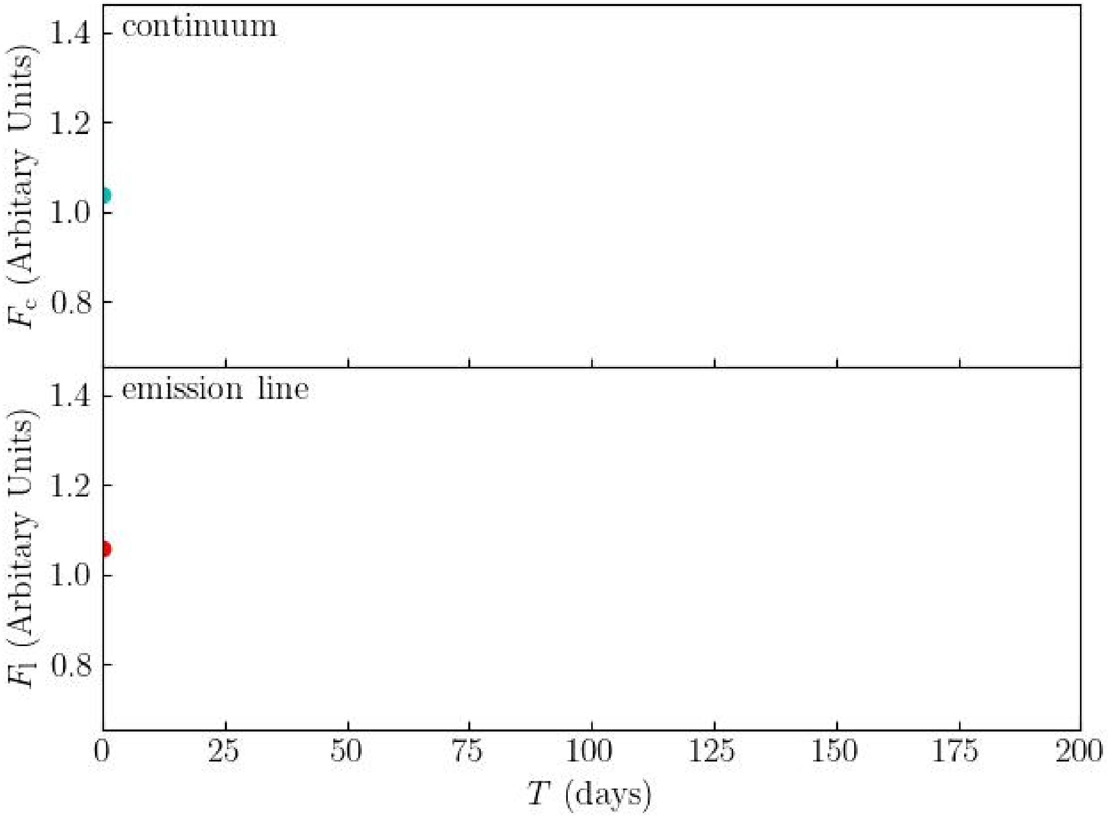
Reverberation Mapping

$$L(v,\ t) = \int \Psi(v,\ \tau) C(t-\tau) d\tau$$

Time lag: τ ➡ Physical size: $\Delta R = c \times \tau$







- reverberation mapping of brad-line regions

  Blandford & McKee (1982)

THE ASTROPHYSICAL JOURNAL, **255**:419–439, 1982 April 15

REVERBERATION MAPPING OF THE EMISSION LINE REGIONS OF SEYFERT GALAXIES AND QUASARS

R. D. BLANDFORD
Theoretical Astrophysics, California Institute of Technology
AND
CHRISTOPHER F. MCKEE

- reverberation mapping of spectroastrometry

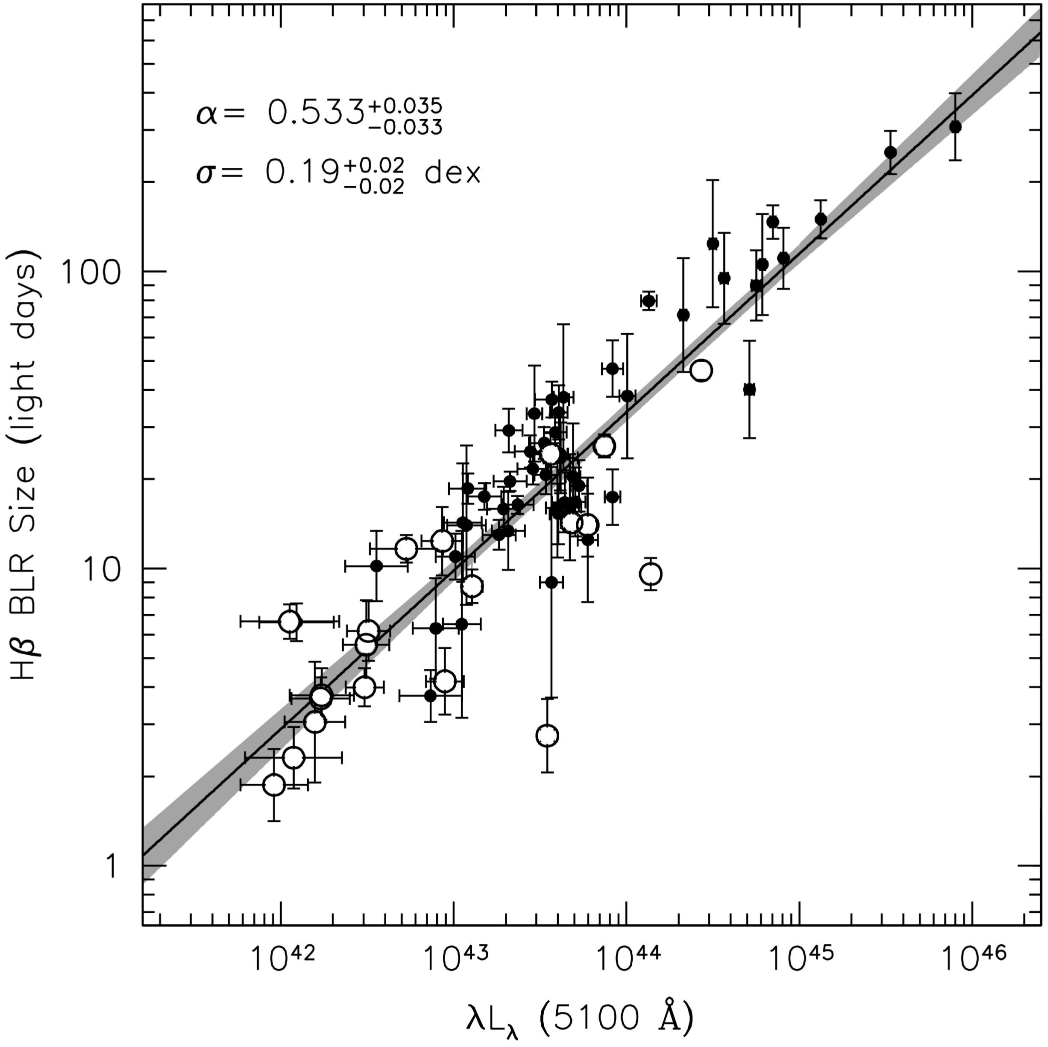
  LYR & Wang (2023)

THE ASTROPHYSICAL JOURNAL, 943:36 (21pp), 2023 January 20 https://doi.org/10.3847/1538-4357/aca66d

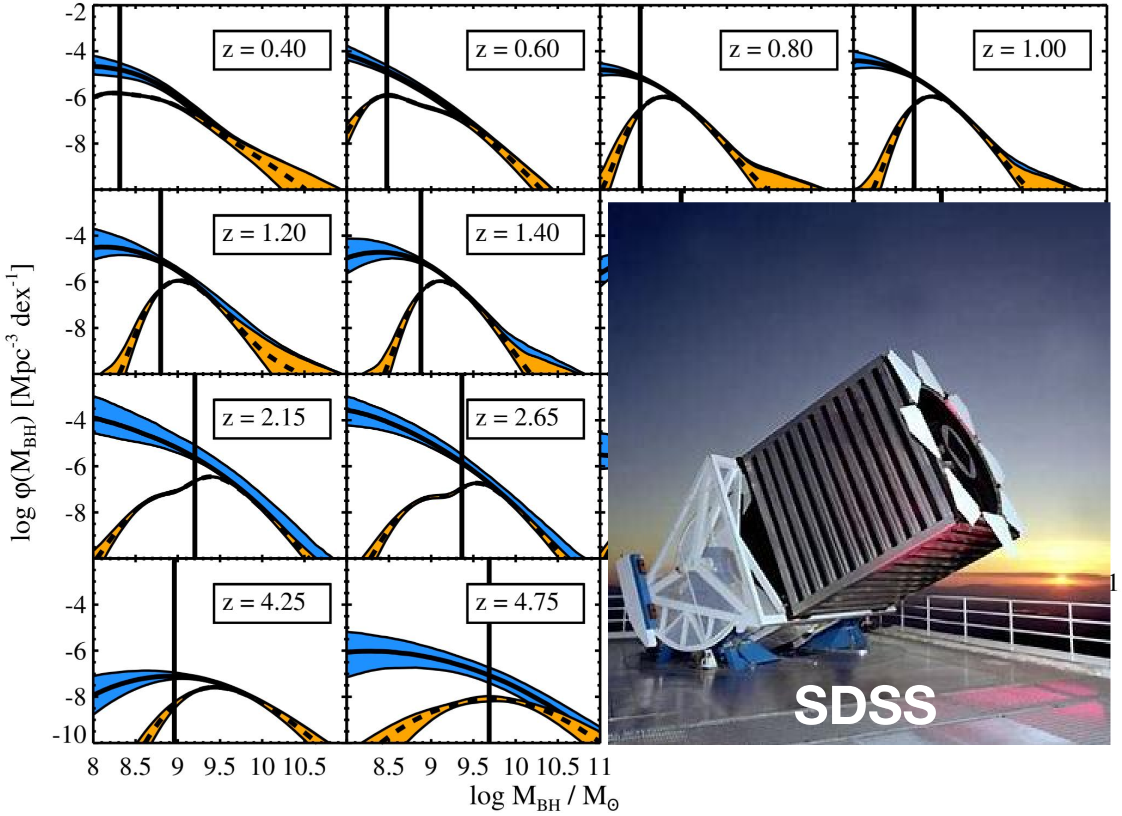
Spectroastrometric Reverberation Mapping of Broad-line Regions

