VII Conference on Active Galactic Nuclei & Gravitational Lensing

Brief Summary and Perspective

Jian-Min Wang
July 20-24, 2026, Vrnjacka Banja, Serbia

The meeting outline

15	27	9	7
lectures	participants	countries	mini-projects

Four thematic sessions, run as talks plus open discussion

- **AGNs, gravitational lenses & polarization**
- **Variability of AGNs and supermassive binary black holes**
- **Processes in AGNs — line emission, disks, machine learning**
- **Atomic processes in AGNs and related objects**

Organised by the Astronomical Observatory Belgrade with the Faculty of Sciences, University of Kragujevac. The programme closed with a round-table on the mini-projects.

One unresolved engine, five observational languages

AGN structure is still spatially unresolved. Progress comes from combining signals that respond to different physics.

01

Spectra

Composition, density, velocity and the geometry of the line-emitting gas

02

Time-domain

Lags, periodicity, propagation and the causal order of events

03

Polarisation

Magnetic-field order, scattering geometry and jet structure

04

Lensing

Source size, substructure and scales otherwise hidden from us

05

GWs

LIGO
PTA

The central challenge

Can all five be explained by one physically consistent picture of the disk, the corona, the broad-line region and the jet? Every talk at the meeting answered part of that question; none of them answered it alone.

SMBH, accretion disk, BLRs

Disk wind and SMBH masses

H. Netzer (Tel Aviv University)

- Disk wind -> SED ->BLRs

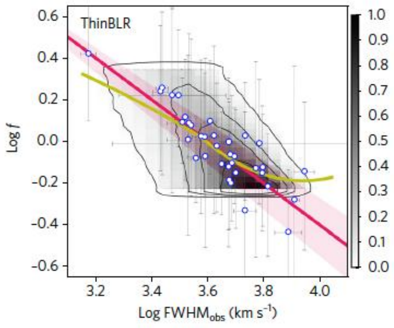
nature astronomy
LETTERS
https://doi.org/10.1038/s41550-017-0305-z

The effect of nuclear gas distribution on the mass determination of supermassive black holes

J. E. Mejía-Restrepo[1*], P. Lira[1], H. Netzer[2], B. Trakhtenbrot[3] and D. M. Capellupo[4]

$$M_{BH} = G^{-1} R_{BLR}\ V^2_{BLR} = f\ G^{-1} R_{BLR}\ \mathrm{FWHM}^2_{obs}$$

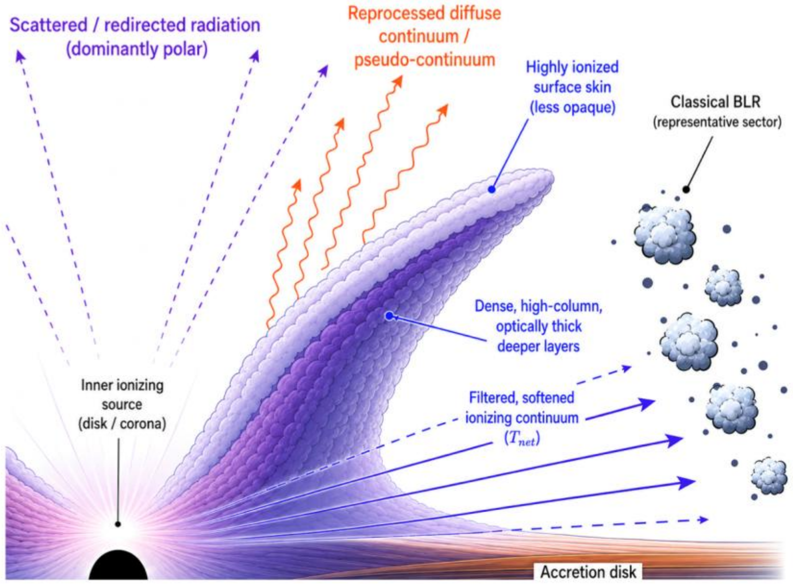
$$R_{BLR} = \alpha L^{\beta}_{5100} \left[1 + a_1 \left(\frac{L_{5100}}{M_{BH}} \right)^{a_2} \right]$$



An inconsistent α-disk closure

M.-H. Naddaf (University of Liège)

- The classical radiation-pressure instability?
- Disk-size tension?



BLR: broad and intermediate regions

The BLR complexity

- resolved the emission into distinct components rather than fitting a single region
- the decomposition, not the total flux, carries the physics.
- **Hβ · Fe II**

A two-component reverberation model for the time-dependent Hβ profile

E. Bon, N. Bon, L. Č. Popović, P. Marziani, S. Panda

- A flattened Keplerian disk produces the velocity-structured wings; a dispersed cloud component fills the line core
- A single ionizing flare propagates through the region, launched centrally or off-centre
- Each observed profile is a retarded-time superposition, not a snapshot — reproducing profile variability

Dissecting Fe II lines in AGN spectra

J. Kovačević Dojčinović, I. Dojčinović, L. Č. Popović

- A flexible template splits the optical Fe II emission into separate line groups across a large SDSS Type 1 sample
- A raised Eddington ratio appears to restructure the BLR, creating conditions for additional Fe II components
- That enhancement then drives correlations such as the quasar main sequence

What is nature of two components?

PART ONE · SESSION HIGHLIGHTS

Hunting sub-parsec binary black holes

270

candidates from SDSS DR16

Broad Hβ peculiarities

A. Deandra et al.

- PCA selection followed by fitting with the PoSKI binary model
- 24 systems flagged for monitoring as possible near-future mergers
- PoSKI shown to reproduce sub-parsec binary Hβ profiles

colour

beats magnitude

Photometric detectability

L. Novićević et al.

- Grid of synthetic light curves over mass, mass ratio, separation, eccentricity, redshift
- Red and white noise included; periods recovered with Lomb-Scargle
- Colour time series recover periods far more reliably than magnitude alone

$T(\lambda)$

a new binary signature

Continuum reverberation

Yan-Rong Li

- A cavity between mini-disks and circumbinary disk leaves a deficit in the continuum
- Lag–wavelength relation stays flat, then breaks to $\lambda^{4/3}$ — unlike a single-black-hole disk
- Applied to PG 1302-102: mass and period agree with independent methods

Common thread: sub-parsec binaries are expected to be ubiquitous yet remain hard to confirm — the field is converging on model-driven searches in survey data.

PART ONE · SESSION HIGHLIGHTS

Polarization, lensing and the multi-messenger view

01

Polarization of AGNs & lensed objects

L. Č. Popović

UV/optical polarisation traces the geometry of the disk, the BLR and the scattering material — and works on gravitationally lensed AGNs too

BLR kinetics and geometry

For H_0?

02

Polarimetry of blazar jets: radio to X-rays

O. Vince

SED fitting alone stays degenerate. Polarisation degree and angle constrain field ordering and emission sites; IXPE now extends this to X-rays.

EC: photon sources?

03

EVPA rotations in 32 blazars

E. V. Shishkina et al.

Long-term photopolarimetry, a proposed completeness criterion for rotations, and a link between rotation amplitude and mean polarisation.

04

Millimetre synchrotron from AGN coronae

E. Shablovinskaia et al.

ALMA shows compact mm emission from the magnetised X-ray corona — a penetrative probe of strong gravity, and a possible steady neutrino source

Fermi Collaboration: TeV emissions.

A&A, 703, A82 (2025)
https://doi.org/10.1051/0004-6361/202555796

Astronomy & Astrophysics

ALMA 3 mm polarimetry of radio-quiet active galactic nuclei

E. Shablovinskaia[1,2,★], C. Ricci[1,3], R. Paladino[4], A. Laor[5], C-S. Chang[6], D. Belfiori[4], T. Kawamuro[7], E. Lopez-Rodriguez[8], D. J. Rosario[9], S. Aalto[10], M. Koss[11,12], R. Mushotzky[13,14], and G. C. Privon[15,16,17]

nature astronomy

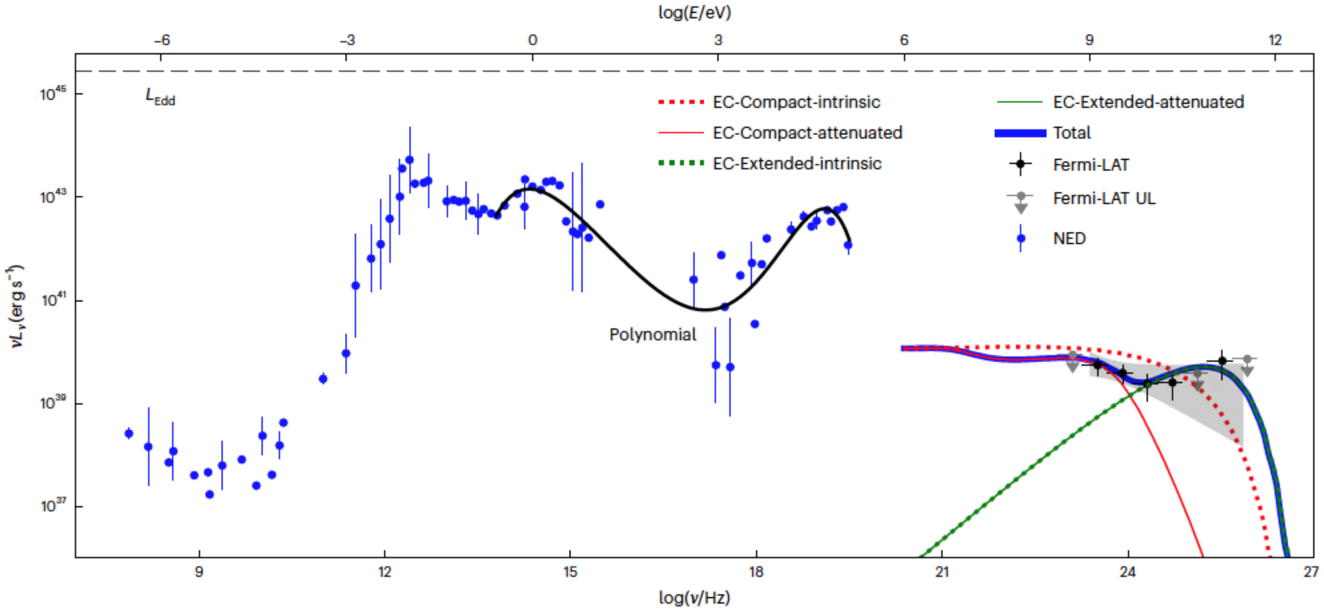
Article
https://doi.org/10.1038/s41550-025-02538-2

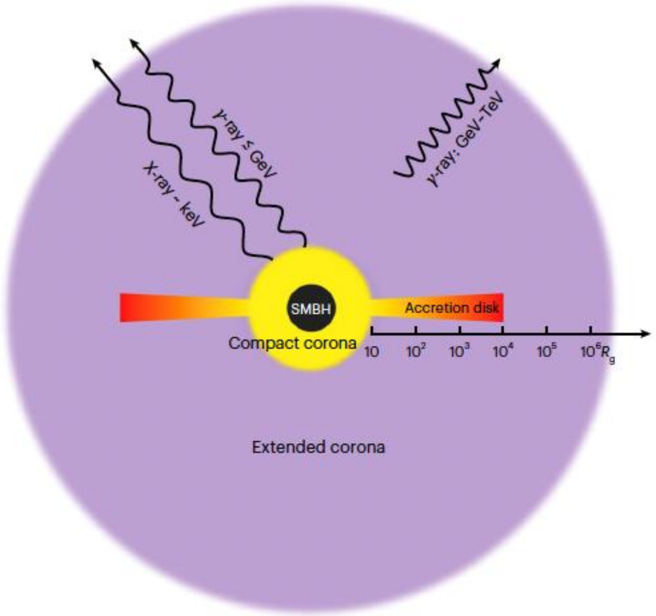
Fermi detection of gamma-ray emission from the hot coronae of radio-quiet active galactic nuclei

Received: 18 June 2024
Accepted: 25 March 2025
Published online: 20 June 2025

Jun-Rong Liu[1,2], Jian-Min Wang[1,2,3] & Fermi-LAT Collaboration*

Relativistic jets around supermassive black holes are well-known powerful γ-ray emitters. In the absence of the jets in radio-quiet active galactic





The survey era moves the bottleneck to trustworthy inference

LSST will not be short of AGN light curves. It will be short of defensible conclusions drawn from them.

01

Irregular data

Sparse cadence, seasonal gaps and heteroscedastic noise

02

Probabilistic reconstruction

ANN learns a distribution of parameters and LC

03

Real-time selection

LSST broker orchestrators prioritise alerts and trigger the follow-up that variability science depends on.

04

Physical validation

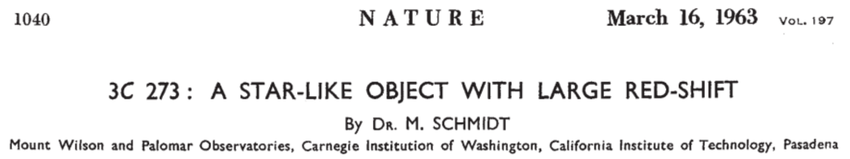
- TDE
- QPE
- Peculiar outburst (AMS)
- SMBH binaries
- GW counterparts

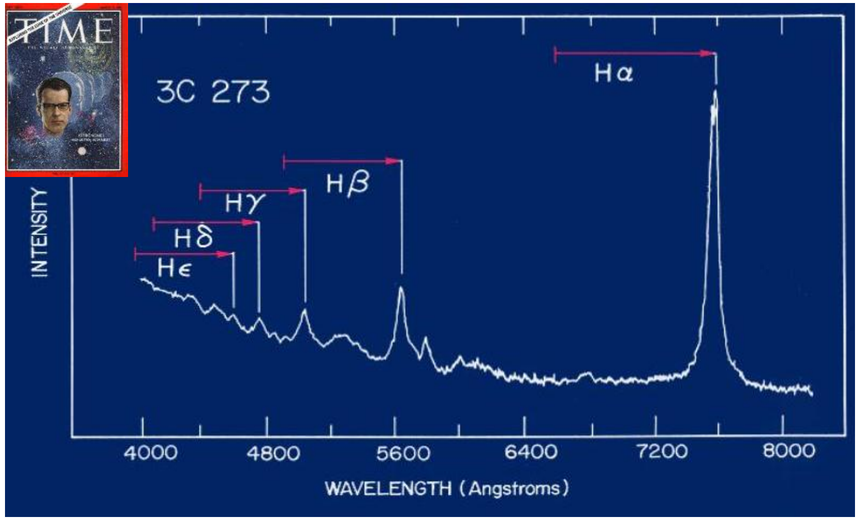
Ilic et al, De Bonis et al, Novicevic et al

The governing principle

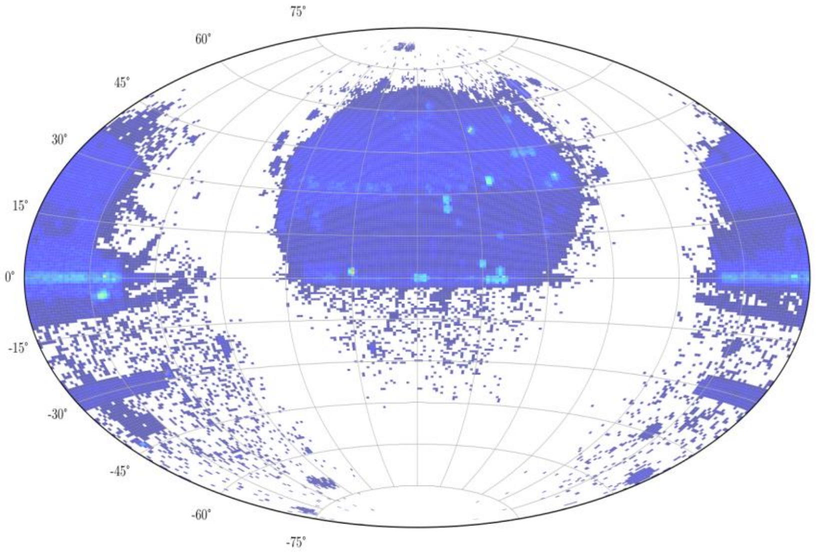
Uncertainty must propagate all the way through — from reconstruction, to classification, to the physical claim. A period, a lag or a binary candidate reported without that chain is not yet a result.

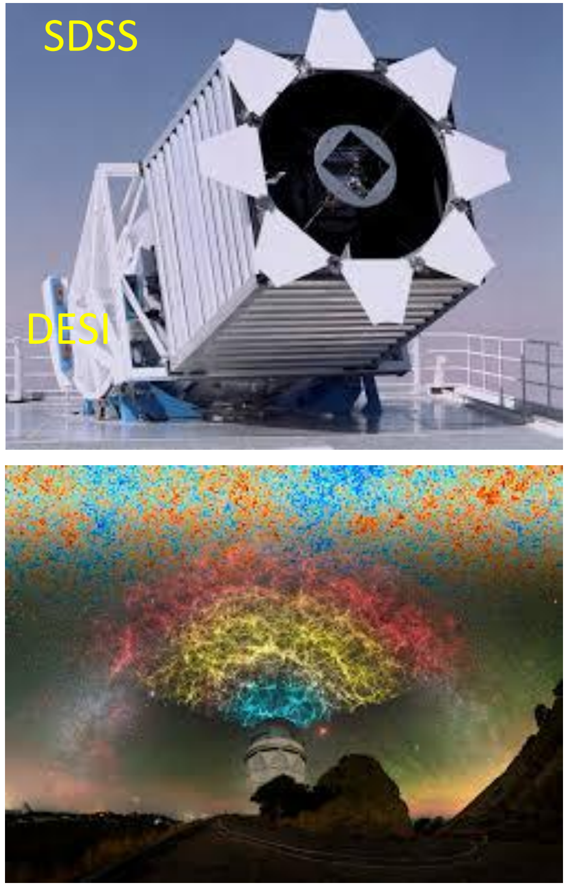
Quasars：discovery over 63 years





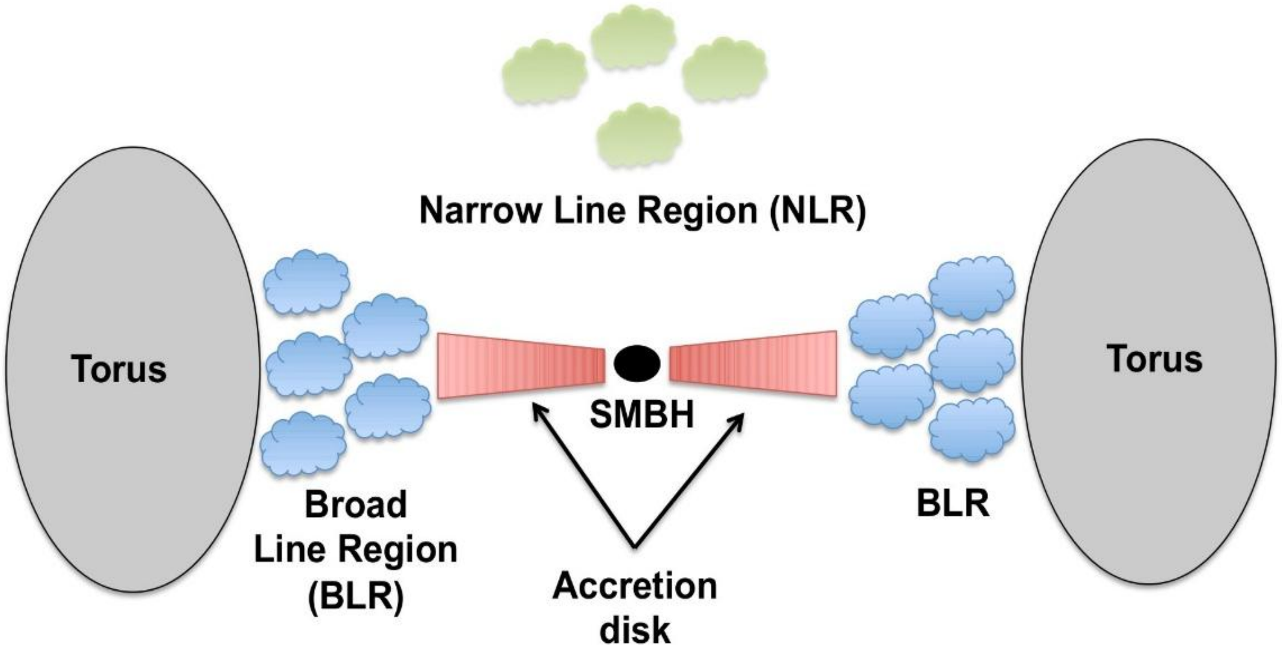
Million Quasars Catalog (Flesch 2023)

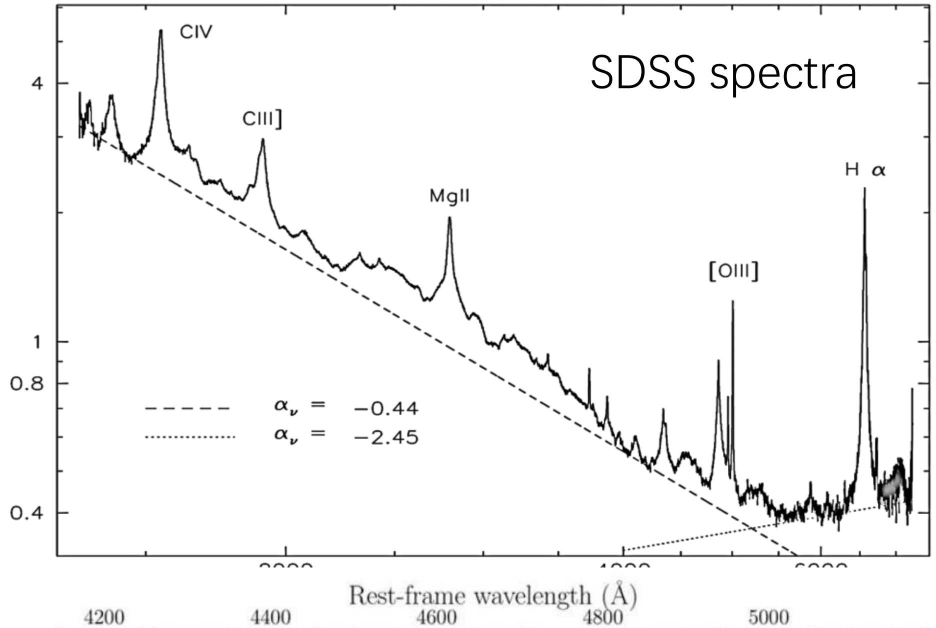


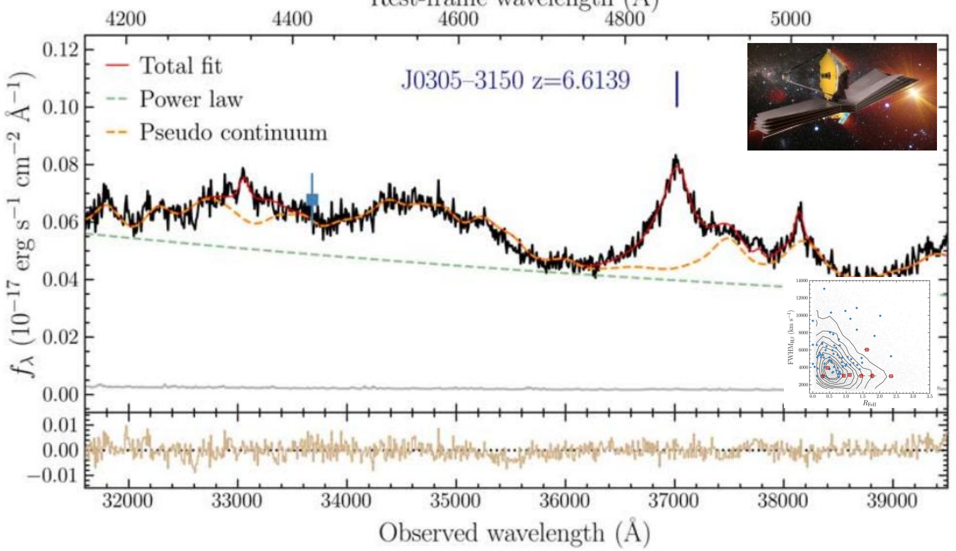


$$\lambda_{\mathrm{Edd}} = \frac{L_{\mathrm{Bol}}}{L_{\mathrm{Edd}}}$$

AGNs: standard model







- ➢ really standard?
- ➢ how to form?
- ➢ evolution （timescales)?

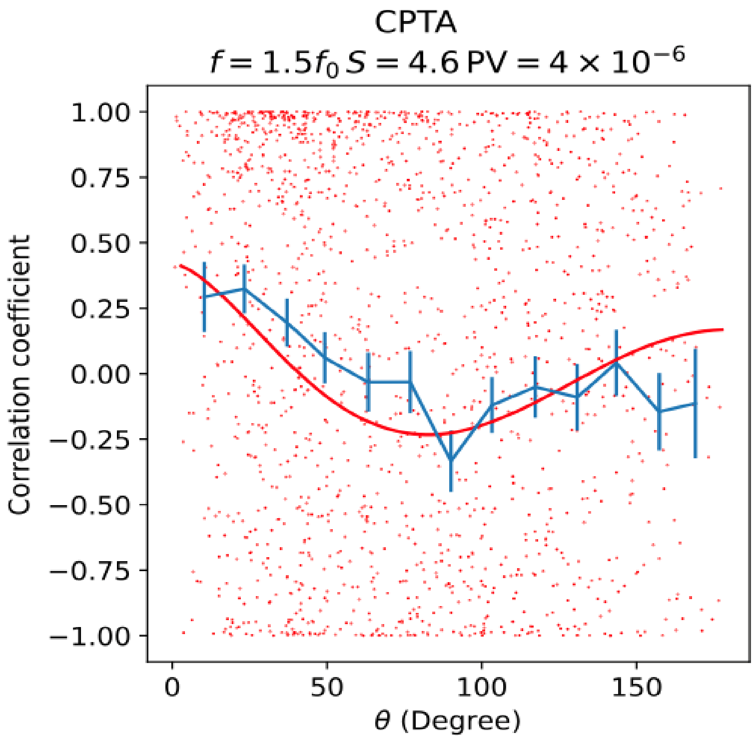
Nano-Hz gravitational waves: where are the SMBH binaries?

Research in Astronomy and Astrophysics, 23:075024 (12pp), 2023 July
https://doi.org/10.1088/1674-4527/acdfa5

CrossMark

Searching for the Nano-Hertz Stochastic Gravitational Wave Background with the Chinese Pulsar Timing Array Data Release I

Heng Xu[1], Siyuan Chen[2,3], Yanjun Guo[4], Jinchen Jiang[1], Bojun Wang[1], Jiangwei Xu[1,2,3], Zihan Xue[1,2,3], R. Nicolas Caballero[2,5], Jianping Yuan[6], Yonghua Xu[7], Jingbo Wang[8], Longfei Hao[7], Jingtao Luo[9], Kejia Lee[1,2,3,10,11], Jinlin Han[1], Peng Jiang[1], Zhiqiang Shen[12], Min Wang[6], Na Wang[5], Renxin Xu[2,3,13], Xiangping Wu[1], Richard Manchester[14], Lei Qian[1], Xin Guan[1], Menglin Huang[1], Chun Sun[1], and Yan Zhu[1]



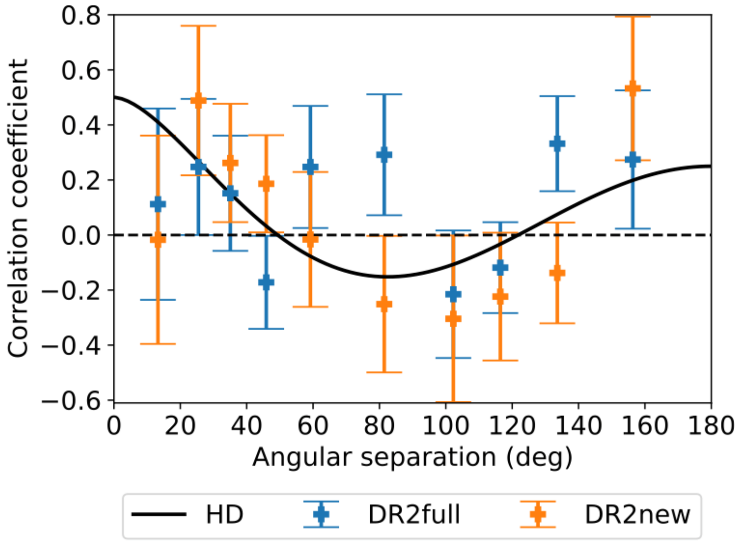
A&A 678, A50 (2023)
https://doi.org/10.1051/0004-6361/202346844

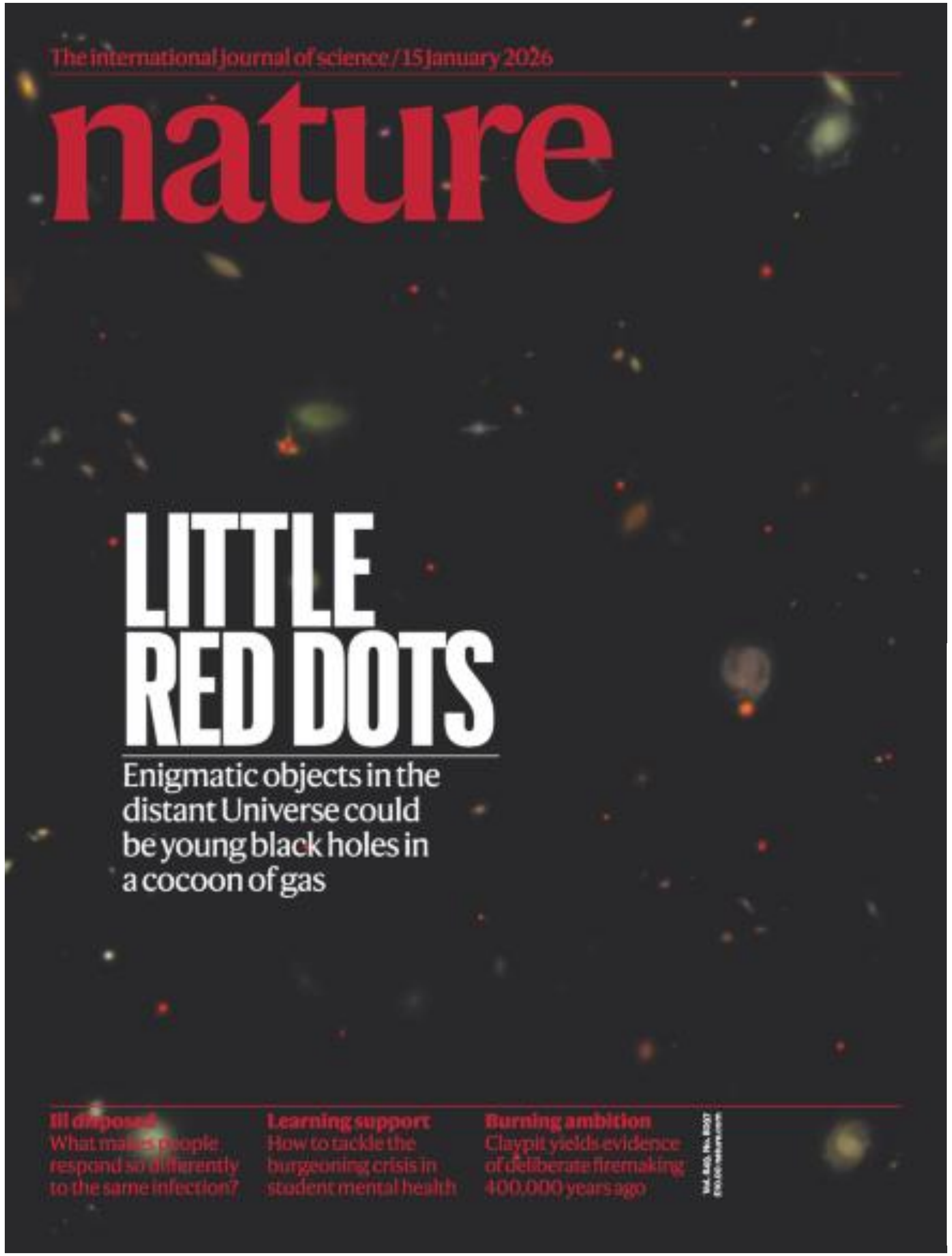
Astronomy & Astrophysics

The second data release from the European Pulsar Timing Array

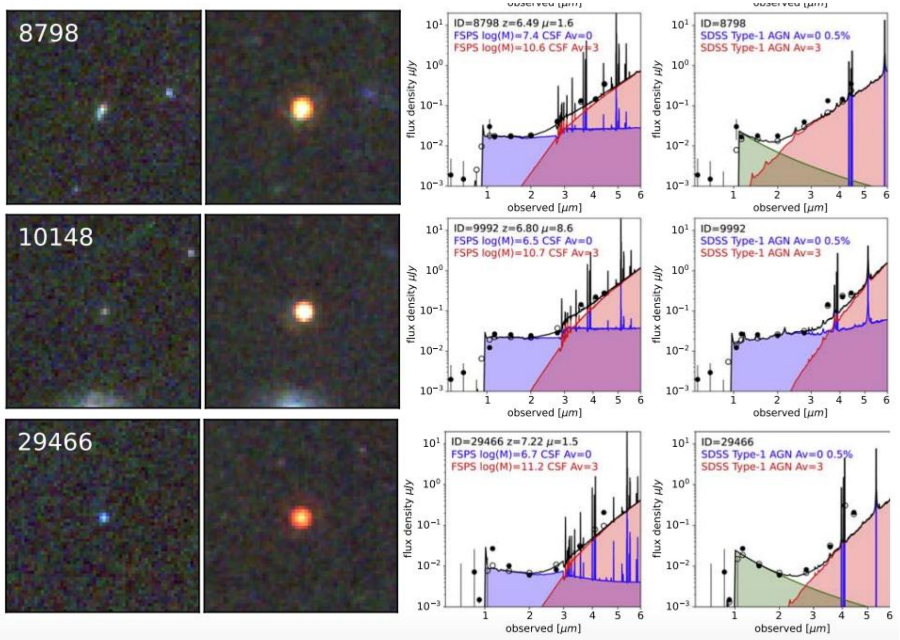
III. Search for gravitational wave signals

