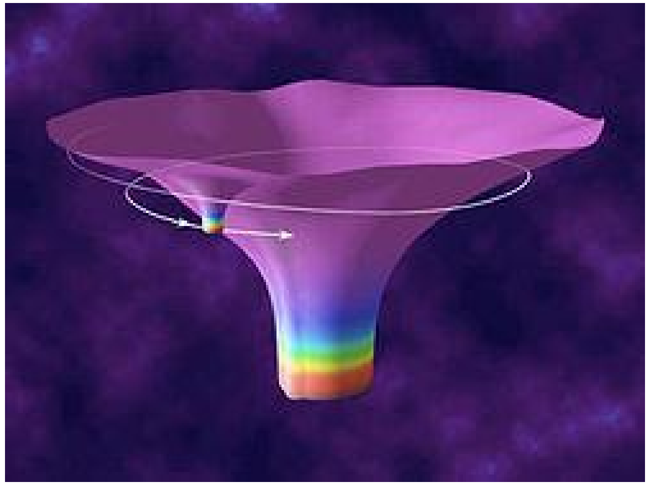
Satellite Black Holes

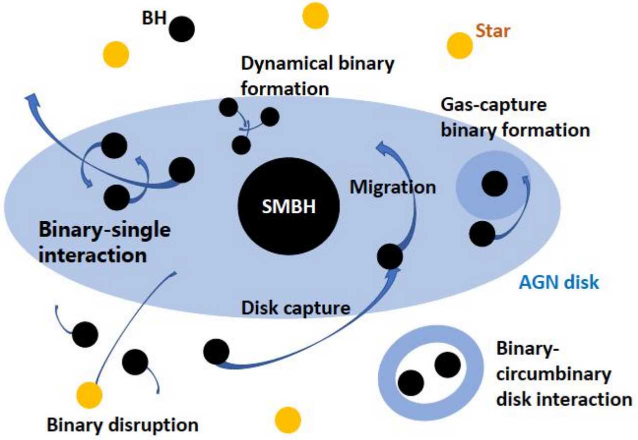
Orbiting Supermassive Black Holes in AGNs

Jian-Min Wang

Institute of High Energy Physics, CAS, Beijing

Lake Qiandao，2025/10/14

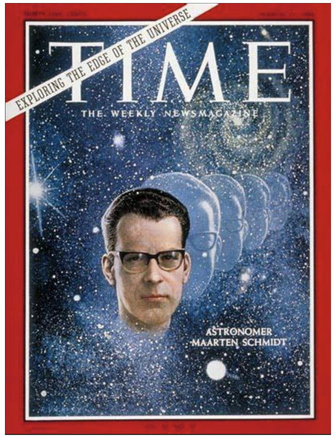


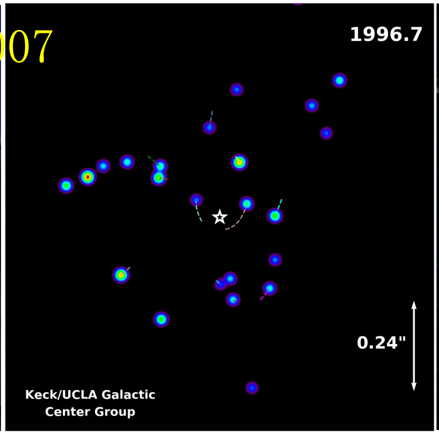


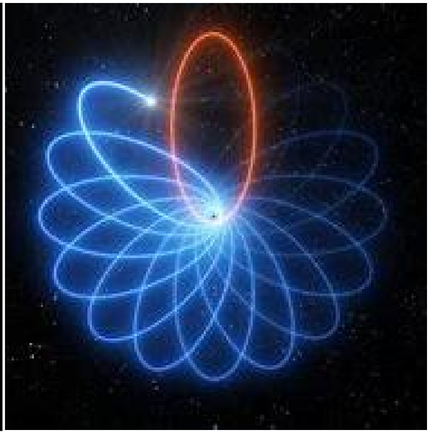
Outline

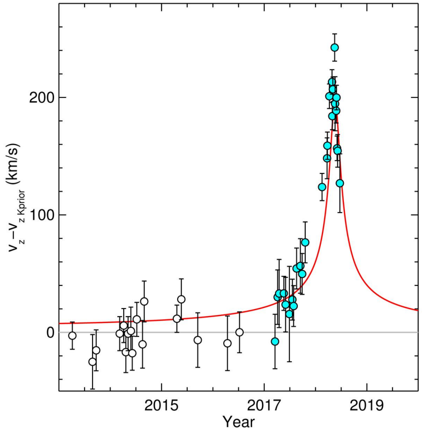
- Heuristic observations of satellite BHs
  - ➢Milky Way Center
  - ➢LIGO detections of massive BH mergers
  - ➢Compact objects in quasars: metallicity
- Future observations
- Conclusions

Supermassive black holes: from MW center to quasars



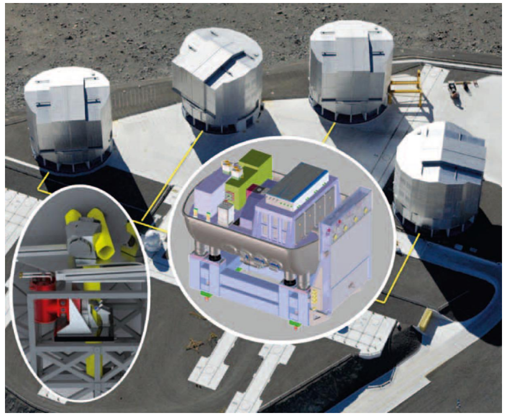






2020

IAU 2021Gruber奖



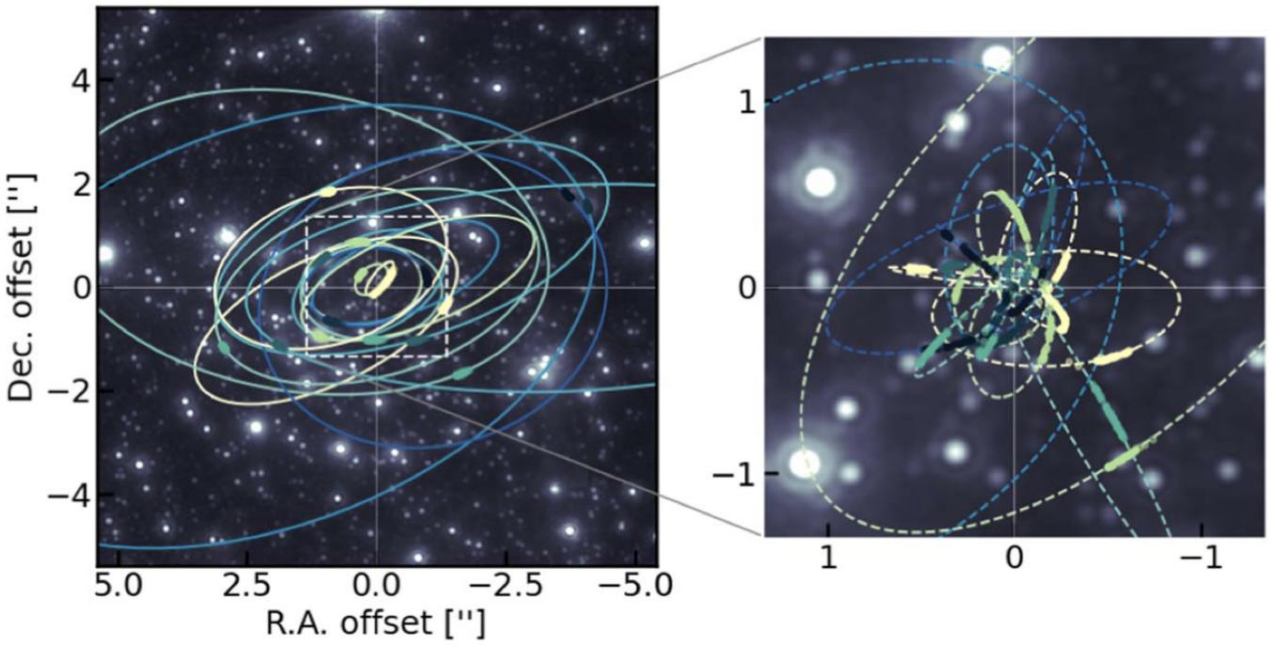
Milky Way Center: Complex Composition

The Astrophysical Journal Letters, 932:L6 (29pp), 2022 June 10
https://doi.org/10.3847/2041-8213/ac68ef