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

Reverberation Mapping



$$M_{\rm BH} = f\,\frac{\Delta R \times V^2}{G}$$

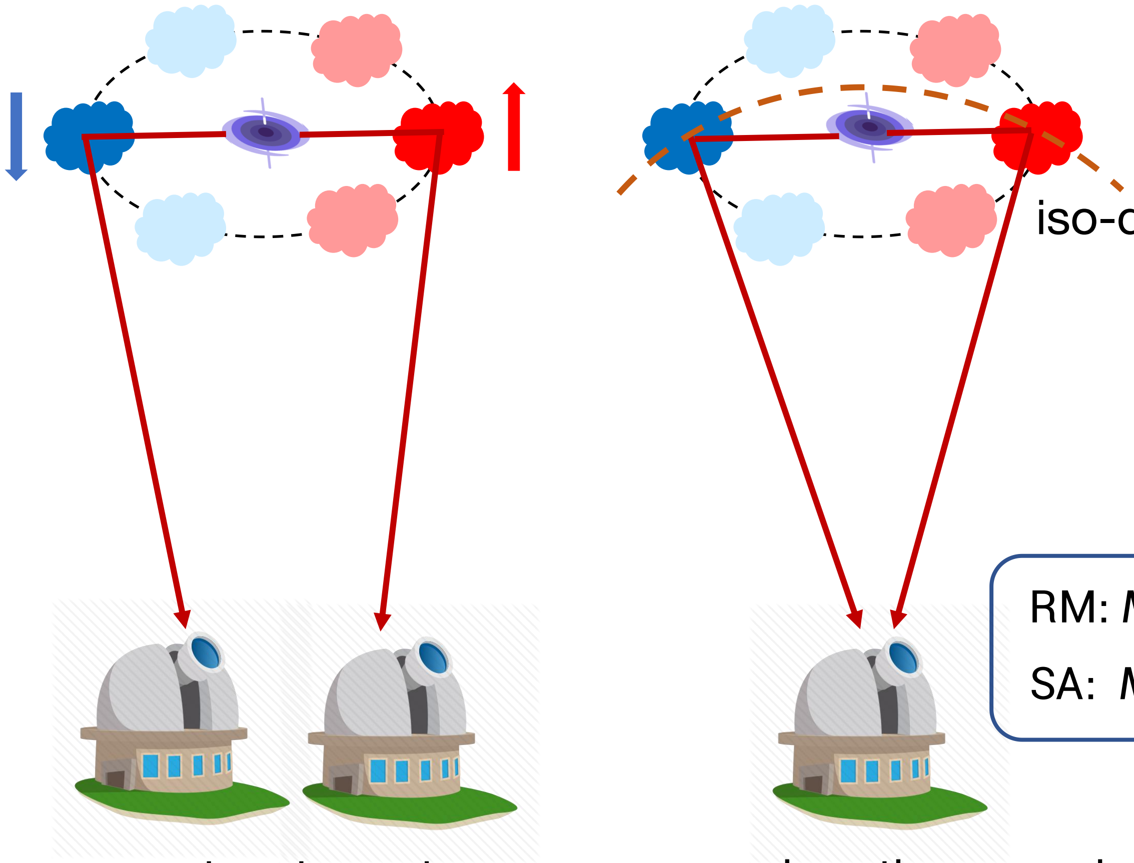


SARM: SpectroAstrometry+Reverberation Mapping

- SA: BLR structure perpendicular to LOS
- RM: BLR structure perpendicular to iso-delay surface

- SA： angular size $\Delta\theta$
- RM： linear size ΔR

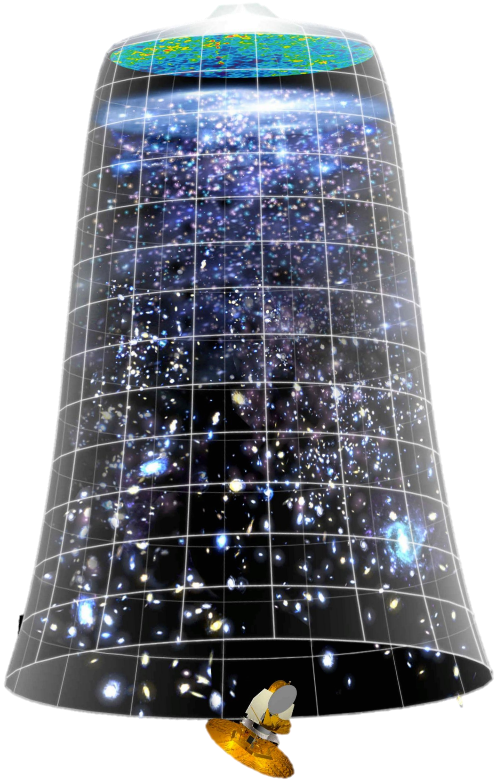
$$D_{A\mathfrak{D}} = \Delta R / \Delta\theta$$



spectoastrometry　　reverberation mapping

RM: $M_{\mathrm{BH}} = R \times V^2$

SA: $M_{\mathrm{BH}} = D_{\mathrm{A}} \times \theta \times V^2$



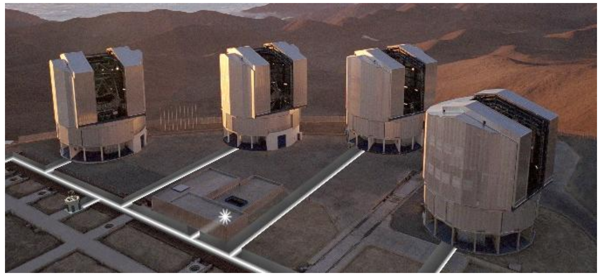
SARM方案：测量黑洞几何距离

ΔR

2米望远镜

流量(一维)　　轮廓(二维)

$\Delta\theta$



干涉阵列

单次　　时域

- 一维SARM：单次SA+一维RM (Wang, Songsheng, **LYR**, et al. 2020)
- 二维SARM：单次SA+二维RM (**LYR** et al. 2022)
- 时域SARM：时域SA+二维RM (**LYR** & Wang 2023)

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

基本数学方程

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]

The Astrophysical Journal, 979:126 (13pp), 2025 February 1 https://doi.org/10.3847/1538-4357/ad9fee

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

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

Spectroastrometry and Reverberation Mapping: The Mass and Geometric Distance of the Supermassive Black Hole in the Quasar 3C 273

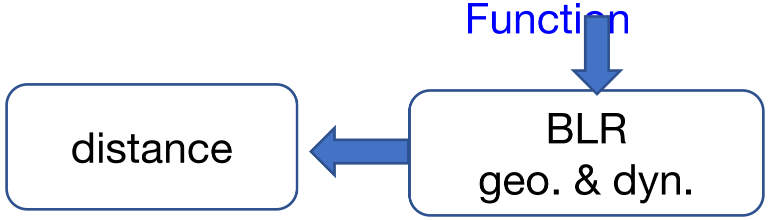
Yan-Rong Li[1], Jian-Min Wang[1,2,3], Yu-Yang Songsheng[1], Zhi-Xiang Zhang[4], Pu Du[1], Chen Hu[1], and Ming Xiao[1]

SARM: SpectroAstrometry+Reverberation Mapping

- Basic equation （**LYR** & Wang 2023）

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

observable Line profile and SA	unknown Transfer Function	observable Continuum



Photocenter : $\boldsymbol{\Theta}_{\rm BLR}(v,t) = \dfrac{\boldsymbol{M}_{\rm BLR}(v,t)}{F_{\rm BLR}(v,t)}$

$$F_{\rm BLR}(v,t) = \iiint \epsilon(\boldsymbol{r}) F_{\rm c}(t-\tau) f(\boldsymbol{r},\boldsymbol{w}) \delta(v + \boldsymbol{w}\cdot\boldsymbol{n}) \times \delta\left(\tau - \frac{r - \boldsymbol{r}\cdot\boldsymbol{n}}{c}\right) d\boldsymbol{r} d\boldsymbol{w} d\tau,$$

$$\boldsymbol{M}_{\rm BLR}(v,t) = \iiint \boldsymbol{r}_{\perp} \epsilon(\boldsymbol{r}) F_{\rm c}(t-\tau) \times f(\boldsymbol{r},\boldsymbol{w}) \delta(v + \boldsymbol{w}\cdot\boldsymbol{n}) \delta\left(\tau - \frac{r - \boldsymbol{r}\cdot\boldsymbol{n}}{c}\right) d\boldsymbol{r} d\boldsymbol{w} d\tau$$

SARM: SpectroAstrometry+Reverberation Mapping

- Basic equation (**LYR** & Wang 2023)

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

observable
Line profile and SA

unknown
Transfer
Function

observable
Continuum

BLR
geo. & dyn.

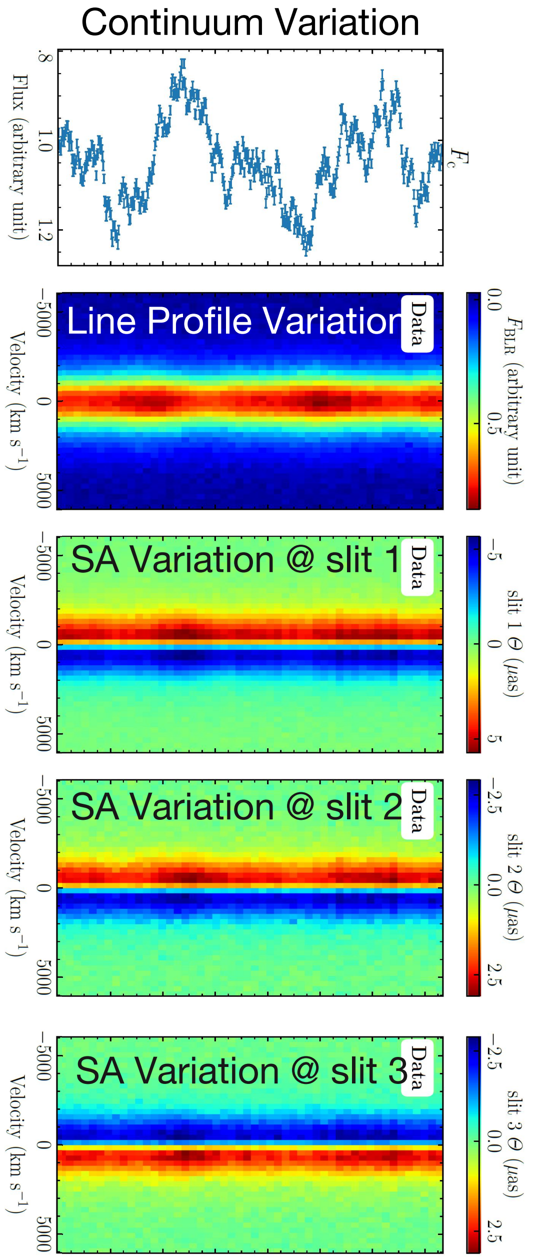
→ distance

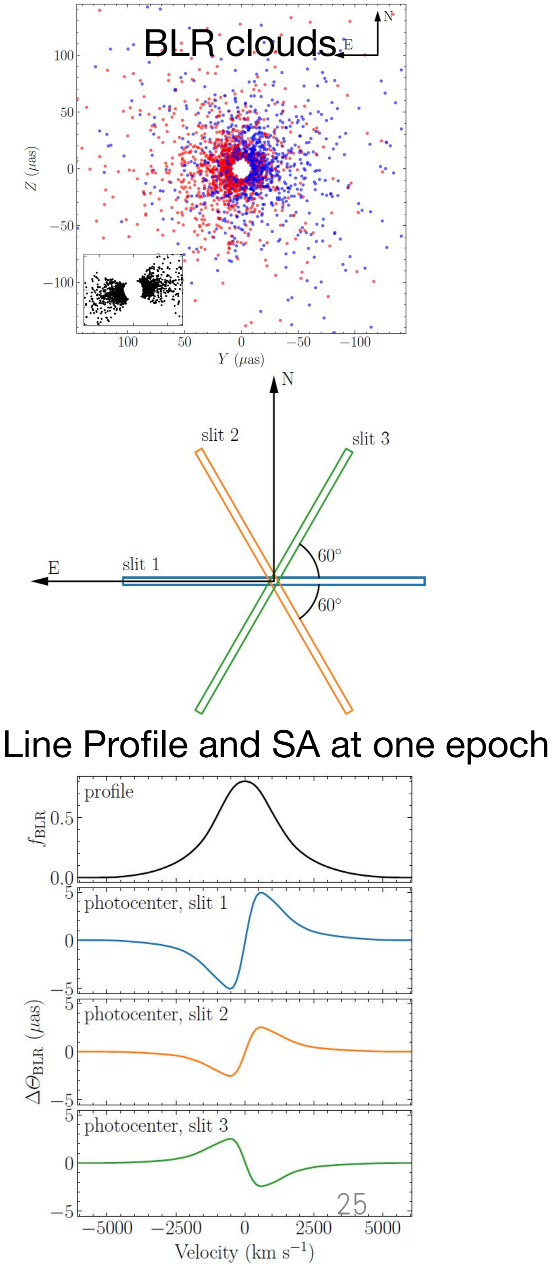
Photocenter: $\boldsymbol{\Theta}_{\rm BLR}(v,t) = \dfrac{\boldsymbol{M}_{\rm BLR}(v,t)}{F_{\rm BLR}(v,t)}$