EPTA Collaboration and InPTA Collaboration: J. Antoniadis (Ιωάννης Αντωνιάδης)[1,2], P. Arumugam[3], S. Arumugam[4], S. Babak[5], M. Bagchi[6,7], A.-S. Bak Nielsen[2,8], C. G. Bassa[9], A. Bathula[10], A. Berthereau[11,12], M. Bonetti[13,14,15], E. Bortolas[13,14,15], P. R. Brook[16], M. Burgay[17], R. N. Caballero[18], A. Chalumeau[13], D. J. Champion[2], S. Chanlaridis[1], S. Chen[19,⋆], I. Cognard[11,12], S. Dandapat[20], D. Deb[6], S. Desai[21], G. Desvignes[2], N. Dhanda-Batra[22], C. Dwivedi[23], M. Falxa[5,11], R. D. Ferdman[24], A. Franchini[13,14], J. R. Gair[25], B. Goncharov[26,27], A. Gopakumar[20], E. Graikou[2], J.-M. Grießmeier[11,12], L. Guillemot[11,12], Y. J. Guo[2,⋆], Y. Gupta[28], S. Hisano[29], H. Hu[2], F. Iraci[30,17], D. Izquierdo-Villalba[13,14], J. Jang[2], J. Jawor[2], G. H. Janssen[9,31], A. Jessner[2], B. C. Joshi[28,3], F. Kareem[32,33], R. Karuppusamy[2], E. F. Keane[34], M. J. Keith[35], D. Kharbanda[21], T. Kikunaga[29], N. Kolhe[36], M. Kramer[2,35], M. A. Krishnakumar[2,8], K. Lackeos[2], K. J. Lee[37,38], K. Liu[2], Y. Liu[38,8], A. G. Lyne[35], J. W. McKee[39,40], Y. Maan[28], R. A. Main[2], M. B. Mickaliger[35], I. C. Niţu[35], K. Nobleson[41], A. K. Paladi[42], A. Parthasarathy[2], B. B. P. Perera[43], D. Perrodin[17], A. Petiteau[44,5], N. K. Porayko[13,2], A. Possenti[17], T. Prabu[45], H. Quelquejay Leclere[5], P. Rana[20], A. Samajdar[46], S. A. Sanidas[35], A. Sesana[13,14,15], G. Shaifullah[13,14,17], J. Singha[3], L. Speri[25], R. Spiewak[35], A. Srivastava[21], B. W. Stappers[35], M. Surnis[47], S. C. Susarla[48], A. Susobhanan[49], K. Takahashi[50,51], P. Tarafdar[6], G. Theureau[11,12,52], C. Tiburzi[17], E. van der Wateren[9,31], A. Vecchio[16], V. Venkatraman Krishnan[2], J. P. W. Verbiest[53,8,2], J. Wang[8,54,55], L. Wang[35], and Z. Wu[38,8]

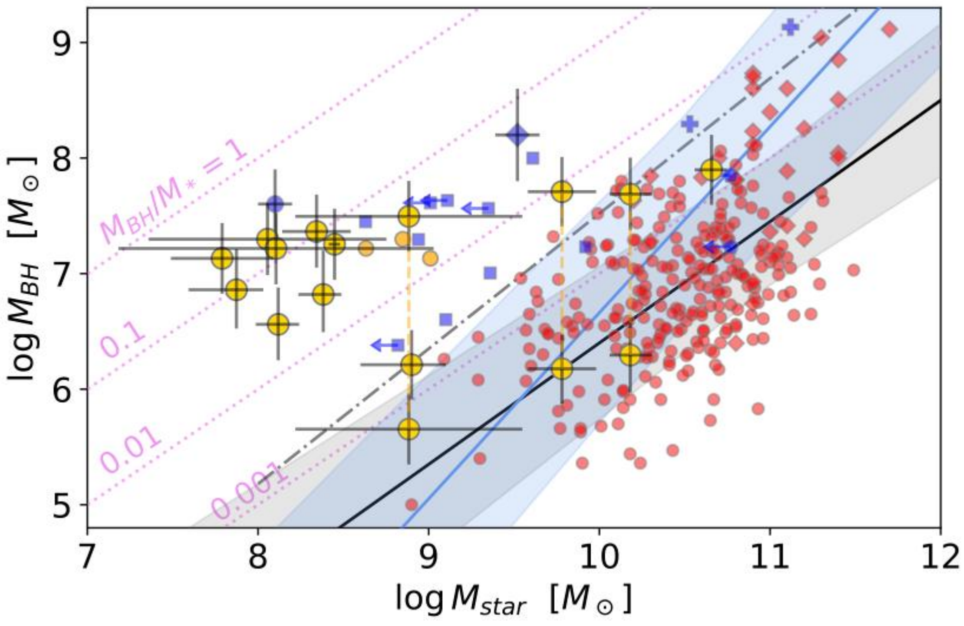




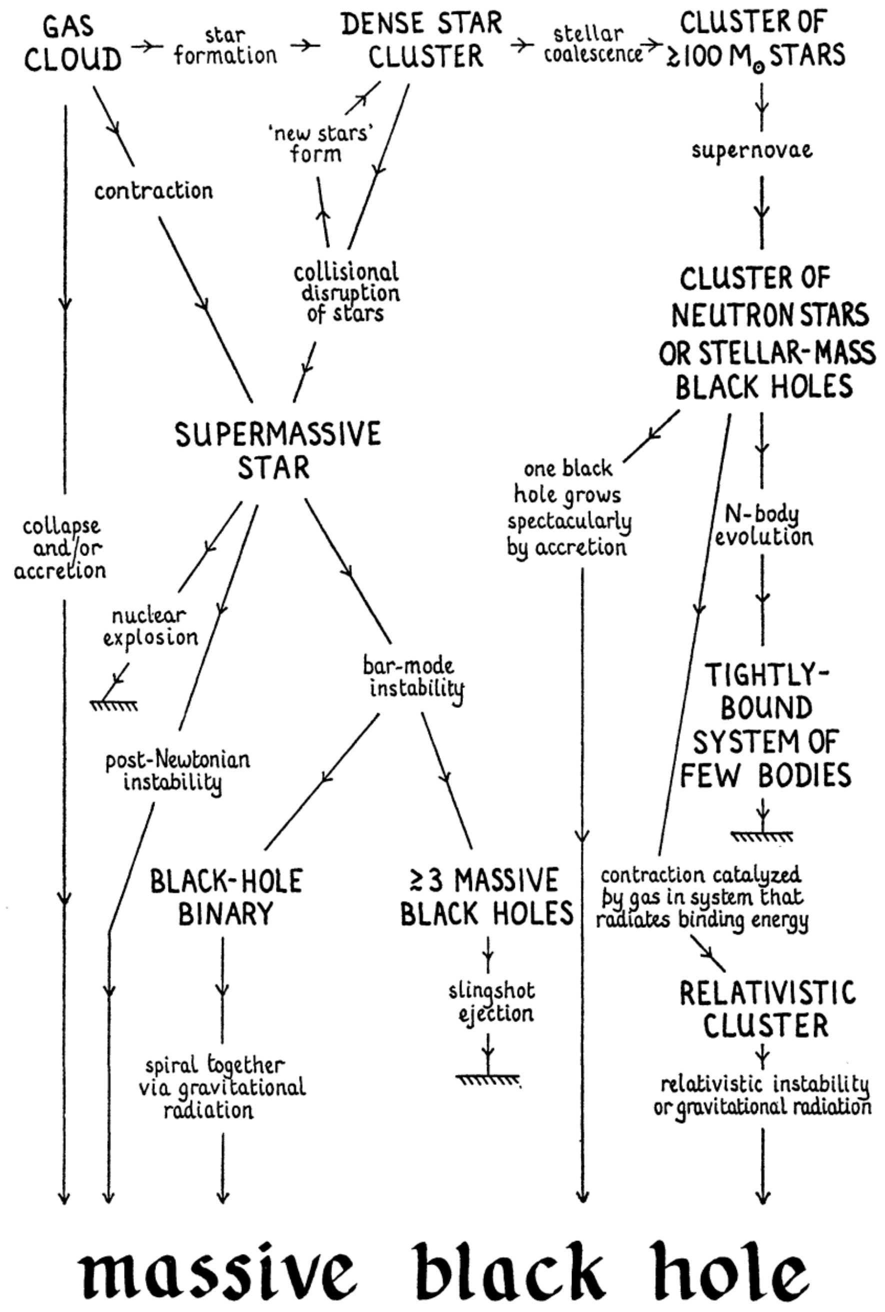
The international journal of science / 15 January 2026
nature
LITTLE RED DOTS
Enigmatic objects in the distant Universe could be young black holes in a cocoon of gas
Ill disposed
What makes people respond so differently to the same infection?
Learning support
How to tackle the burgeoning crisis in student mental health
Burning ambition
Claypit yields evidence of deliberate firemaking 400,000 years ago

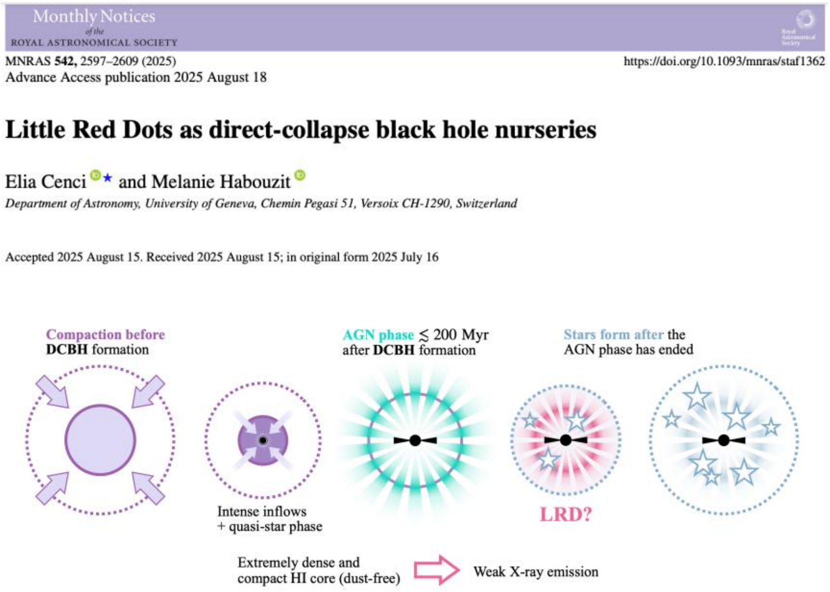


8798
10148
29466
ID=8798 z=6.49 μ=1.6
FSPS log(M)=7.4 CSF Av=0
FSPS log(M)=10.6 CSF Av=3
ID=8798
SDSS Type-1 AGN Av=0 0.5%
SDSS Type-1 AGN Av=3
ID=9992 z=6.80 μ=8.6
FSPS log(M)=6.5 CSF Av=0
FSPS log(M)=10.7 CSF Av=3
ID=9992
SDSS Type-1 AGN Av=0 0.5%
SDSS Type-1 AGN Av=3
ID=29466 z=7.22 μ=1.5
FSPS log(M)=6.7 CSF Av=0
FSPS log(M)=11.2 CSF Av=3
ID=29466
SDSS Type-1 AGN Av=0 0.5%
SDSS Type-1 AGN Av=3
flux density μJy
observed [μm]



$M_{BH}/M_* = 1$
0.1
0.01
0.001
$\log M_{BH}$ $[M_\odot]$
$\log M_{star}$ $[M_\odot]$





Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS 542, 2597–2609 (2025) https://doi.org/10.1093/mnras/staf1362
Advance Access publication 2025 August 18

Little Red Dots as direct-collapse black hole nurseries

Elia Cenci ★ and Melanie Habouzit
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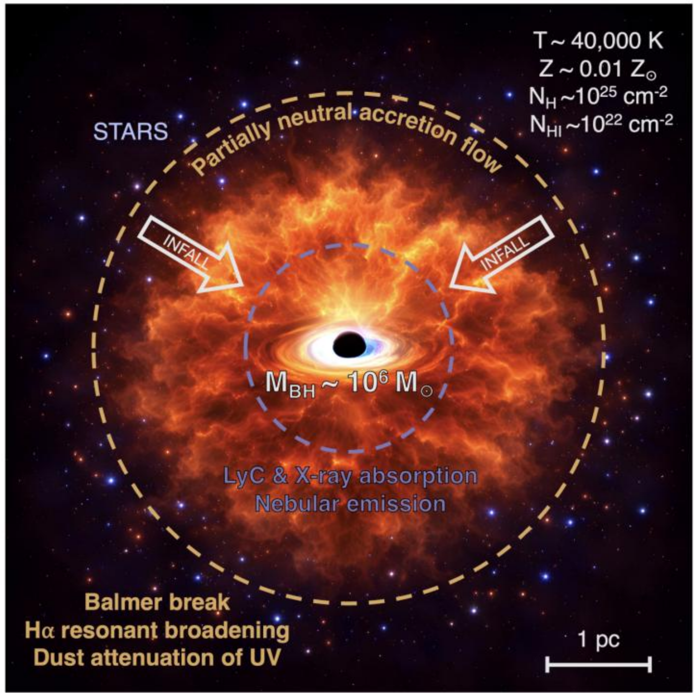

Pacucci et al. 2025 arXiv:2601.14368

Revisiting the Unified Model of Active Galactic Nuclei

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Annu. Rev. Astron. Astrophys. 2015. 53:365–408

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This article's doi: 10.1146/annurev-astro-082214-122302

Keywords

active galaxies, unification, black holes, accretion disks, central torus, star formation, AGN surveys, interferometry, mergers

Abstract

This review describes recent developments related to the unified model of active galactic nuclei (AGNs). It focuses on new ideas about the origin and properties of the central obscurer (torus) and the connection to its surroundings. The review does not address radio unification. AGN tori must

An interesting variant of the general torus formation scenario, proposed by Wang et al. (2010, 2011b), moves the SF activity to inside the dust sublimation radius. This model is not concerned with the issues of torus formation and stability. It merely assumes the existence of a central torus that serves as a source of mass supply to the innermost region. The model includes a thin, central accretion disk around the central BH and fragmented clouds between R_{SG} and the inner walls of the torus. SF activity and SN explosions take place inside the torus walls, and the duration of one accretion episode is estimated to be *few* $\times 10^6$ years. This would result in approximately 10^6 stars that may eventually settle into a central star cluster.

Formation:

- Metallicity?
- Torus-> BLR?
- Compact objects?

Observ. Evidence?

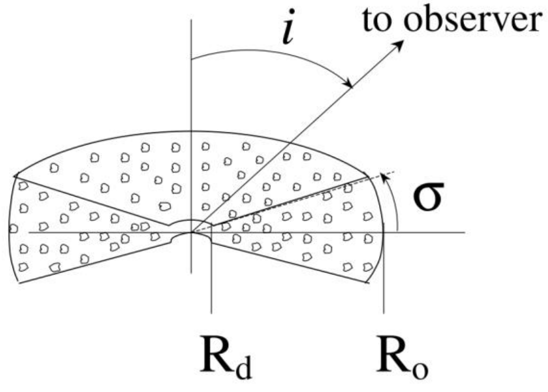
- Reverb. mapping
- Outbursts?
- LIGO detections?

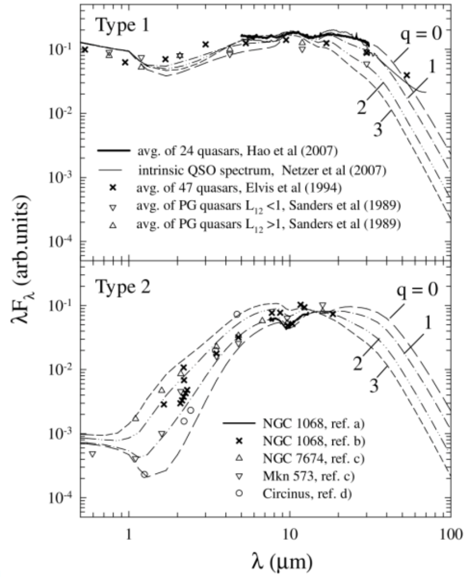
Formation of AGN structure

THE ASTROPHYSICAL JOURNAL, 685:160–180, 2008 September 20

AGN DUSTY TORI. II. OBSERVATIONAL IMPLICATIONS OF CLUMPINESS

MAIA NENKOVA,[1] MATTHEW M. SIROCKY,[2] ROBERT NIKUTTA,[2] ŽELJKO IVEZIĆ,[3] AND MOSHE ELITZUR[2]
Received 2007 October 31; accepted 2008 May 30





nature astronomy

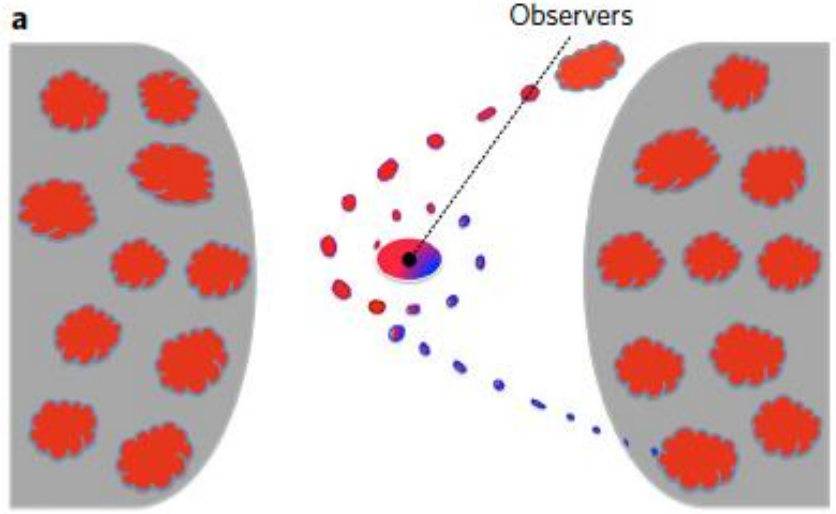
2017

LETTERS

DOI: 10.1038/s41550-017-0264-4

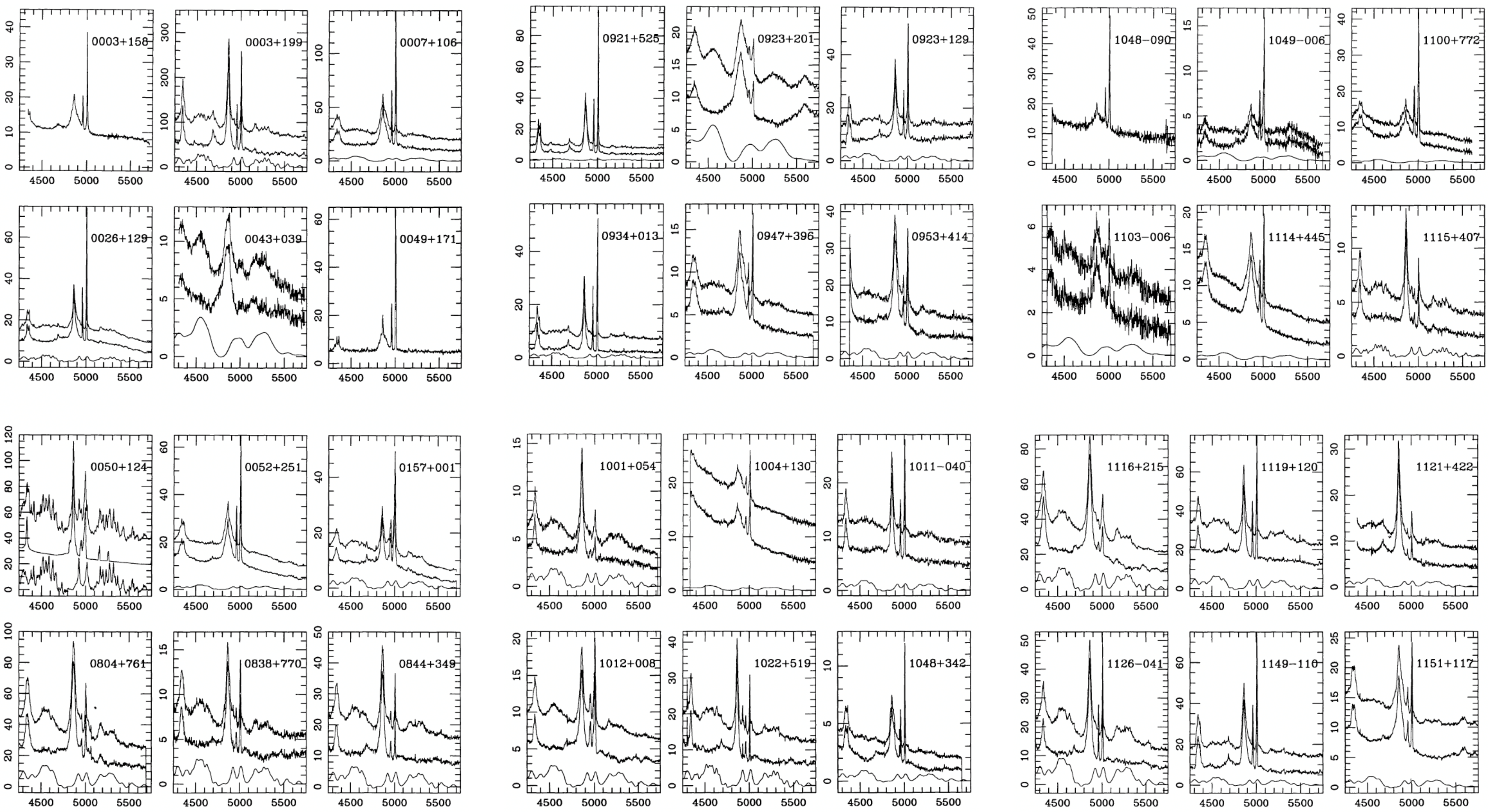
Tidally disrupted dusty clumps as the origin of broad emission lines in active galactic nuclei

Jian-Min Wang[1,2,3*], Pu Du[1], Michael S. Brotherton[4], Chen Hu[1], Yu-Yang Songsheng[1], Yan-Rong Li[1], Yong Shi[5] and Zhi-Xiang Zhang[1]

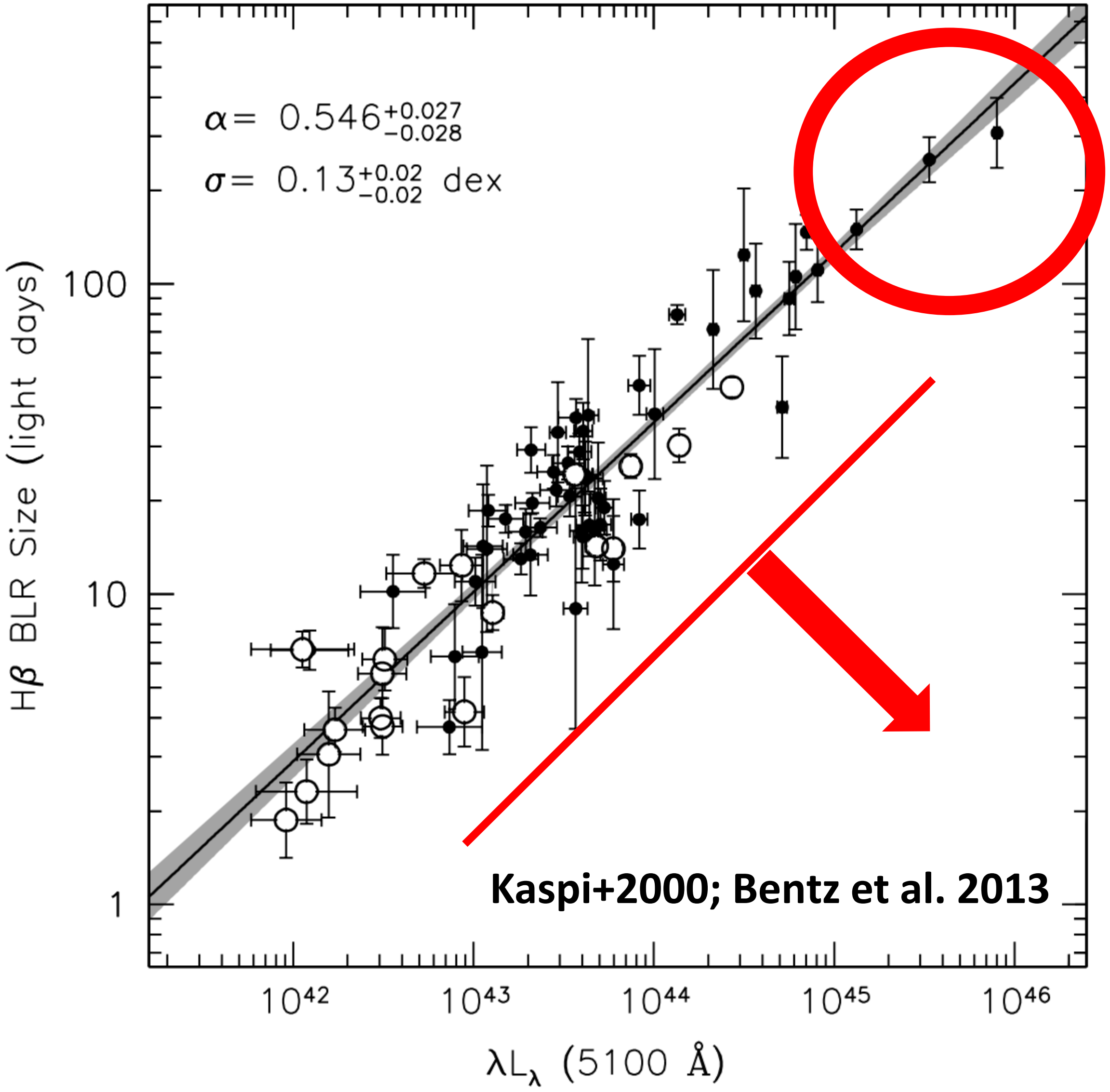


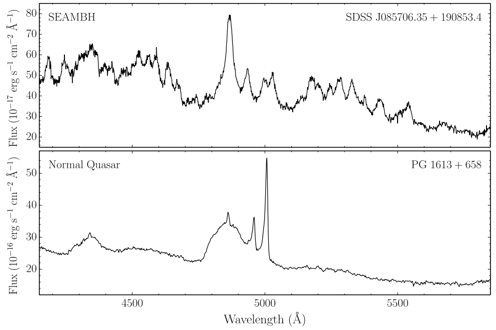
Intermediate-line regions

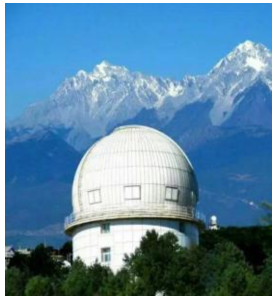
Boroson & Green (1992): 1/3 of FeII-strong objects

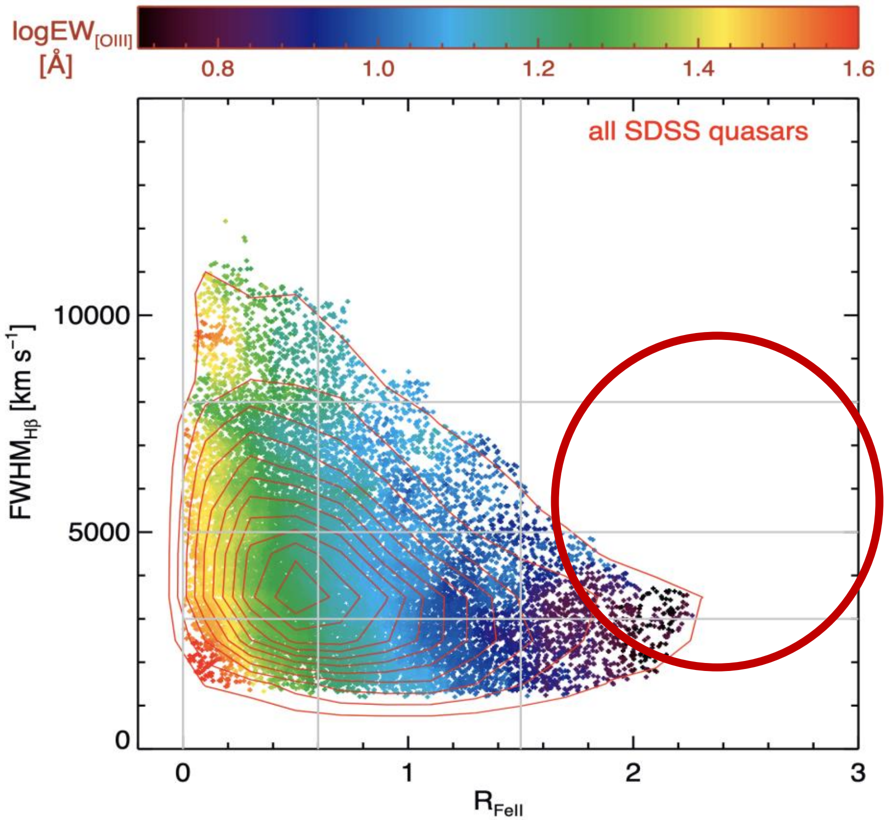


BLR size: *L*-driven?





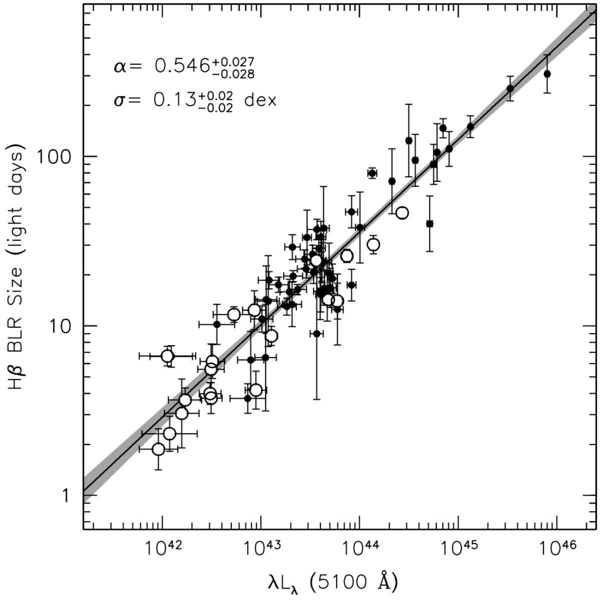


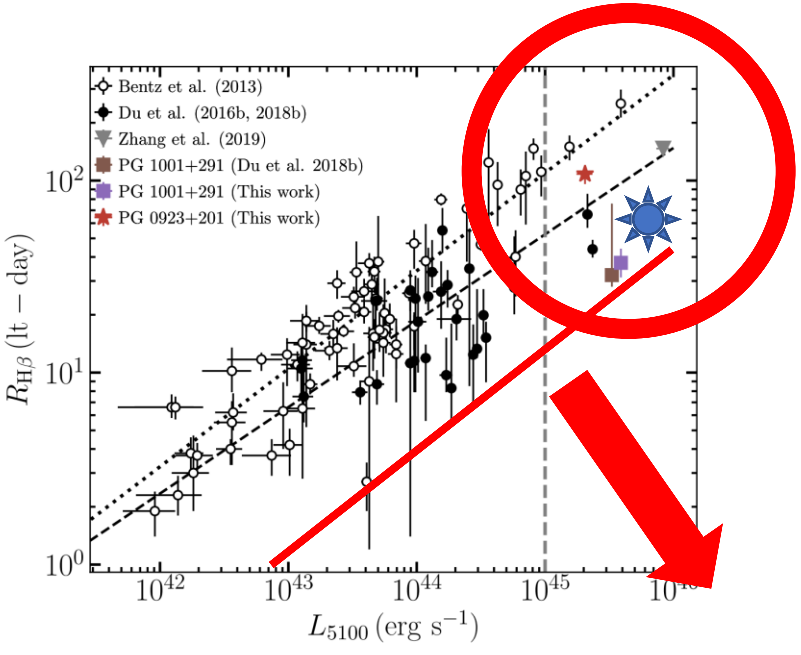


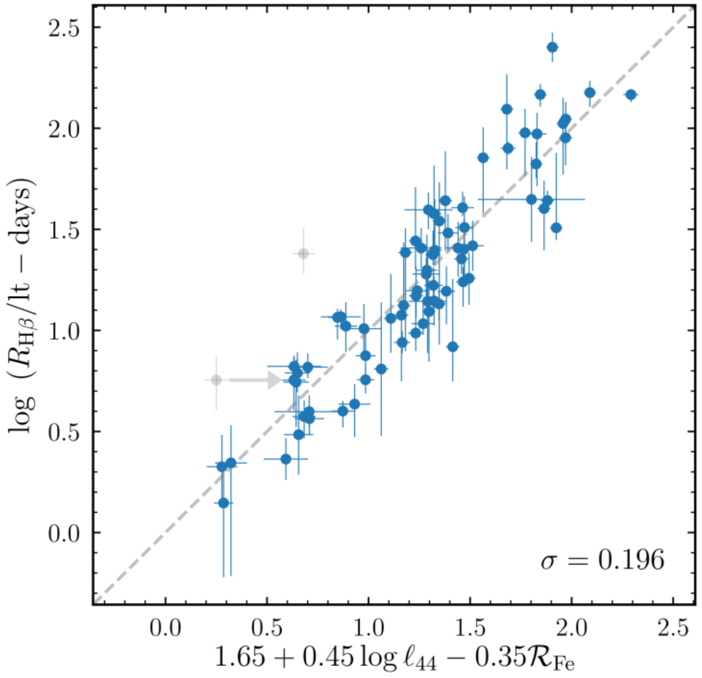
Boroson & Green (1992), Sulentic et al. (2000), Marziani et al. (2002), Shen &Ho (2014)

BLR size: *L*-driven? Others?

SEAMBH collaboration: I-XV





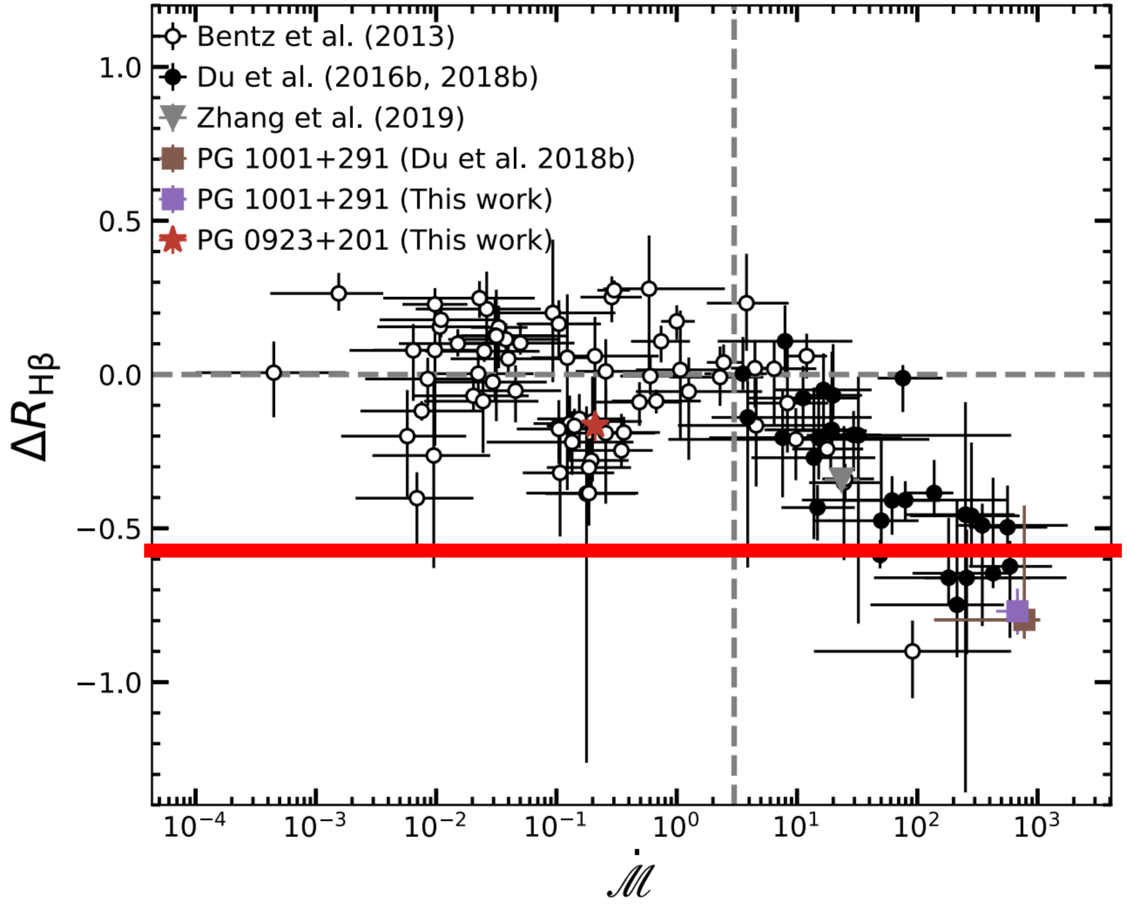


Kaspi+2000; Bentz et al. 2013

Du et al. (2014; 2015; 2016a; 2018),
Wang et al. (2014), Hu et al. (2015), Li et al. (2021,2026)

R-L relation:

over-estimate by factors of 3-8



- Why shortened?
- Why FeII as an indicator?
- What is largest shortening?