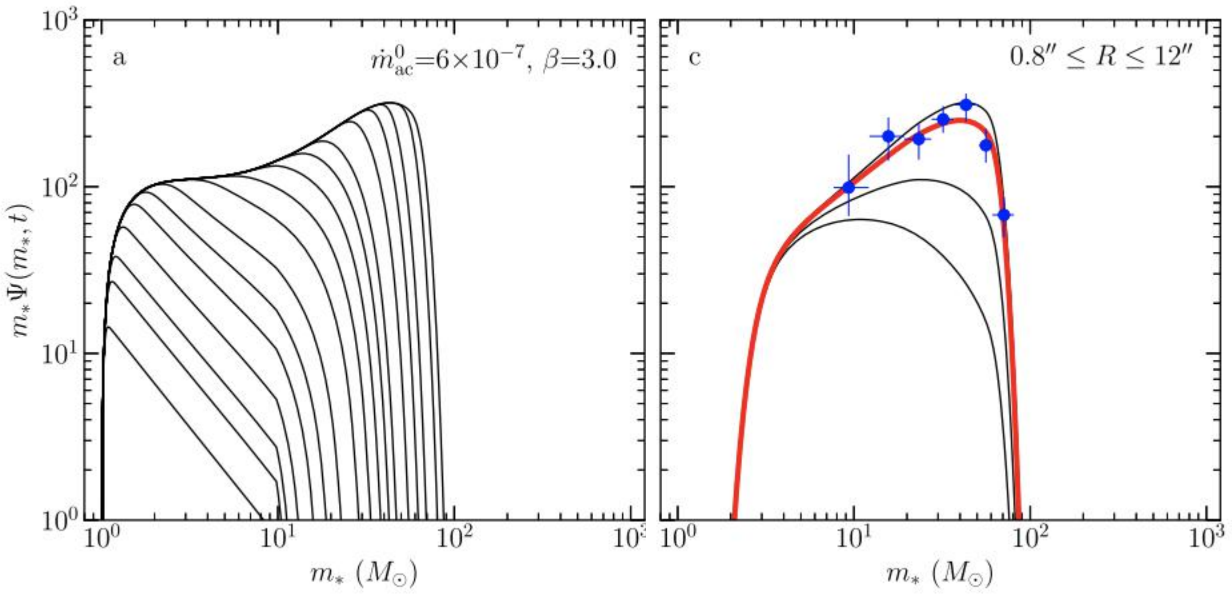
The Young Stars in the Galactic Center

Sebastiano D. von Fellenberg[1,2], Stefan Gillessen[2], Julia Stadler[3], Michi Bauböck[4], Reinhard Genzel[2,5], Tim de Zeeuw[2,6], Oliver Pfuhl[7], Pau Amaro Seoane[2,8,9,10], Antonia Drescher[2], Frank Eisenhauer[2], Maryam Habibi[2], Thomas Ott[2], Felix Widmann[2], and Alice Young[2]

Young stellar disks: counter rotating



Mass function

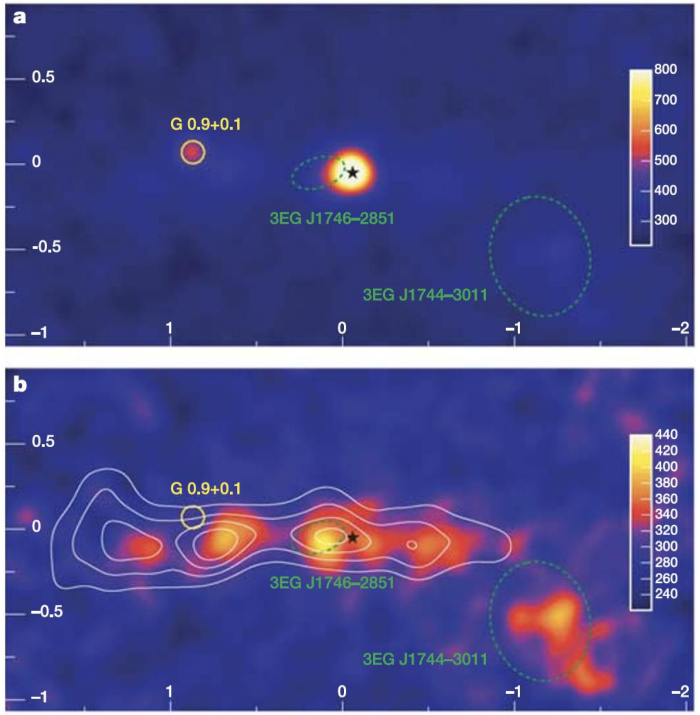


Vol 439|9 February 2006|doi:10.1038/nature04467 nature

LETTERS

Discovery of very-high-energy γ-rays from the Galactic Centre ridge

F. Aharonian[1], A. G. Akhperjanian[2], A. R. Bazer-Bachi[3], M. Beilicke[4], W. Benbow[1], D. Berge[1], K. Bernlöhr[1,5], C. Boisson[6], O. Bolz[1], V. Borrel[3], I. Braun[1], F. Breitling[5], A. M. Brown[7], P. M. Chadwick[7], L.-M. Chounet[8], R. Cornils[4], L. Costamante[1,20], B. Degrange[8], H. J. Dickinson[7], A. Djannati-Ataï[9], L. O'C. Drury[10], G. Dubus[8], D. Emmanoulopoulos[11], P. Espigat[9], F. Feinstein[12], G. Fontaine[8], Y. Fuchs[13], S. Funk[1], Y. A. Gallant[12], B. Giebels[8], S. Gillessen[1], J. F. Glicenstein[14], P. Goret[14], C. Hadjichristidis[7], D. Hauser[1], M. Hauser[11], G. Heinzelmann[4], G. Henri[13], G. Hermann[1], J. A. Hinton[1], W. Hofmann[1], M. Holleran[15], D. Horns[1], A. Jacholkowska[12], O. C. de Jager[15], B. Khélifi[1], S. Klages[1], Nu. Komin[5], A. Konopelko[5], I. J. Latham[7], R. Le Gallou[7], A. Lemière[9], M. Lemoine-Goumard[8], N. Leroy[8], T. Lohse[5], A. Marcowith[3], J. M. Martin[6], O. Martineau-Huynh[16], C. Masterson[1,20], T. J. L. McComb[7], M. de Naurois[16], S. J. Nolan[7], A. Noutsos[7], K. J. Orford[7], J. L. Osborne[7], M. Ouchrif[16,20], M. Panter[1], G. Pelletier[13], S. Pita[9], G. Pühlhofer[11], M. Punch[9], B. C. Raubenheimer[15], M. Raue[4], J. Raux[16], S. M. Rayner[7], A. Reimer[17], O. Reimer[17], J. Ripken[4], L. Rob[18], L. Rolland[16], G. Rowell[1], V. Sahakian[2], L. Saugé[13], S. Schlenker[5], R. Schlickeiser[17], C. Schuster[17], U. Schwanke[5], M. Siewert[17], H. Sol[6], D. Spangler[7], R. Steenkamp[19], C. Stegmann[5], J.-P. Tavernet[16], R. Terrier[9], C. G. Théoret[9], M. Tluczykont[8,20], C. van Eldik[1], G. Vasileiadis[12], C. Venter[15], P. Vincent[16], H. J. Völk[1] & S. J. Wagner[11]

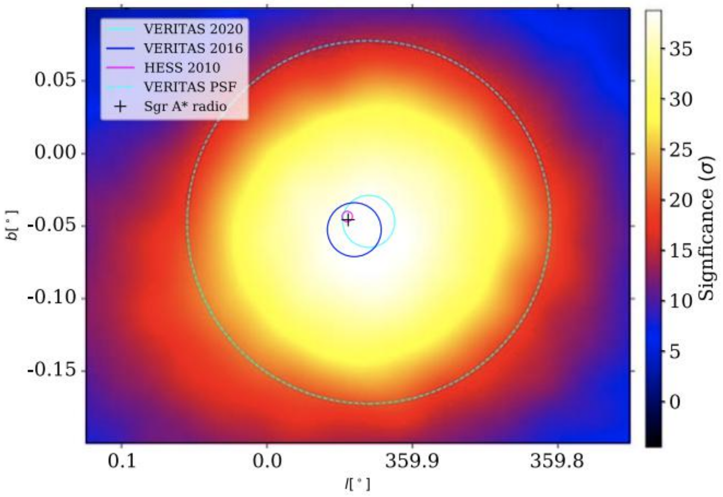


The Astrophysical Journal, 913:115 (11pp), 2021 June 1 https://doi.org/10.3847/1538-4357/abf926

CrossMark

VERITAS Observations of the Galactic Center Region at Multi-TeV Gamma-Ray Energies

C. B. Adams[1], W. Benbow[2], A. Brill[3], R. Brose[4], M. Buchovecky[5], M. Capasso[1], J. L. Christiansen[6], A. J. Chromey[7], M. K. Daniel[2], M. Errando[8], A. Falcone[9], Q. Feng[1], J. P. Finley[10], L. Fortson[11], A. Furniss[12], A. Gent[13], G. H. Gillanders[14], C. Giuri[15], D. Hanna[16], O. Hervet[17], J. Holder[18], G. Hughes[2], T. B. Humensky[3], W. Jin[19], P. Kaaret[20], N. Kelley-Hoskins[15], M. Kertzman[21], D. Kieda[22], F. Krennrich[7], S. Kumar[16], M. J. Lang[14], M. Lundy[16], G. Maier[15], P. Moriarty[14], R. Mukherjee[1], D. Nieto[23], M. Nievas-Rosillo[15], S. O'Brien[16], R. A. Ong[5], A. N. Otte[13], K. Pfrang[15], M. Pohl[4], R. R. Prado[15], E. Pueschel[15], J. Quinn[24], K. Ragan[16], P. T. Reynolds[25], D. Ribeiro[3], G. T. Richards[18], E. Roache[2], J. L. Ryan[5], M. Santander[19], S. Schlenstedt[26], G. H. Sembroski[10], R. Shang[5], B. Stevenson[5], S. P. Wakely[27], A. Weinstein[7], and D. A. Williams[17]