$$F_{\rm BLR}(v,t) = \iiint \epsilon(\boldsymbol{r}) F_{\rm c}(t-\tau) f(\boldsymbol{r},\boldsymbol{w}) \delta(v + \boldsymbol{w}\cdot\boldsymbol{n}) \times \delta\left(\tau - \frac{r - \boldsymbol{r}\cdot\boldsymbol{n}}{c}\right) d\boldsymbol{r} d\boldsymbol{w} d\tau,$$

$$\boldsymbol{M}_{\rm BLR}(v,t) = \iiint \boldsymbol{r}_{\perp} \epsilon(\boldsymbol{r}) F_{\rm c}(t-\tau) \times f(\boldsymbol{r},\boldsymbol{w}) \delta(v + \boldsymbol{w}\cdot\boldsymbol{n}) \delta\left(\tau - \frac{r - \boldsymbol{r}\cdot\boldsymbol{n}}{c}\right) d\boldsymbol{r} d\boldsymbol{w} d\tau$$

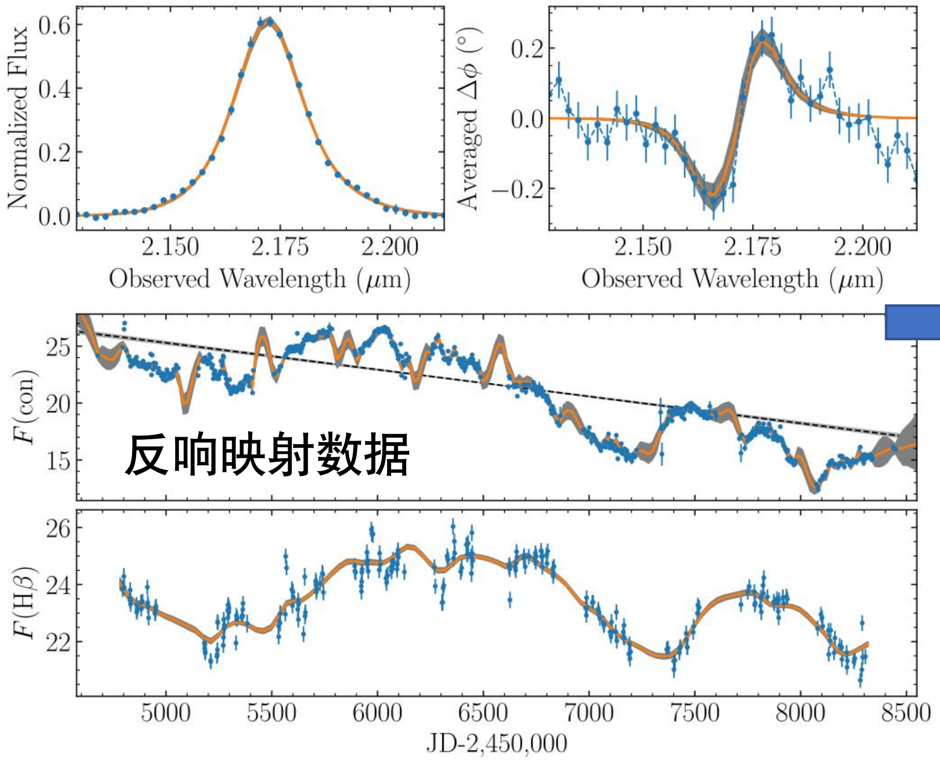
Super-cluster →

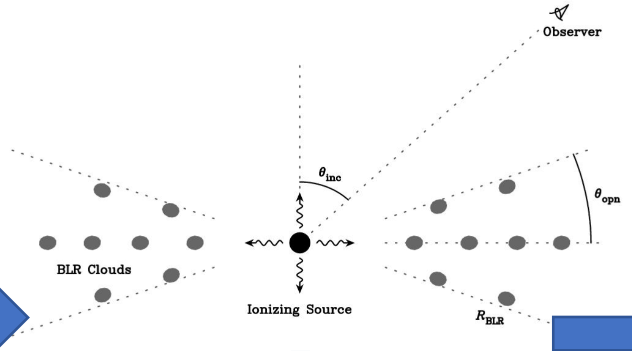




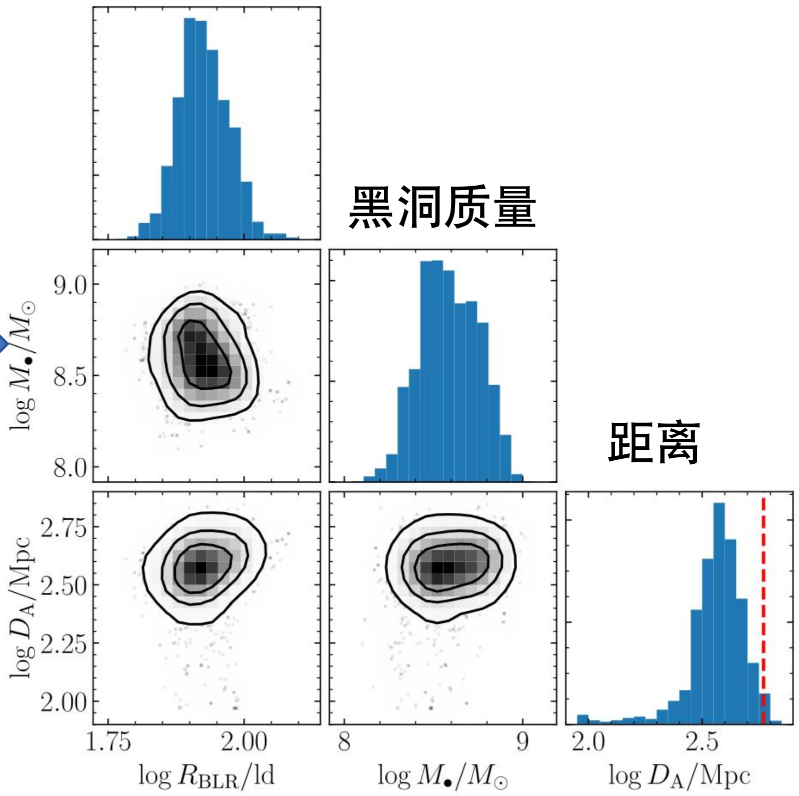
SARM: 分析流程

谱线轮廓 相位曲线

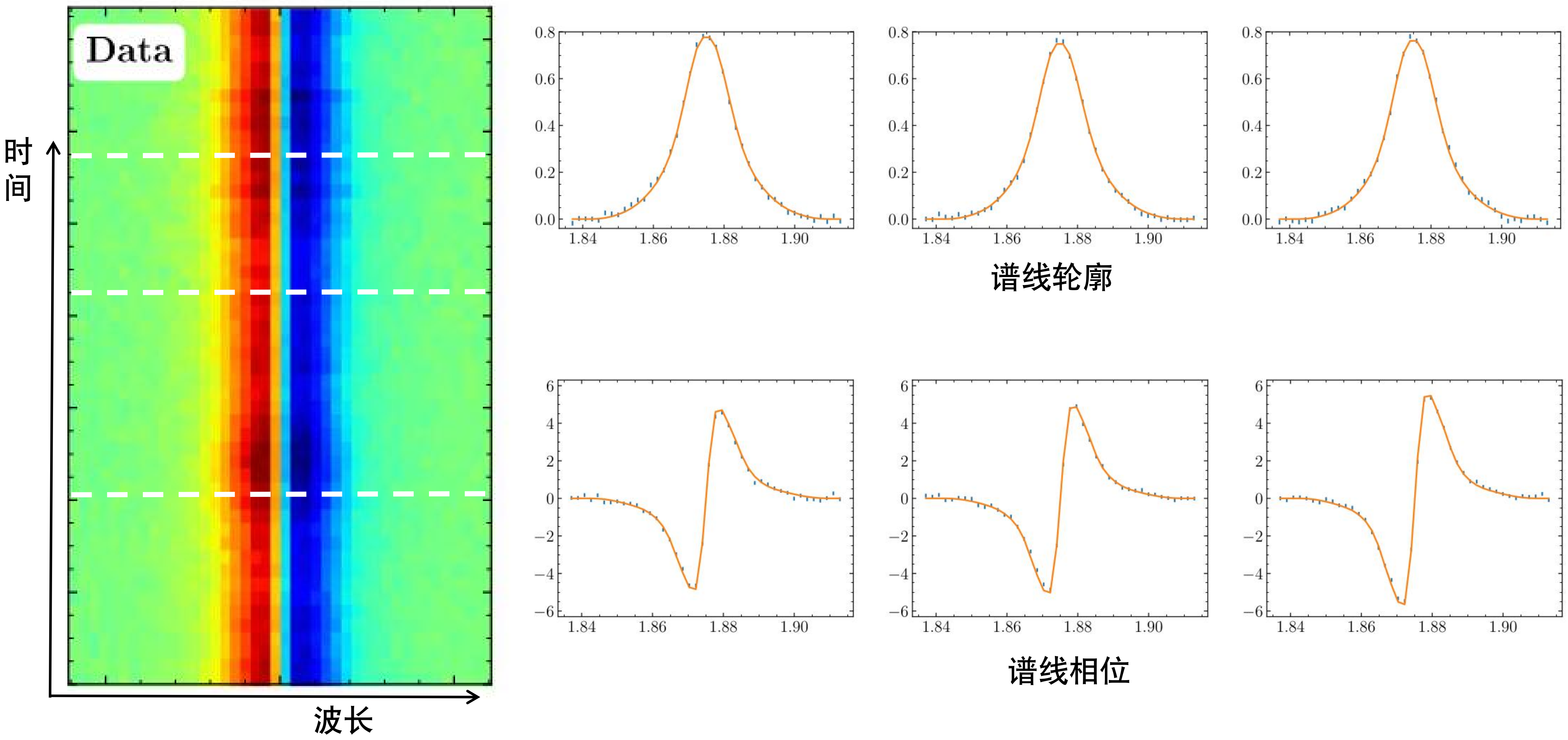




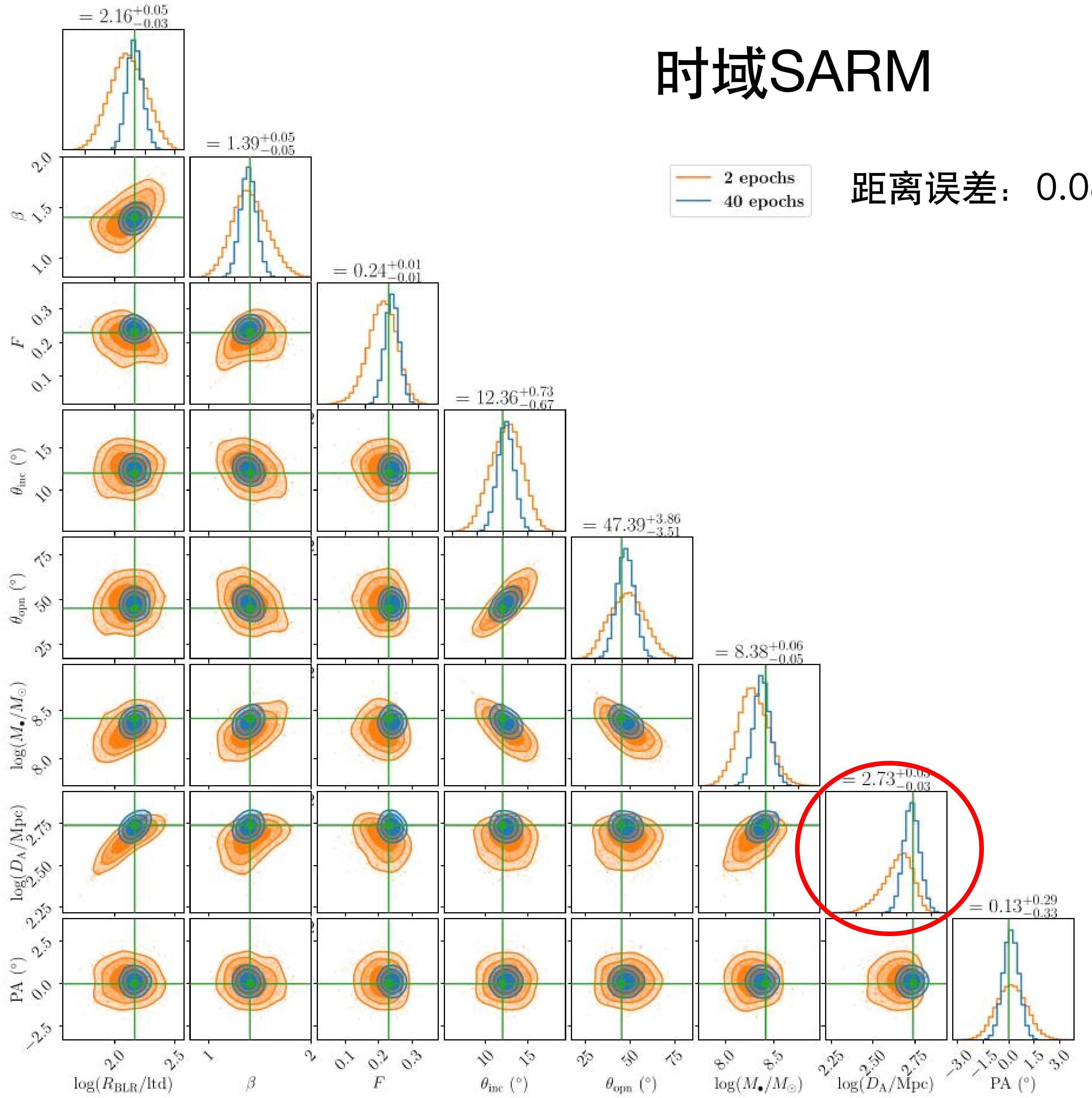
宽线区尺度



时域SARM



时域SARM



距离误差：0.08dex –> 0.03dex

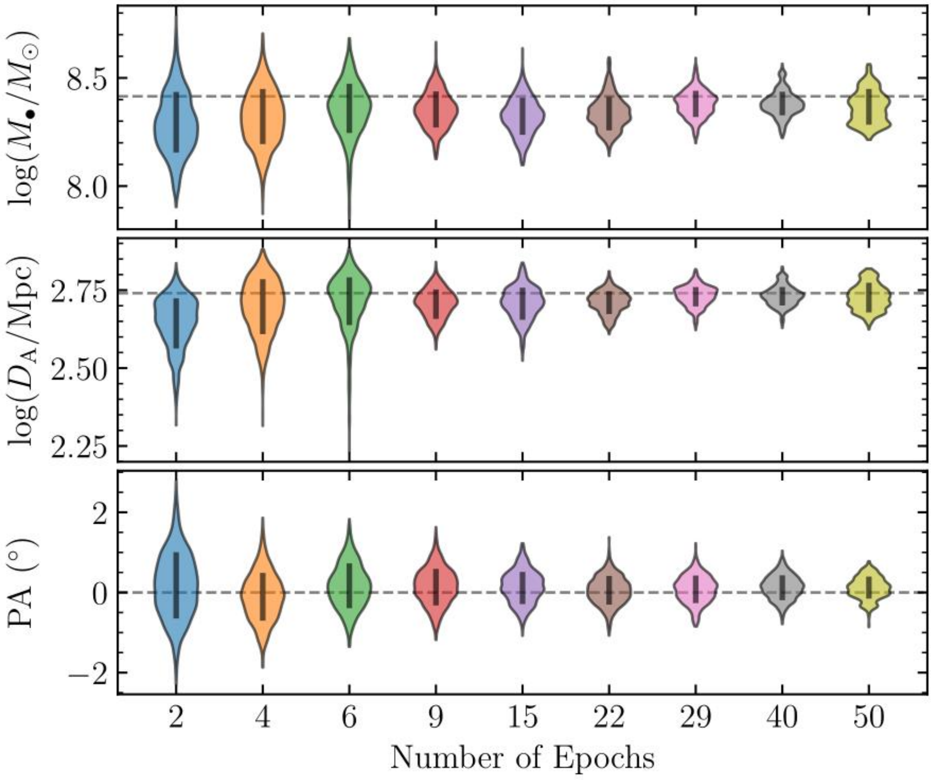
18% –> 7%

时域SARM

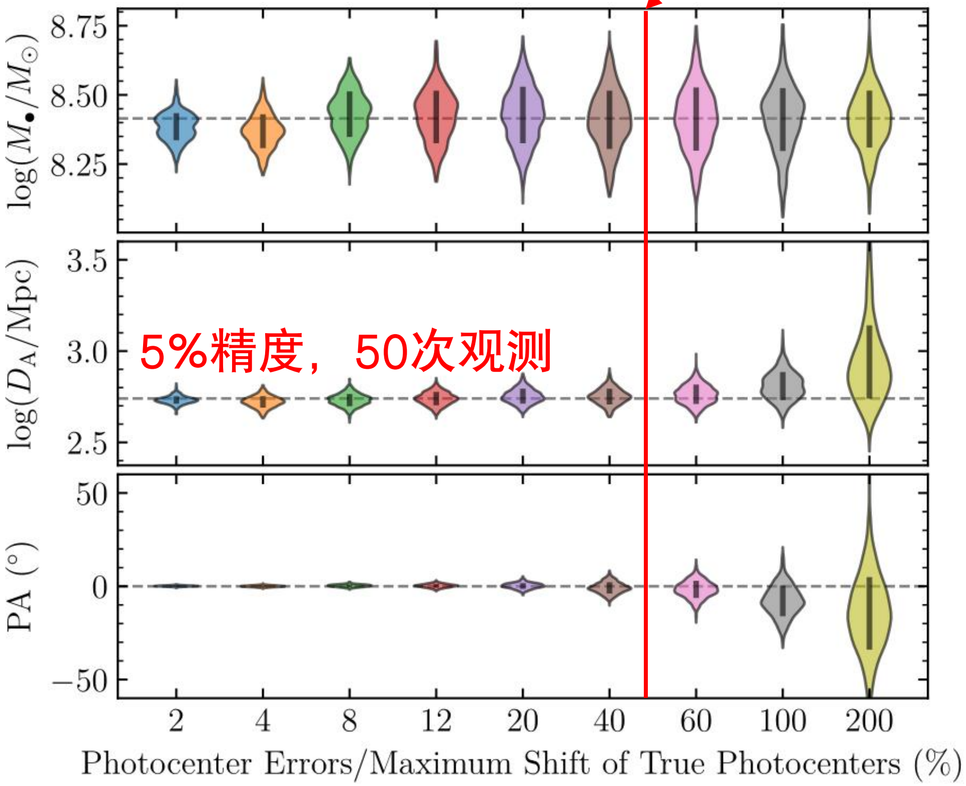
$$\begin{bmatrix} F_{\rm BLR}(v,\, t) \\ \boldsymbol{M}_{\rm BLR}(v,\, t) \end{bmatrix} = \begin{bmatrix} \Psi(v,\, t) \\ \boldsymbol{\Pi}(v,\, t) \end{bmatrix} \otimes F_{\rm c}(t)$$