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
California Institute of Technology; and Departments of Physics and Astronomy, University of California, Berkeley,
Received 1981 June 8; accepted 1981 September 23

We assume that the central ionizing source is small compared to the emission line region and that the recombination time ($\sim n_{e9}^{-1}$ hr, where n_{e9} is the electron density in units of 10^9 cm^{-3}) is negligible compared to the variability time. Then together with the assumptions discussed in § II*a* above, we can express the emissivity as

$$j(\boldsymbol{r}, t') = \frac{\varepsilon(\boldsymbol{r}) L_c(t' - r)}{4\pi r^2}, \tag{2.13}$$

when the reprocessing coefficient $\varepsilon(\boldsymbol{r})$ has dimensions of inverse length. Since $j(\boldsymbol{r}, t)$ is limited by the blackbody

- Basic assumption：point approximation of ionizing source （×）
- Possibility: extended ionizing sources?
- Expectation: zero or even negative lags?

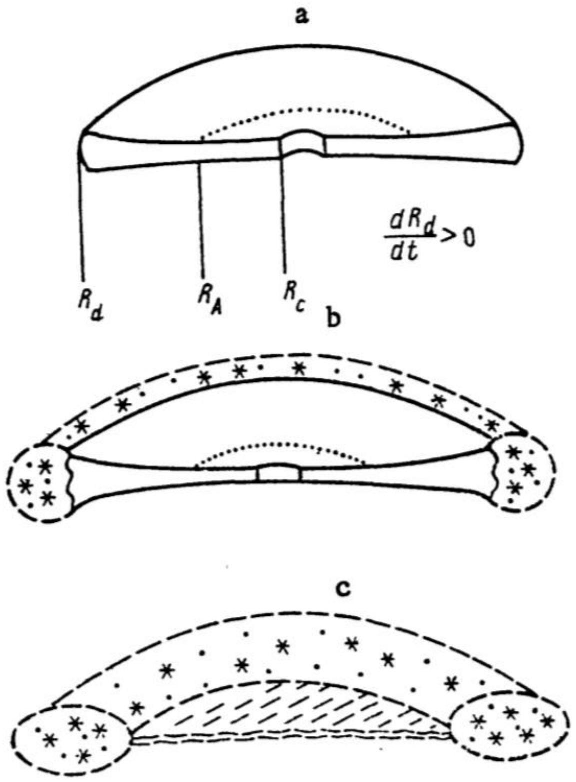
The outer parts of the accretion disks around supermassive black holes in galaxy nuclei and quasars

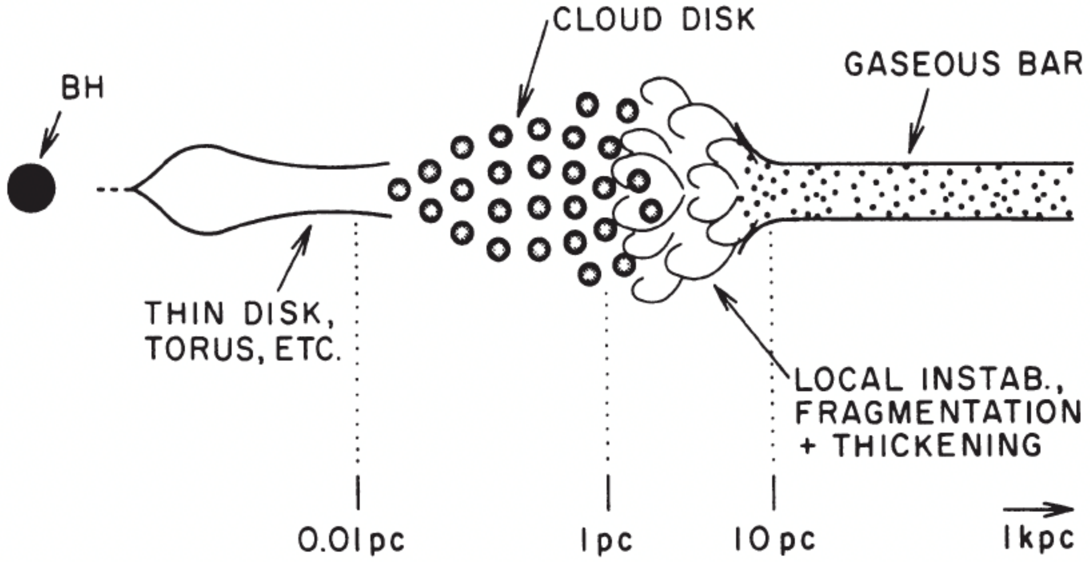
P. I. Kolykhalov and R. A. Syunyaev

Institute for Space Research, USSR Academy of Sciences, Moscow

(Submitted August 15, 1980)

Pis'ma Astron. Zh. **6**, 680–686 (November 1980)





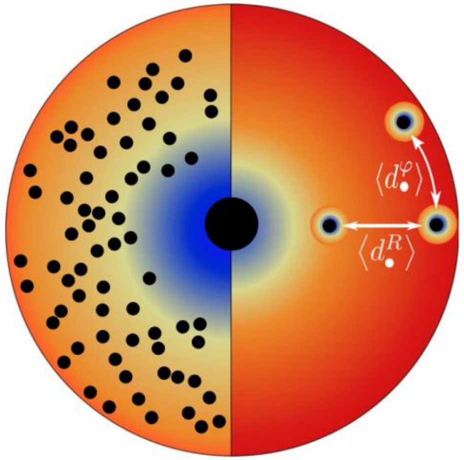
Begelman+(1989)

The Astrophysical Journal, 928:191 (26pp), 2022 April 1 https://doi.org/10.3847/1538-4357/ac4ded

CrossMark

Feedback-dominated Accretion Flows

Shmuel Gilbaum[1] and Nicholas C. Stone[1,2,3]
[1] Racah Institute of Physics, The Hebrew University, Jerusalem, 91904, Israel; shmuel.gilbaum@mail.huji.ac.il
[2] Department of Astronomy, University of Maryland, Stadium Drive, College Park, MD 20742, USA
[3] Department of Physics, Department of Astronomy, and Columbia Astrophysics Laboratory, Columbia University, New York, NY 10027, USA
Received 2021 July 18; revised 2021 December 26; accepted 2022 January 18; published 2022 April 7



The Astrophysical Journal Letters, 966:L9 (8pp), 2024 May 1 https://doi.org/10.3847/2041-8213/ad3c3f

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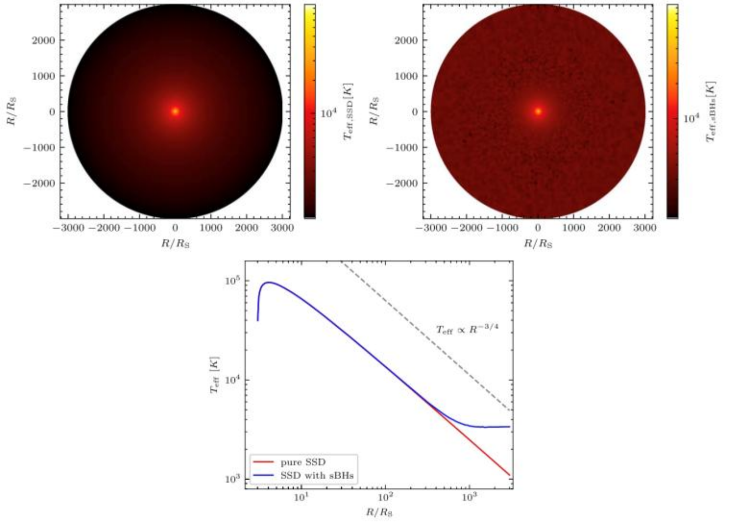
Stellar Black Holes Can "Stretch" Supermassive Black Hole Accretion Disks

Shuying Zhou[1], Mouyuan Sun[1], Tong Liu[1], Jian-Min Wang[2,3,4], Jun-Xian Wang[5,6], and Yongquan Xue[5,6]
[1] Department of Astronomy, Xiamen University, Xiamen, Fujian 361005, People's Republic of China; msun88@xmu.edu.cn
[2] Key Laboratory for Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, 19B Yuquan Road, Beijing 100049, People's Republic of China
[3] School of Astronomy and Space Sciences, University of Chinese Academy of Sciences, 19A Yuquan Road, Beijing 100049, People's Republic of China
[4] National Astronomical Observatory of China, 20A Datun Road, Beijing 100020, People's Republic of China
[5] Department of Astronomy, University of Science and Technology of China, Hefei 230026, People's Republic of China
[6] School of Astronomy and Space Science, University of Science and Technology of China, Hefei 230026, People's Republic of China
Received 2024 February 7; revised 2024 April 5; accepted 2024 April 8; published 2024 April 24



Soltan argument: low-mass BHs

Mon. Not. R. astr. Soc. (1982) **200**, 115–122

Masses of quasars

Andrzej Sołtan *N. Copernicus Astronomical Centre, Bartycka 18, 00-716 Warsaw, Poland*

Received 1981 October 18; in original form 1981 August 19

Mon. Not. R. Astron. Soc. (1992) **259**, 421–424

Remnants of the quasars

Arati Chokshi★ and Edwin L. Turner
Princeton University Observatory, Peyton Hall, Princeton, NJ 08544, USA

Accepted 1992 May 19. Received 1992 May 11; in original form 1992 February 3

Mon. Not. R. Astron. Soc. **335**, 965–976 (2002)

Observational constraints on growth of massive black holes

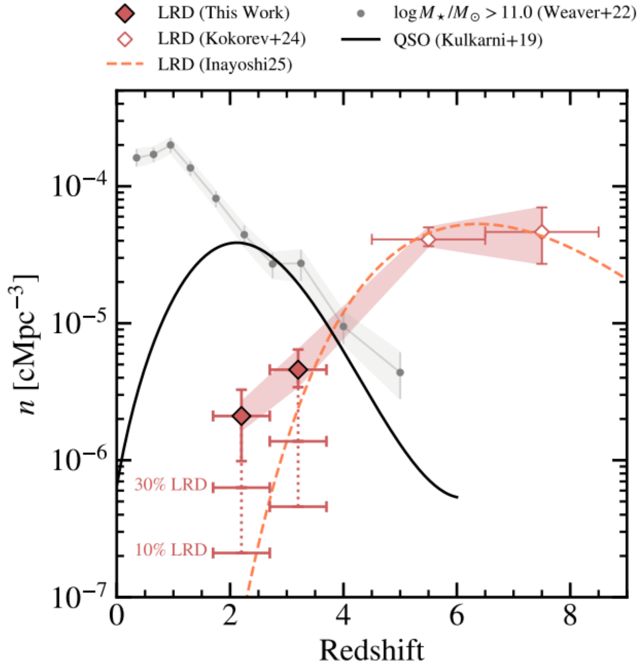
Qingjuan Yu★ and Scott Tremaine★
Princeton University Observatory, Peyton Hall, Princeton, NJ 08544-1001, USA

Accepted 2002 May 13. Received 2002 May 3; in original form 2002 February 24

Draft version April 14, 2025
Typeset using LaTeX **twocolumn** style in AASTeX7

Counting Little Red Dots at $z < 4$ with Ground-based Surveys and Spectroscopic Follow-up

Yilun Ma (马逸伦)[1], Jenny E. Greene[1], David J. Setton[1], Andy D. Goulding[1], Marianna Annunziatella[2], Xiaohui Fan[3], Vasily Kokorev[4], Ivo Labbe[5], Jiaxuan Li (李嘉轩)[1], Xiaojing Lin[3], Danilo Marchesini[6], Jorryt Matthee[7], Luke Robbins[6], Anna Sajina[6], Marcin Sawicki[8] and O. Grace Telford[1,9]



$$\rho_{\rm acc}(z=0) = \int_0^\infty \left(\frac{{\rm d}t}{{\rm d}z}\right) {\rm d}z \int_0^\infty \Phi_{\rm QSO}\left(\frac{L_{\rm Bol}}{\eta_\bullet c^2}\right) {\rm d}L_{\rm Bol} + \int_0^\infty \left(\frac{{\rm d}t}{{\rm d}z}\right) {\rm d}z \int_0^\infty \Phi_{\rm LRD}\left(\frac{L_{\rm Bol}}{\eta_\bullet c^2}\right) {\rm d}L_{\rm Bol},$$

$$\langle M_\bullet \rangle_{\rm G} = \langle M_\bullet \rangle_{\rm QSO} + \zeta_z \langle M_\bullet \rangle_{\rm LRD}.$$

$$\langle M_\bullet \rangle_{\rm LRD} = \zeta_z^{-1} \delta \langle M_\bullet \rangle \lesssim 10^6\, \zeta_2^{-1} \delta \langle M_\bullet \rangle_8\, M_\odot,$$

LRDs：X-ray weak, less variable, metal-poor, dust-poor, radio-weak

DRAFT VERSION 2025-11-13
Typeset using LATEX default style in AASTeX631

Little red dots as embryos of active galactic nuclei

JIAN-MIN WANG,[1,2,3] YI-LIN WANG,[1,2] YONG-JIE CHEN,[4] JUN-RONG LIU,[1] YU-YANG SONGSHENG,[1] CHENG CHENG,[3] YAN-RONG LI,[1] PU DU,[1] HAO ZHANG,[1,2] AND YU ZHAO[1,2]

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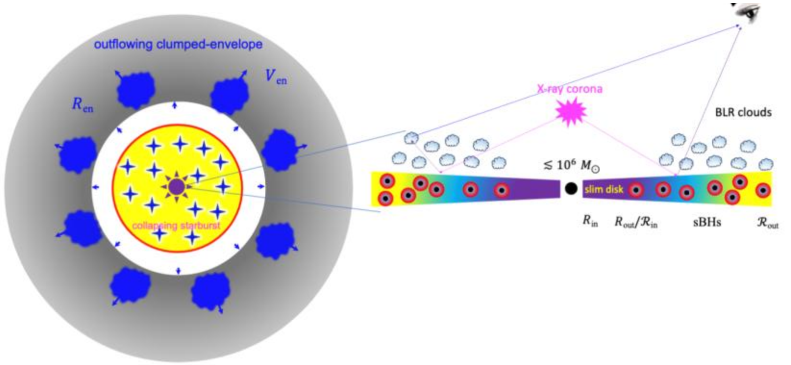
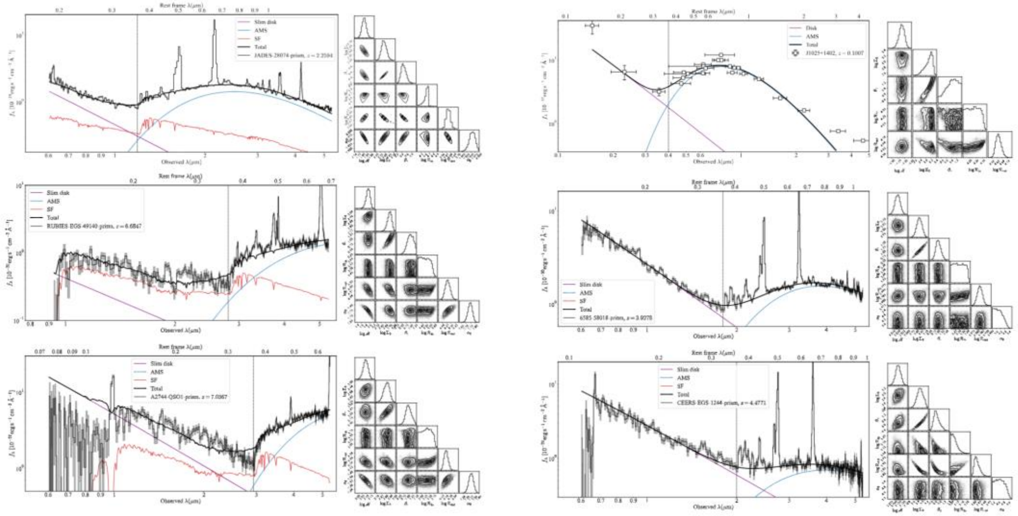
[2]School of Astronomy and Space Science, School of Physical Sciences, University of Chinese Academy of Sciences, 19A Yuquan Road, Beijing 100049, P. R. China
[3]National Astronomical Observatories of China, Chinese Academy of Sciences, 20A Datun Road, Beijing 100020, P. R. China
[4]Technology and Engineering Center for Space Utilization, Chinese Academy of Sciences, Beijing 100094, P. R. China





DRAFT VERSION FEBRUARY 10, 2026
Typeset using LATEX **twocolumn** style in AASTeX631

Spectral Appearance of Self-gravitating AGN Disks Powered by Stellar Objects: Universal Effective Temperature in the Optical Continuum and Application to Little Red Dots

YI-XIAN CHEN,[1] HANPU LIU,[1] RUANCUN LI,[2] BINGJIE WANG,[1,*] YILUN MA,[1] YAN-FEI JIANG,[3] JENNY E. GREENE,[1] ELIOT QUATAERT,[1] AND JEREMY GOODMAN[1]

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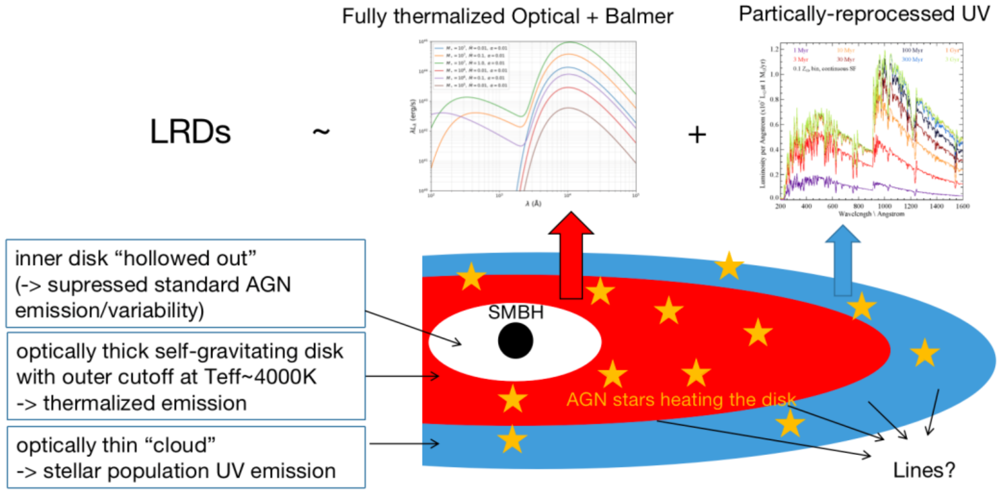
[2]Max-Planck-Institut für extraterrestrische Physik, Gießenbachstraße 1, 85748 Garching bei München, Germany
[3]Center for Computational Astrophysics, Flatiron Institute, New York, NY 10010, USA



V-shaped SEDs: super-Eddington BH+sMBHs

Super-Eddington AGNs?

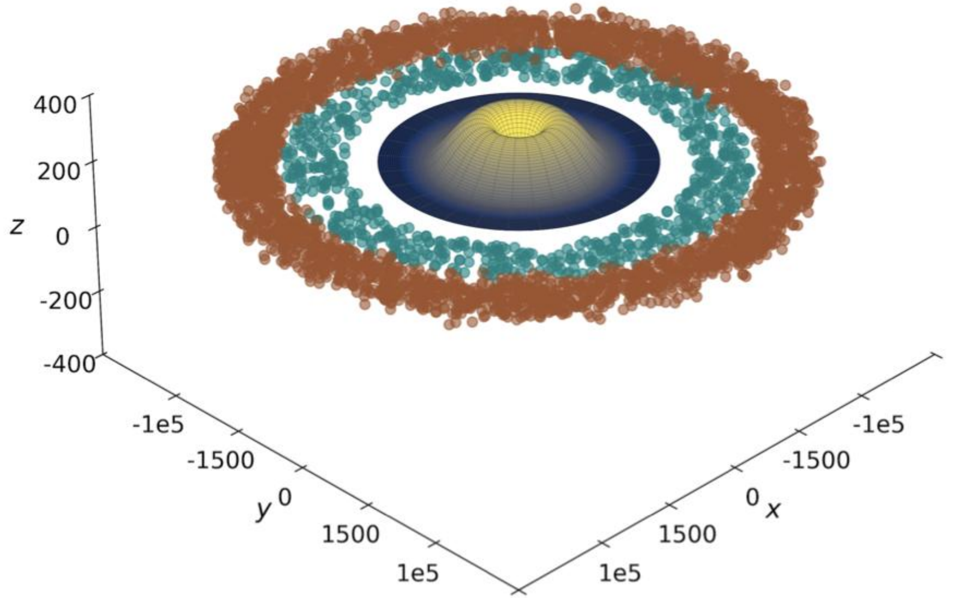
Astronomy & Astrophysics manuscript no. paper
February 27, 2026

Little red dots as obscured little blue dots: a super-Eddington unification model

Piero Madau[1,2] and Roberto Maiolino[3,4,5]

[1] Dipartimento di Fisica "G. Occhialini," Università degli Studi di Milano-Bicocca, Piazza della Scienza 3, I-20126 Milano, Italy
[2] Department of Astronomy & Astrophysics, University of California, 1156 High Street, Santa Cruz, CA 95064, USA
[3] Kavli Institute for Cosmology, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK
[4] Cavendish Laboratory, University of Cambridge, 19 JJ Thomson Avenue, Cambridge CB3 0HE, UK
[5] Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, UK

February 27, 2026

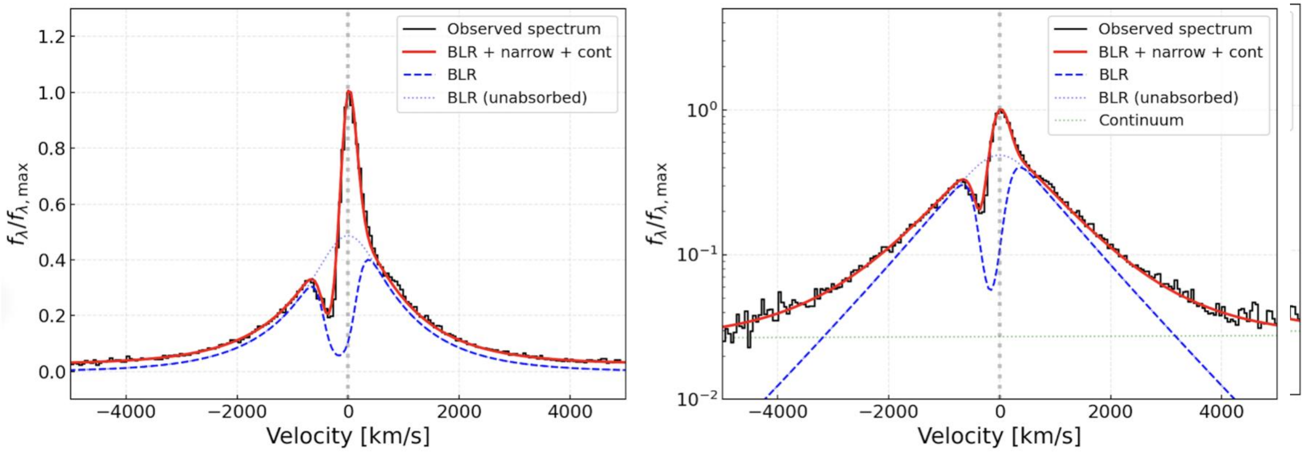


Astronomy & Astrophysics manuscript no. paper
April 7, 2026

Wings of little dots: Exponential broad lines from a stratified BLR

Piero Madau[1,2], Roberto Maiolino[3,4,5], Jan Scholtz[3,4], and Francesco D'Eugenio[3,4]

[1] Dipartimento di Fisica "G. Occhialini," Università degli Studi di Milano-Bicocca, Piazza della Scienza 3, I-20126 Milano, Italy
[2] Department of Astronomy & Astrophysics, University of California, 1156 High Street, Santa Cruz, CA 95064, USA
[3] Kavli Institute for Cosmology, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK
[4] Cavendish Laboratory, University of Cambridge, 19 JJ Thomson Avenue, Cambridge CB3 0HE, UK
[5] Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, UK



Hardly formed by stellar evolution

PHYSICAL REVIEW LETTERS **125,** 101102 (2020)

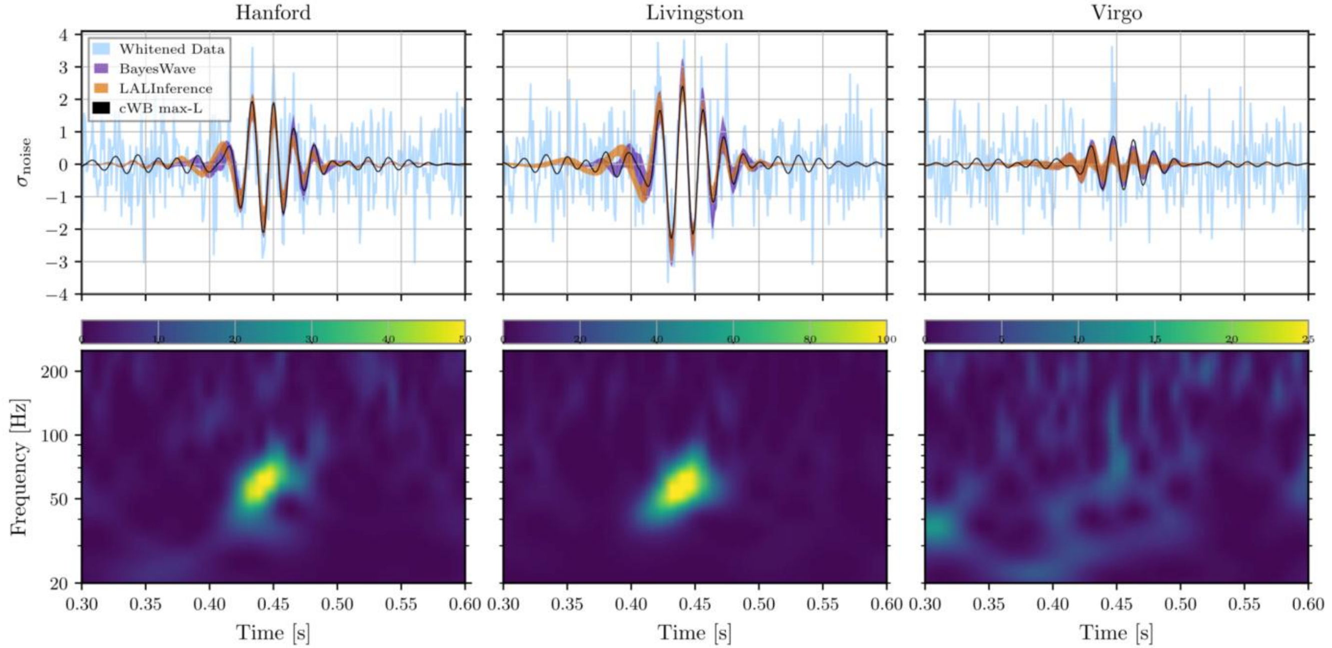
Editors' Suggestion | Featured in Physics

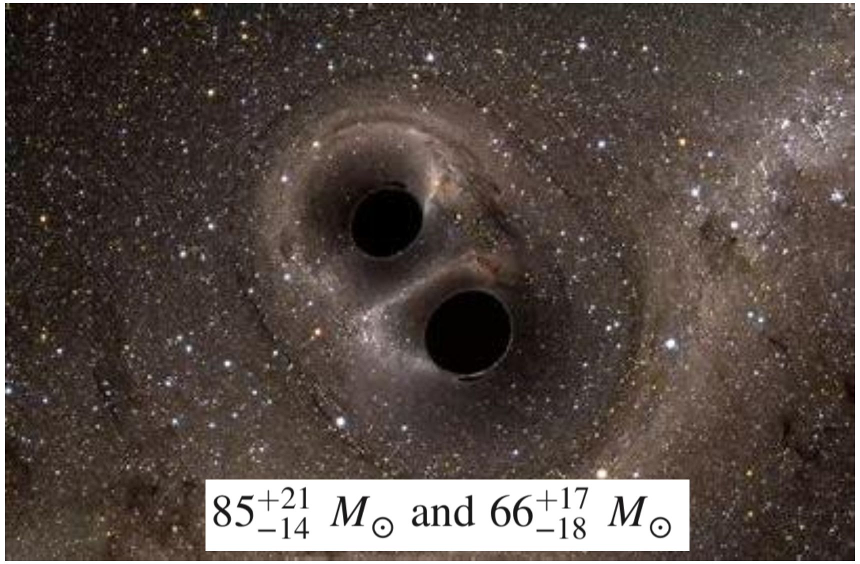
GW190521: A Binary Black Hole Merger with a Total Mass of 150 $M_\odot$

R. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 30 May 2020; revised 19 June 2020; accepted 9 July 2020; published 2 September 2020)



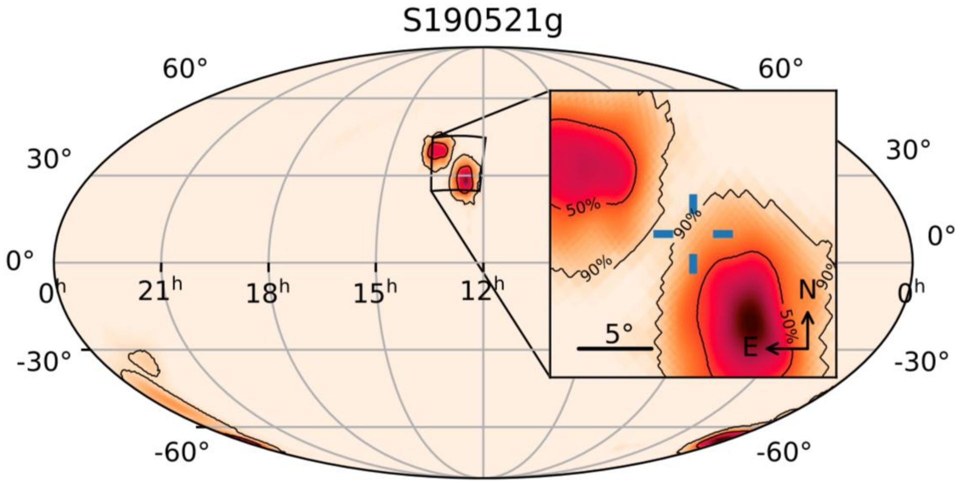


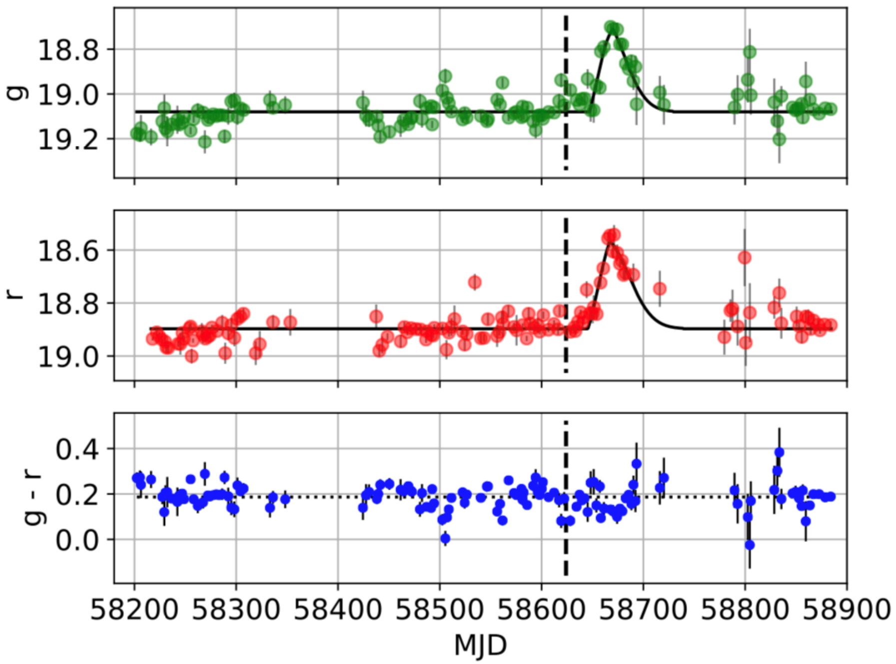
PHYSICAL REVIEW LETTERS **124,** 251102 (2020)

Editors' Suggestion | Featured in Physics

Candidate Electromagnetic Counterpart to the Binary Black Hole Merger Gravitational-Wave Event S190521g*

M. J. Graham,[1,†] K. E. S. Ford,[2,3,4] B. McKernan,[2,3,4] N. P. Ross,[5] D. Stern,[6] K. Burdge,[1] M. Coughlin,[7,8] S. G. Djorgovski,[1] A. J. Drake,[1] D. Duev,[1] M. Kasliwal,[1] A. A. Mahabal,[1] S. van Velzen,[9,10] J. Belecki,[11] E. C. Bellm,[12] R. Burruss,[11] S. B. Cenko,[13,14] V. Cunningham,[9] G. Helou,[15] S. R. Kulkarni,[1] F. J. Masci,[15] T. Prince,[1] D. Reiley,[11] H. Rodriguez,[11] B. Rusholme,[15] R. M. Smith,[11] and M. T. Soumagnac[16,17]



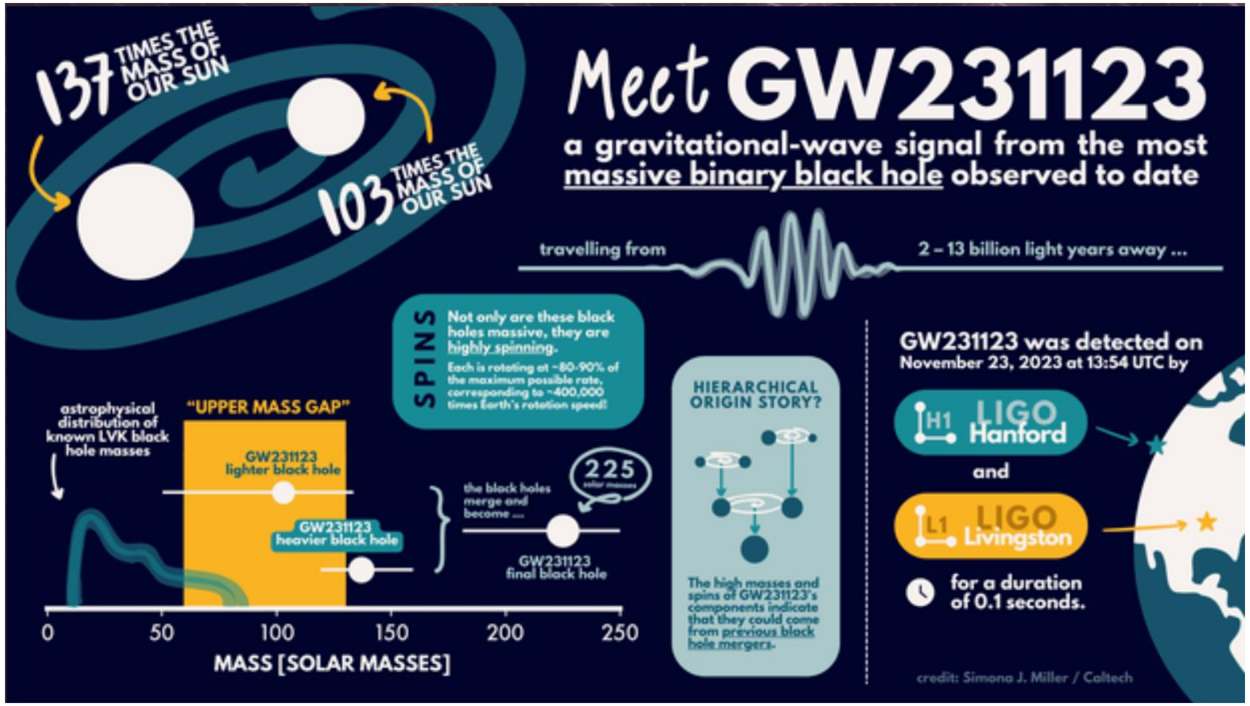


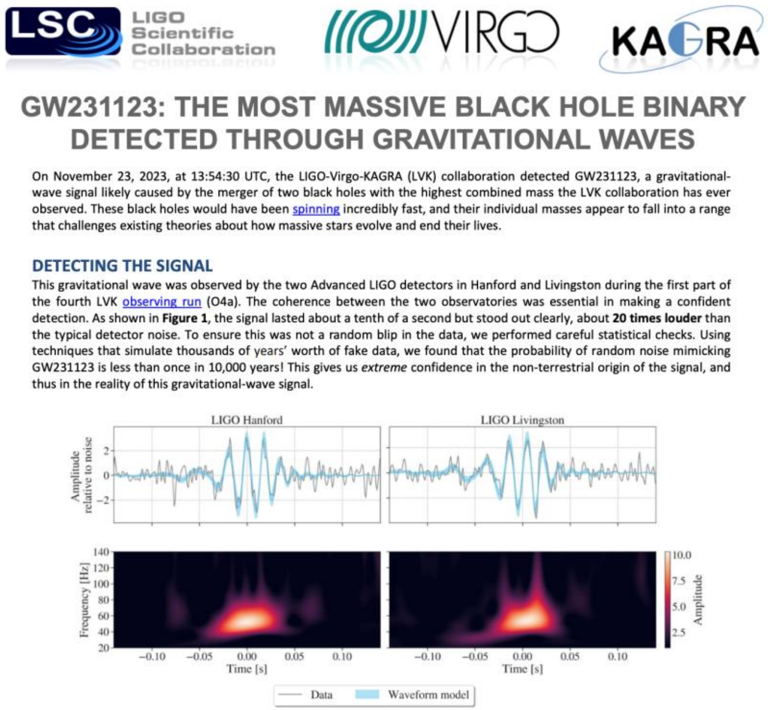
Questions: 1) how to form $80M_{\odot}$?