Hardly formed by stellar evolution

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

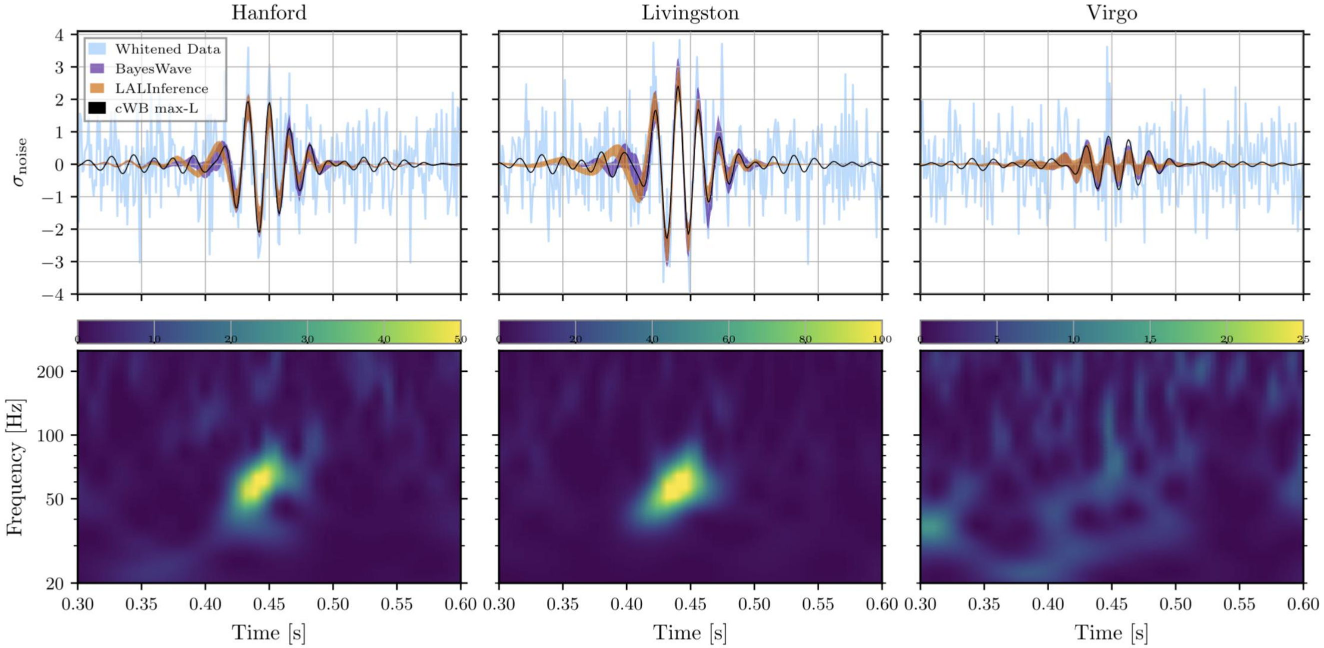
Editors' Suggestion **Featured in Physics**

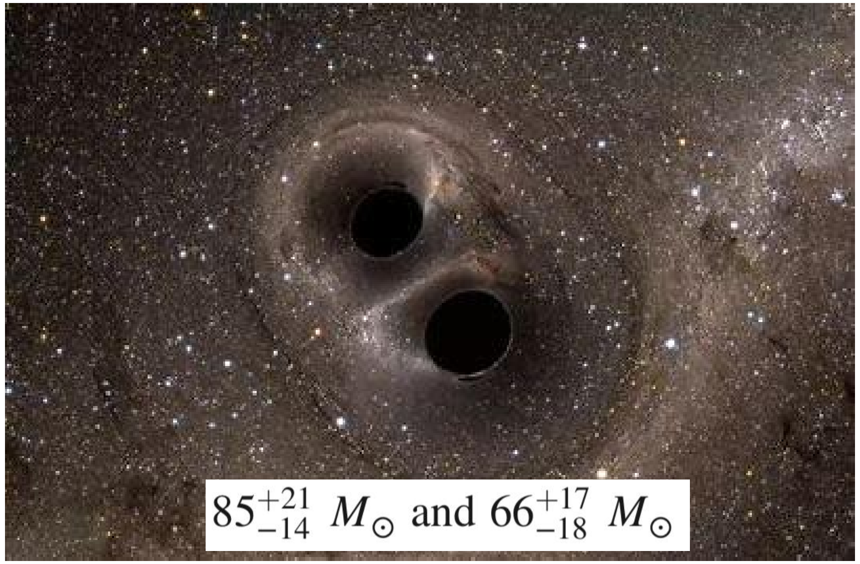
GW190521: A Binary Black Hole Merger with a Total Mass of 150 $M_\odot$

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)



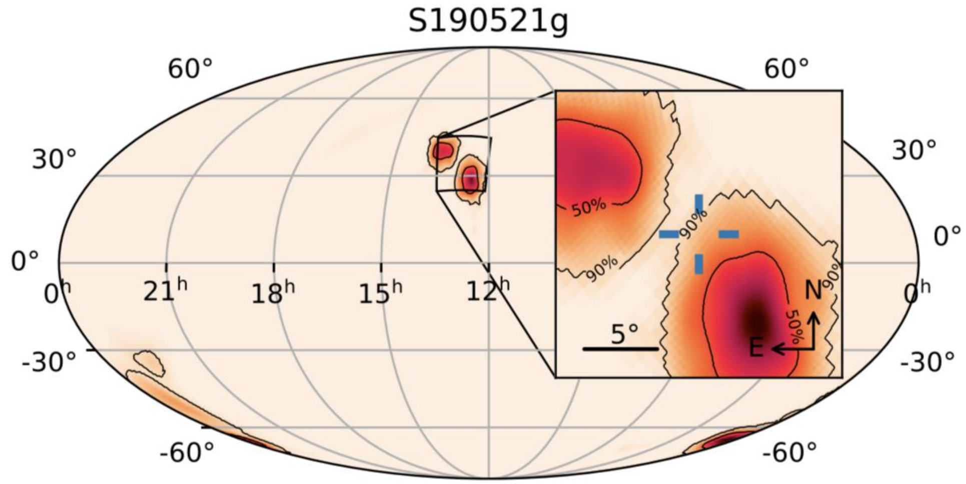


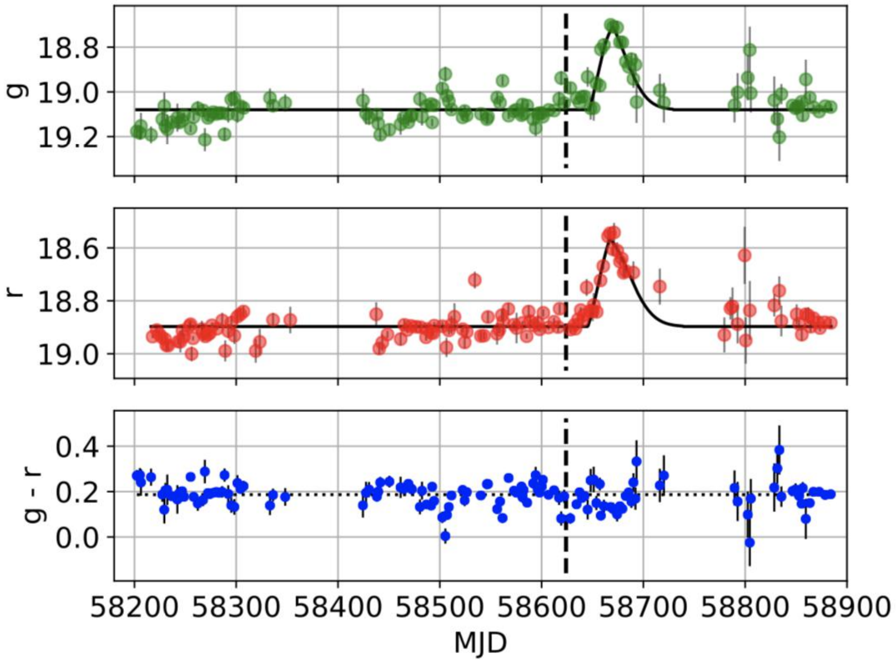
PHYSICAL REVIEW LETTERS **124,** 251102 (2020)

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?

nature astronomy

Article https://doi.org/10.1038/s41550-023-01998-8

A long-duration gamma-ray burst of dynamical origin from the nucleus of an ancient galaxy

Received: 9 February 2023

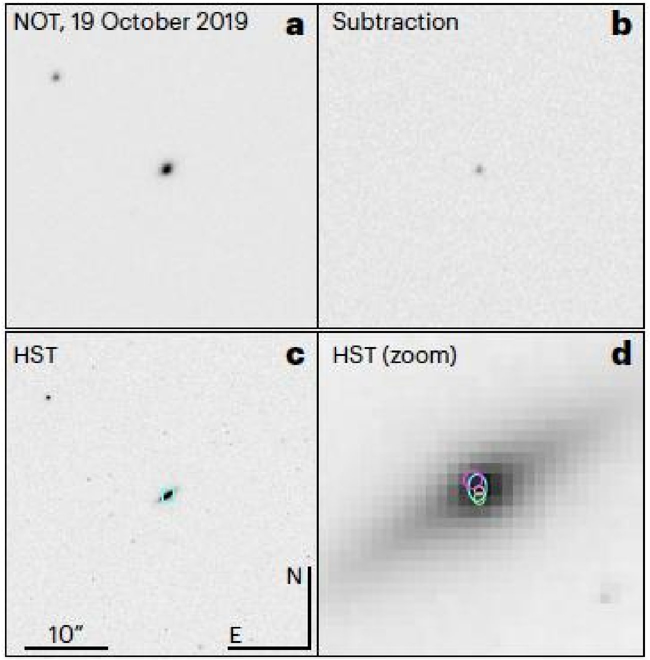
Accepted: 5 May 2023

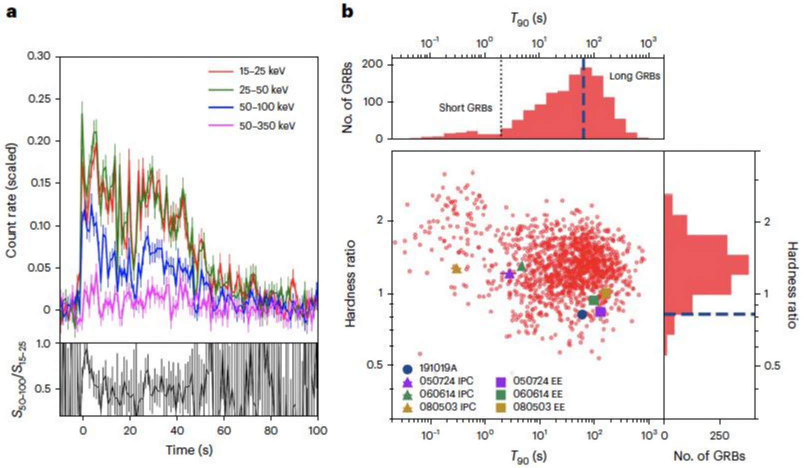
Published online: 22 June 2023

Check for updates

Andrew J. Levan[1,2], Daniele B. Malesani[1,3,4,5], Benjamin P. Gompertz[6], Anya E. Nugent[7], Matt Nicholl[6], Samantha R. Oates[6], Daniel A. Perley[8], Jillian Rastinejad[7], Brian D. Metzger[9,10], Steve Schulze[11], Elizabeth R. Stanway[2], Anne Inkenhaag[1,12], Tayyaba Zafar[13,14], J. Feliciano Agüí Fernández[15], Ashley A. Chrimes[1], Kornpob Bhirombhakdi[16], Antonio de Ugarte Postigo[17], Wen-fai Fong[7], Andrew S. Fruchter[16], Giacomo Fragione[7], Johan P. U. Fynbo[3,4], Nicola Gaspari[1], Kasper E. Heintz[3,4], Jens Hjorth[18], Pall Jakobsson[19], Peter G. Jonker[1,12], Gavin P. Lamb[8,20], Ilya Mandel[21,22], Soheb Mandhai[23], Maria E. Ravasio[1,24], Jesper Sollerman[25] & Nial R. Tanvir[20]