S/N of VLTI 3C 273 data

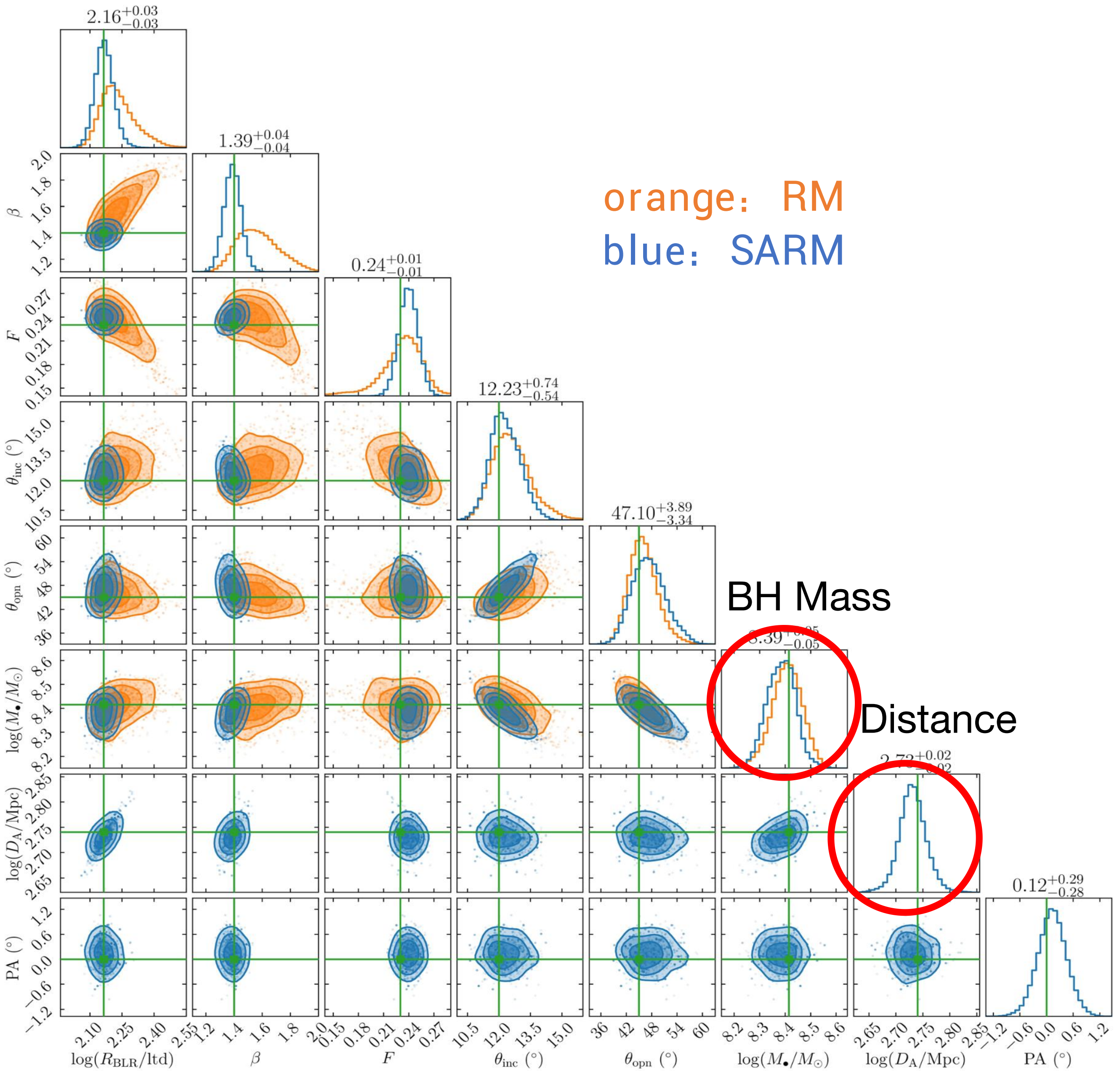
Epochs



S/Ns



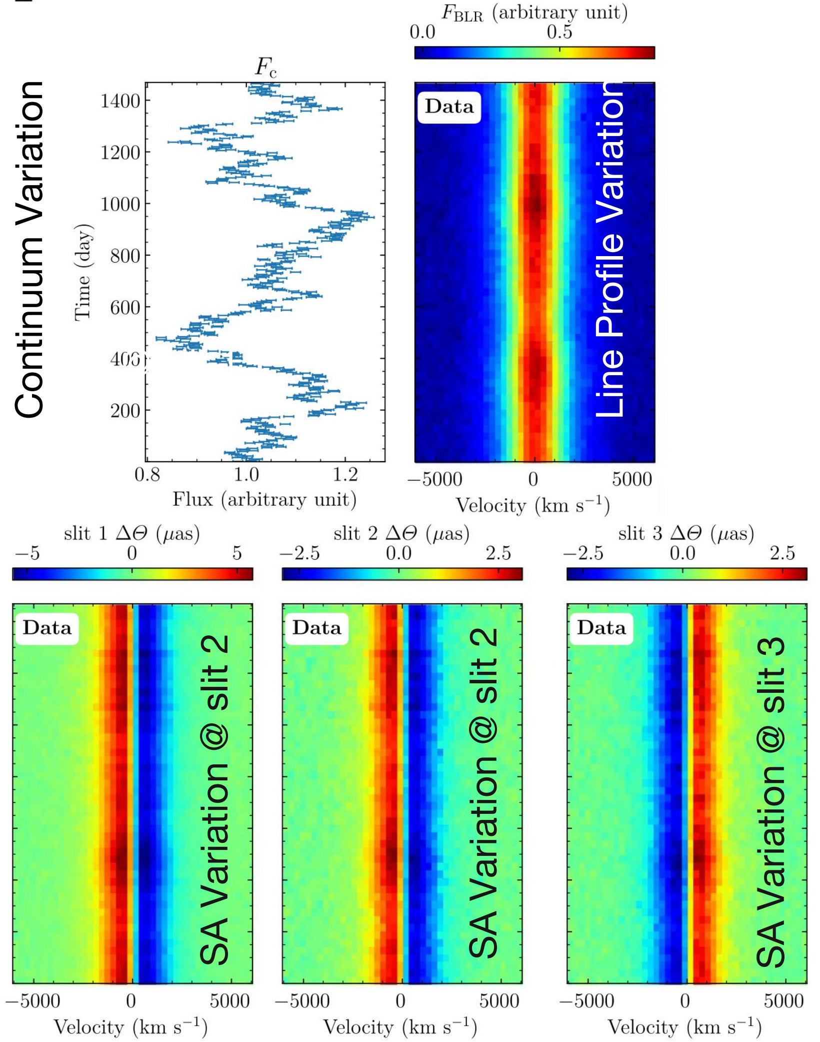
SARM: SpectroAstrometry+Reverberation Mapping



orange: RM

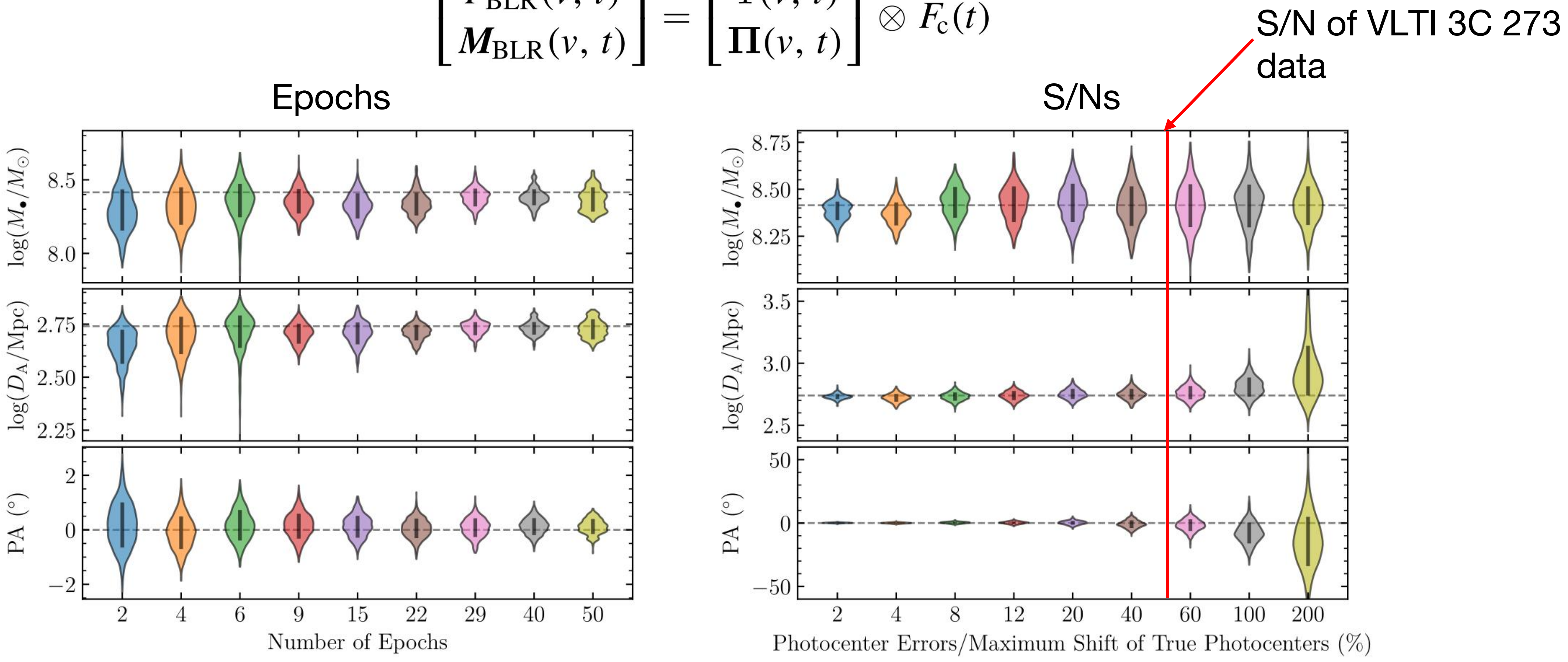
blue: SARM

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



SARM: SpectroAstrometry+Reverberation Mapping

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



Advantages: Serval SA epochs sufficient to constrain BLR properties

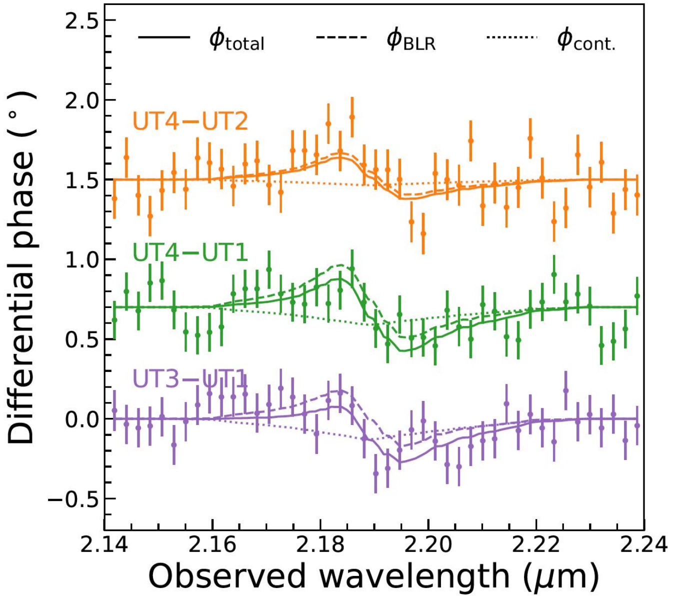
Application to NGC 3783

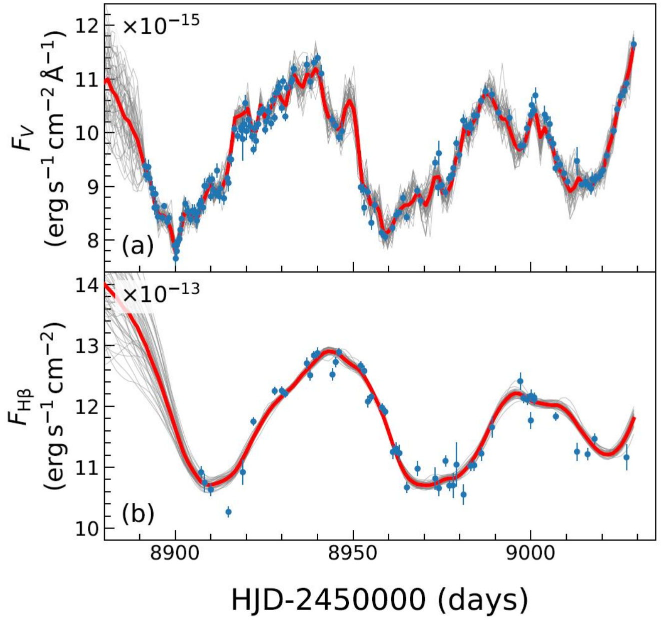
A&A 654, A85 (2021)
https://doi.org/10.1051/0004-6361/202141426