2) host galaxy?

LIGO detection: June 15, 2025

Origin: ?



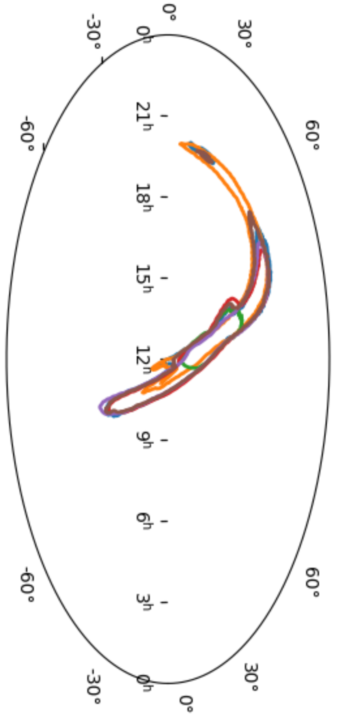

LSC LIGO Scientific Collaboration VIRGO KAGRA

GW231123: THE MOST MASSIVE BLACK HOLE BINARY DETECTED THROUGH GRAVITATIONAL WAVES

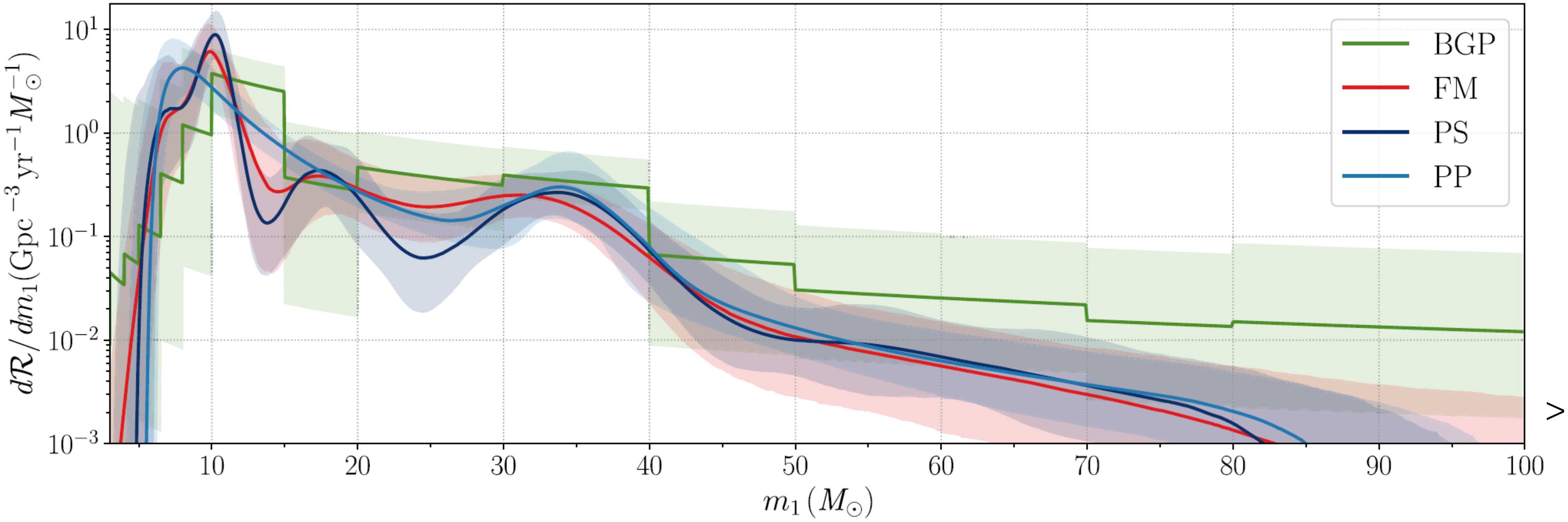
On November 23, 2023, at 13:54:30 UTC, the LIGO-Virgo-KAGRA (LVK) collaboration detected GW231123, a gravitational-wave signal likely caused by the merger of two black holes with the highest combined mass the LVK collaboration has ever observed. These black holes would have been spinning incredibly fast, and their individual masses appear to fall into a range that challenges existing theories about how massive stars evolve and end their lives.

DETECTING THE SIGNAL

This gravitational wave was observed by the two Advanced LIGO detectors in Hanford and Livingston during the first part of the fourth LVK observing run (O4a). The coherence between the two observatories was essential in making a confident detection. As shown in **Figure 1**, the signal lasted about a tenth of a second but stood out clearly, about **20 times louder** than the typical detector noise. To ensure this was not a random blip in the data, we performed careful statistical checks. Using techniques that simulate thousands of years' worth of fake data, we found that the probability of random noise mimicking GW231123 is less than once in 10,000 years! This gives us *extreme* confidence in the non-terrestrial origin of the signal, and thus in the reality of this gravitational-wave signal.



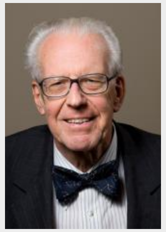
BH mass function detected by LIGO



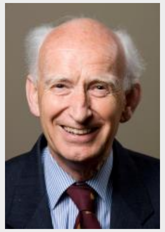
$>100M_\odot$

Breakthrough Opportunity

QSOs
2008 Kavli Prize

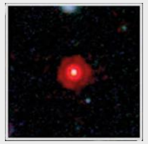


M. Schmidt

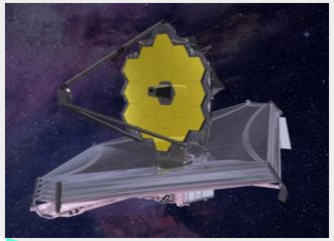


D. Lynden-Bell

LRDs: new type



?



JWST

Primordial BHs?

Collapse. of self-interacting DM

Embryos of SMBH ?

1963 — **2018** — **2023**

R. Genzel & A. Ghez

$(4 \times 10^6 M_{\odot})$

SMBH
2020 Nobel

Close binaries of SMBHs

THE ASTROPHYSICAL JOURNAL, 862:171 (10pp), 2018 August 1 https://doi.org/10.3847/1538-4357/aacdfa

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Kinematic Signatures of Reverberation Mapping of Close Binaries of Supermassive Black Holes in Active Galactic Nuclei

Jian-Min Wang[1,2,3], Yu-Yang Songsheng[1,2], Yan-Rong Li[1], and Zhe Yu[1,2]

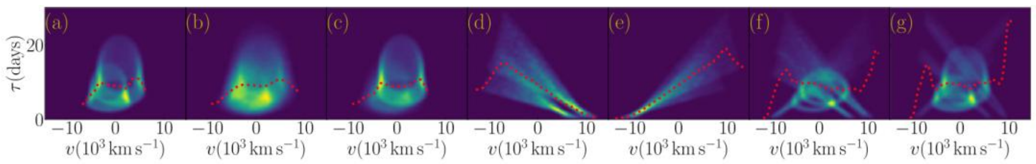


Figure 3. The 2D TFs for compositions of the same kinds of BLR geometries and the corresponding (v, τ)-plane (red lines) with (i_0, ϕ_0) = (30°, 150°); ($\epsilon_{1,2,3}$; $\gamma_{1,2,3}$; α_0, α; β_0, β) are the same as a single BLR. (a): 2⊗thin-disks, (b): 2⊗thick-disks, (c): (thin⊗thick) disks, (d): 2⊗inflows, (e): 2⊗outflows, (f): 2⊗(thin-disk+inflows+outflows) with smaller $R_{\rm mid}$, (g): with larger $R_{\rm mid}$. Generally, they are different from a single AGN. Here the symbol ⊗ represents a composition of one binary system.

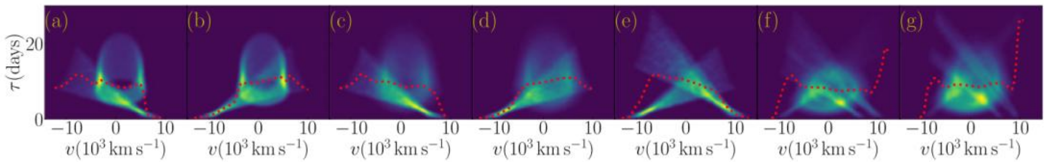


Figure 4. 2D TF for compositions of different kinds of BLR geometries and corresponding (v, τ)-planes (red lines). The parameters are the same as in Figure 3. (a): thin-disk⊗inflows, (b): thin-disk⊗outflows, (c): thick-disk⊗inflows, (d): thick-disk⊗outflows, (e): inflows⊗outflows, (f): 2⊗(thick-disk+inflows+outflows) with small $R_{\rm mid}$, (g): with large $R_{\rm mid}$. They are significantly different from a single AGN.

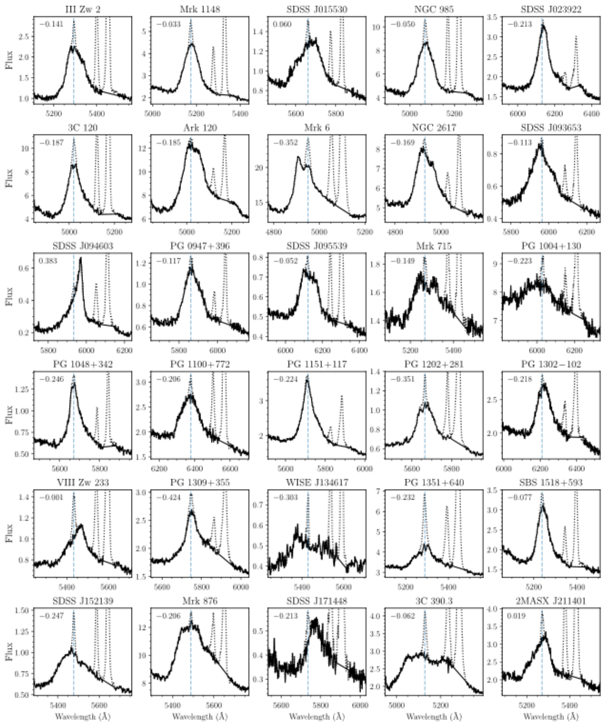
THE ASTROPHYSICAL JOURNAL, 869:142 (17pp), 2018 December 20 https://doi.org/10.3847/1538-4357/aaed2c

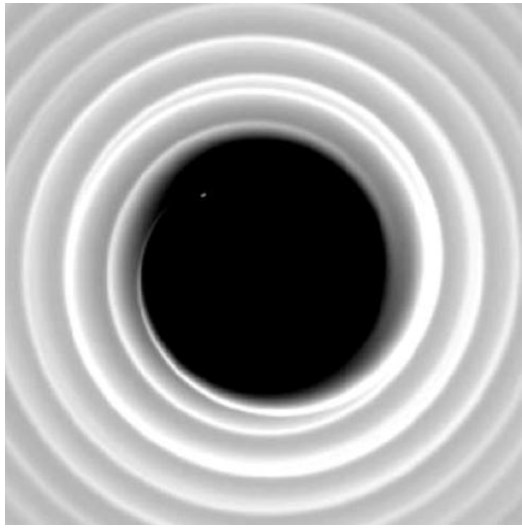
OPEN ACCESS

CrossMark

Monitoring AGNs with Hβ Asymmetry. I. First Results: Velocity-resolved Reverberation Mapping

Pu Du[1], Michael S. Brotherton[2], Kai Wang[1], Zheng-Peng Huang[1], Chen Hu[1], David H. Kasper[2], William T. Chick[2], My L. Nguyen[2], Jaya Maithil[2], Derek Hand[2], Yan-Rong Li[1], Luis C. Ho[3,4], Jin-Ming Bai[5], Wei-Hao Bian[6], and Jian-Min Wang[1,7,8,9]
(MAHA Collaboration)





Armitage+(2002):
Spiral arm?

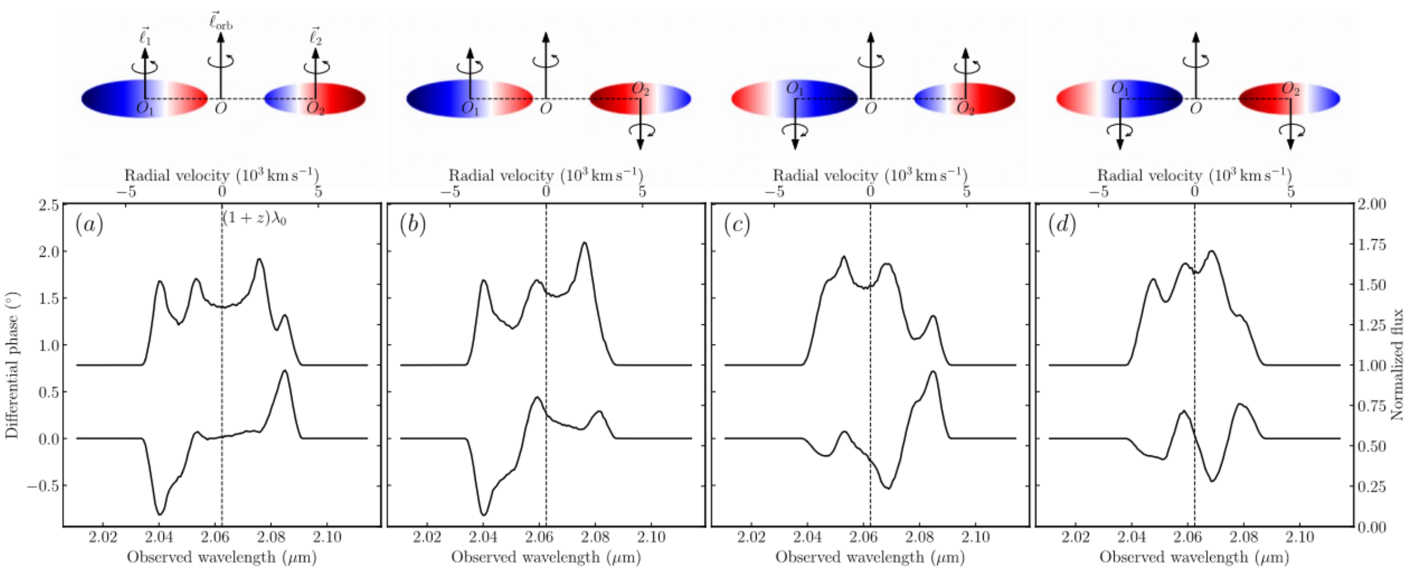
CB-SMBHs: orbits for nano-Hz GWs of PTA

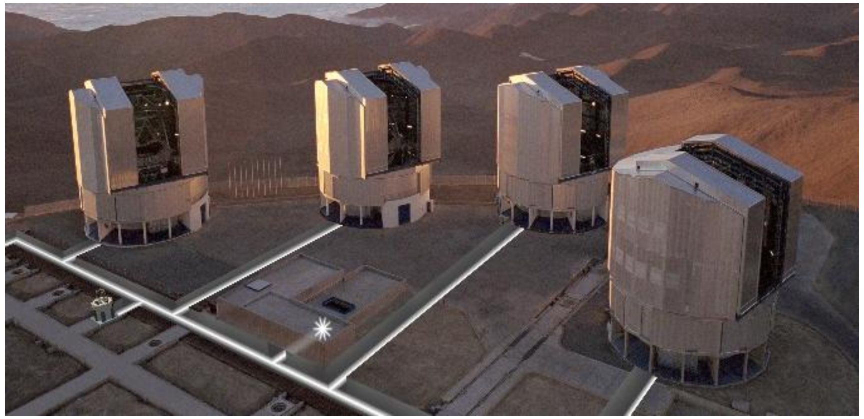
Interferometry/VLTI

THE ASTROPHYSICAL JOURNAL, 881:140 (12pp), 2019 August 20
https://doi.org/10.3847/1538-4357/ab2e00

Differential Interferometric Signatures of Close Binaries of Supermassive Black Holes in Active Galactic Nuclei

Yu-Yang Songsheng[1,2], Jian-Min Wang[1,2,3], Yan-Rong Li[1,2], and Pu Du[1,2]
[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



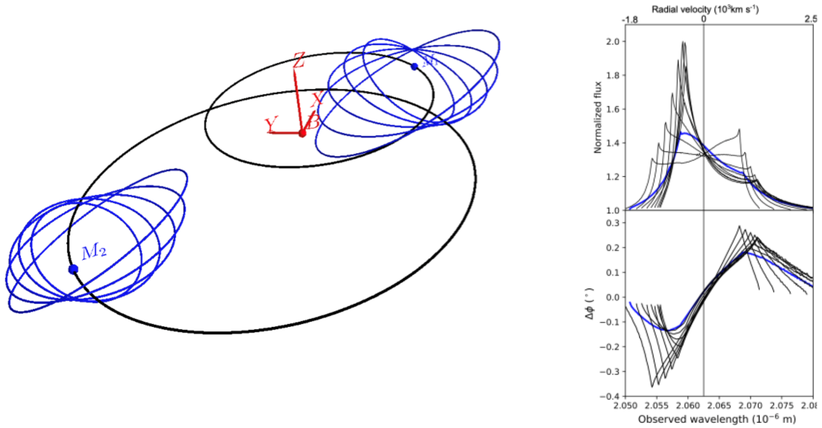


A&A 644, A88 (2020)
https://doi.org/10.1051/0004-6361/202038733

Astronomy & Astrophysics

Probing the elliptical orbital configuration of the close binary of supermassive black holes with differential interferometry

Andjelka B. Kovačević[1], Yu-Yang Songsheng[2,3], Jian-Min Wang[2,3,4], and Luka Č. Popović[5,1]



Close binaries of SMBHs

Photometric and Spectroscopic Search

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS 505, 5192–5211 (2021)
Advance Access publication 2021 May 27
https://doi.org/10.1093/mnras/stab1510

Detecting subparsec supermassive binary black holes: Long-term monitoring perspective

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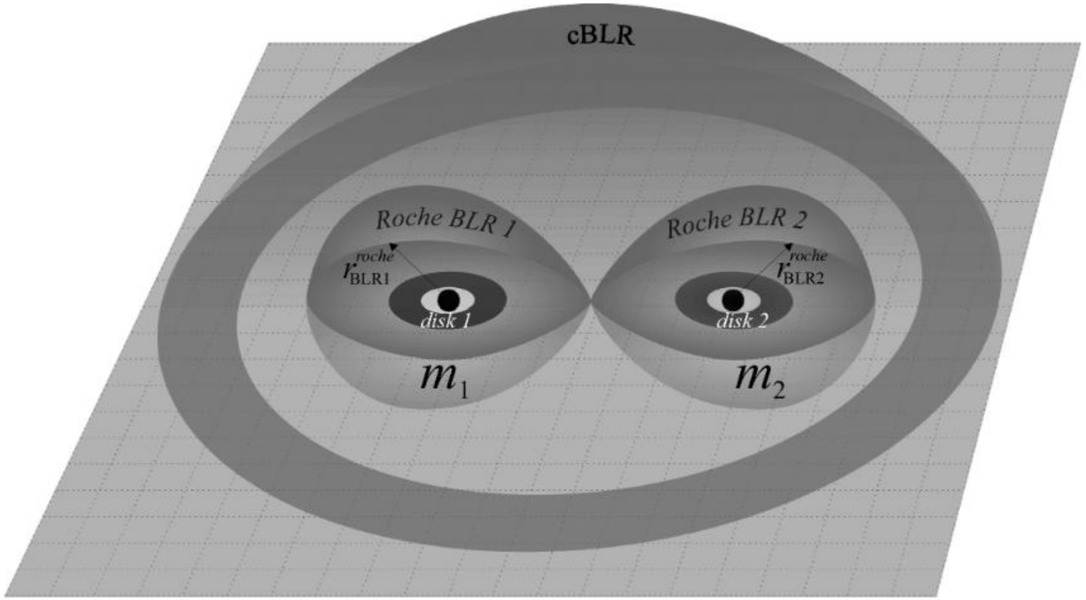
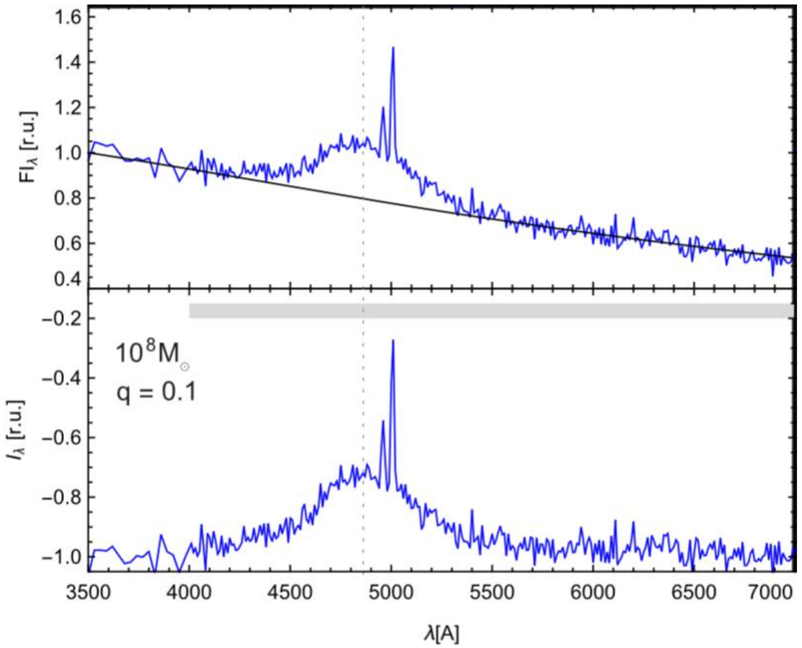
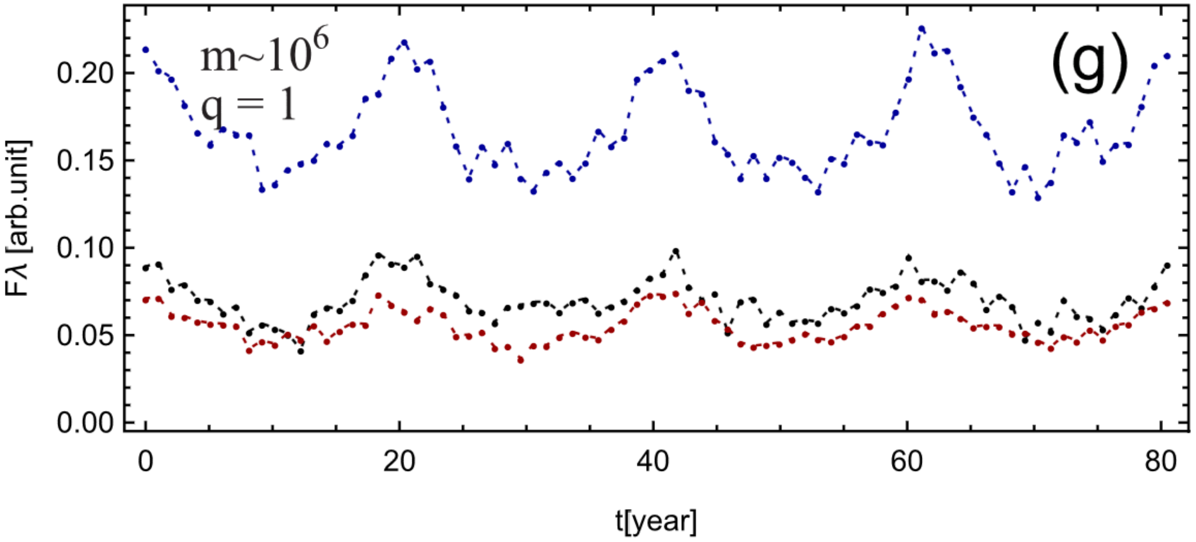
[1]Astronomical Observatory, Volgina 7, 11000 Belgrade, Serbia
[2]Department of Astronomy, Faculty of Mathematics, University of Belgrade, Studentski trg 16, 11000 Belgrade, Serbia
[3]Faculty of Science, University of Kragujevac, Radoja Domanovića 12, 34000 Kragujevac, Serbia
[4]Humboldt Research Fellow, Hamburger Sternwarte, Universität Hamburg, Gojenbergsweg 112, D-21029 Hamburg, Germany







Close binaries of SMBHs

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

Royal Astronomical Society

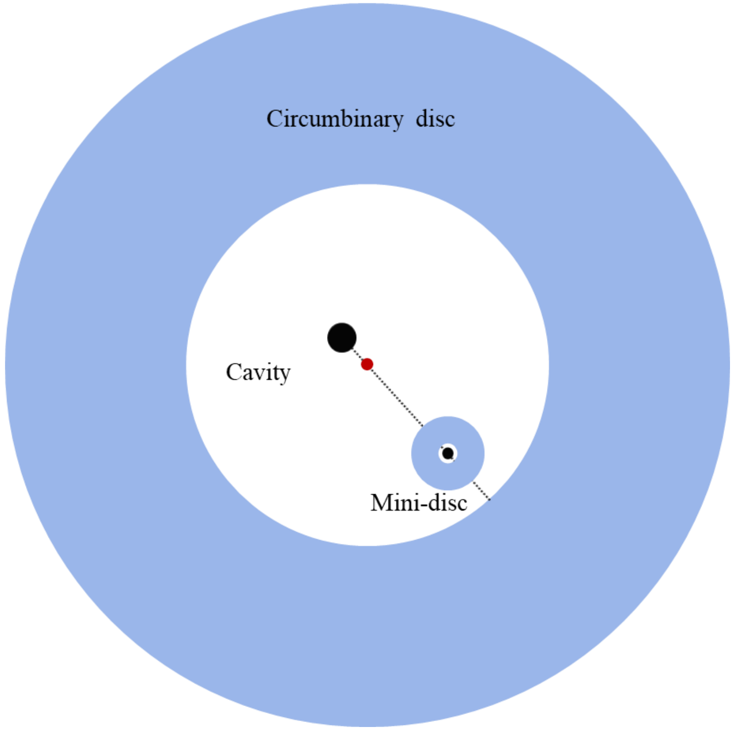
MNRAS **543,** 2093–2115 (2025)

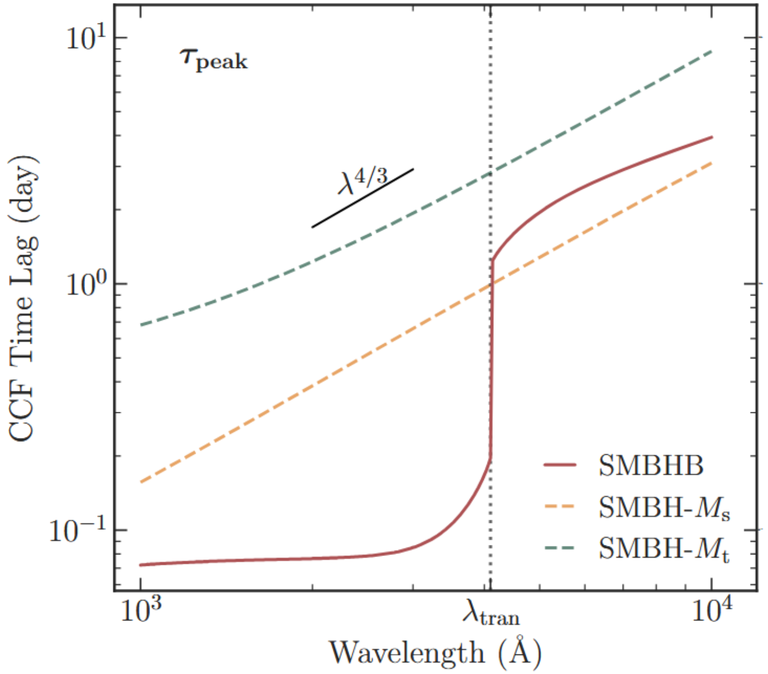
https://doi.org/10.1093/mnras/staf1473

Advance Access publication 2025 September 04

Continuum reverberation mapping of accretion discs surrounding supermassive black hole binaries: observational signatures

Yi-Xin Fu[1,2] Yan-Rong Li[1★] Jian-Min Wang[1,3,4★] Keith Horne[5] Juan V. Hernández Santisteban[5] Roberta Vieliute[5] Rick Edelson[6] Tingting Liu[7] Michael S. Brotherton[8] Luka Č. Popović[9,10] Andjelka B. Kovačević[9] and Shuo Zhai[4]





A&A 677, L10 (2023)
https://doi.org/10.1051/0004-6361/202347416

Astronomy & Astrophysics

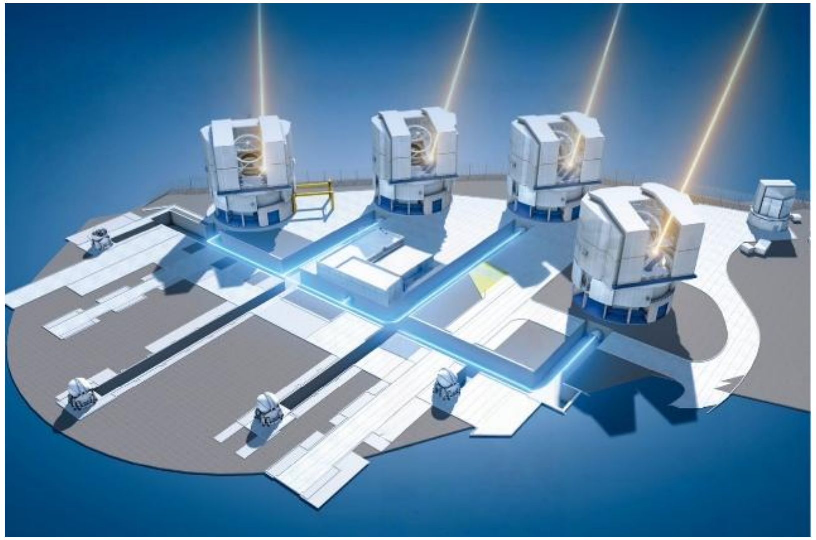
Letter to the Editor

Polarimetry and astrometry of NIR flares as event horizon scale, dynamical probes for the mass of Sgr A*★