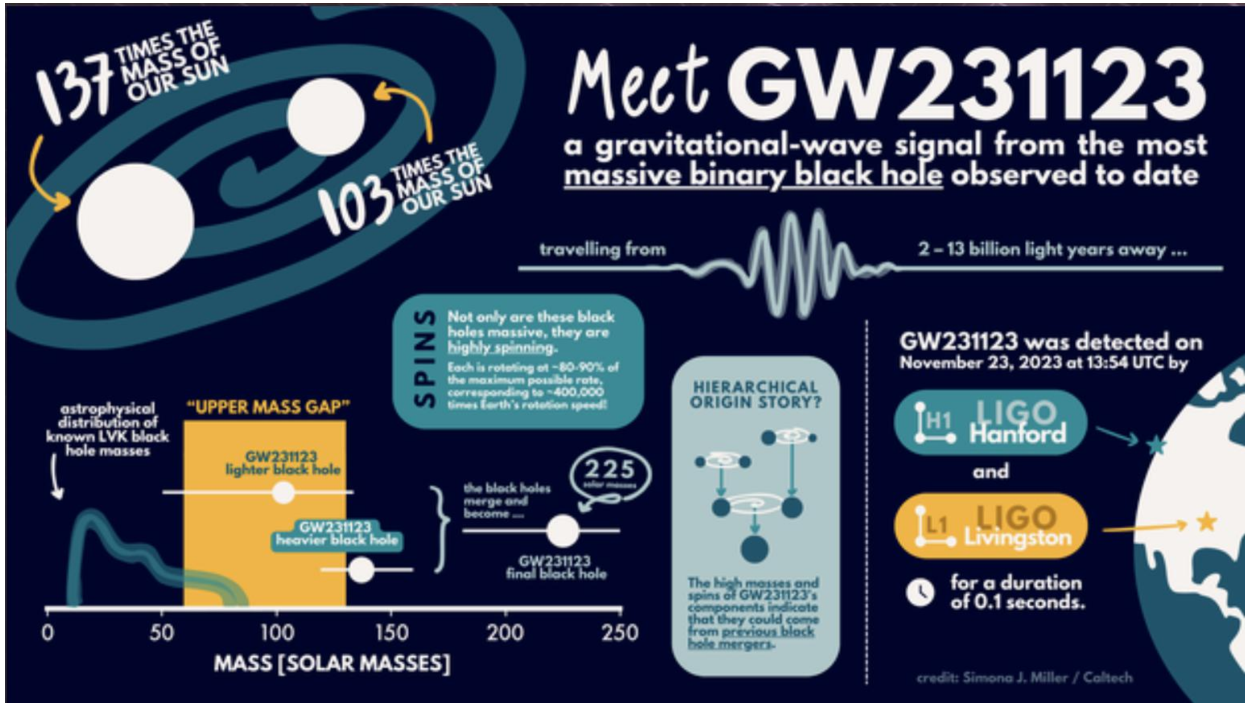
The majority of long-duration (>2 s) gamma-ray bursts (GRBs) arise from the collapse of massive stars, with a small proportion created from the merger of compact objects. Most of these systems form via standard stellar evolution pathways. However, a fraction of GRBs may result from dynamical interactions in dense environments. These channels could also contribute substantially to the samples of compact object mergers detected as gravitational wave sources. Here we report the case of GRB 191019A, a long GRB (a duration of $T_{90} = 64.4 \pm 4.5$ s), which we pinpoint close (≲100 pc projected) to the nucleus of an ancient (>1 Gyr old) host galaxy at $z = 0.248$. The lack of evidence for star formation and deep limits on any supernova emission disfavour a massive star origin. The most likely route for progenitor formation is via dynamical interactions in the dense nucleus of the host. The progenitor, in this case, could be a compact object merger. These may form in dense nuclear clusters or originate in a gaseous disc around the supermassive black hole. Identifying, to the best of our knowledge, a first example of a dynamically produced GRB demonstrates the role that such bursts may have in probing dense environments and constraining dynamical fractions in gravitational wave populations.

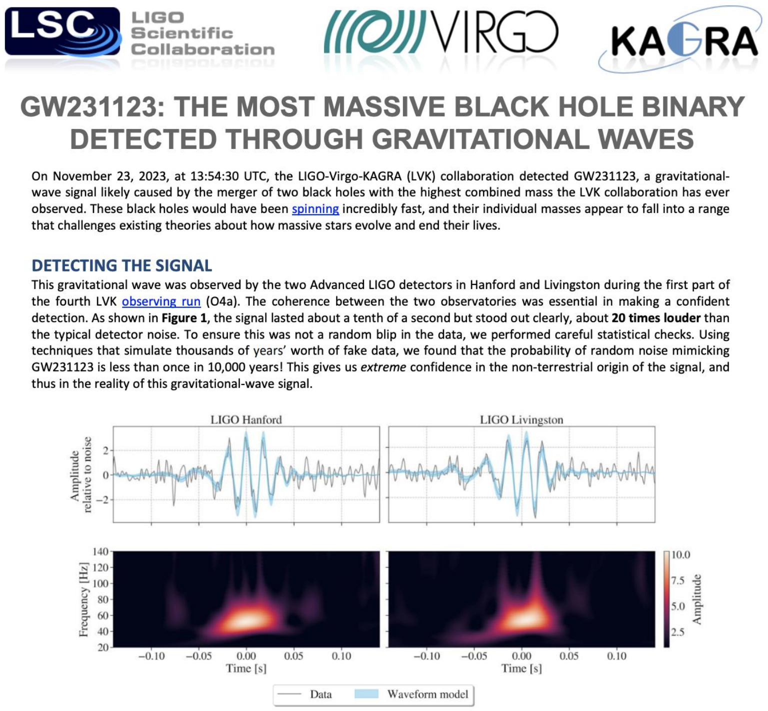




LIGO detection: June 15, 2025

Origin: ?





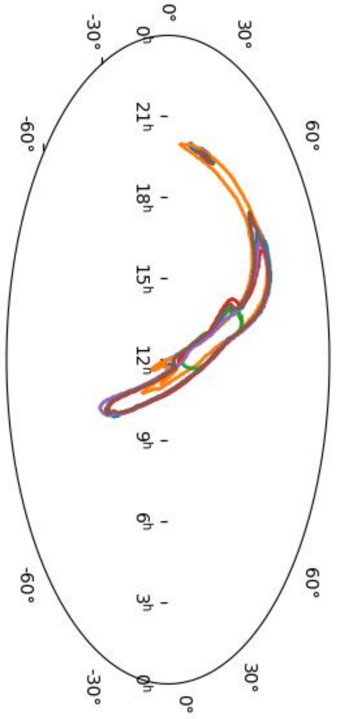
LSC LIGO Scientific Collaboration VIRGO KAGRA

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

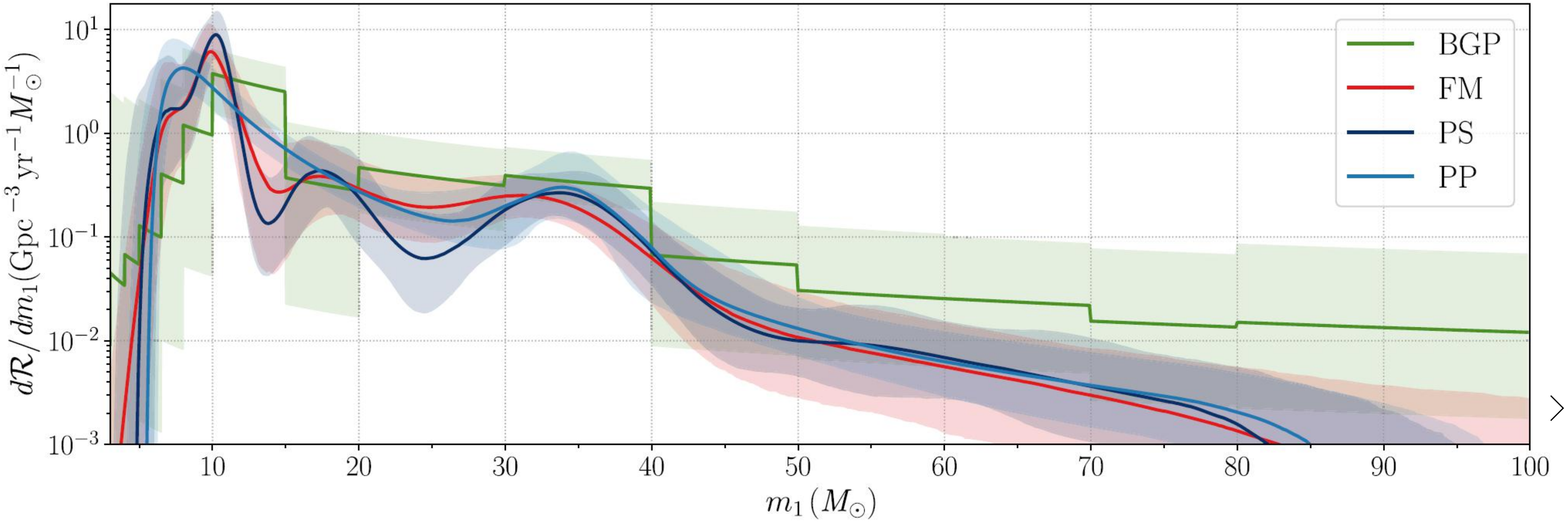
On November 23, 2023, at 13:54:30 UTC, the LIGO-Virgo-KAGRA (LVK) collaboration detected GW231123, a gravitational-wave signal likely caused by the merger of two black holes with the highest combined mass the LVK collaboration has ever observed. These black holes would have been spinning incredibly fast, 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.