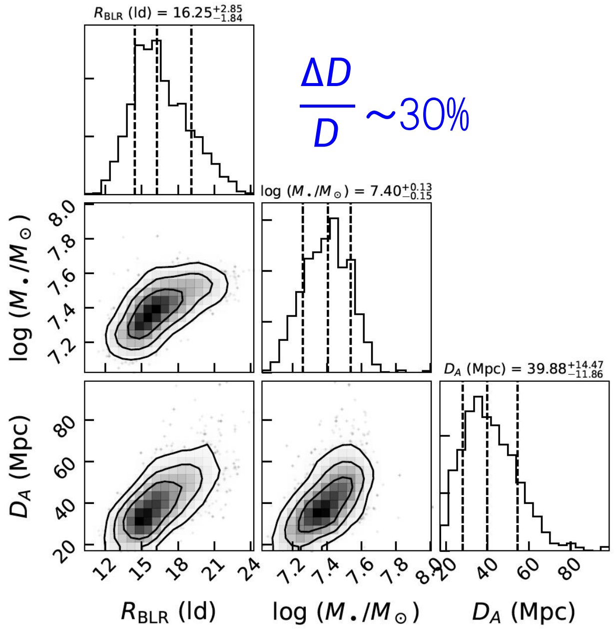
Astronomy & Astrophysics

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]