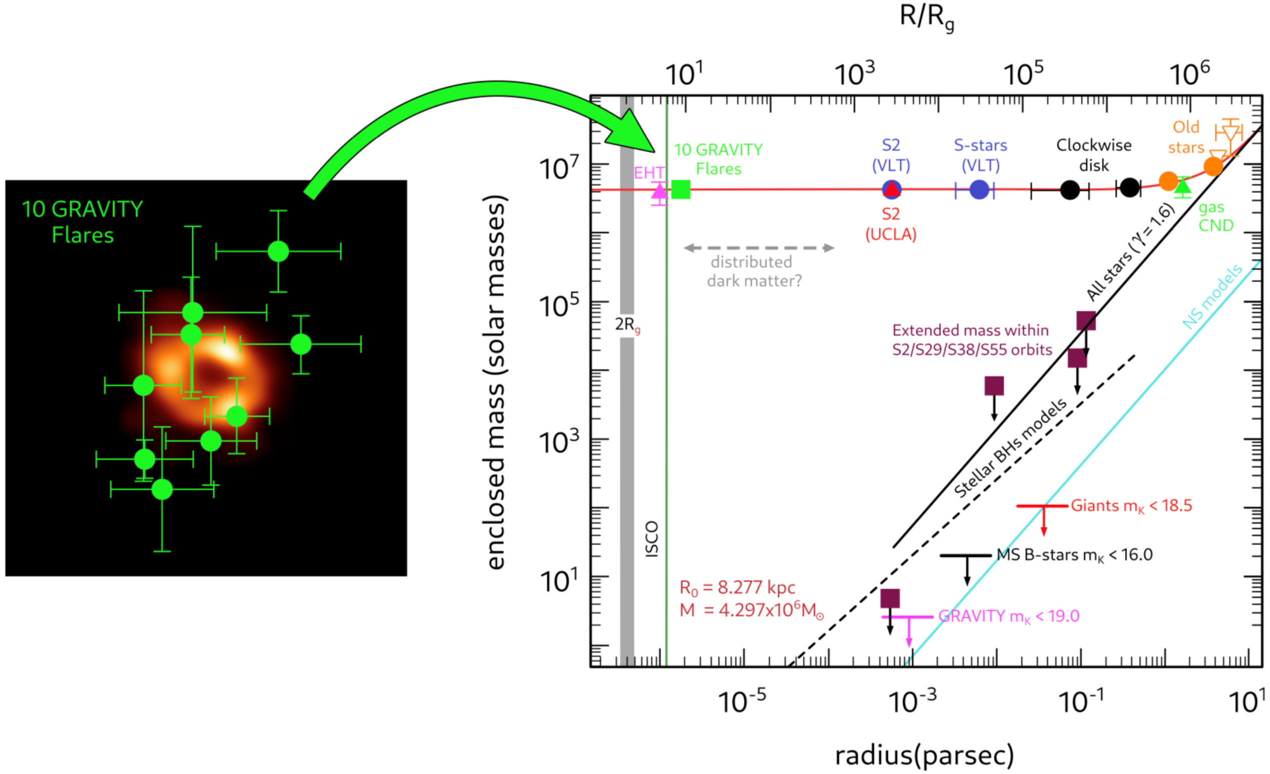
GRAVITY Collaboration: R. Abuter[4], N. Aimar[2,★★], P. Amaro Seoane[18,1,25,19], A. Amorim[8,7], M. Bauböck[16], J. P. Berger[3,4], H. Bonnet[4], G. Bourdarot[1], W. Brandner[5], V. Cardoso[7,21], Y. Clénet[2], R. Davies[1], P. T. de Zeeuw[24], J. Dexter[11], A. Drescher[1,★★], A. Eckart[6,17], F. Eisenhauer[1,23], H. Feuchtgruber[1], G. Finger[1], N. M. Förster Schreiber[1], A. Foschi[7,10], P. Garcia[12,7], F. Gao[13,1], Z. Gelles[26], E. Gendron[2], R. Genzel[1,14], S. Gillessen[1], M. Hartl[1], X. Haubois[9], F. Haussmann[1], G. Heißel[20,2], T. Henning[5], S. Hippler[5], M. Horrobin[6], L. Jochum[9], L. Jocou[3], A. Kaufer[9], P. Kervella[2], S. Lacour[2], V. Lapeyrère[2], J.-B. Le Bouquin[3], P. Léna[2], D. Lutz[1], F. Mang[1], N. More[1], T. Ott[1], T. Paumard[2], K. Perraut[3], G. Perrin[2], O. Pfuhl[4,1], S. Rabien[1], D. C. Ribeiro[1,★★], M. Sadun Bordoni[1], S. Scheithauer[5], J. Shangguan[1], T. Shimizu[1], J. Stadler[15,1], O. Straub[1,22], C. Straubmeier[6], E. Sturm[1], L. J. Tacconi[1], F. Vincent[2], S. von Fellenberg[17,1], F. Widmann[1], M. Wielgus[17], E. Wieprecht[1], E. Wiezorrek[1], and J. Woillez[4]

(Affiliations can be found after the references)

Received 10 July 2023 / Accepted 2 August 2023



Parameter	Posterior mean
Radius	$R = 8.9^{+1.5}_{-1.3} R_g$
Inclination	$i = 154.9^{+4.6°}_{-4.6°}$
Position angle	$\Omega = 177.3^{+24°}_{-23°}$
Enclosed mass	$M_{enc} = 4.2^{+1.2}_{-0.9} \times 10^6 M_\odot$

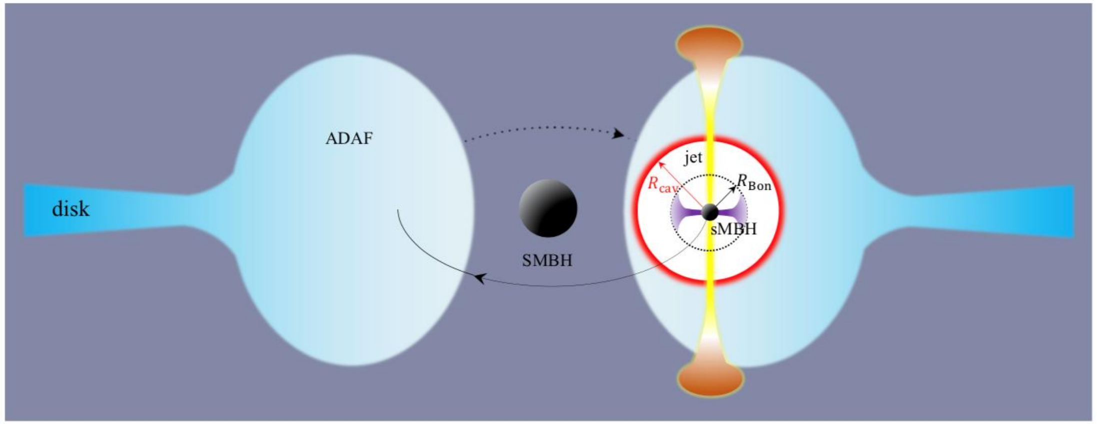


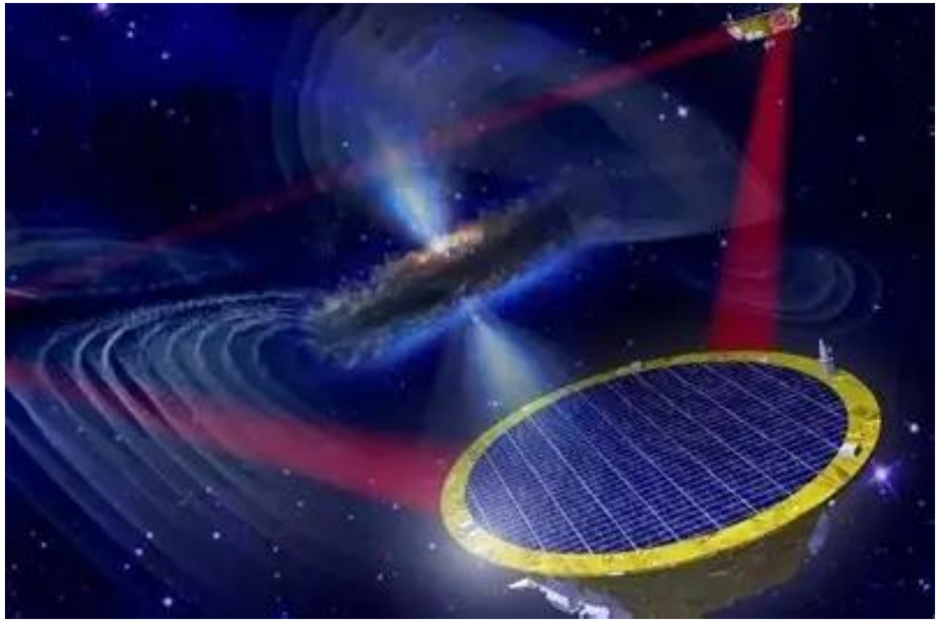
可以证明银心吸积盘光变：

磁重联产生的耀斑不可能半径位置固定，

因此，卫星黑洞存在解释耀斑

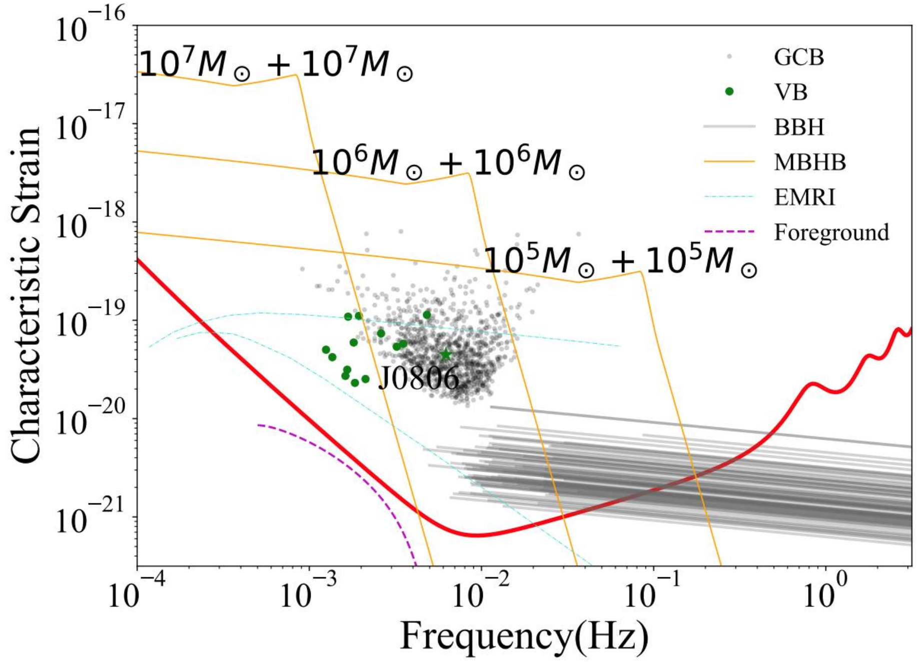
LISA：Sgy A*





$$h_s = \left(\frac{128}{15}\right)^{1/2} \frac{(GM_c)^{5/3}}{c^4 d_L} (\pi f)^{2/3}$$
$$= 7.6 \times 10^{-17} d_{10\,\mathrm{kpc}}^{-1} a_1^{-1} q_{\bar{5}} \left(\frac{M_6}{4}\right),$$

$$f = \frac{2}{P_{\mathrm{orb}}} = 0.5(1+q)^{-1/2} a_1^{-3/2} \left(\frac{M_6}{4}\right)^{-1} \mathrm{mHz},$$



Discovery of a star sensitive to the spin of Sgr A*

K. Abd El Dayem[1], R. Abuter[2], N. Aimar[3,4], P. Amaro-Seoane[5,6], A. Berdeu[2,1], J.-P. Berger[7], G. Bourdarot[6], W. Brandner[8], A. Burkert[9,6], D. Calderon[10], C. Correia[3,4], J. Cuadra[11,12], R. Davies[6], D. Defrère[13], L. Delit[1], A. Drescher[7,6], F. Eisenhauer[6,14], L. Esteras Otal[2], M. Fabricius[6], H. Feuchtgruber[6], N.M. Förster Schreiber[6], A. Foschi[1], P. Garcia[3,4], R. Garcia Lopez[15], A. Generozov[16], R. Genzel[6,17], S. Gillessen[6,†], F. Gonté[2], X. Haubois[18], S.F. Hönig[19], M. Houllé[7], S. Joharle[6], A. Kaufer[18], J. Kammerer[2], P. Kervella[1,20], J. Kolb[2], L. Kreidberg[8], L. Labadie[21], S. Lacour[1], O. Lai[22], R. Laugier[13], J.-B. Le Bouquin[7], J. Leftley[18,19], B. Lopez[22], D. Lutz[6], F. Mang[6,14,†], A. Mérand[2], F. Millour[22], M. Montargès[1], N. Morujão[3,4], H. Nowacki[22], M. Nowak[1], S. Oberti[2], J. Osorno[1,†], T. Ott[6], T. Paumard[1], C. Paladini[18], H.B. Perets[23], K. Perraut[7], G. Perrin[1], R. Petrov[22], P.O. Petrucci[7], T. Piran[24], N. Pourré[7], S. Rabien[6], D.C. Ribeiro[6], S. Robbe-Dubois[22], M. Sadun Bordoni[6], J. Sánchez Bermúdez[25], D. Santos[6], R. Sari[24], J. Sauter[8], S. Scheithauer[8], J. Scigliuto[22], J. Shangguan[6], T.T. Shimizu[6], F. Soulez[26], J. Stadler[9], C. Straubmeier[21], E. Sturm[6], M. Subroweit[21], C. Sykes[19], L.J. Tacconi[6], P. Thévenet[1], I. Urso[1], F. Vincent[1], J. Woillez[2], G. Zins[18]

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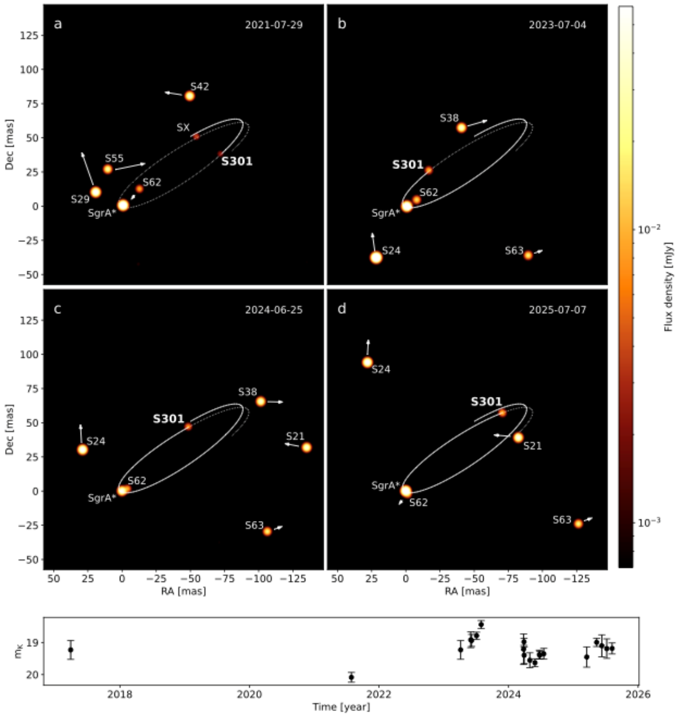
[2] *European Southern Observatory, Karl-Schwarzschild-Straße 2, 85748 Garching, Germany*

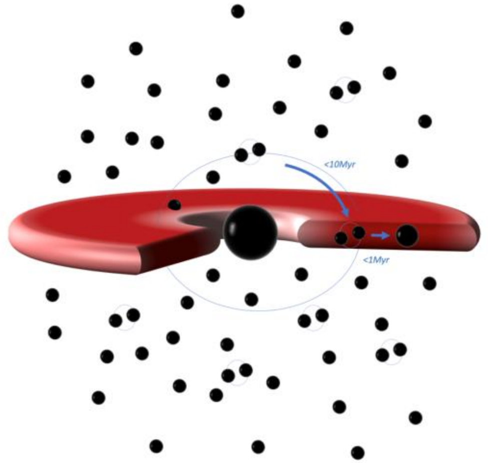
[3] *Faculdade de Engenharia, Universidade do Porto, rua Dr. Roberto Frias, 4200-465 Porto, Portugal*

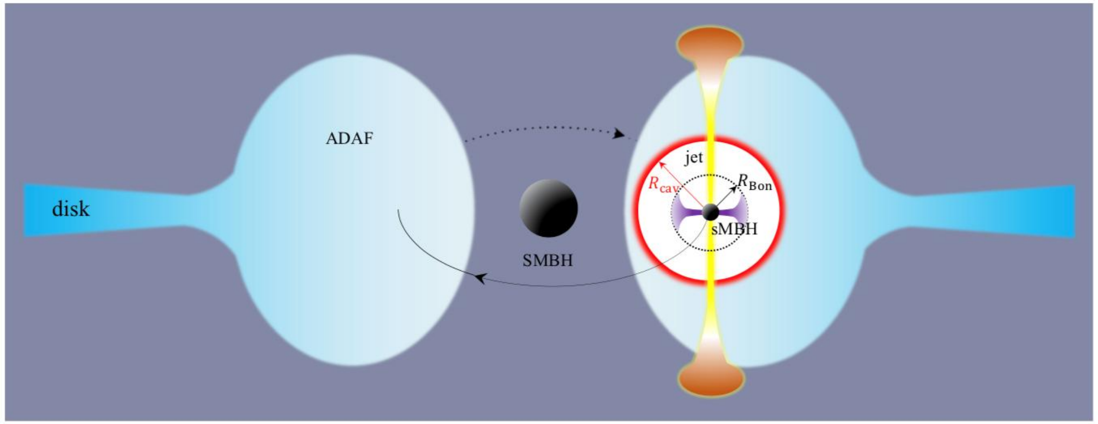
[4] *CENTRA - Centro de Astrofísica e Gravitação, IST, Universidade de Lisboa, 1049-001 Lisboa, Portugal*

1

A new star: $1000R_s \rightarrow 140R_s$





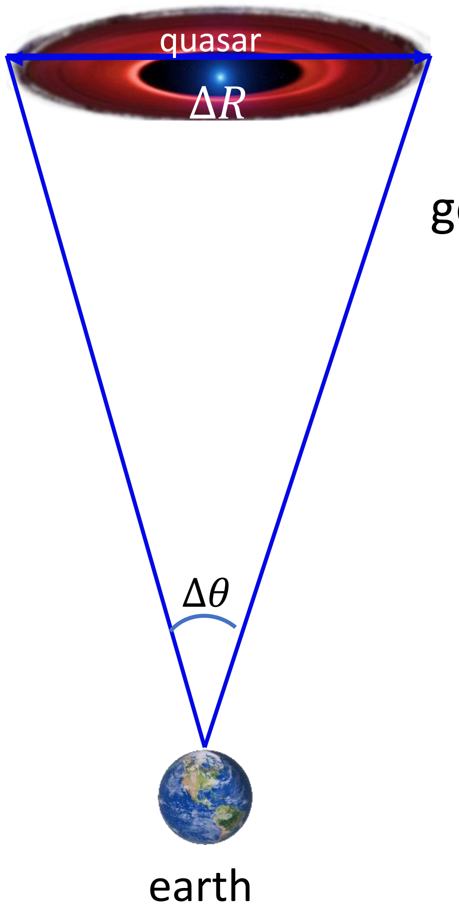


SARM: Spectroastrometry + Reverberation Mapping

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]

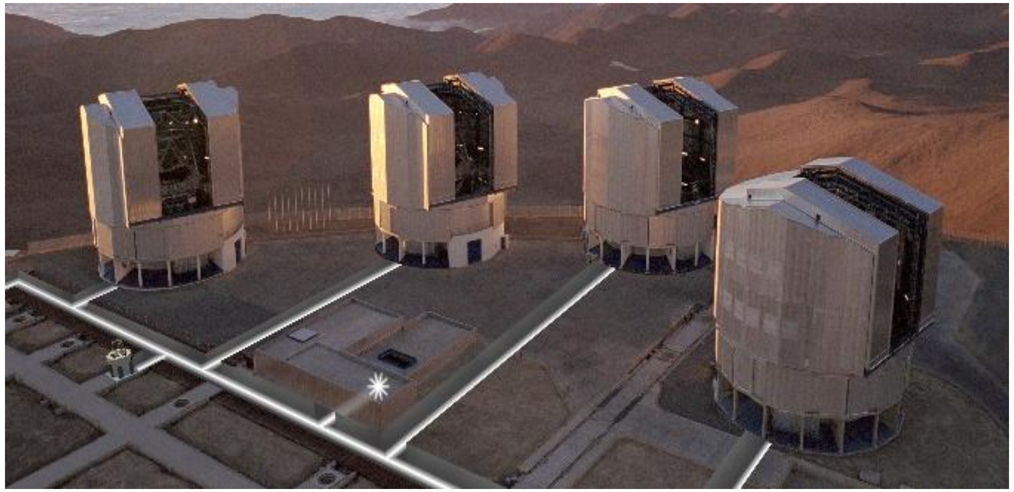


geometric distance:

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

Reverberation Mapping

Spectroastrometry with interferometry



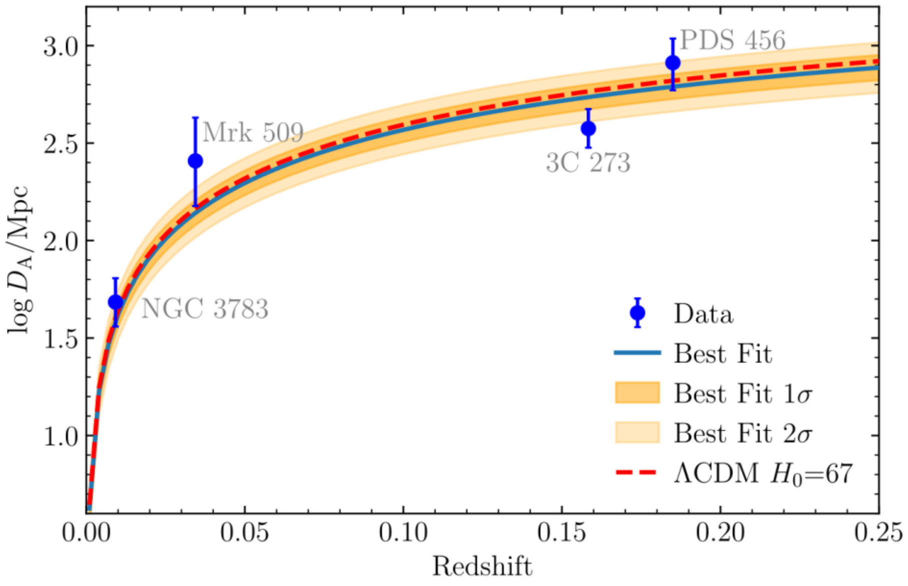
Latest progress: four quasars

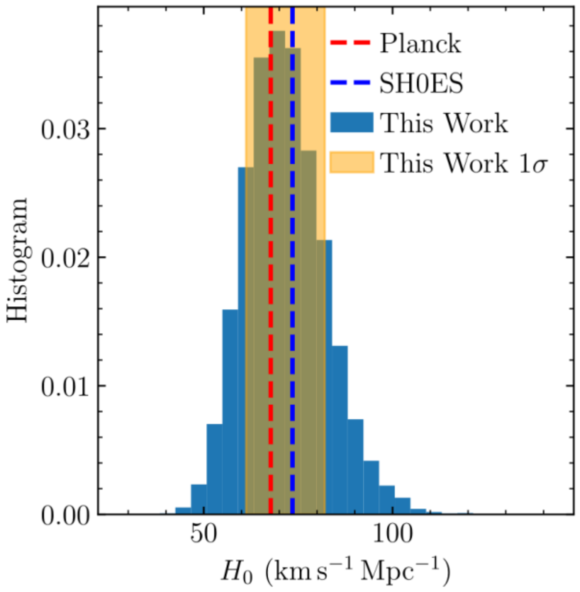
$H_0 = 69^{+12}_{-10}$ km s^{-1} Mpc^{-1} Precision: 15%

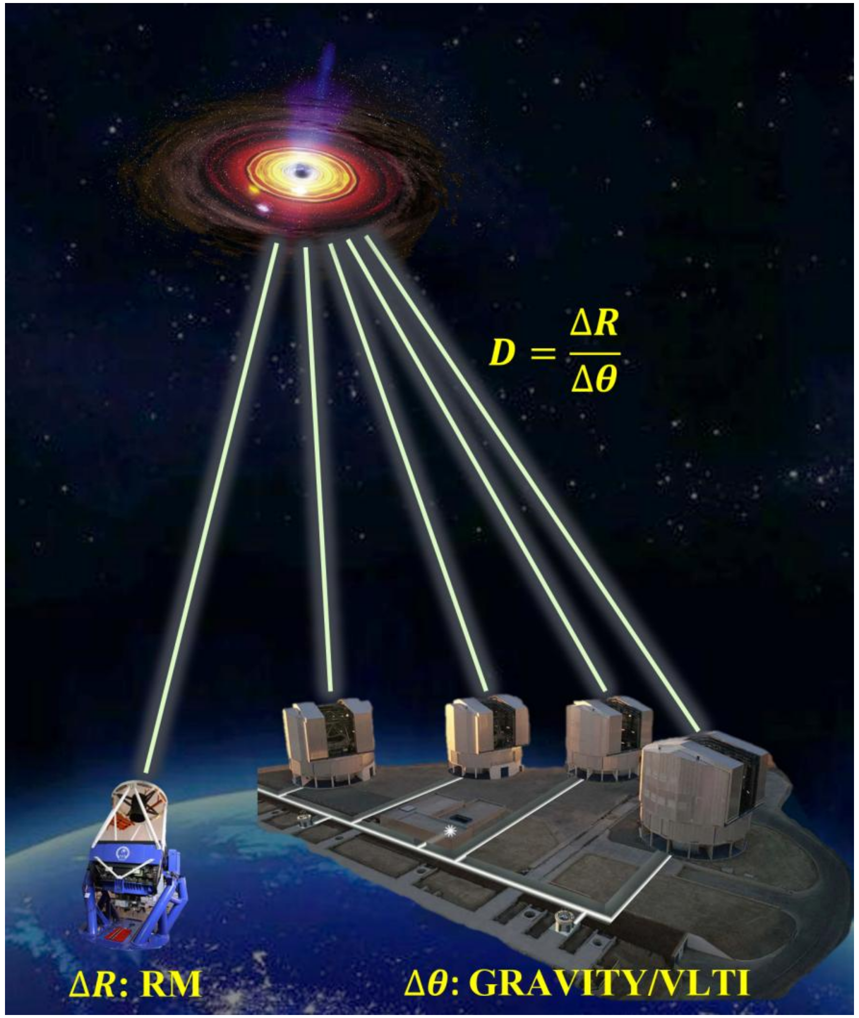
THE ASTROPHYSICAL JOURNAL, 988:42 (19pp), 2025 July 20 https://doi.org/10.3847/1538-4357/addf40

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

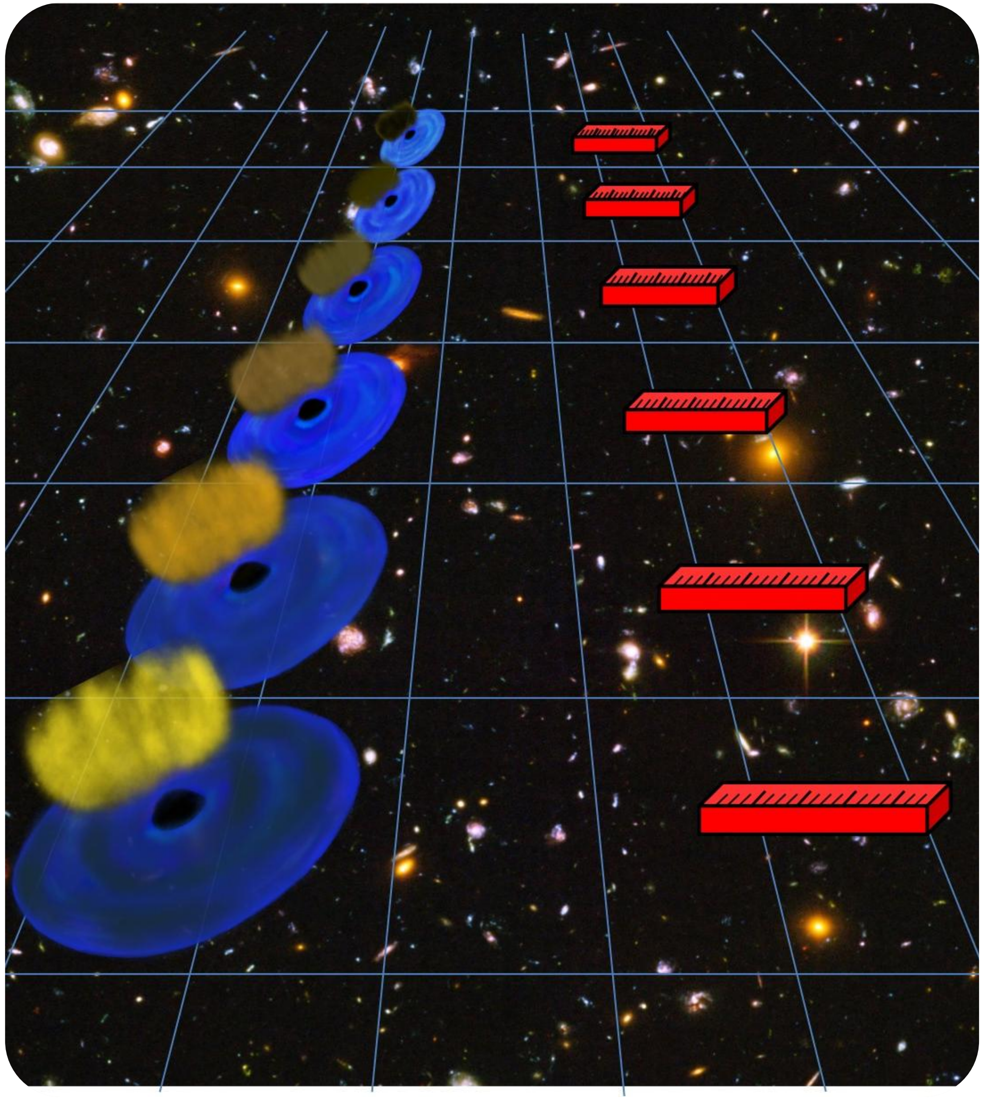
Yan-Rong Li[1], Jinyi Shangguan[2,3], Jian-Min Wang[1,4,5], Ric Davies[3], Daryl J. D. Santos[3], Frank Eisenhauer[3], Yu-Yang Songsheng[1], Hartmut Winkler[6], Jesús Aceituno[7,8], Hua-Rui Bai[1,9], Jin-Ming Bai[10], Michael S. Brotherton[11], Yixian Cao[3], Yong-Jie Chen[1,12], Pu Du[1], Feng-Na Fang[1,9],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







Quasar as a geometric probe for cosmology



New Astronomy 128 (2026) 102592

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New Astronomy

journal homepage: www.elsevier.com/locate/newast

ELSEVIER

Precision near-IR spectroscopy for understanding AGN physics and shed light on the H_0 tension☆

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[f] INAF – Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, I-35122, Padova, Italy
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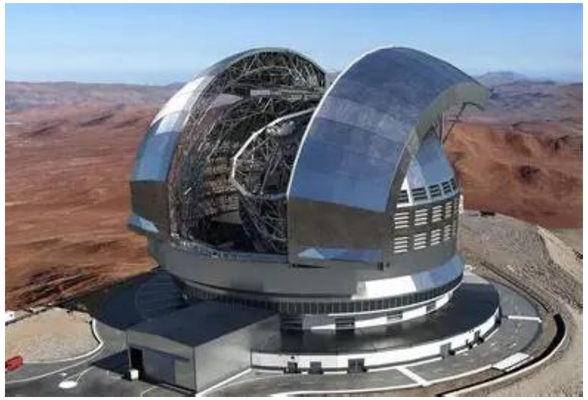
ARTICLE INFO

Keywords:
Cosmology
Cosmological tensions
Cosmological distances
AGN
Broad Line Region: Reverberation Mapping

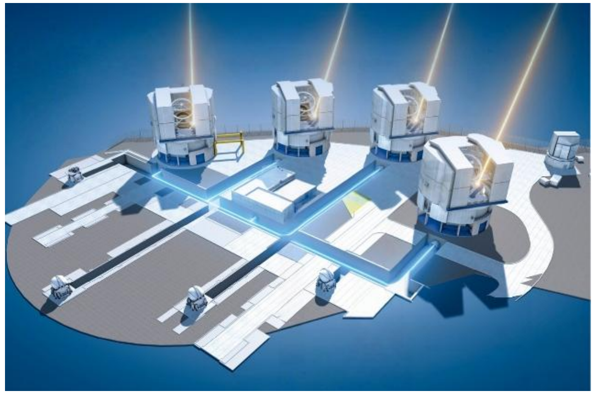
ABSTRACT

The persistent tension between early- and late-Universe measurements of the Hubble constant (H_0) remains one of the most significant challenges in modern cosmology. The Spectroastrometry and Reverberation Mapping (SARM) method offers a promising, calibration-independent approach to address this issue by combining time-delay measurements of the Broad-Line Region (BLR) with interferometric angular size determinations. Current implementations of SARM, however, are limited by the difficulty of performing near-infrared reverberation mapping (RM) on the same emission lines observed by GRAVITY, restricting applications to only a few bright AGN. We propose using the capabilities of SHARP, the next-generation near-infrared spectrograph for the Extremely Large Telescope (ELT), to overcome these limitations. SHARP's sensitivity and multi-object spectroscopy will enable (1) efficient long-term monitoring of existing GRAVITY targets with minimal time investment, and (2) systematic RM campaigns for the fainter AGN that will be observed by GRAVITY+. These advances will give us precise infrared lags for tens of AGN, enabling geometric distance measurements and a robust, calibration-free determination of H_0. Beyond cosmology, SHARP will allow detailed studies of BLR structure and kinematics in the infrared, advancing our understanding of AGN physics and with repercussions on the measurements of Supermassive Black Holes (SMBH) masses.

ELT: SHARP RM



GRAVITY+: angular size



Telescopes and observations: for AGN

- Optical/IR telescope
  - ➢GRAVITY+/VLTI
  - ➢JWST
  - ➢Roman
  - ➢Rubin Telescope
  - ➢Extremely Large Telescope (ELT)
- Gravitational Waves
  - ➢LIGO
  - ➢PTA (E-PTA, Nano-Grav, CPTA)
  - ➢Einstein Telescope
  - ➢LISA

Questions:

- ●How to measure SMBH masses?
- ●Spatial structure of AGNs? $D_{\rm QSO}$? H_0?
- ●Variability? Lensed QSOs: H_0?
- ●Close binaries of SMBHs? and GWs
- ●Accretion-modified stars and GWs
- ●Polarizations: BLR kinetics
- ➢How to form the structure?
- ➢How to form SMBHs? Metallicity?
- ➢What is nature of the LRDs?

Six questions the field carries forward

01
Accretion
Which disk assumptions are physically necessary, and which are inherited convenience? Disks look larger and lag longer than standard theory predicts.

02
BLR
Geometry, ionisation and time delays are entangled. Line shape and variability are still fitted as separate problems instead of jointly.