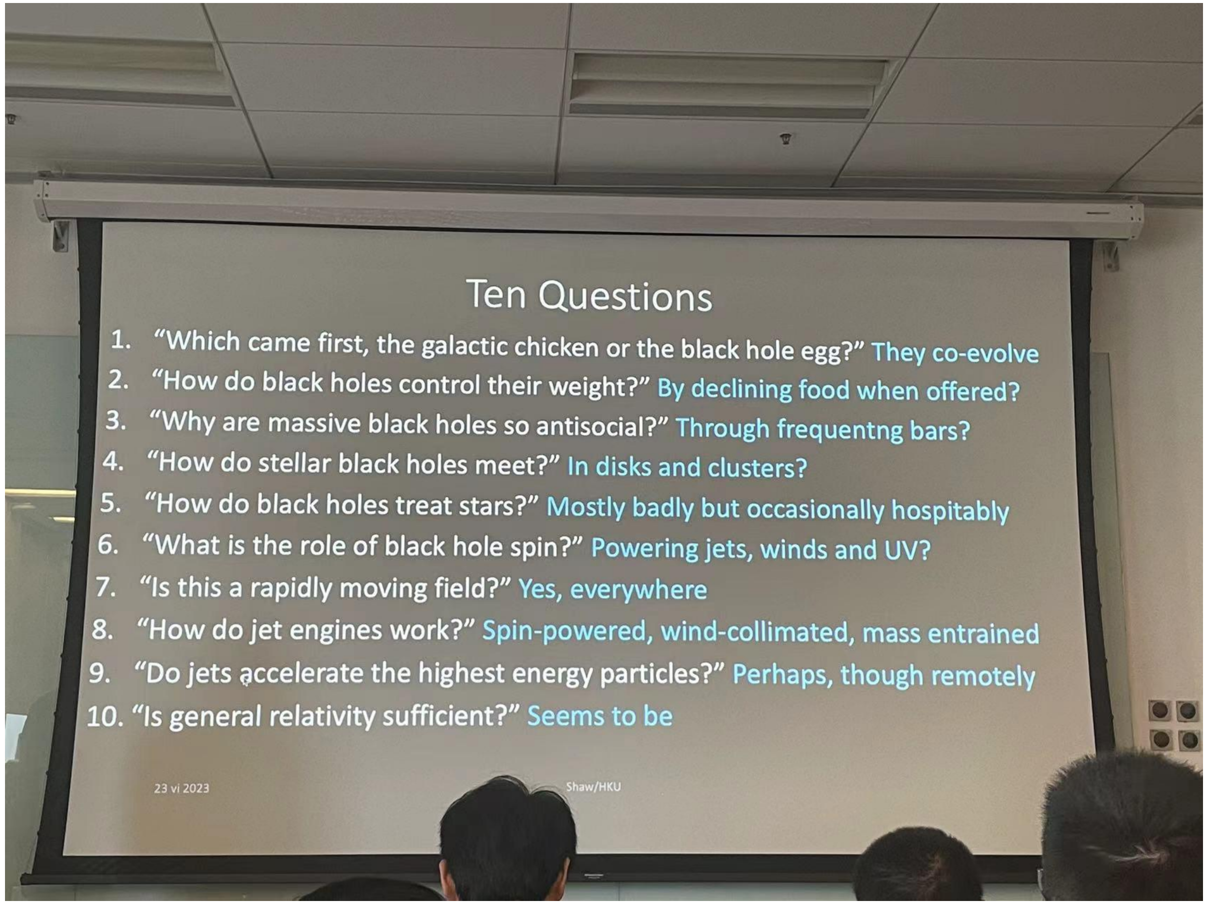


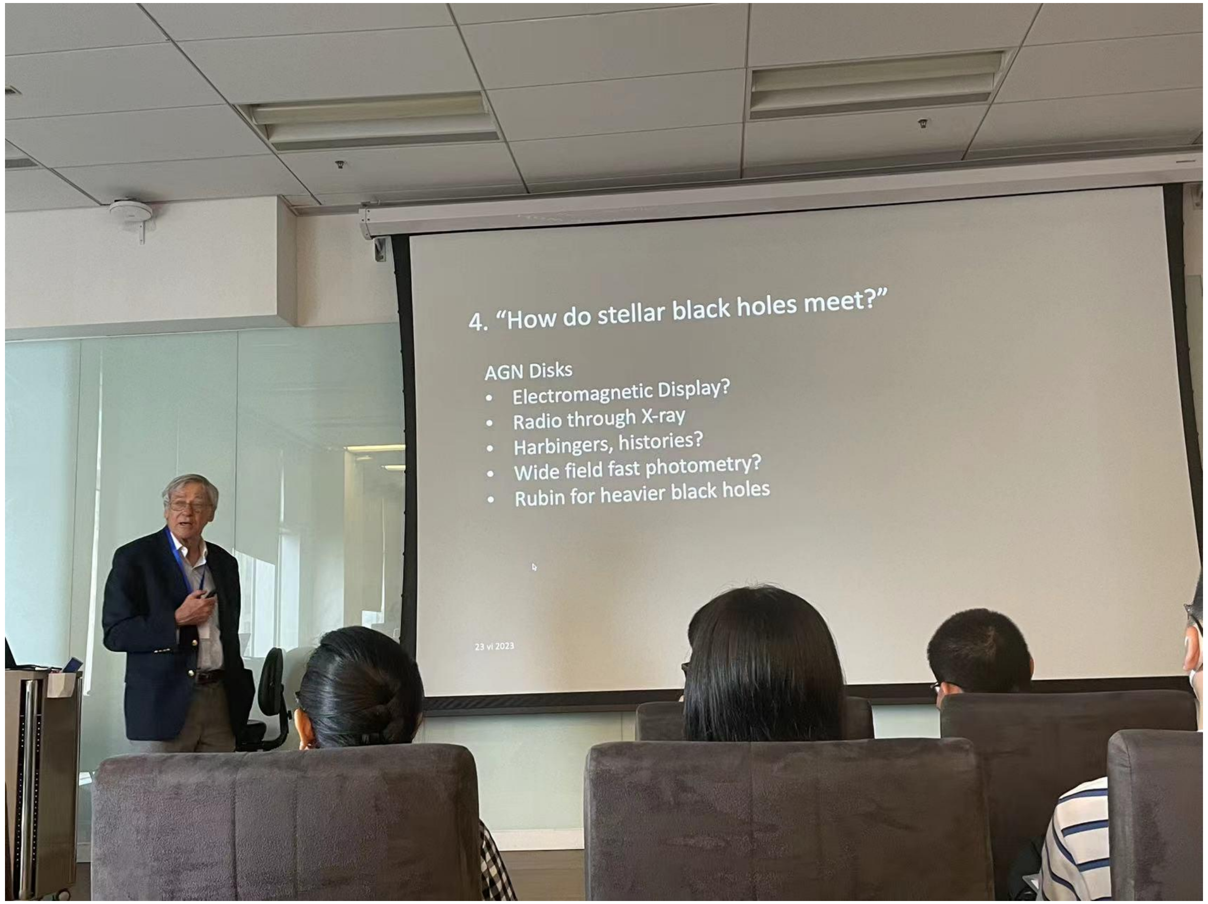
BH mass function detected by LIGO



$>100 M_\odot$

In Hongkong, June, 2023





SMBH-accretion disk：
mergers of compact objects and GWs

THE ASTROPHYSICAL JOURNAL, 521:502–508, 1999 August 20

THE FORMATION AND MERGER OF COMPACT OBJECTS IN THE CENTRAL ENGINE OF ACTIVE GALACTIC NUCLEI AND QUASARS: GAMMA-RAY BURST AND GRAVITATIONAL RADIATION

K. S. CHENG
Physics Department, University of Hong Kong, Hong Kong, People's Republic of China

AND

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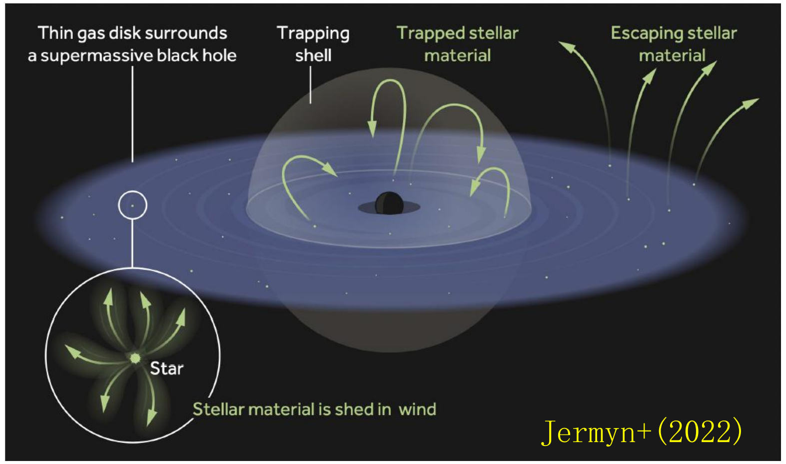
Received 1998 October 7; accepted 1999 April 1