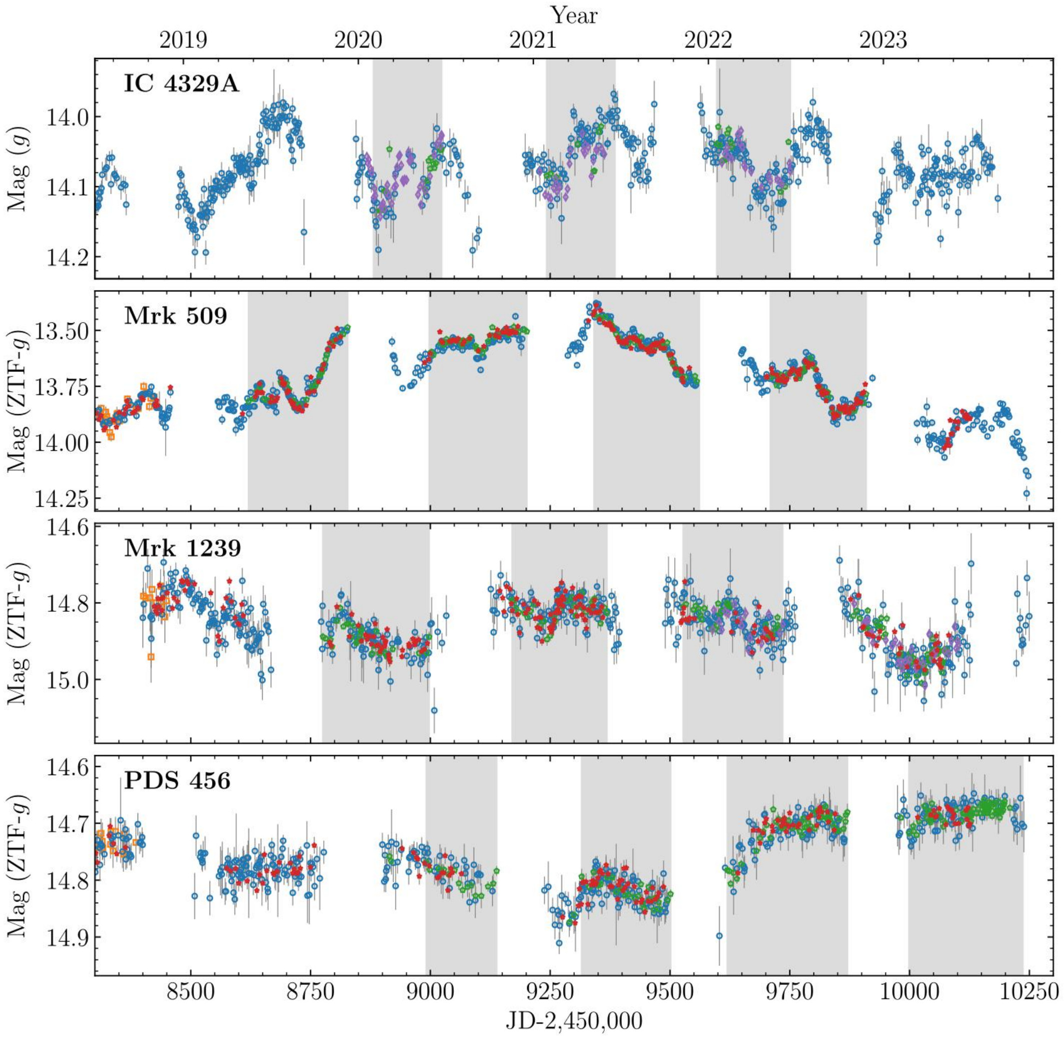




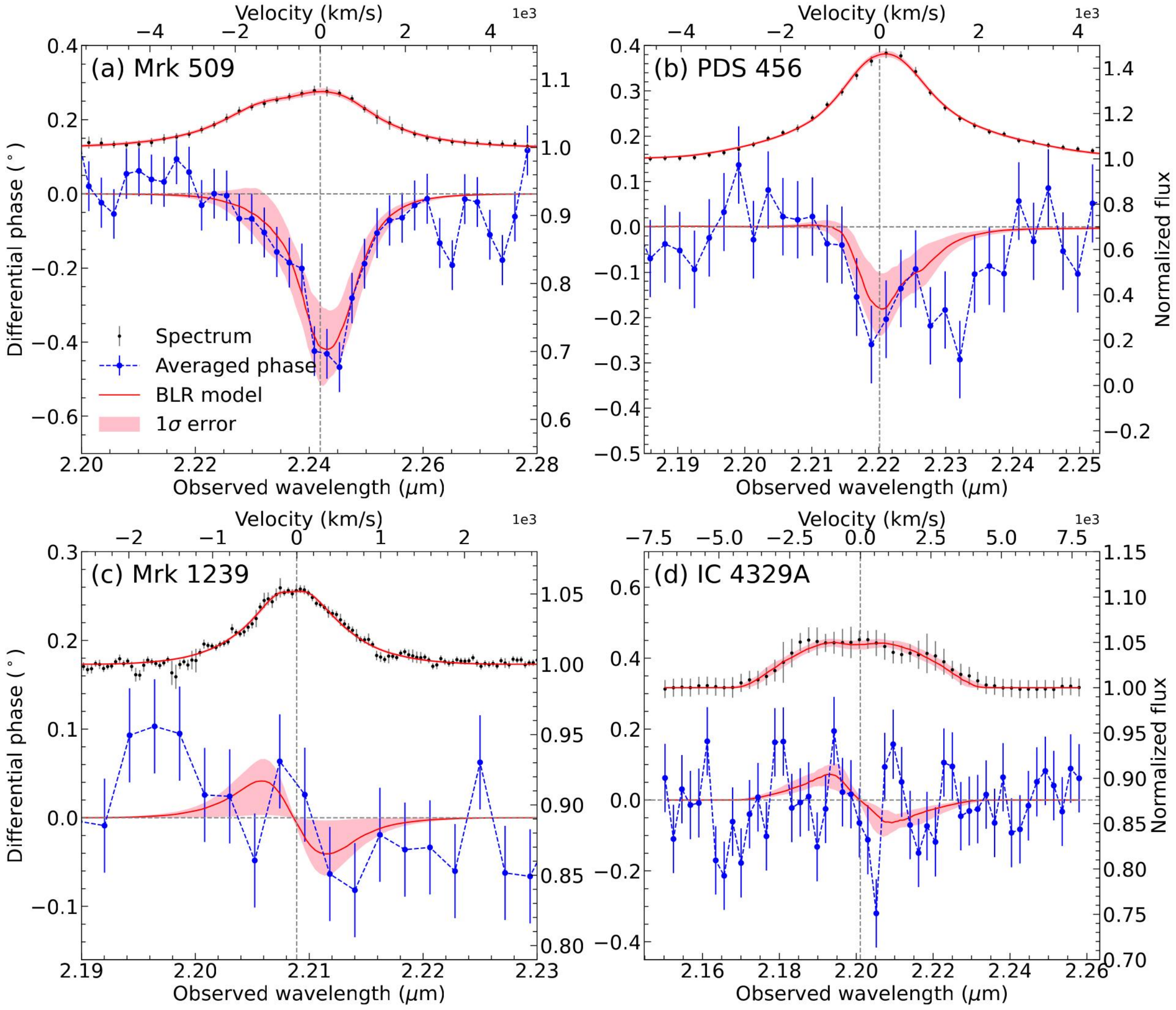
$\frac{\Delta D}{D} \sim 30\%$

Application to more quasars

- SARM analysis on four quasars in collaboration with GRAVITY team



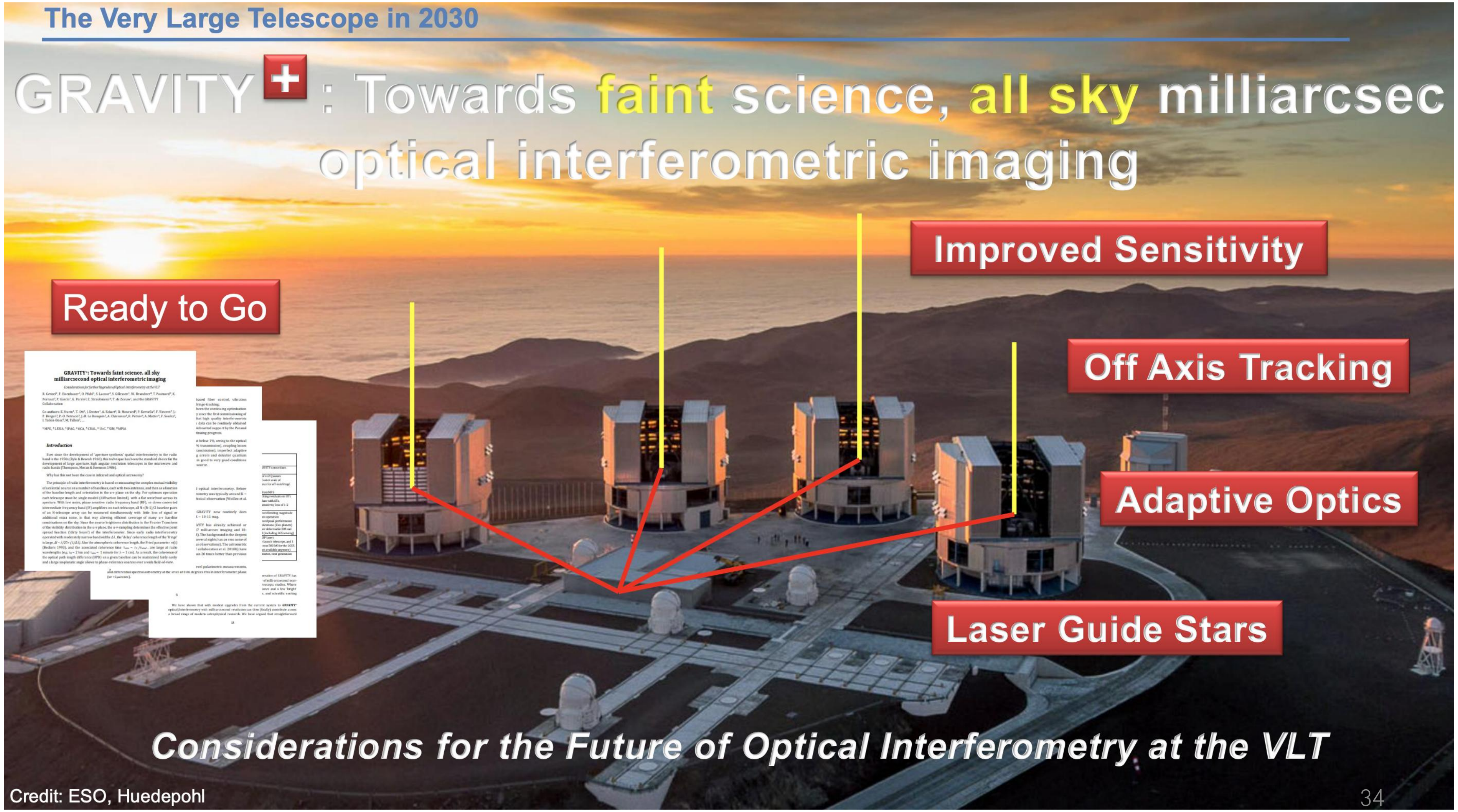
LYR+2024



GRAVITY Collaboration+2024

Future Perspectives

- GRAVITY+ by 2025: sensitivity × 15; 300-500 quasars observable



The Astrophysical Journal Supplement Series, 253:57 (15pp), 2021 April
https://doi.org/10.3847/1538-4365/abe539

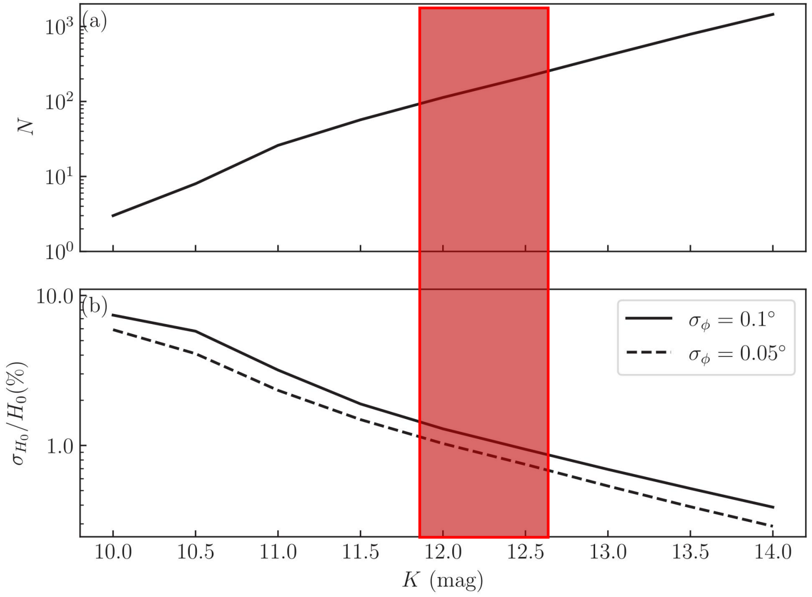
Quasar as a cosmic probe

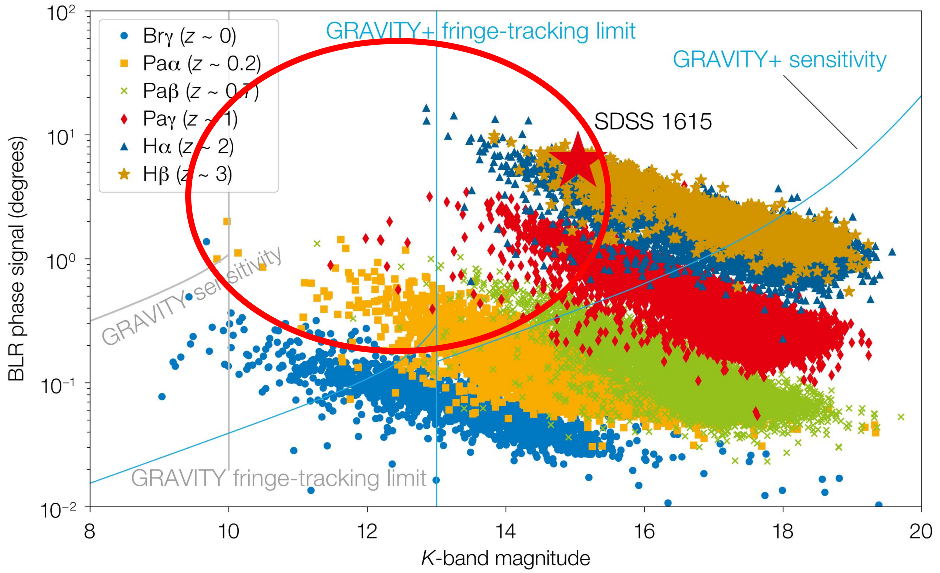
CrossMark

Geometric Distances of Quasars Measured by Spectroastrometry and Reverberation Mapping: Monte Carlo Simulations

Yu-Yang Songsheng[1,2], Yan-Rong Li[1], Pu Du[1], and Jian-Min Wang[1,2,3]
[1] Key Laboratory for Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, 19B Yuquan Road, Beijing 100049, People's Republic of China; wangjm@ihep.ac.cn
[2] University of Chinese Academy of Sciences, 19A Yuquan Road, Beijing 100049, People's Republic of China