03
Binary SMBH/GWs
No single signature is sufficient. What combination of observables makes a sub-parsec binary claim robust enough to publish?

04
Jets and coronae
Where — and how — are particles accelerated? SED fitting alone still admits both leptonic and hadronic scenarios.

05
Gravitational lensing
How compact are the emitting regions, and how clumpy is the dark matter? The two are usually inferred separately from the same data.

06
Data and Astrostatistics
The bottleneck has moved from detection to trustworthy inference.

Propagets uncertainty from sparse data to a physical claim?

Each question was raised by more than one speaker — which is why they are the ones that survive the meeting.

Future: connect scales, messengers and methods

01
Joint inference
Fit spectra, lags, polarisation and lensing constraints inside shared physical models.

02
Long baselines
Prioritise cadence and duration together; confirm persistence of signals and reject false positives

03
Fast follow-up
Link Rubin alerts to spectroscopy, polarimetry, ALMA, X-ray and neutrino facilities.

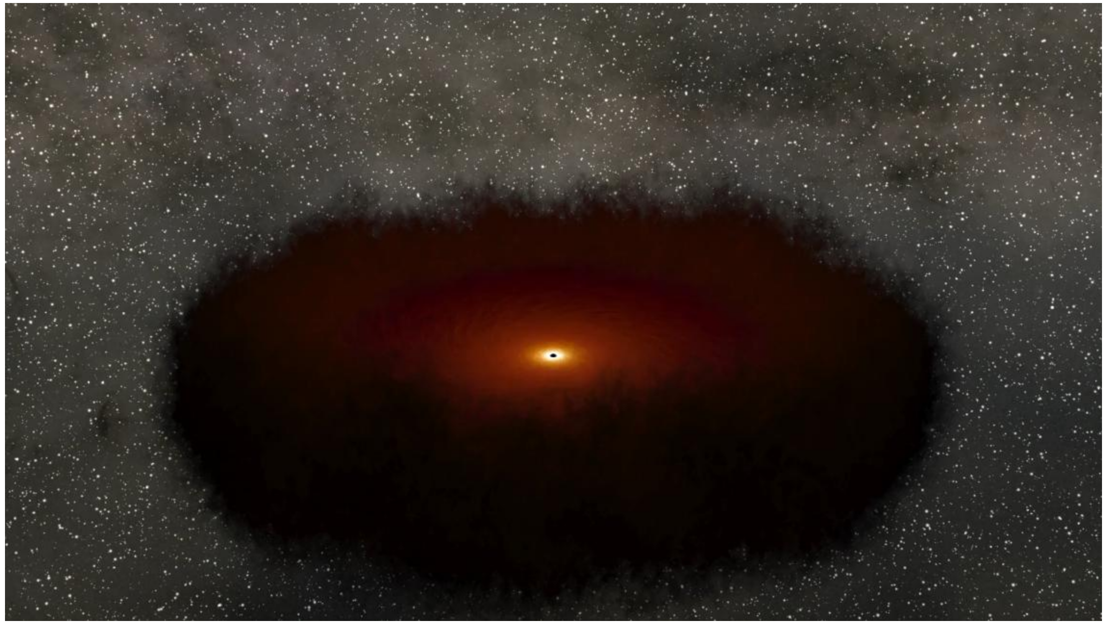
04
Calibrated AI
Train on realistic simulations; report coverage, degeneracy and out-of-distribution failure.

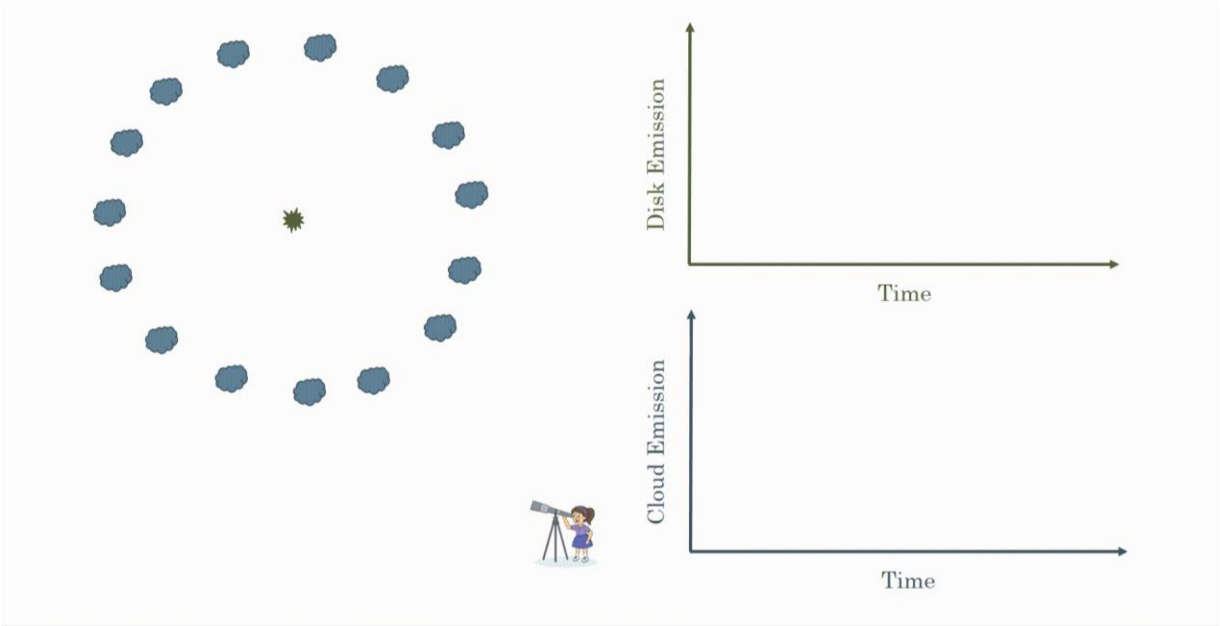
05
Open infrastructure
Interoperable databases, reproducible benchmarks and shared candidate ledgers.

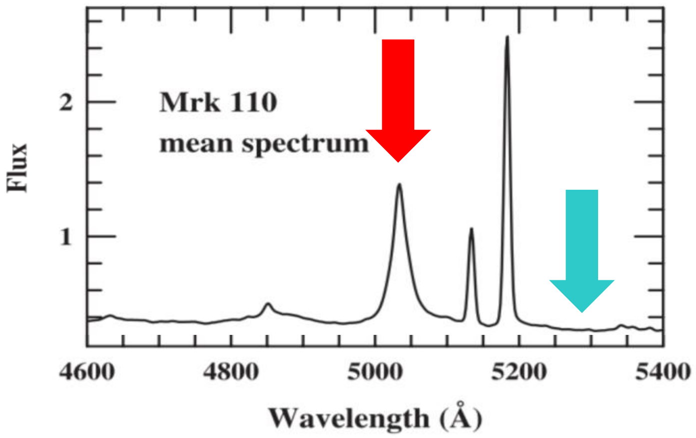
06
Cross-scale laboratories
Use other accreting systems to test microphysics on accessible timescales.

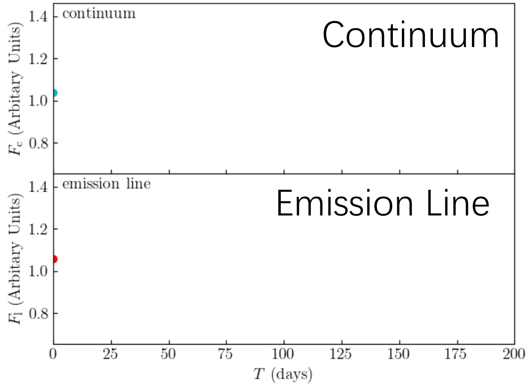
The future is not one new instrument. It is coordinated evidence of multimessenger data cubes.

Reverberation mapping









THE ASTROPHYSICAL JOURNAL, 521:L95–L98, 1999 August 20

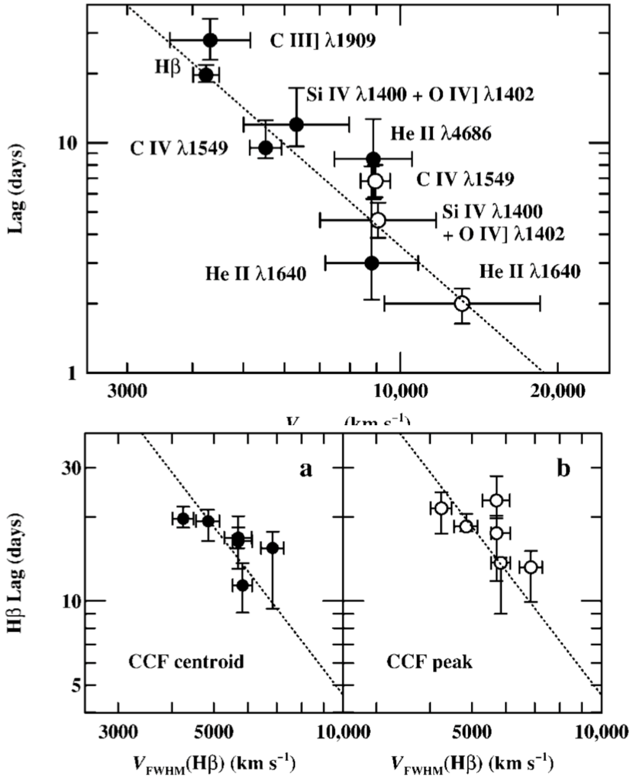
THE ASTROPHYSICAL JOURNAL, 540:L13–L16, 2000 September 1

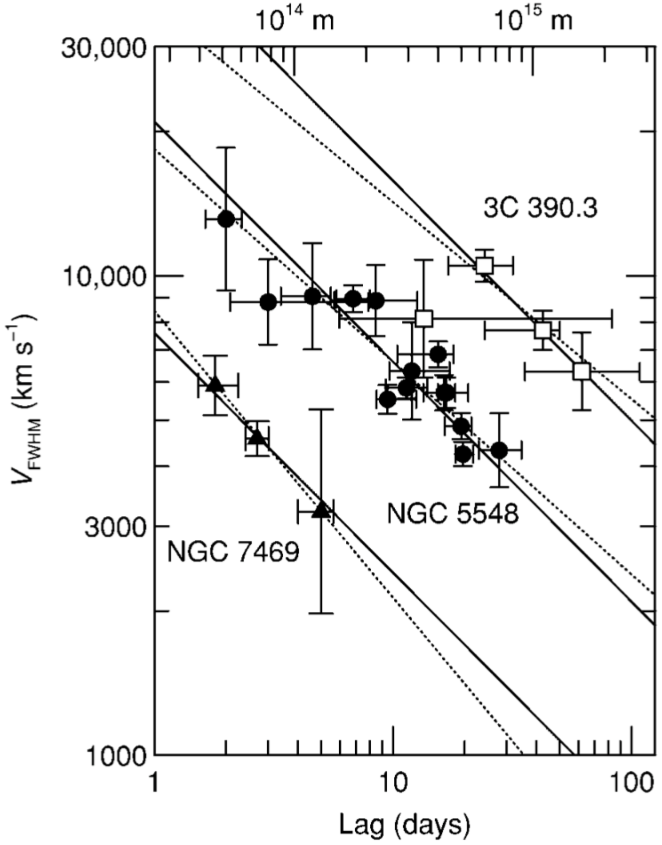
KEPLERIAN MOTION OF BROAD-LINE REGION GAS AS EVIDENCE FOR SUPERMASSIVE BLACK HOLES IN ACTIVE GALACTIC NUCLEI

BRADLEY M. PETERSON[1] AND AMRI WANDEL[2,3]
Received 1999 February 3; accepted 1999 June 3; published 1999 July 21

EVIDENCE FOR SUPERMASSIVE BLACK HOLES IN ACTIVE GALACTIC NUCLEI FROM EMISSION-LINE REVERBERATION

BRADLEY M. PETERSON[1] AND AMRI WANDEL[2]
Received 2000 May 3; accepted 2000 July 11; published 2000 August 23





$$R_{\rm BLR} = c \times \tau = \alpha \left(\frac{\lambda L_\lambda}{10^{44} {\rm erg\ s^{-1}}} \right)^{\beta}$$

+

$$M_\bullet = f \frac{c\tau \times V^2}{G}$$

- Virial BH mass estimator:

$$M_{\rm BH} = \alpha \left(\frac{\Delta V}{1000\ {\rm km\ s^{-1}}} \right)^2 \left(\frac{\lambda L_\lambda}{10^{44}\ {\rm erg\ s^{-1}}} \right)$$

A&A 388, 771–786 (2002)
DOI: 10.1051/0004-6361:20020550

Astronomy & Astrophysics

Are quasars accreting at super-Eddington rates?

S. Collin[1], C. Boisson[1], M. Mouchet[1,2], A.-M. Dumont[1],
S. Coupé[1], D. Porquet[3], and E. Rokaki[4]

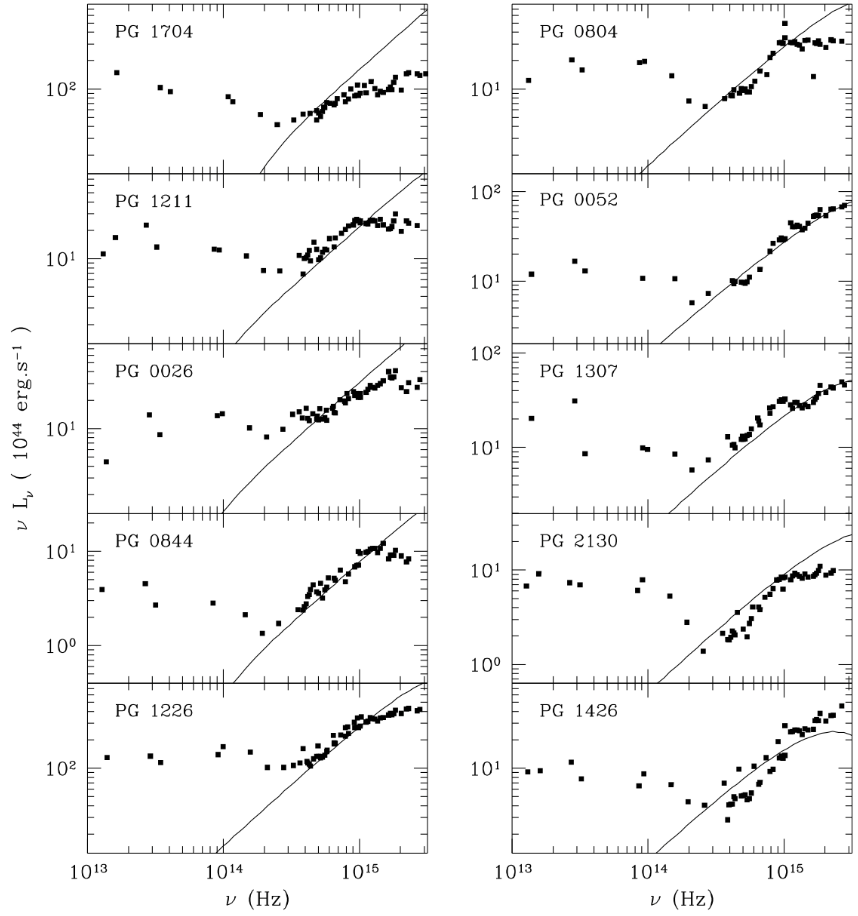


Table 1. Observed properties of the PG quasars from the Kaspi et al. sample, and Eddington ratios.

name	z	M7(mean)	L5100)(1)	V(2)	L(2-10keV)(3)	L(.5-4.5keV)(4)	$\dot{M}/\dot{M}_{Edd}$(5
PG 0026+129	0.142	5.40e+00	1.58e+01	1.58	6.20e+00**	7.60e+00	3.96e+00
PG 0052+251	0.155	2.20e+01	1.46e+01	2.93	1.02e+01**	9.50e+00	2.42e-01
PG 0804+761	0.100	1.89e+01	1.49e+01	2.51	1.70e+01*,**	5.80e+00	3.29e-01
PG 0844+349	0.064	2.16e+00	3.87e+00	2.16	4.40e-01*		2.99e+00
PG 0953+414	0.239	1.84e+01	2.68e+01	2.52	7.10e+00*		8.13e-01
PG 1211+143	0.085	4.05e+00	1.11e+01	1.45	9.10e-01*	1.18e+01	4.12e+00
PG 1226+023	0.158	5.50e+01	1.45e+02	2.72	1.12e+02**	1.17e+02	1.17e+00
PG 1229+204	0.064	7.50e+00	2.12e+00	2.80	4.50e+00**	1.45e+00	1.13e-01
PG 1307+085	0.155	2.80e+01	1.19e+01	3.43	7.10e+00**	7.70e+00	1.15e-01
PG 1351+640	0.087	4.60e+00	9.86e+00	1.03		0.99e-01	2.71e+00
PG 1411+442	0.089	8.00e+00	7.31e+00	2.02	7.60e-01*		6.03e-01
PG 1426+015	0.086	4.70e+01	9.20e+00	5.08	1.70e+00**	6.65e+00	3.17e-02
PG 1613+658	0.129	2.41e+01	1.57e+01	5.68	4.90e+00**	3.35e+00	2.25e-01
PG 1617+175	0.114	2.73e+01	5.33e+00	4.09		1.70e+00	3.91e-02
PG 1700+518	0.292	6.00e+00	6.10e+01	1.89	< 3.20e-01*		2.37e+01
PG 1704+608	0.371	3.70e+00	8.01e+01	0.78		9.20e+00	9.27e+01
PG 2130+099	0.061	1.44e+01	4.86e+00	1.94	7.90e-01**	1.80e+00	1.10e-01

(1): isotropic luminosity, in 10^{44} ergs s^{-1}, for Ho=50 km s^{-1} Mpc^{-1}, qo=0.5

(2): velocity $\sqrt{GM/R(BLR)}$ in 1000 km s^{-1}

(3): isotropic luminosity, in 10^{44} ergs s^{-1}, for Ho=50 km s^{-1} Mpc^{-1}, qo=0.5, * from George et al. 2000, ** from Lawson & Turner 1987

(4): isotropic luminosity, in 10^{44} ergs s^{-1}, for Ho=50 km s^{-1} Mpc^{-1}, qo=0.5, from Tananbaum et al. 1986

(5): for a Kerr BH, this ratio must be multiplied by 5.6

THE ASTROPHYSICAL JOURNAL, 764:45 (25pp), 2013 February 10 doi:10.1088/0004-637X/764/1/45

THE DEMOGRAPHICS OF BROAD-LINE QUASARS IN THE MASS–LUMINOSITY PLANE. II. BLACK HOLE MASS AND EDDINGTON RATIO FUNCTIONS

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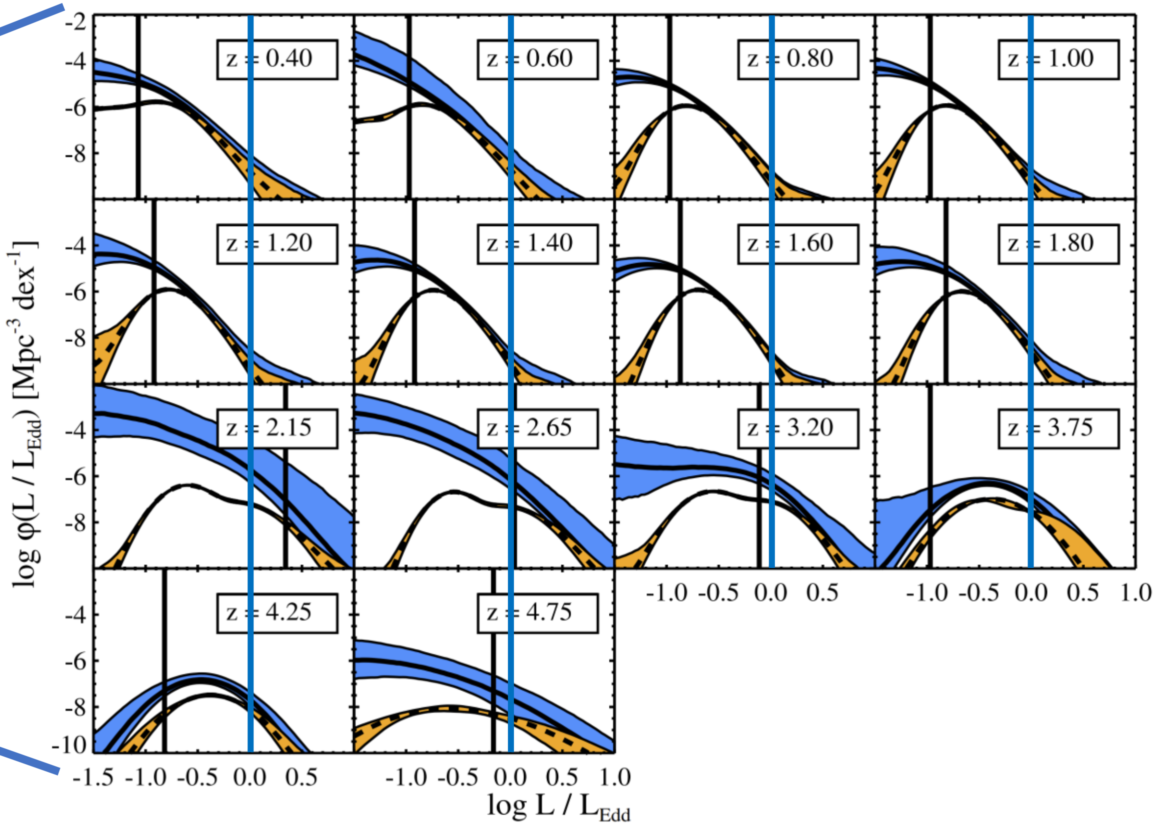
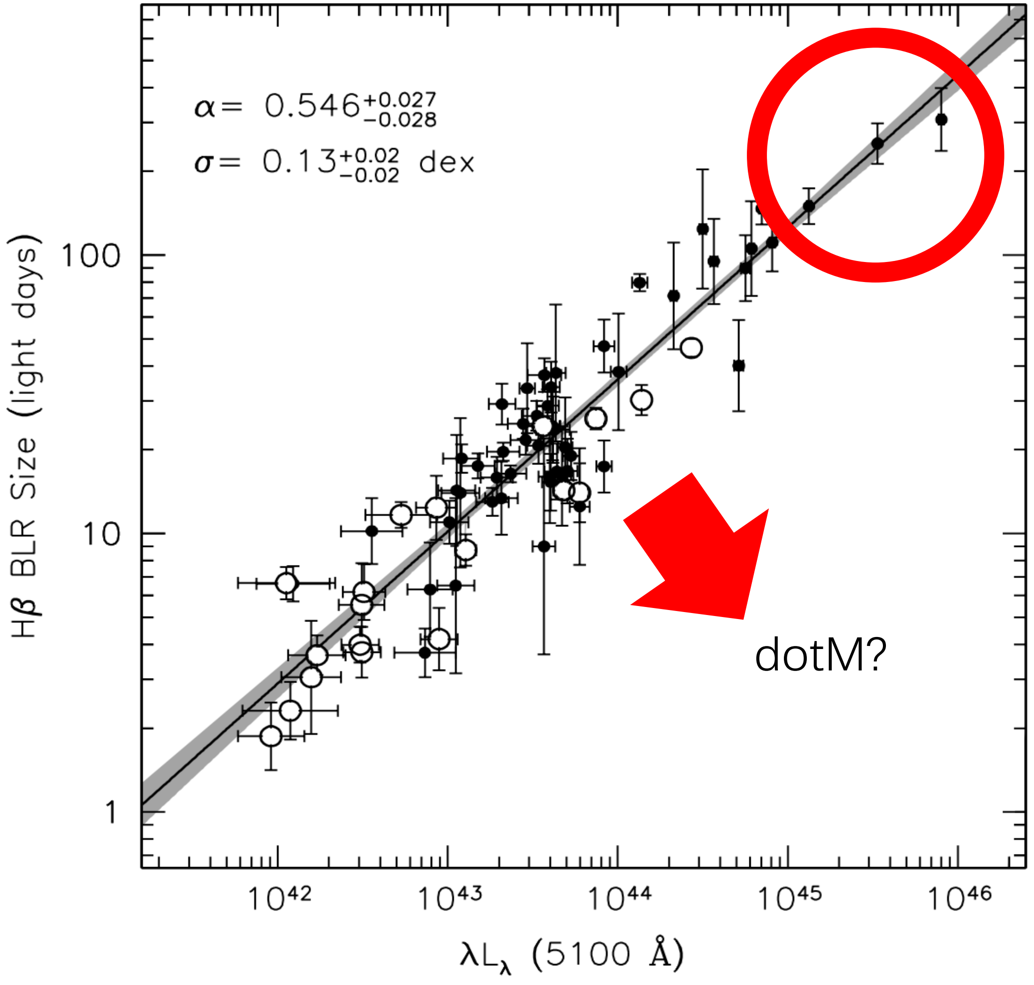
Super-Eddington AGNs??



BLR size: *L*-driven? Others?

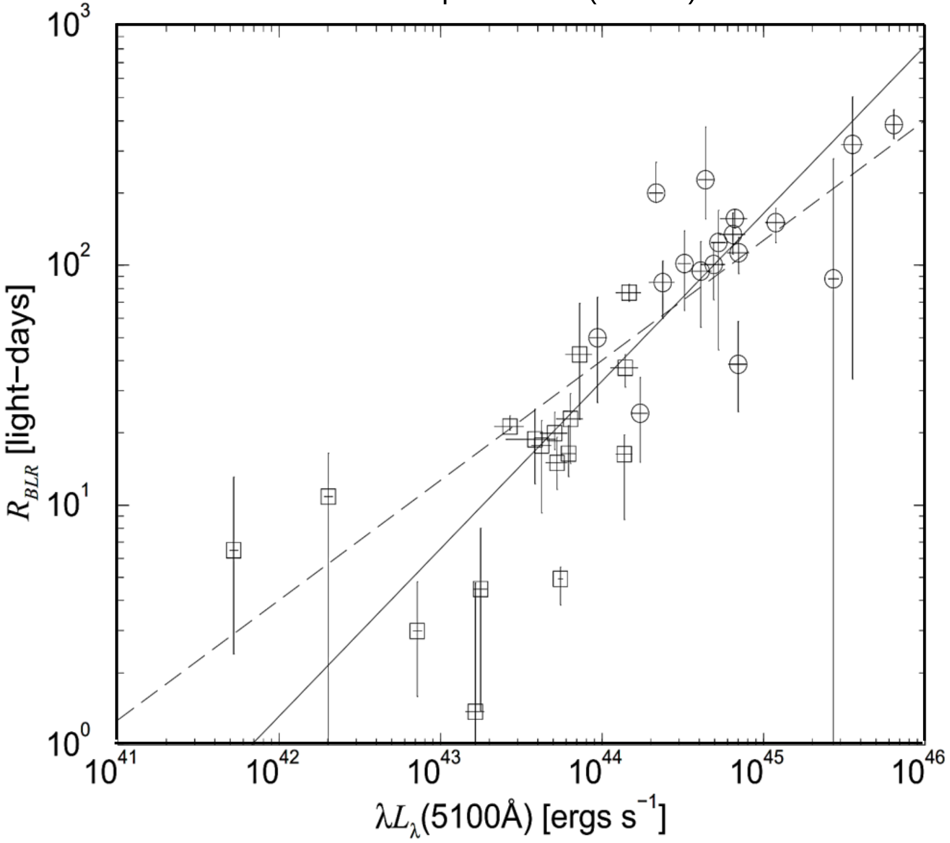


Bentz et al. 2013

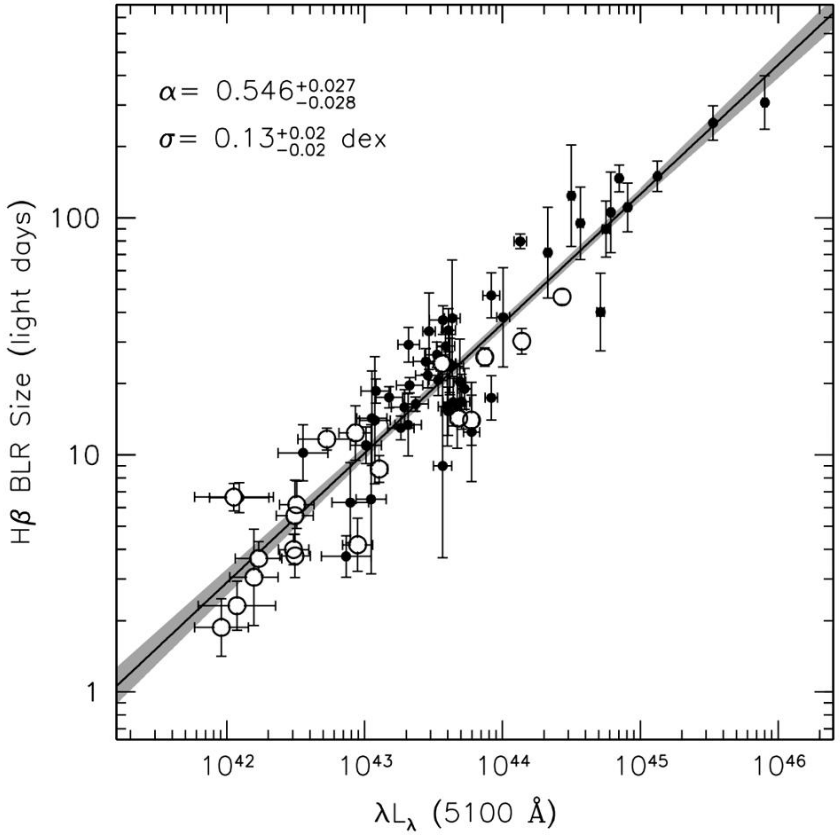
- Lack of luminous quasars
- Dependence of BLR on dotM?

R-*L* relation: BLR structure of sub-Eddington AGNs

Kaspi et al. (2000)



Bentz et al. (2013)

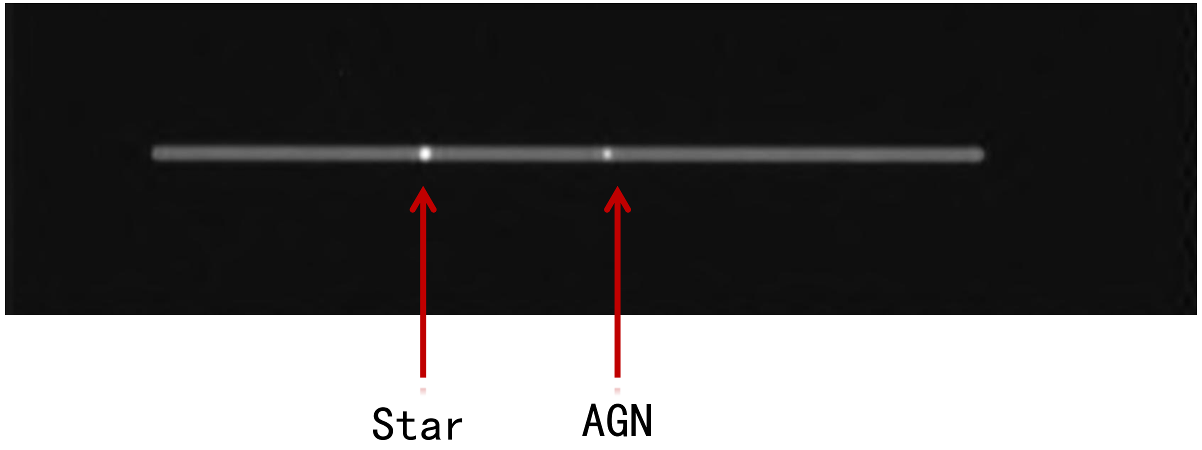


Super-Eddington Massive Black Holes (SEAMBHs)

Observation and Spectrophotometric calibration

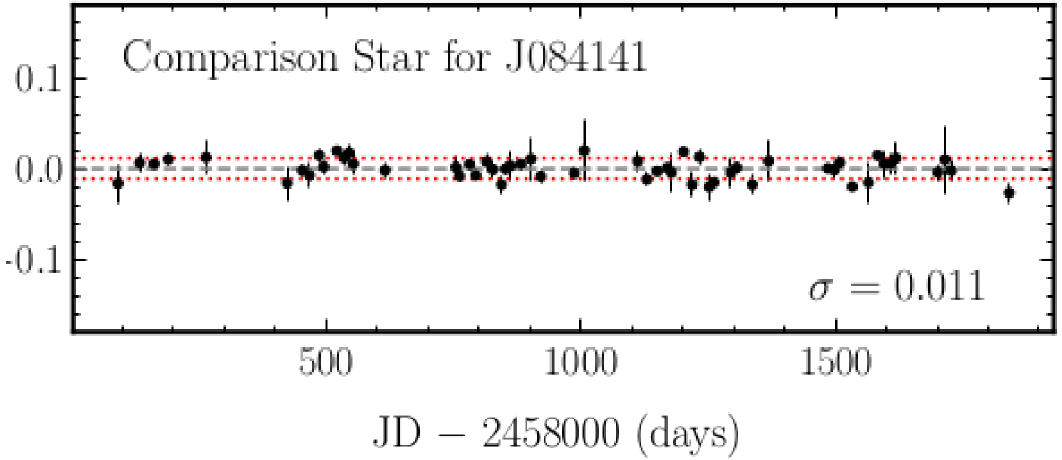
Spectroscopy：

- calibration：in-slit comparison star

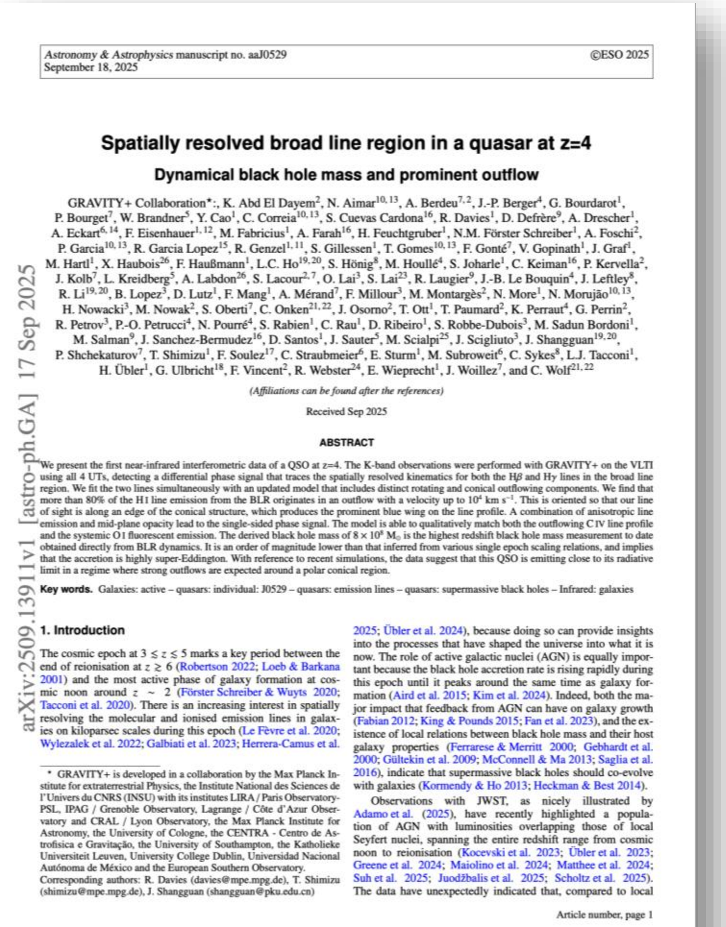


Photometry：

- Cross-check
- Ensure comparison star is not variable



GRAVITY+ interferometry



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September 18, 2025

arXiv:2509.13911v1 [astro-ph.GA] 17 Sep 2025

Spatially resolved broad line region in a quasar at z=4

Dynamical black hole mass and prominent outflow

GRAVITY+ Collaboration*:, K. Abd El Dayem[2], N. Aimar[10,13], A. Berdeu[7,2], J.-P. Berger[4], G. Bourdarot[1], P. Bourget[7], W. Brandner[5], Y. Cao[1], C. Correia[10,13], S. Cuevas Cardona[16], R. Davies[1], D. Defrère[9], A. Drescher[1], A. Eckart[6,14], F. Eisenhauer[1,12], M. Fabricius[1], A. Farah[16], H. Feuchtgruber[1], N.M. Förster Schreiber[1], A. Foschi[2], P. Garcia[10,13], R. Garcia Lopez[15], R. Genzel[1,11], S. Gillessen[1], T. Gomes[10,13], F. Gonté[7], V. Gopinath[1], J. Graf[1], M. Hartl[1], X. Haubois[26], F. Haußmann[1], L.C. Ho[19,20], S. Hönig[8], M. Houllé[4], S. Joharle[1], C. Keiman[16], P. Kervella[2], J. Kolb[7], L. Kreidberg[5], A. Labdon[26], S. Lacour[2,7], O. Lai[3], S. Lai[23], R. Laugier[9], J.-B. Le Bouquin[4], J. Leftley[8], R. Li[19,20], B. Lopez[3], D. Lutz[1], F. Mang[1], A. Mérand[7], F. Millour[3], M. Montargès[2], N. More[1], N. Morujão[10,13], H. Nowacki[3], M. Nowak[2], S. Oberti[7], C. Onken[21,22], J. Osorno[2], T. Ott[1], T. Paumard[2], K. Perraut[4], G. Perrin[2], R. Petrov[3], P.-O. Petrucci[4], N. Pourré[4], S. Rabien[1], C. Rau[1], D. Ribeiro[1], S. Robbe-Dubois[3], M. Sadun Bordoni[1], M. Salman[9], J. Sanchez-Bermudez[16], D. Santos[1], J. Sauter[5], M. Scialpi[25], J. Scigliuto[3], J. Shangguan[19,20], P. Shchekaturov[7], T. Shimizu[1], F. Soulez[17], C. Straubmeier[6], E. Sturm[1], M. Subroweit[6], C. Sykes[8], L.J. Tacconi[1], H. Übler[1], G. Ulbricht[18], F. Vincent[2], R. Webster[24], E. Wieprecht[1], J. Woillez[7], and C. Wolf[21,22]

(Affiliations can be found after the references)

Received Sep 2025

ABSTRACT

We present the first near-infrared interferometric data of a QSO at z=4. The K-band observations were performed with GRAVITY+ on the VLTI using all 4 UTs, detecting a differential phase signal that traces the spatially resolved kinematics for both the Hβ and Hγ lines in the broad line region. We fit the two lines simultaneously with an updated model that includes distinct rotating and conical outflowing components. We find that more than 80% of the H I line emission from the BLR originates in an outflow with a velocity up to 10^4 km s^{-1}. This is oriented so that our line of sight is along an edge of the conical structure, which produces the prominent blue wing on the line profile. A combination of anisotropic line emission and mid-plane opacity lead to the single-sided phase signal. The model is able to qualitatively match both the outflowing C IV line profile and the systemic O I fluorescent emission. The derived black hole mass of 8×10^8 $M_\odot$ is the highest redshift black hole mass measurement to date obtained directly from BLR dynamics. It is an order of magnitude lower than that inferred from various single epoch scaling relations, and implies that the accretion is highly super-Eddington. With reference to recent simulations, the data suggest that this QSO is emitting close to its radiative limit in a regime where strong outflows are expected around a polar conical region.