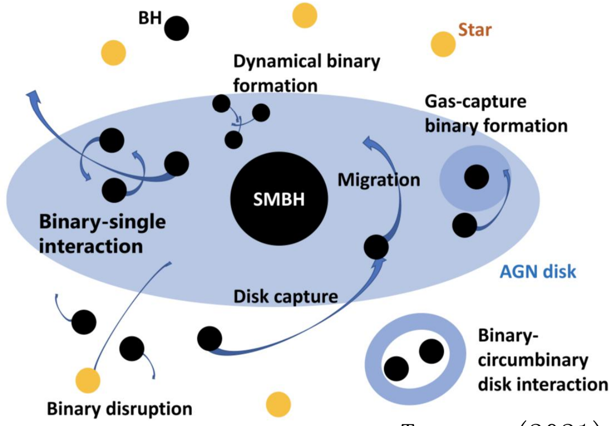
Fast rising field： stars and BHs in AGN-disk

evolutions of massive stars

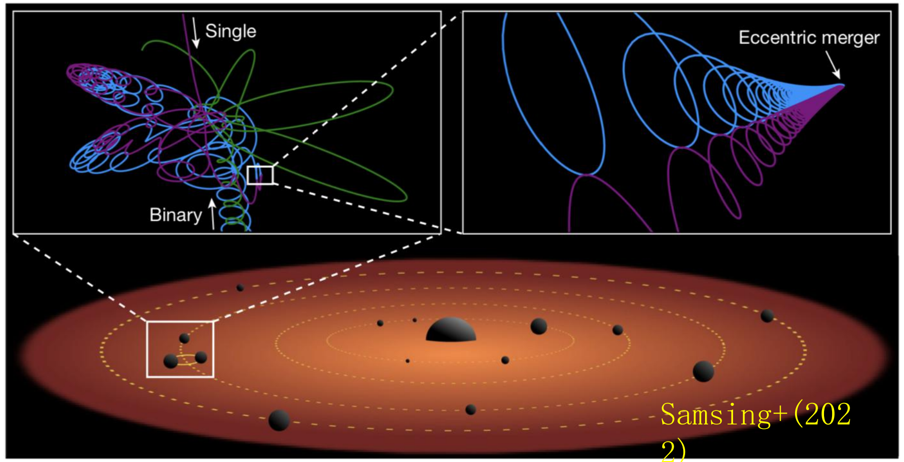
binaries of compact objects



Jermyn+(2022)



Tagawa+(2021)



Samsing+(2022)