[3] National Astronomical Observatories of China, Chinese Academy of Sciences, 20A Datun Road, Beijing 100020, People's Republic of China
Received 2020 November 25; revised 2021 January 28; accepted 2021 February 9; published 2021 April 13

- 100-200 quasars，Hubble constant with a precision ~1%



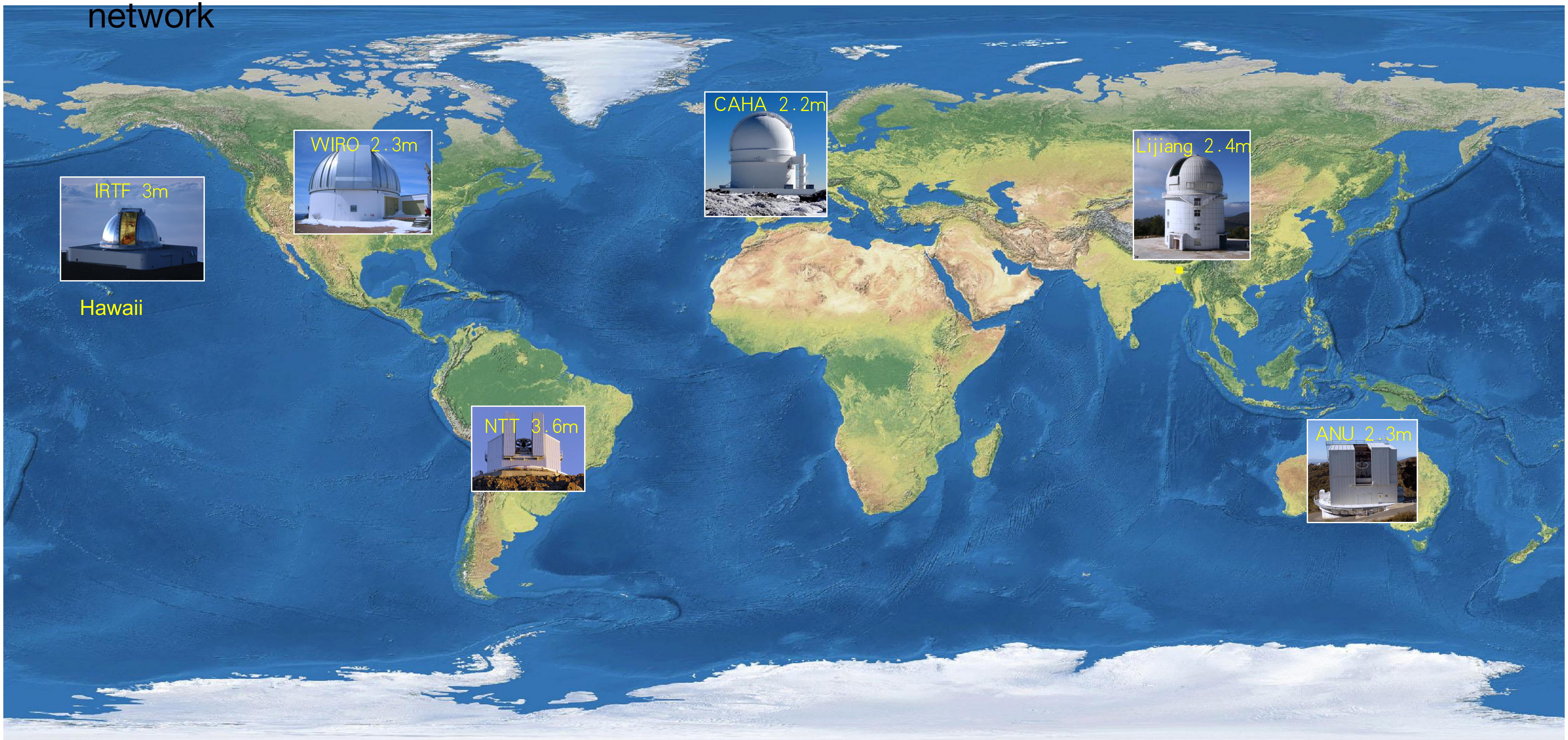


Songsheng, **LYR**+2021

GRAVITY

Quasar spectral monitoring campaign

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



Ten-Kilometer Baselines: Thousands m^2 Collecting Area Optical / IR

Credit: ESO/H. Heyer, L. Calçada

Ten–Kilometer Baselines
Thousands m^2 Collecting Area
Optical / IR

Resolution ~ λ/B = 10 μas

Sensitivity ~ ELT ~ 28 (23) mag_{AB}

Point Source Imaging (Spectroscopy), 10ks, 10σ

Astrometry ~ 0.1 μas

From GRAVITY(+) Towards a Kilometers Baseline, Large Telescope Interferometer

10 µas angular resolution

Fundamental Physics

Cosmology

Galaxies — >1 Gpc — 1/10 pc SN1987A

100 Mpc — 1000 AU TDEs

Black Holes — 1 Mpc — 10 AU Saturn Orbit

Stars/-formation — 10 kpc — 0.1 AU = 1 Schwarzschild R.