Key words. Galaxies: active – quasars: individual: J0529 – quasars: emission lines – quasars: supermassive black holes – Infrared: galaxies

1. Introduction

The cosmic epoch at $3 \lesssim z \lesssim 5$ marks a key period between the end of reionisation at $z \gtrsim 6$ (Robertson 2022; Loeb & Barkana 2001) and the most active phase of galaxy formation at cosmic noon around $z \sim 2$ (Förster Schreiber & Wuyts 2020; Tacconi et al. 2020). There is an increasing interest in spatially resolving the molecular and ionised emission lines in galaxies on kiloparsec scales during this epoch (Le Fèvre et al. 2020; Wylezalek et al. 2022; Galbiati et al. 2023; Herrera-Camus et al. 2025; Übler et al. 2024), because doing so can provide insights into the processes that have shaped the universe into what it is now. The role of active galactic nuclei (AGN) is equally important because the black hole accretion rate is rising rapidly during this epoch until it peaks around the same time as galaxy formation (Aird et al. 2015; Kim et al. 2024). Indeed, both the major impact that feedback from AGN can have on galaxy growth (Fabian 2012; King & Pounds 2015; Fan et al. 2023), and the existence of local relations between black hole mass and their host galaxy properties (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Gültekin et al. 2009; McConnell & Ma 2013; Saglia et al. 2016), indicate that supermassive black holes should co-evolve with galaxies (Kormendy & Ho 2013; Heckman & Best 2014).

Observations with JWST, as nicely illustrated by Adamo et al. (2025), have recently highlighted a population of AGN with luminosities overlapping those of local Seyfert nuclei, spanning the entire redshift range from cosmic noon to reionisation (Kocevski et al. 2023; Übler et al. 2023; Greene et al. 2024; Maiolino et al. 2024; Matthee et al. 2024; Suh et al. 2025; Juodžbalis et al. 2025; Scholtz et al. 2025). The data have unexpectedly indicated that, compared to local

* GRAVITY+ is developed in a collaboration by the Max Planck Institute for extraterrestrial Physics, the Institute National des Sciences de l'Univers du CNRS (INSU) with its institutes LIRA / Paris Observatory-PSL, IPAG / Grenoble Observatory, Lagrange / Côte d'Azur Observatory and CRAL / Lyon Observatory, the Max Planck Institute for Astronomy, the University of Cologne, the CENTRA - Centro de Astrofisica e Gravitação, the University of Southampton, the Katholieke Universiteit Leuven, University College Dublin, Universidad Nacional Autónoma de México and the European Southern Observatory.
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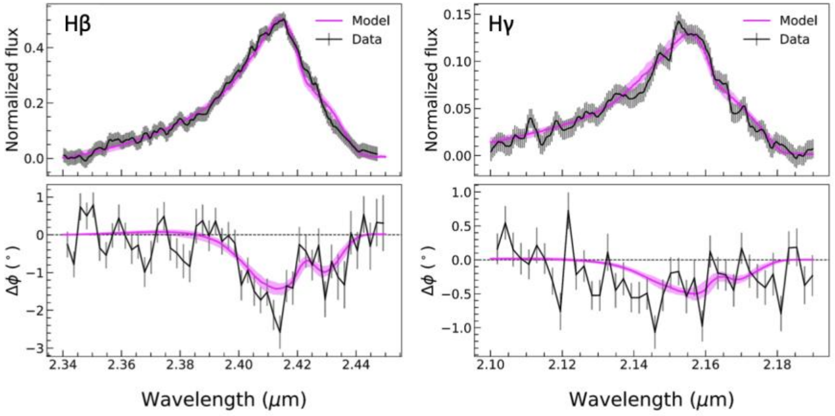
Article number, page 1

a quasar with $z > 4$



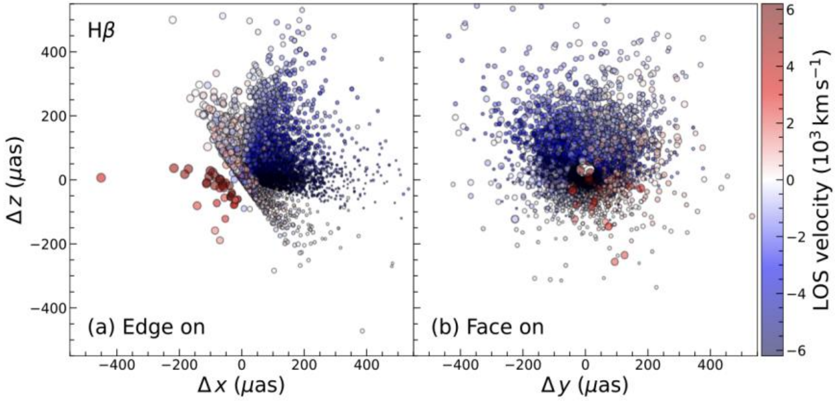


Table 2: BLR size estimates from Hβ scaling relations

$R_{\rm BLR}$ (pc)	Reference	Note
1.74	Bentz et al. (2013)	commonly used
1.47	Du et al. (2018)	lower $\dot{M}_{\rm acc}$ subsample
1.22	Du & Wang (2019)	without $\mathcal{R}_{\rm Fe}$ correction
0.94	Du & Wang (2019)	with $\mathcal{R}_{\rm Fe}$ correction
0.65	Woo et al. (2024)	47 AGN sample
0.50	Du et al. (2018)	higher $\dot{M}_{\rm acc}$ subsample
0.48	Woo et al. (2024)	240 AGN sample

The average radius for the BLR is $\mu = 1.0$ pc for Hβ and $\mu = 0.9$ pc for Hγ. While these are the same within their uncertainties (see Table A.1 and Fig. A.2), this difference is expected both observationally, based on RM delays for different lines (Bentz et al. 2010), and on modelling of radiation pressure confined BLR clouds (Netzer 2020).

While the size appears to match that inferred by applying a $\mathcal{R}_{\rm Fe}$ correction to the R-L relation favoured by Du & Wang (2019), this does not provide an explanation of why $\mathcal{R}_{\rm Fe}$ is so low. Indeed, from the plot of FWHM versus $\mathcal{R}_{\rm Fe}$ in Shen & Ho (2014), both of these values for J0529 seem rather typical of QSOs generally. Instead we propose that much of the deviation from the scaling relations that has previously been attributed to luminosity or accretion rate, could, analogous to the C IV line, be due to the impact of the outflow on the H I line properties. Indeed, the disky part of the BLR in Fig. 5 contains only 27% of the total line luminosity. Applying this to the typical equation which

GRAVITY: BLR shrinkage & $R_{\mathrm{H\beta}} - (L_{5100}, \mathcal{R}_{\mathrm{Fe}})$ relation works in high-z universe

Article

A dynamical measure of the black hole mass in a quasar 11 billion years ago

$z \approx 2$

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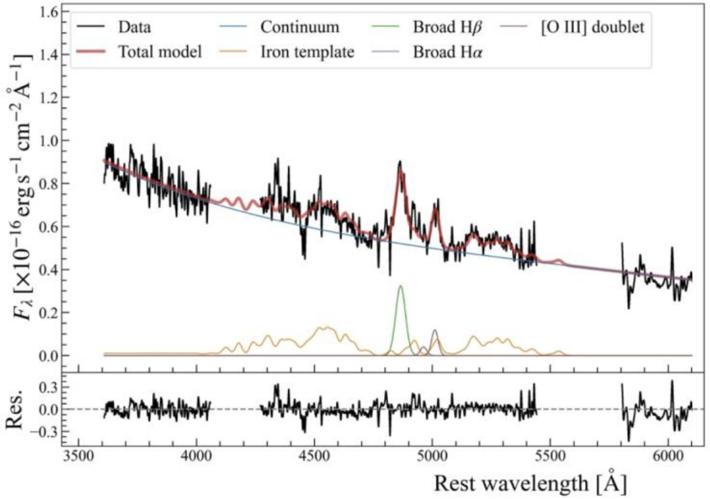

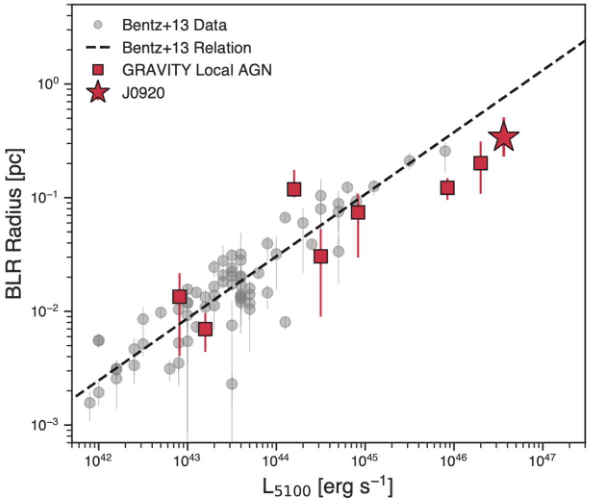

Astronomy & Astrophysics

$z \approx 4$

Spatially resolved broad-line region in a quasar at $z = 4$

Dynamical black hole mass and prominent outflow

GRAVITY+ Collaboration: K. Abd El Dayem[2], N. Aimar[10,13], A. Berdeu[7,2], J.-P. Berger[4], G. Bourdarot[1], P. Bourget[7], W. Brandner[5], Y. Cao[1], C. Correia[10,13], S. Cuevas Cardona[16], R. Davies[1,★], D. Defrère[9], A. Drescher[1], A. Eckart[6,14], F. Eisenhauer[1,12], M. Fabricius[1], A. Farah[16], H. Feuchtgruber[1], N. M. Förster Schreiber[1], A. Foschi[2], P. Garcia[10,13], R. Garcia Lopez[15], R. Genzel[1,11], S. Gillessen[1], T. Gomes[10,13], F. Gonté[7], V. Gopinath[1], J. Graf[1], M. Hartl[1], X. Haubois[26], F. Haußmann[1], L. C. Ho[19,20], S. Hönig[8], M. Houllé[4], S. Joharle[1], C. Keiman[16], P. Kervella[2], J. Kolb[7], L. Kreidberg[5], A. Labdon[26], S. Lacour[2,7], O. Lai[3], S. Lai[23], R. Laugier[9], J.-B. Le Bouquin[4], J. Leftley[8], R. Li[19,20], B. Lopez[3], D. Lutz[1], F. Mang[1], A. Mérand[7], F. Millour[3], M. Montargès[2], N. More[1], N. Morujão[10,13], H. Nowacki[3], M. Nowak[2], S. Oberti[7], C. Onken[21,22], J. Osorno[2], T. Ott[1], T. Paumard[2], K. Perraut[4], G. Perrin[2], R. Petrov[3], P.-O. Petrucci[4], N. Pourré[4], S. Rabien[1], C. Rau[1], D. C. Ribeiro[1], S. Robbe-Dubois[3], M. Sadun Bordoni[1], M. Salman[9], J. Sanchez-Bermudez[16], D. Santos[1], J. Sauter[5], M. Scialpi[25], J. Scigliuto[3], J. Shangguan[19,20,★], P. Shchekaturov[7], T. Shimizu[1,★], F. Soulez[17], C. Straubmeier[6], E. Sturm[1], M. Subroweit[6], C. Sykes[8], L. J. Tacconi[1], H. Übler[1], G. Ulbricht[18], F. Vincent[2], R. Webster[24], E. Wieprecht[1], J. Woillez[7], and C. Wolf[21,22]

(Affiliations can be found after the references)

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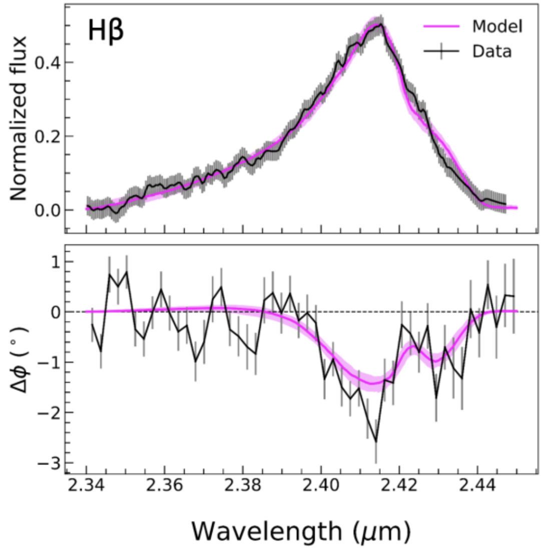
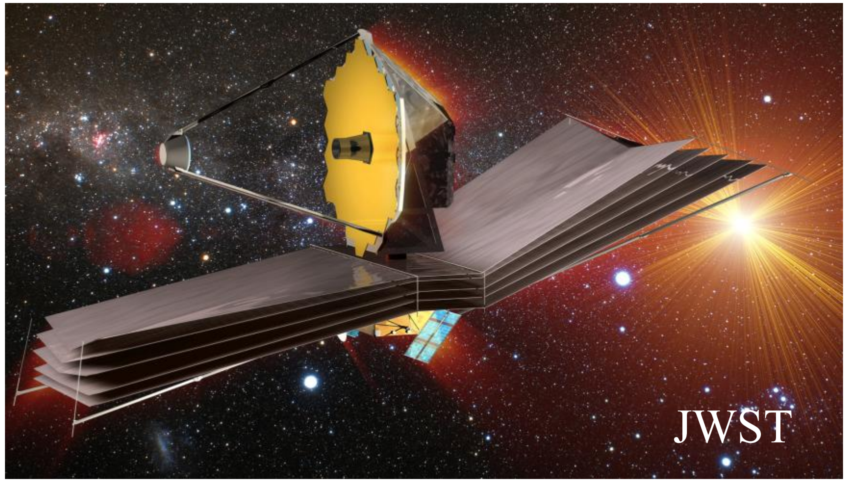
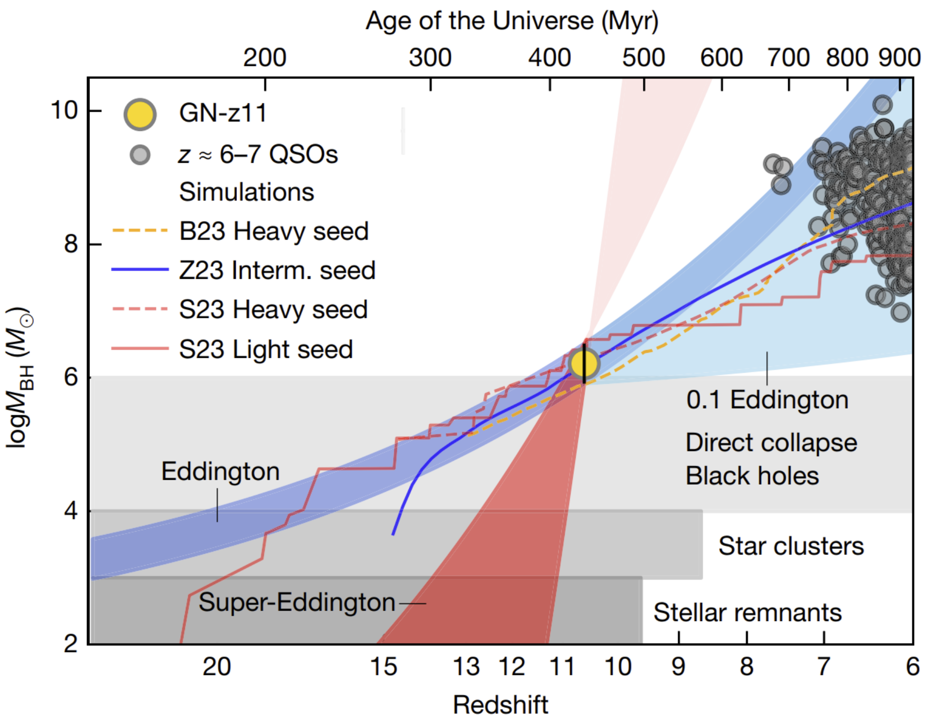


Super-Eddington AGNs





Article

A small and vigorous black hole in the early Universe

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Several theories have been proposed to describe the formation of black hole seeds in the early Universe and to explain the emergence of very massive black holes observed in the first thousand million years after the Big Bang[1–3]. Models consider different seeding and accretion scenarios[4–7], which require the detection and characterization of black holes in the first few hundred million years after the Big Bang to be validated. Here we present an extensive analysis of the JWST-NIRSpec spectrum of GN-z11
an exceptiona
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and blueshifte
800–1,000 km s^{-1}, probabl
galactic nucleus. Assuming local
virial relations, we der
hole mass of $\log(M_{BH}/M_{\odot}) = 6.2 \pm 0.3$, accreting at about five times the Eddington rate. These properties are consistent with both heavy seeds scenarios and scenarios considering intermediate and light seeds experiencing episodic super-Eddington phases. Our finding explains the high luminosity of GN-z11 and can also provide an explanation for its exceptionally high nitrogen abundance.

GN-z11 was recently observed with JWST. The analysis of the NIRCam images revealed an unresolved nuclear component and a disc-like component with a few 100 parsec (pc) radius[8]. A first NIRSpec spectrum was presented in ref. 9, which found it to be consistent with star formation, although the presence of an active galactic nucleus (AGN) was not excluded. Here we explore the latter scenario using a deeper spectrum of GN-z11.

Figure 1a shows the detection of the [NeIV]λλ2422,2424 doublet. As NeIV requires photons more energetic than 63.5 eV, this line is an unambiguous AGN tracer[10–12] and not seen in star-forming galaxies, not even those hosting the Wolf–Rayet (WR) stars[13].

We also detect CII*λ1335 emission (Fig. 1e). This line is commonly observed in AGN[14–16]. In star-forming galaxies, this line is generally totally undetected; when detected, it is extremely faint and always associated with deep CIIλ1334 resonant absorption[17], not seen in GN-z11.

The [NIV]λ1483, NIV]λ1486 doublet is very sensitive to the gas density (and insensitive to ionization parameter, metallicity and shape of the ionizing spectrum). Figure 1c shows the detection of the semi-forbidden NIV]λ1486 line (critical density 4.7×10^{9} cm^{-3}) and the non-detection of the forbidden [NIV]λ1483 line (critical density 1.5×10^{5} cm^{-3}), which indicate densities much higher than 10^{5} cm^{-3}. Specifically, the various photoionization models shown in Fig. 2a (see the Methods for details)

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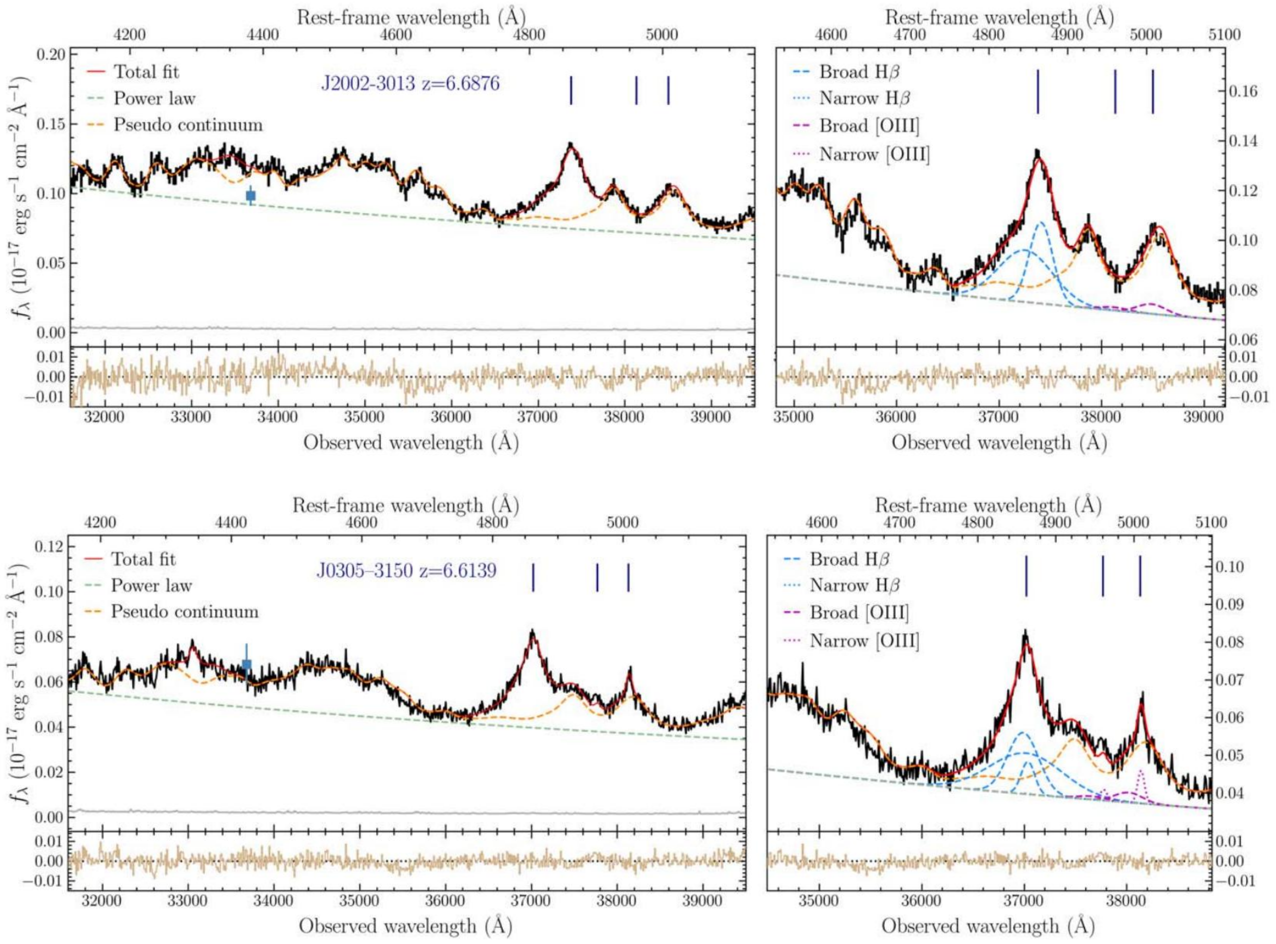
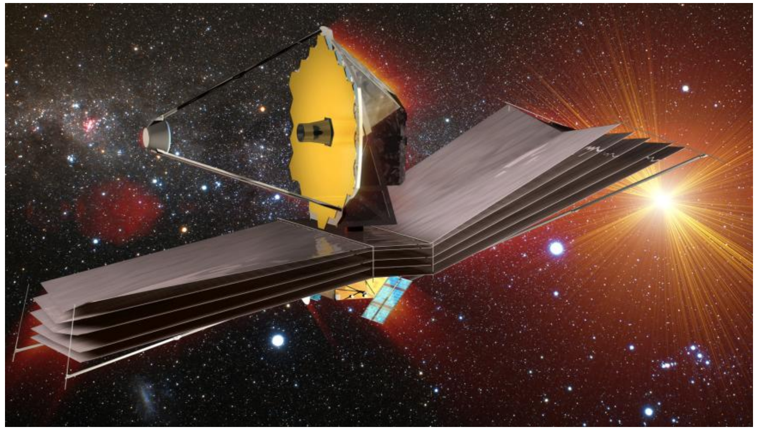
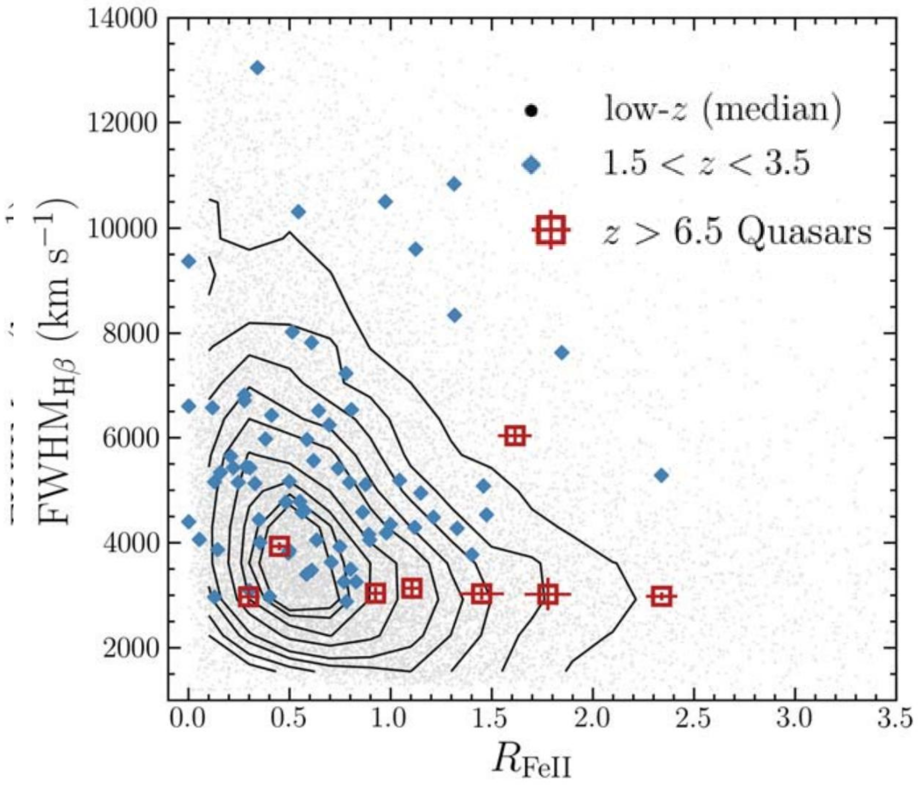
5 times the Eddington Rate

Super-Eddington AGNs







Yang et al. (2023)

How many SEAMBHs: 1/3 in PG quasars

THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 80:109–135, 1992 May

THE EMISSION-LINE PROPERTIES OF LOW-REDSHIFT QUASI-STELLAR OBJECTS

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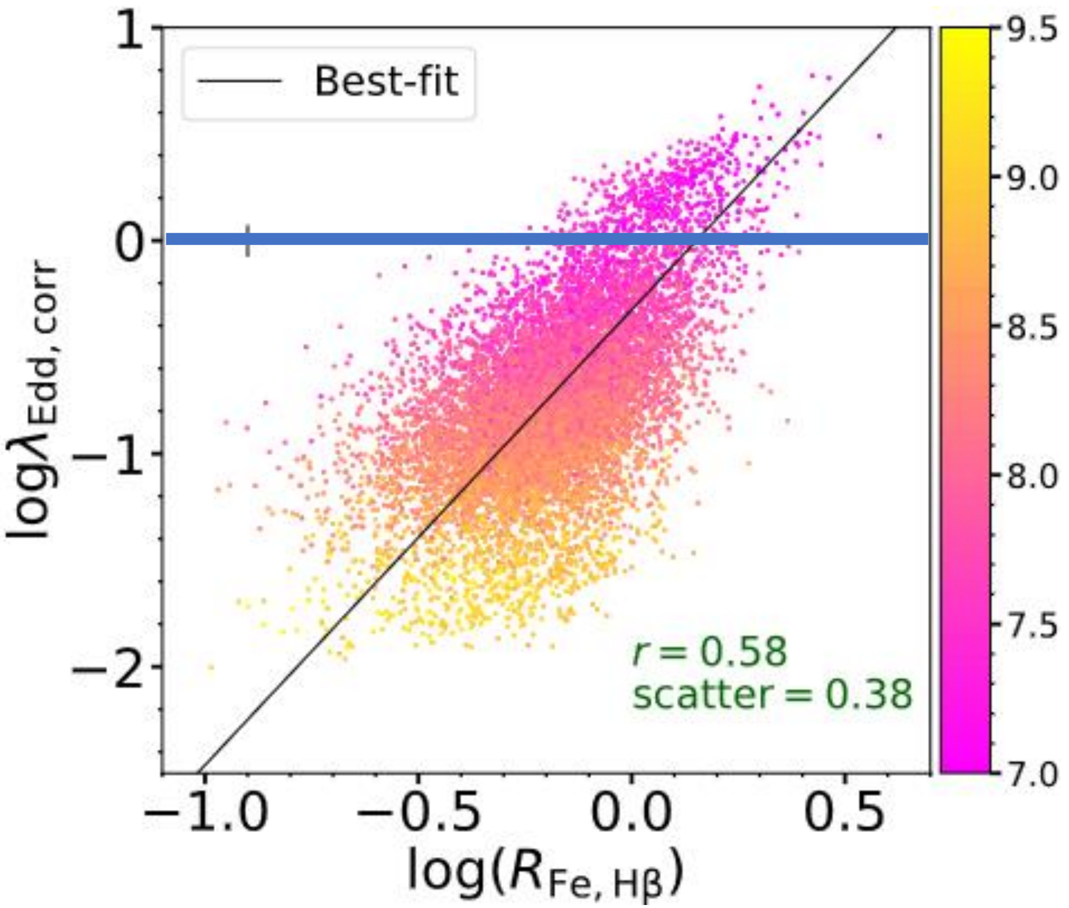
Received 1991 August 2; accepted 1991 October 14

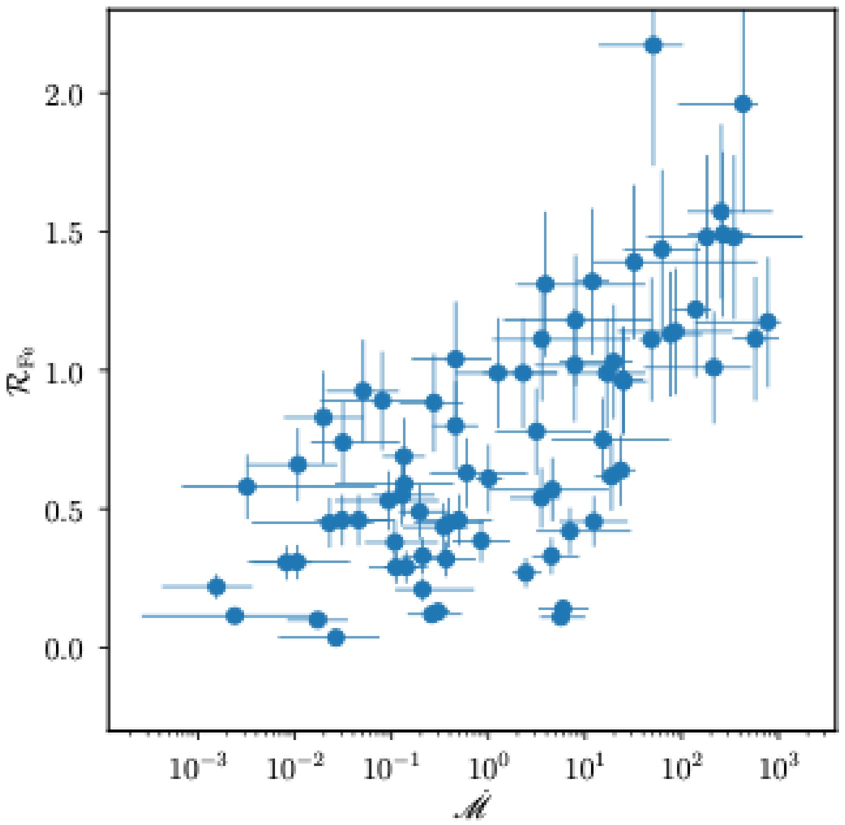
Shakura-Sunyaev disk: $\dot{\mathscr{M}} = 20.1\left(\frac{l_{44}}{\cos i}\right)^{3/2} m_7^{-2},$