Many questions: challenges and opportunities

1040 NATURE March 16, 1963 Vol. 197

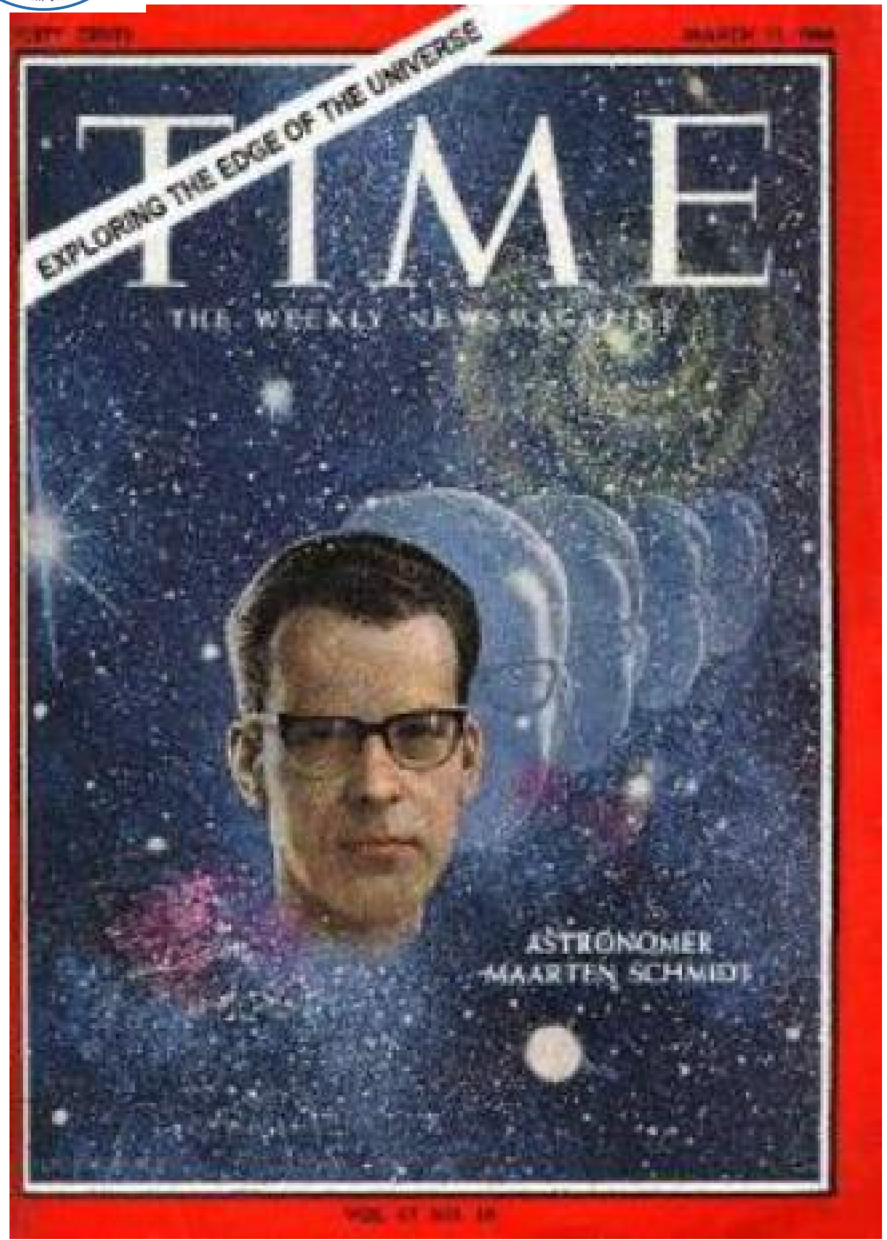
3C 273 : A STAR-LIKE OBJECT WITH LARGE RED-SHIFT

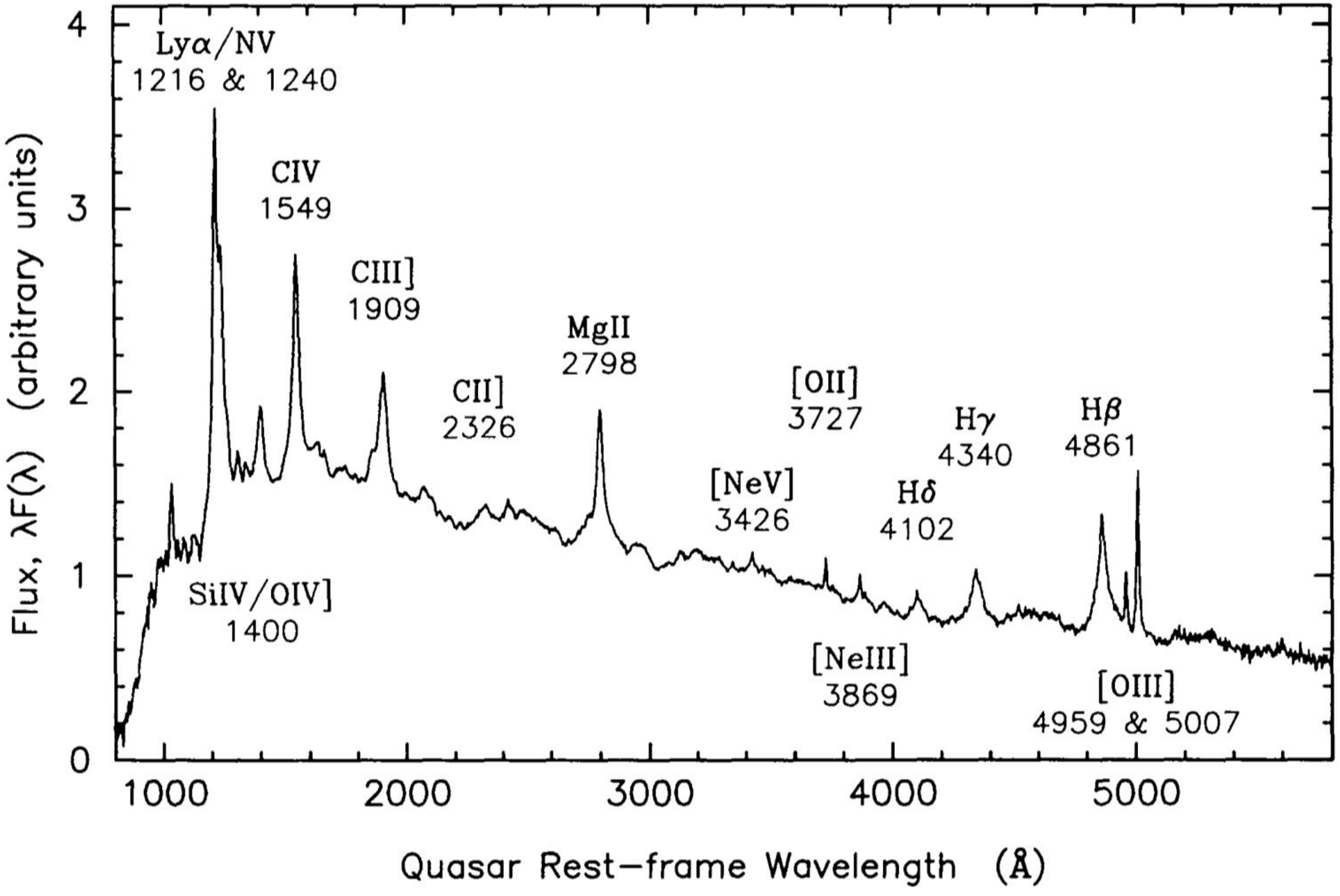
By Dr. M. SCHMIDT

Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena

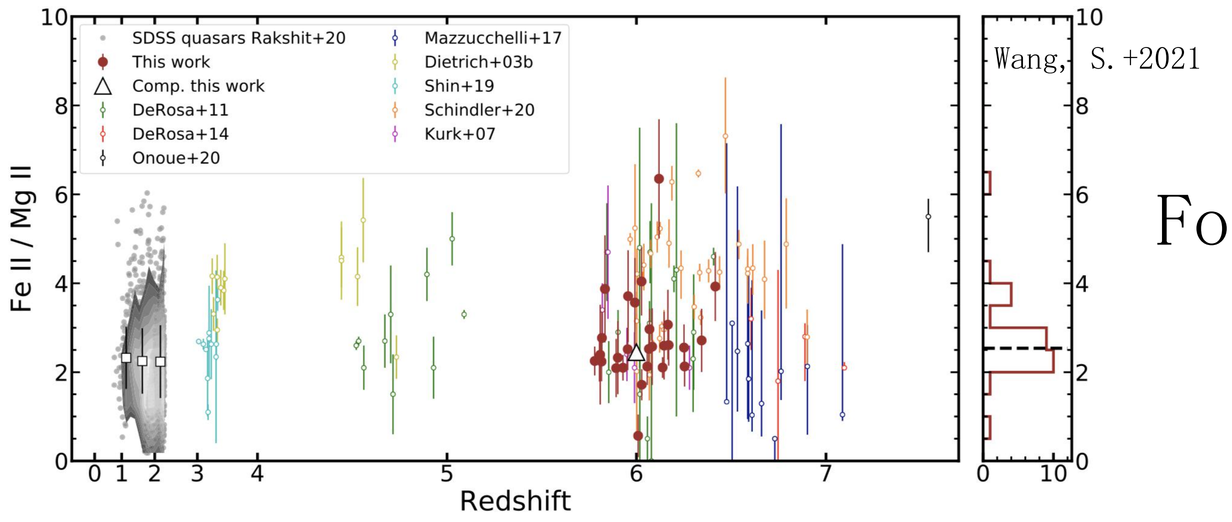
SMBH basic parameters:

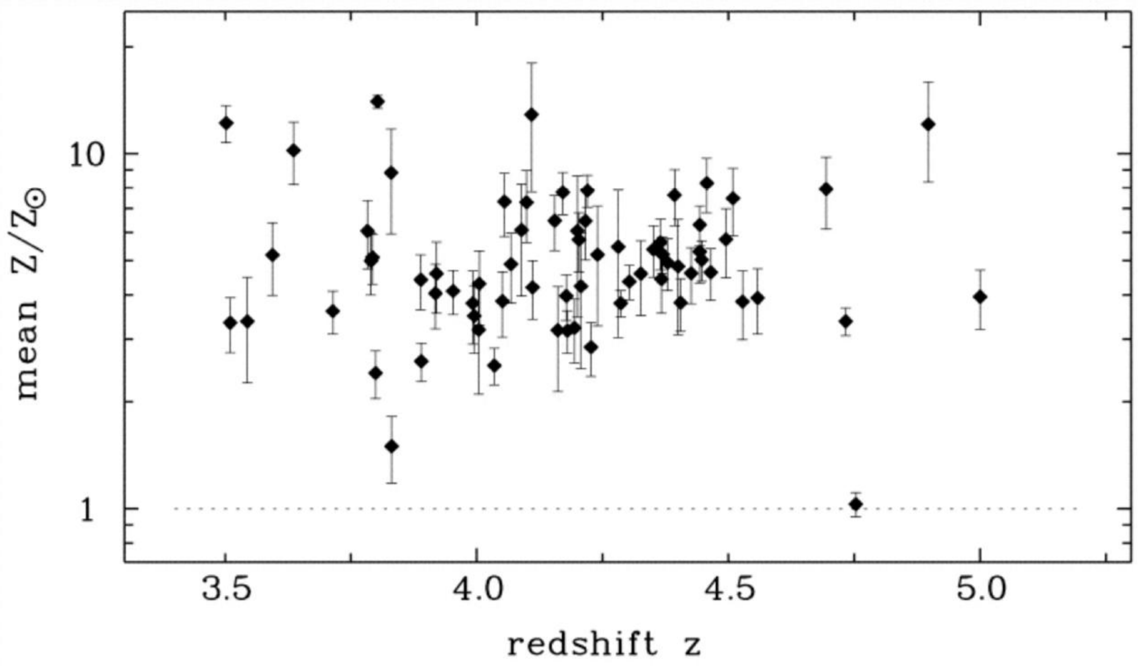
Masses, accretion rates and metallicity





Metallicity of quasars: cosmic evolution?

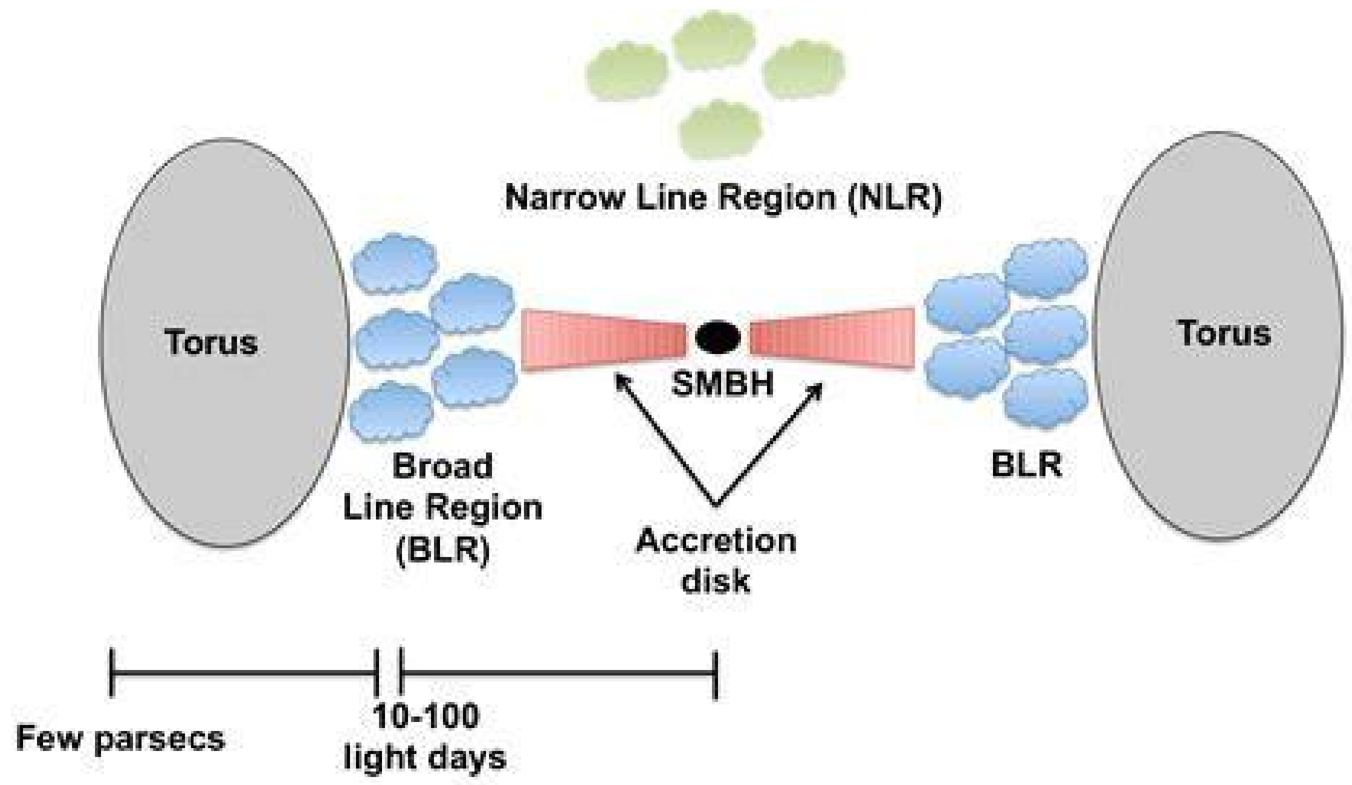


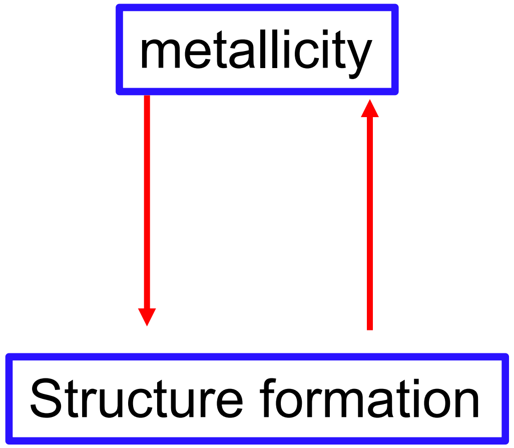


Formation and evolution of stars:

- AGN structure
- metallicity
- Compact objects
- Gravitational waves

AGN structure: how to form?





AGN structure: standard model correct?