Exoplanets — 10 pc — Earth — 150 km

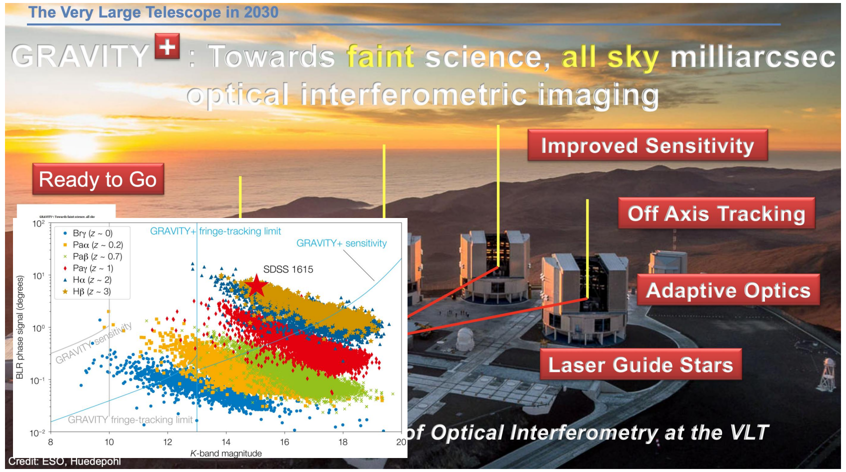
astrometry

1 pc — 1500 km Greenland — 15 km

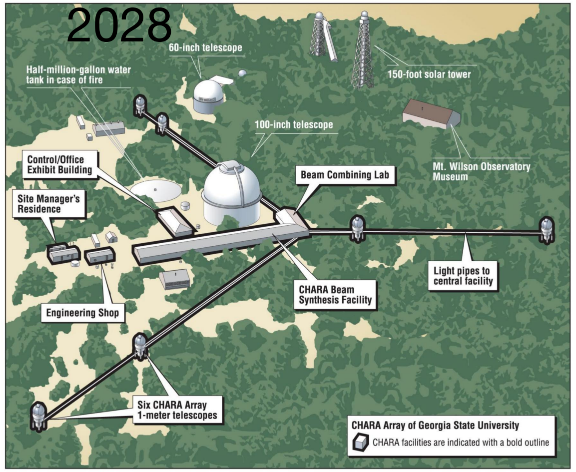
结论：光干涉将高精度测量宇宙几何

Future SA observations

GRAVITY+: 4*8m, by 2025



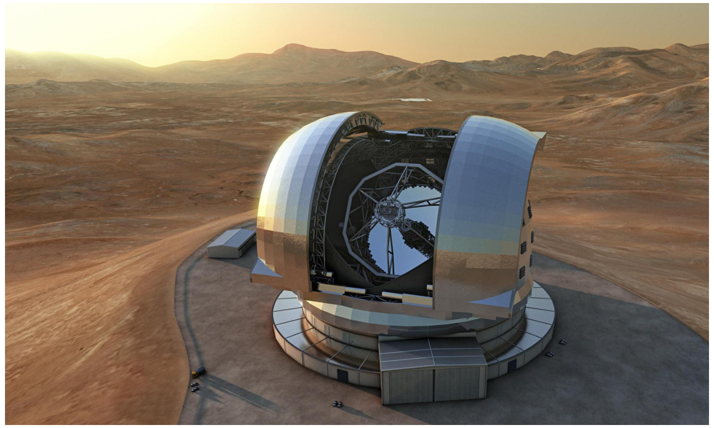
CHARA: 12*2m, by 2028



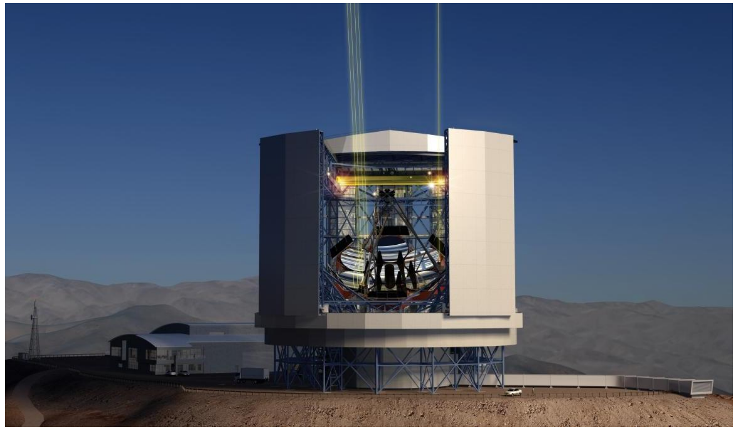
MROI: 10*1.4m, by 2027

TMT

ELT

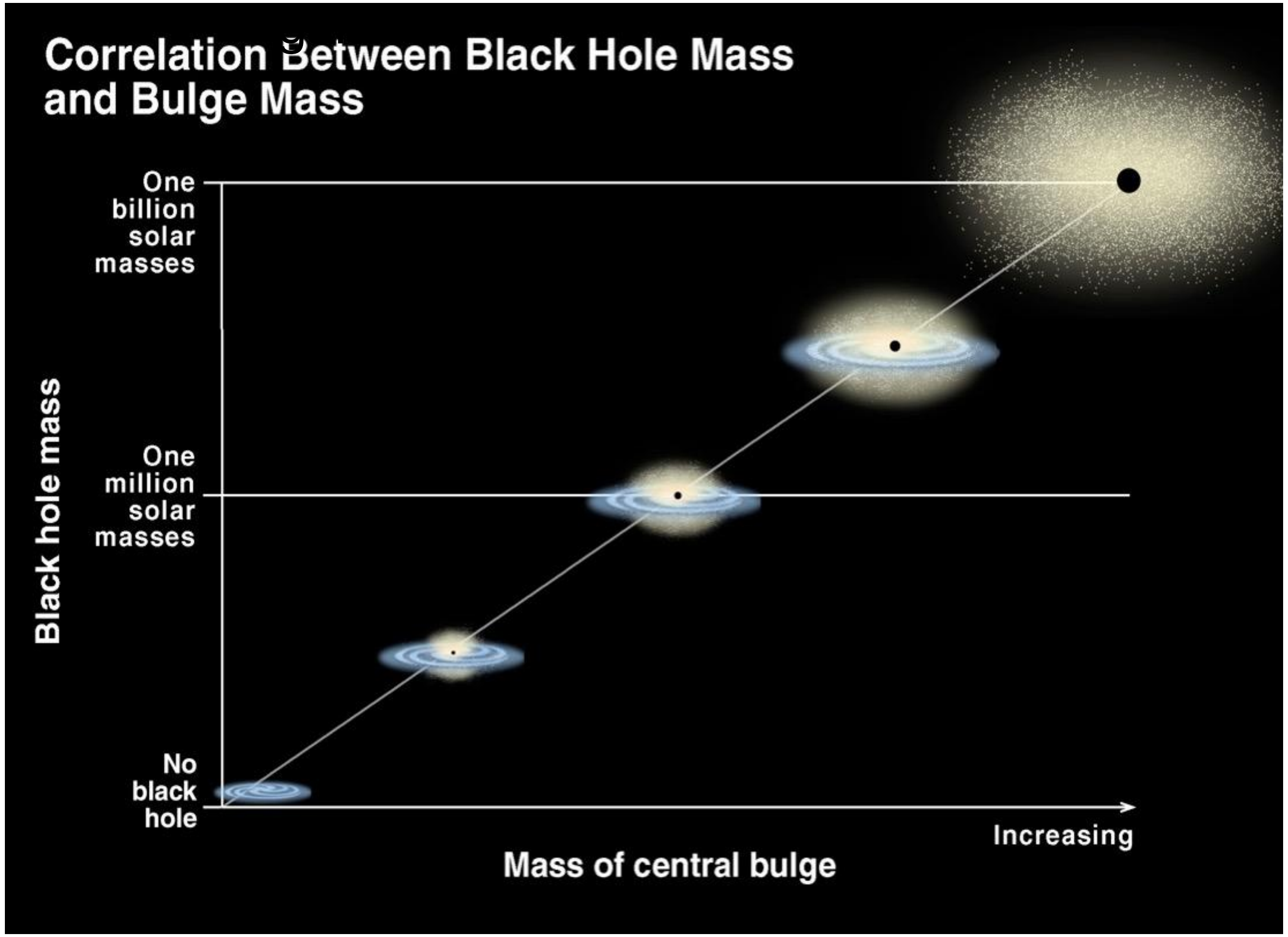


GMT

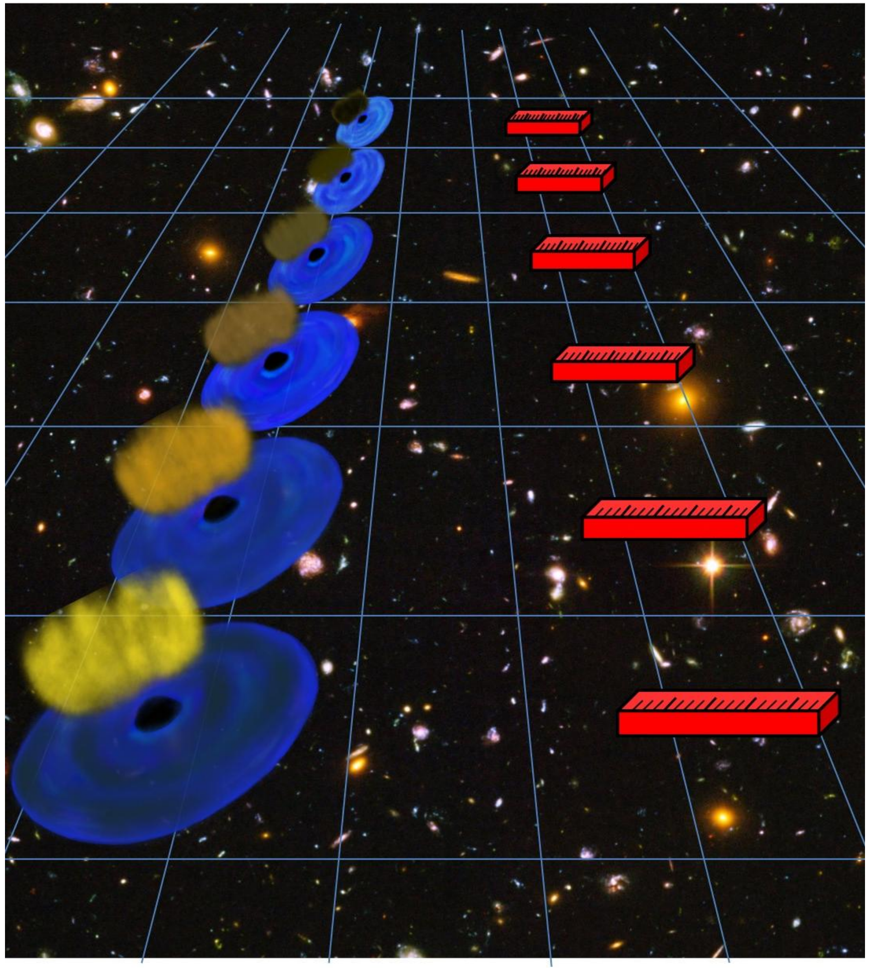


Quasars, galaxies and cosmology

Quasars coevolve with



Quasar rulers for cosmos



Thank you for listening!