DESI quasar sample



(Pan et al. 2025)

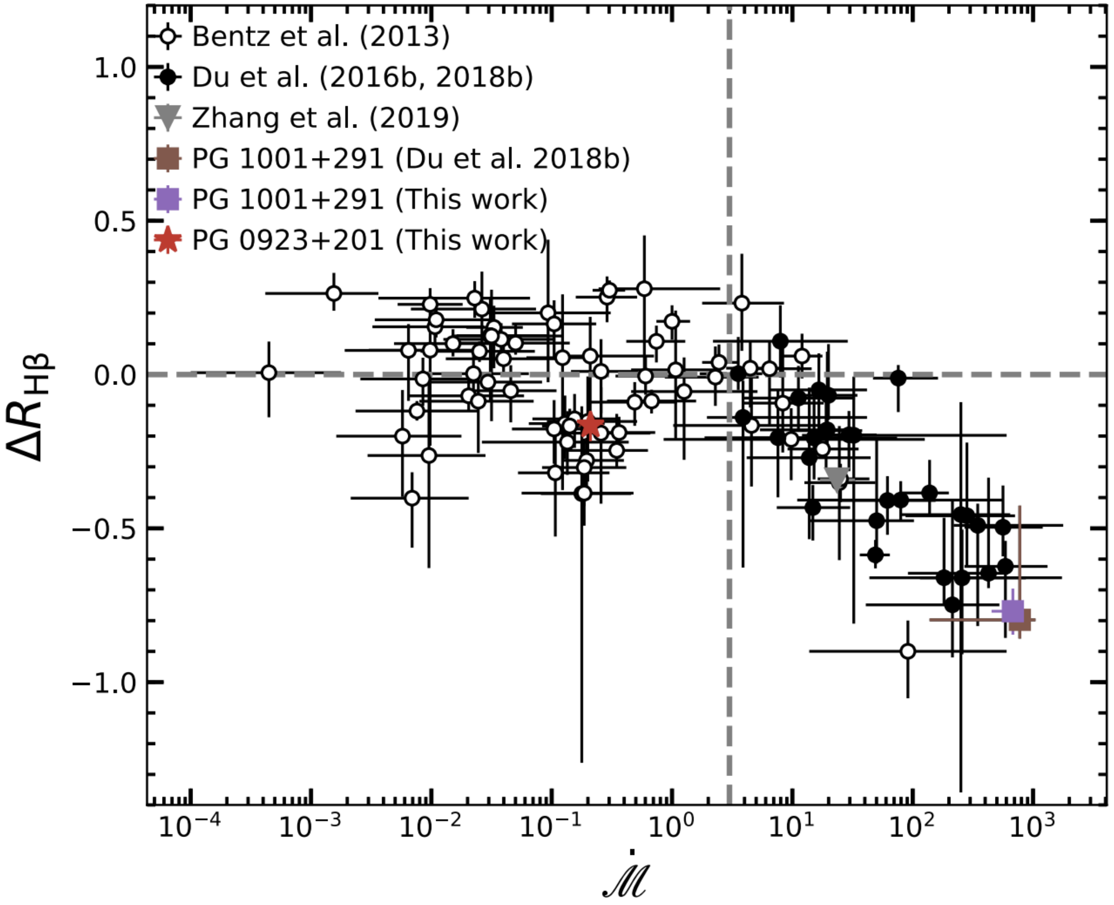
Hβ RM sample



(sample in Du & Wang 2019)

R-*L* relation:

over-estimate by factors of 3-8



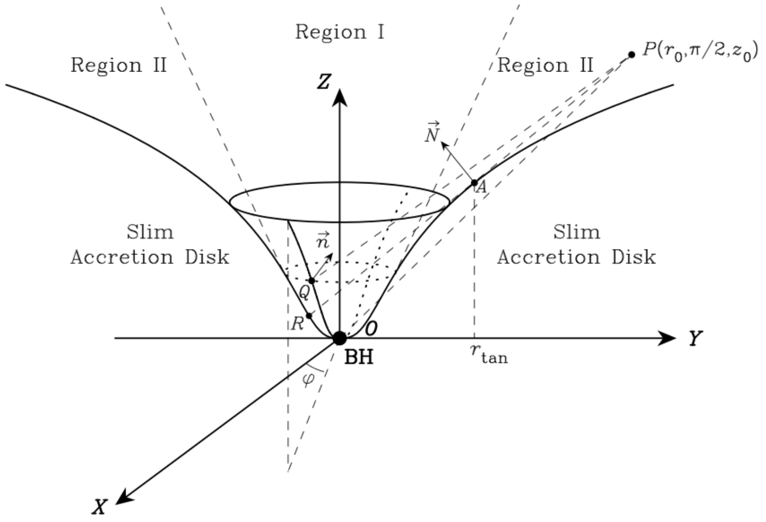
Why shortened?

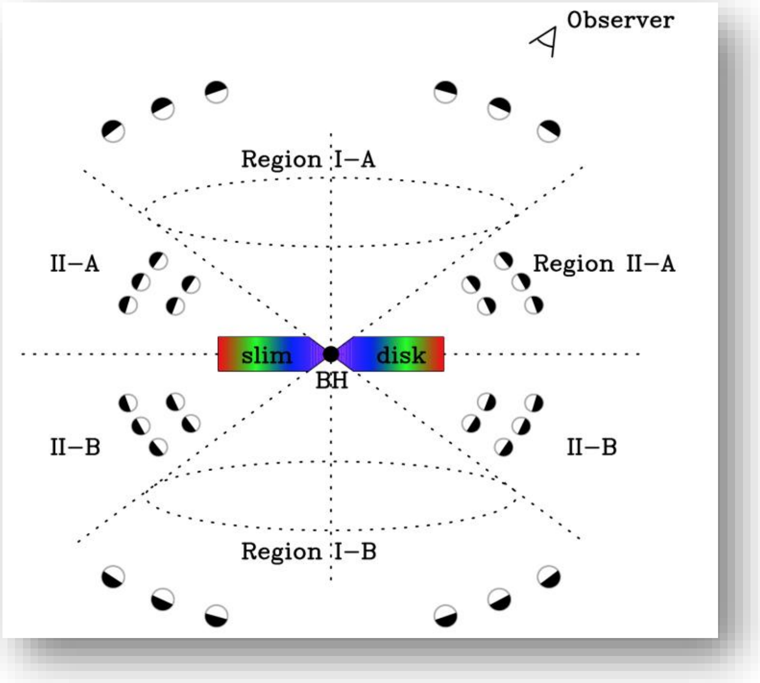
Why FeII as an indicator?

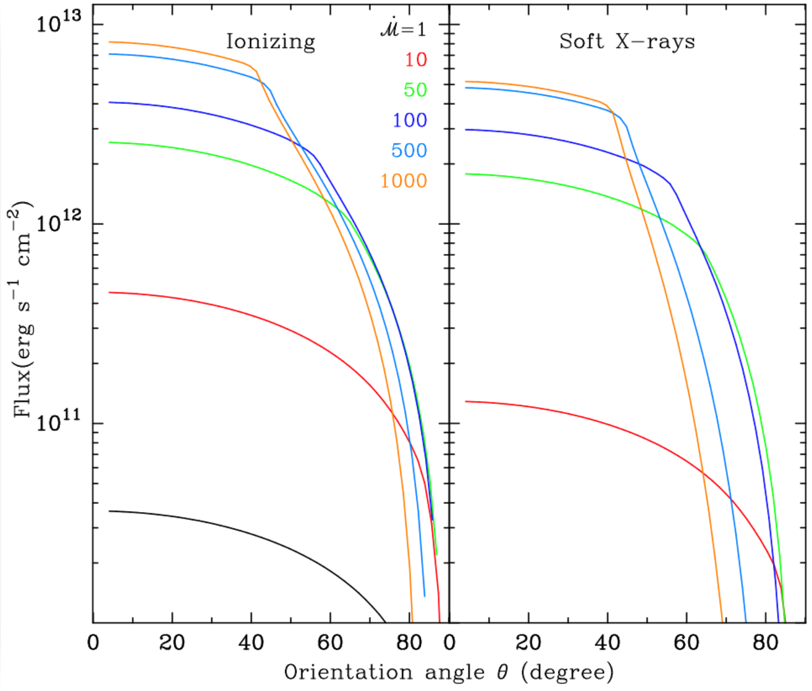
THE ASTROPHYSICAL JOURNAL, 797:65 (13pp), 2014 December 10
doi:10.1088/0004-637X/797/1/65

SELF-SHADOWING EFFECTS OF SLIM ACCRETION DISKS IN ACTIVE GALACTIC NUCLEI: THE DIVERSE APPEARANCE OF THE BROAD-LINE REGION

JIAN-MIN WANG[1,2], JIE QIU[1], PU DU[1], AND LUIS C. HO[3,4]





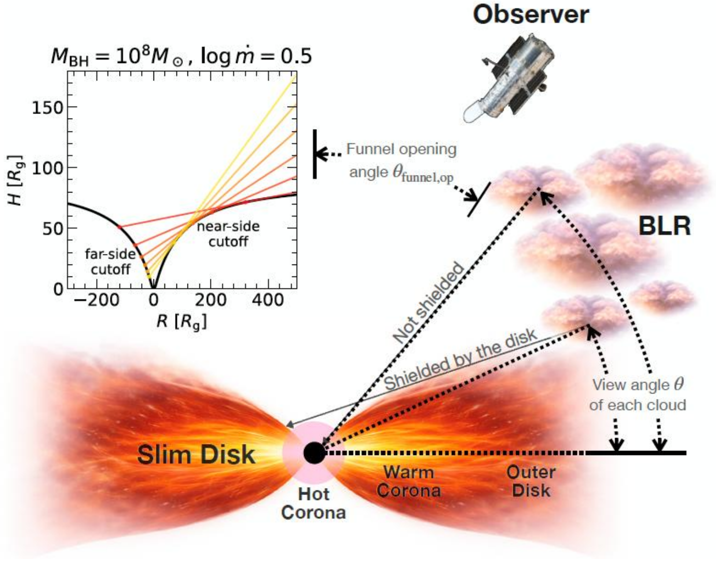


$$\frac{R_{\rm BLR,I}}{R_{\rm BLR,II}} = \left(\frac{L_{\rm ion,I}}{L_{\rm ion,II}}\right)^{1/2} = \left(\frac{F_{\rm ion,I}}{F_{\rm ion,II}}\right)^{1/2}, \quad \frac{R_{\rm BLR,I}}{R_{\rm BLR,II}} \approx 2.0\dot{\mathscr{M}}_{50}^{0.3},$$

Draft version June 2, 2026
Typeset using LaTeX twocolumn style in AASTeX631

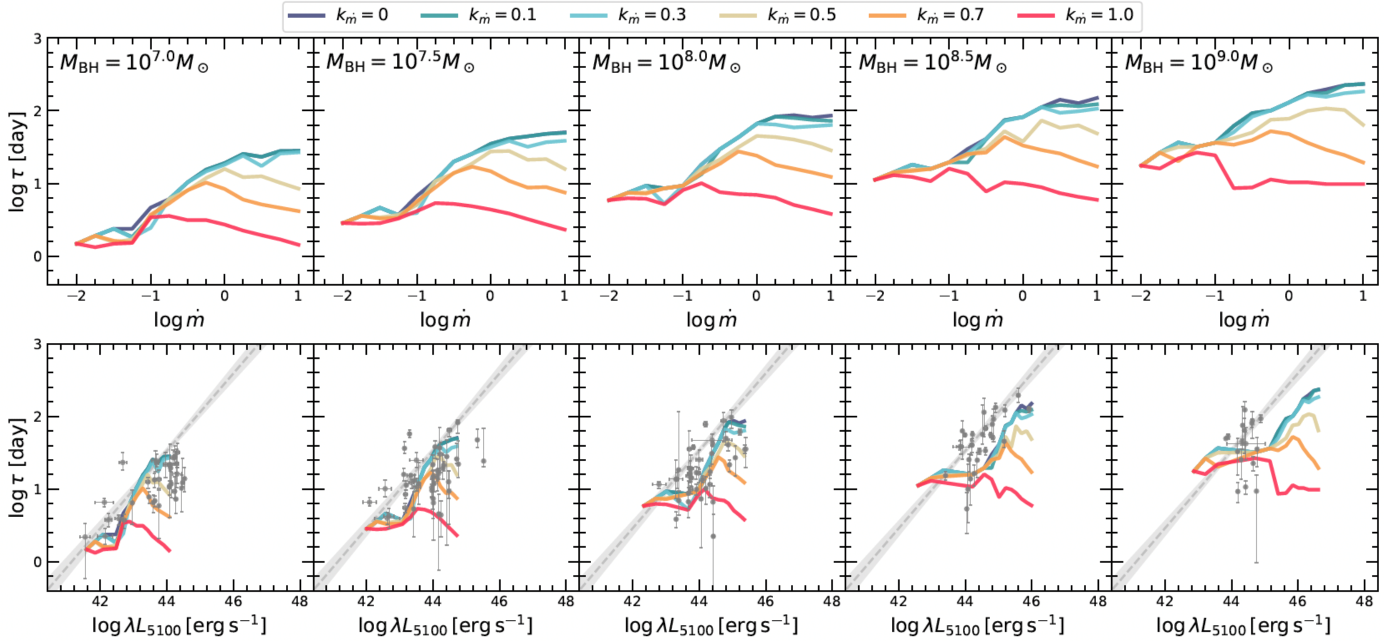
Understanding the Broad-line Region of Active Galactic Nuclei with Photoionization. II. Slim disks, Self-shadowing, and BLR sizes

Qiaoya Wu[1], Yue Shen[1,2], Chris Done[3], Michael R. Goad[4] and Scott Hagen[5,6,7]



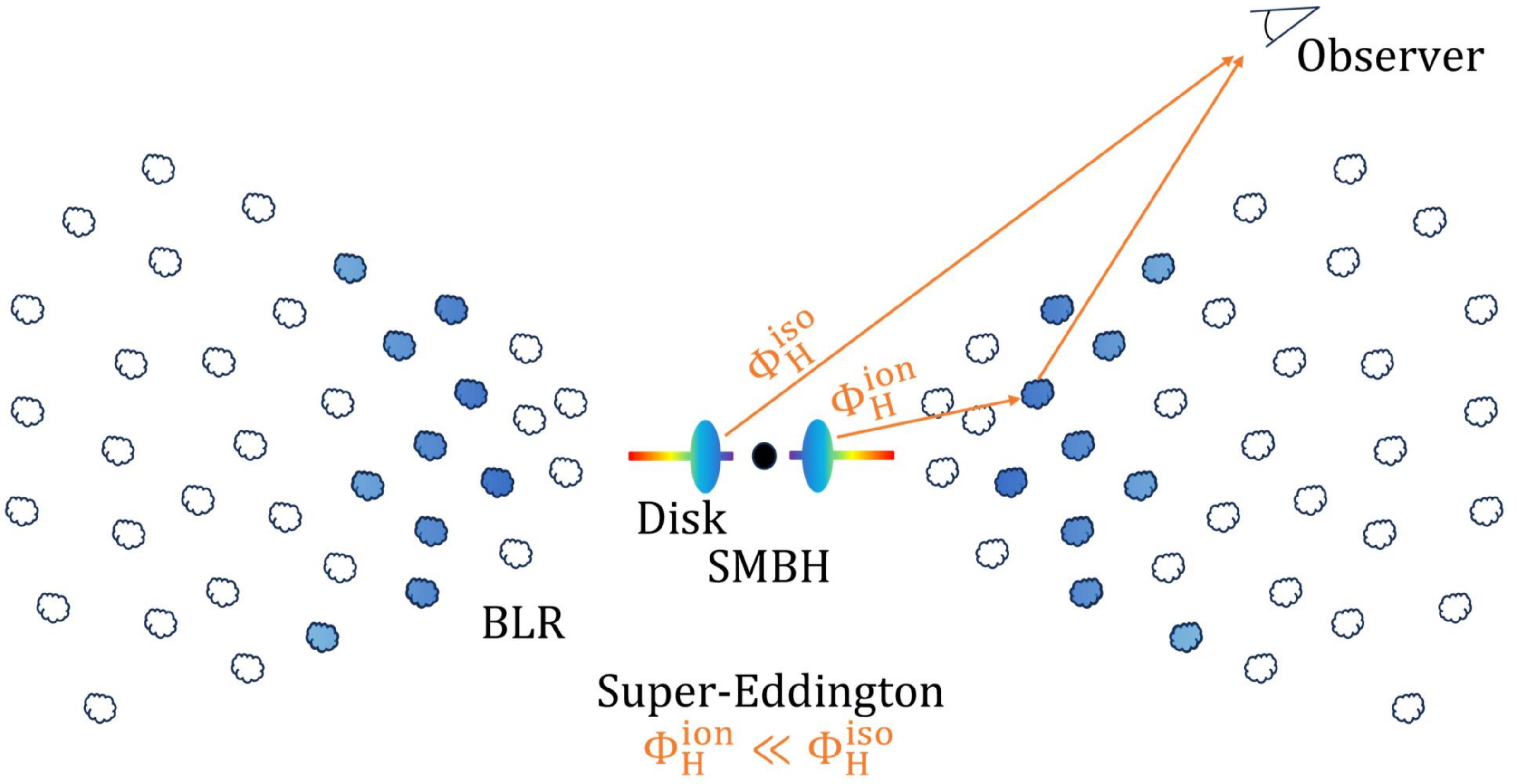
$$\Delta \log n_{H} = k_{\dot{m}} \times \log \Delta\dot{m}$$

Increasing cloud density



Dense clouds shortened lags, but profiles highly asymmetric.

Anisotropic radiation in SEAMBHs: observational evidence



Ionizing Photons under the Isotropic Assumption

$$\Phi_{\rm H}^{\rm iso} = \frac{Q({\rm H})}{4\pi R_{\rm H\beta}^2} = \frac{D_{\rm AGN}^2}{R_{\rm H\beta}^2} \cdot \frac{F_\nu}{h\nu},$$

Ionizing Photons incident on BLR clouds

$\Phi_{\rm H}^{\rm ion}$ ← derived from responsivity & photoionization

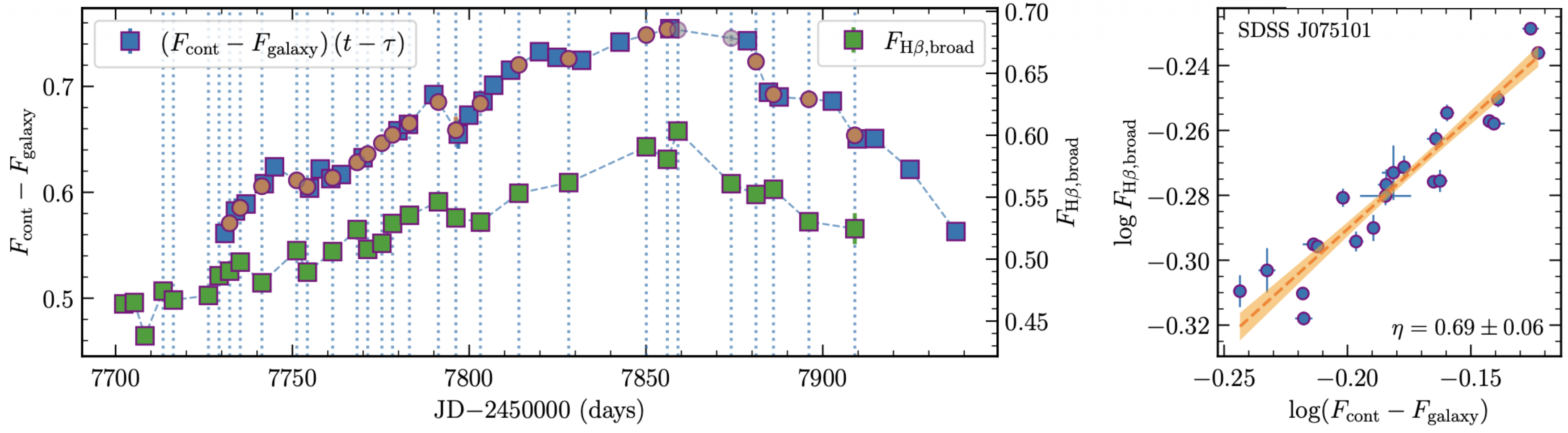
$\Phi_{\rm H}^{\rm iso}$ and $\Phi_{\rm H}^{\rm ion}$ are different in SEAMBHs?

Fang+2026, ApJ submitted

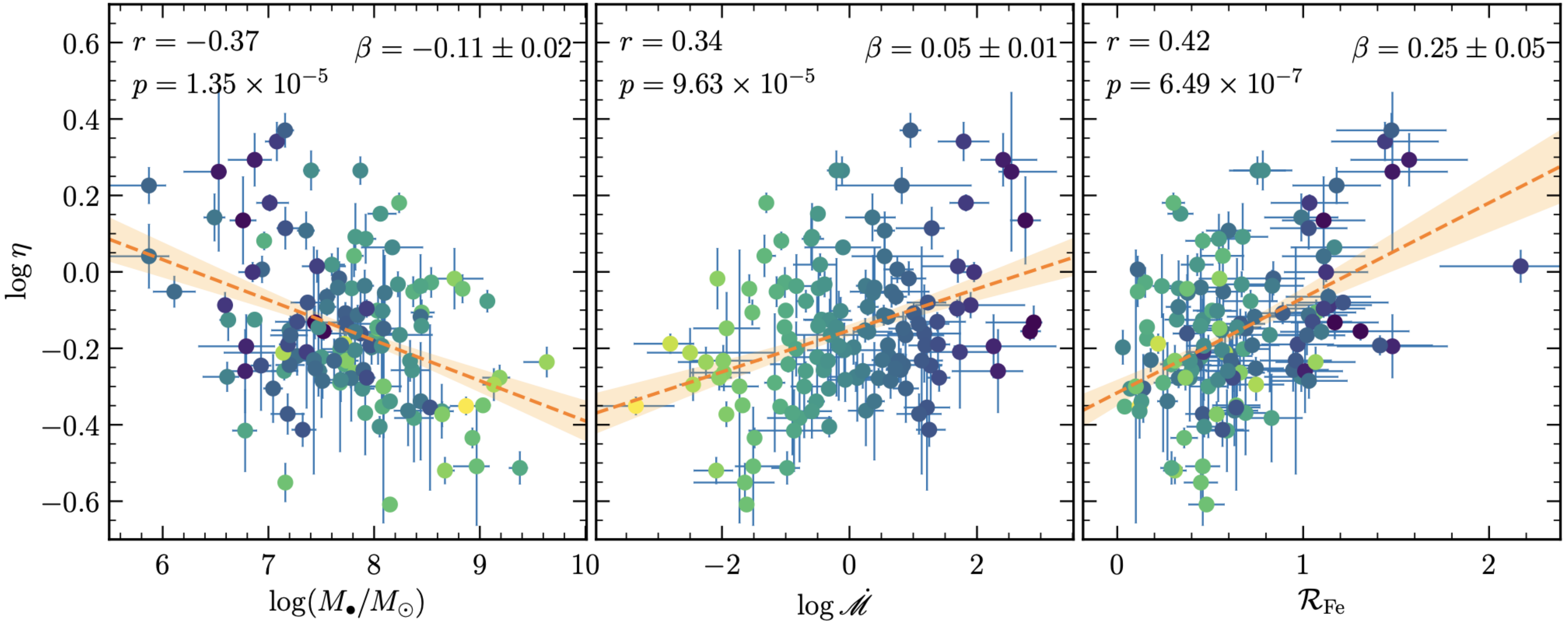
Hβ Responsivity: Higher in SEAMBHs

$$\eta = \frac{\Delta \log F_{\rm line}}{\Delta \log F_{\rm cont}},$$

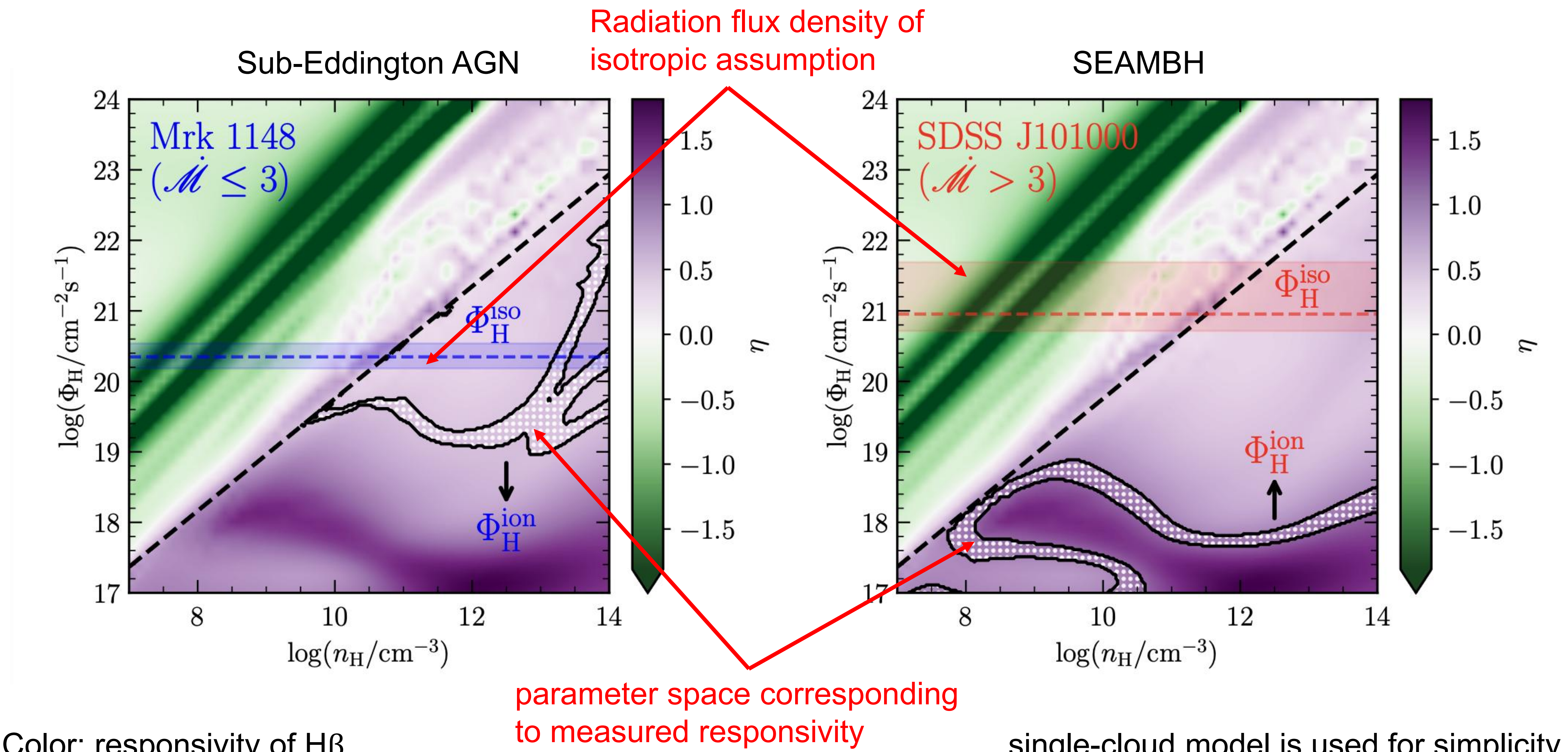
An example of measurement



RM sample



CLOUDY calculation: Ionizing Photons incident on BLR clouds



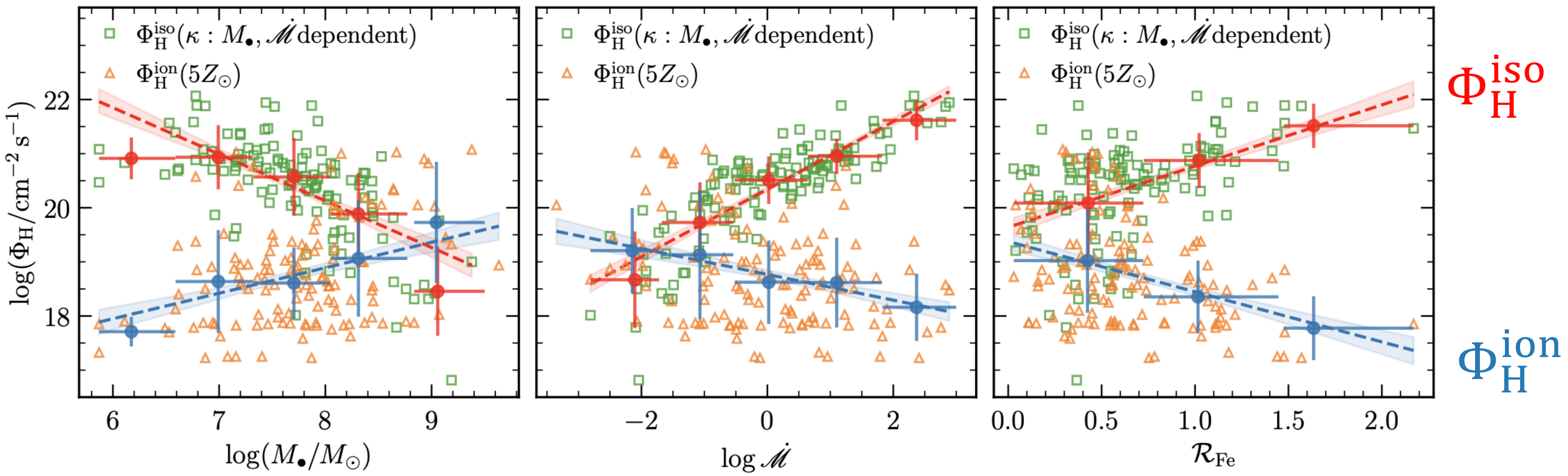
Color: responsivity of Hβ

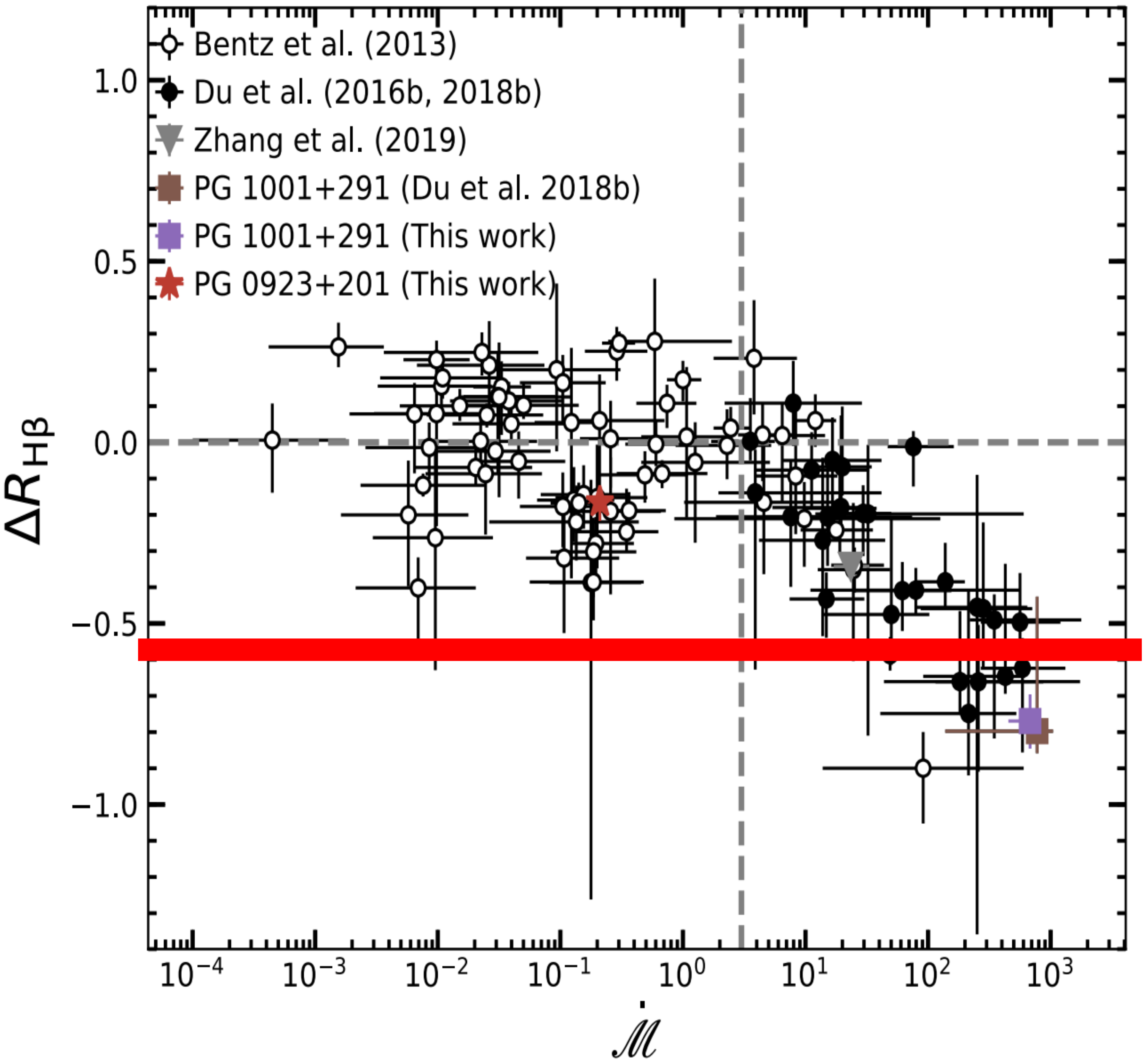
single-cloud model is used for simplicity

$\Phi_{\rm H}^{\rm iso}$ and $\Phi_{\rm H}^{\rm ion}$: similar in sub-Eddington AGNs, but different in SEAMBHs

$$F_{912\,\text{Å}} \approx \kappa\, F_{5100\,\text{Å}}$$

κ from accretion disk model





Questions：

- more extreme?
- why?

Conclusions

- R_{FeII}: a robust indicator of SEAMBHs
- SEAMBHs: shrinking BLRs
- R-L relation: R-(R_{FeII}, L) relation
- How extreme the shortening factors?
- How common SEAMBHs in the Universe?
- How long the accretion of super-Eddington status?