Formation and Evolution of Stars

科学通报 CHINESE SCIENCE BULLETIN (KEXUE TONGBAO) (旬刊) 目次
70卷 第2期 2025年1月20日 www.scichina.com csb.scichina.com

超大质量黑洞吸积盘中恒星的形成和演化专题

目次 科学通报 CHINESE SCIENCE BULLETIN

OURNAL, 409:592–603, 1993 June 1

STAR TRAPPING AND METALLICITY ENRICHMENT IN QUASARS AND ACTIVE GALACTIC NUCLEI[1]

PAWEŁ ARTYMOWICZ,[2,3] D. N. C. LIN,[2,4] AND E. JOSEPH WAMPLER[5]

Received 1992 August 3; accepted 1992 December 7

THE ASTROPHYSICAL JOURNAL, 910:94 (22pp), 2021 April 1
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Stellar Evolution in AGN Disks

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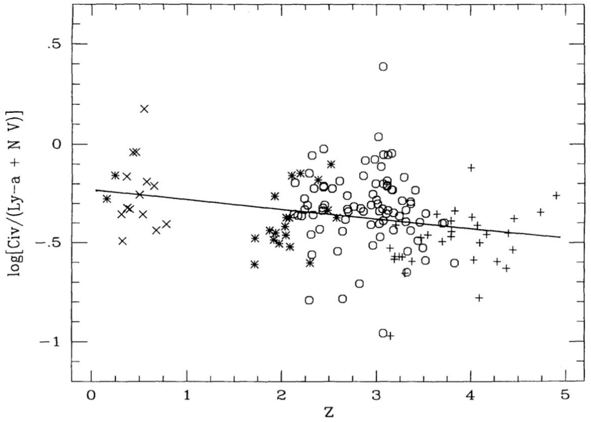
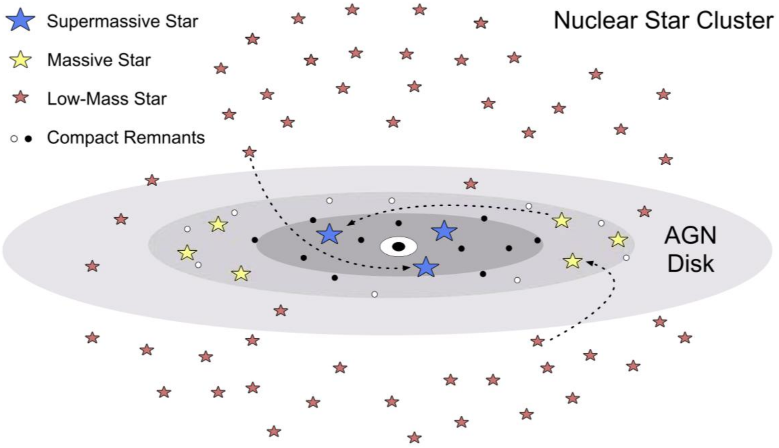
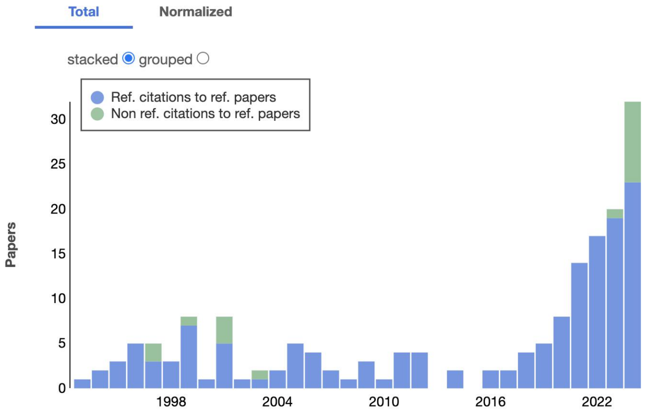
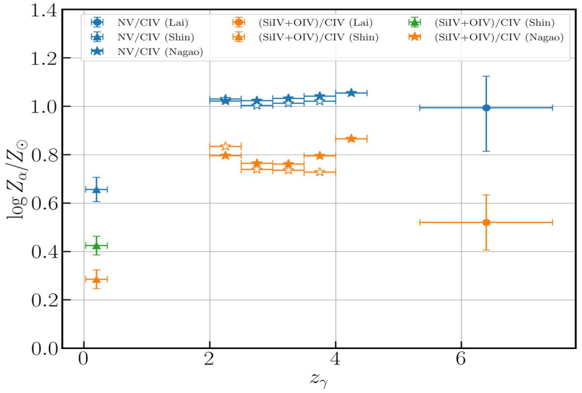
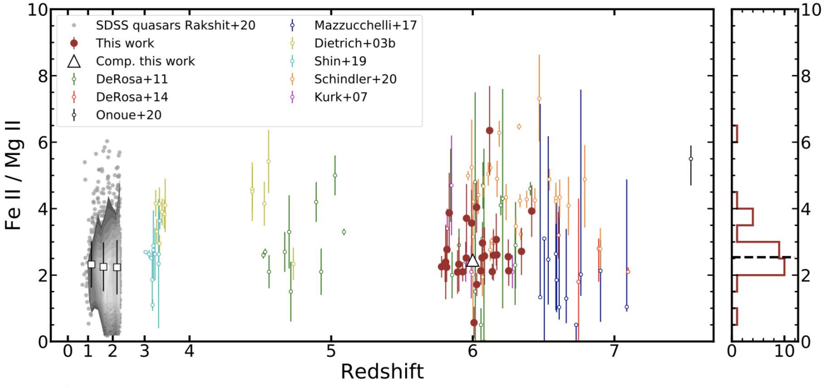
[4] Institute for Advanced Studies, Tsinghua University, Beijing, 100086, People's Republic of China
Received 2020 September 8; revised 2021 January 13; accepted 2021 January 17; published 2021 March 30











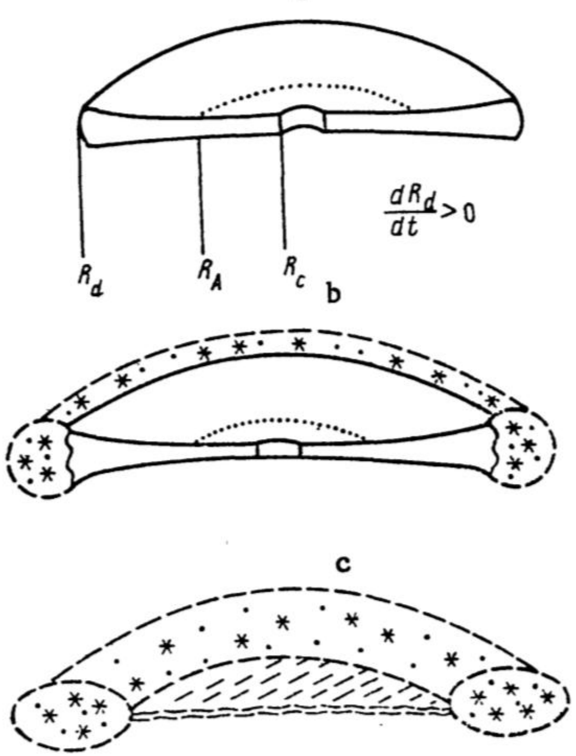
The outer parts of the accretion disks around supermassive black holes in galaxy nuclei and quasars

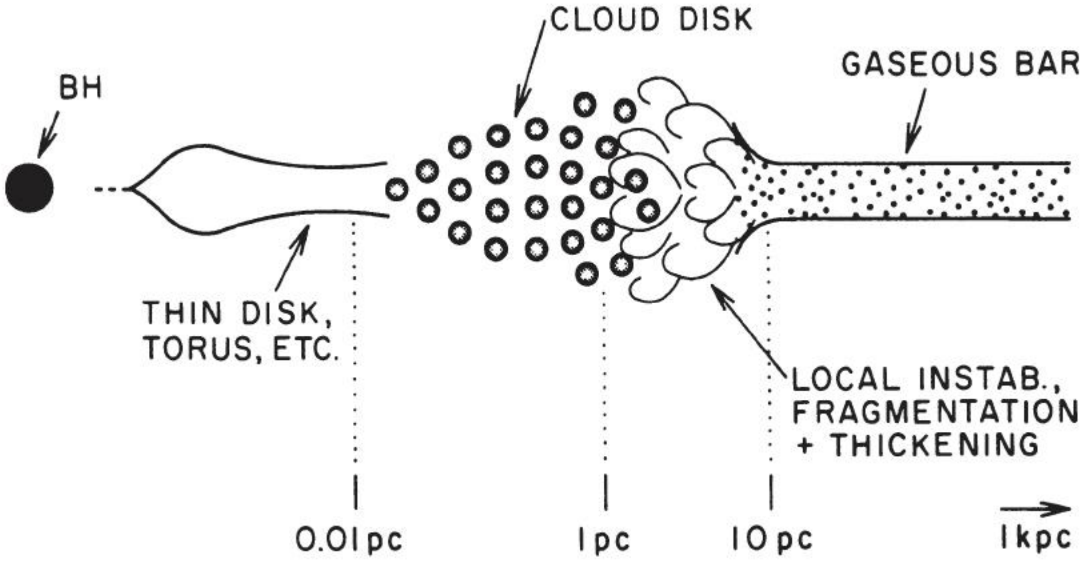
P. I. Kolykhalov and R. A. Syunyaev

Institute for Space Research, USSR Academy of Sciences, Moscow

(Submitted August 15, 1980)

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





Begelman+(1989)

First idea: compact objects in SMBH-disk？

THE ASTROPHYSICAL JOURNAL, 521:502–508, 1999 August 20

THE FORMATION AND MERGER OF COMPACT OBJECTS IN THE CENTRAL ENGINE OF ACTIVE GALACTIC NUCLEI AND QUASARS: GAMMA-RAY BURST AND GRAVITATIONAL RADIATION

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AND

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Monthly Notices of the Royal Astronomical Society LETTERS

Mon. Not. R. Astron. Soc. **417,** L103–L107 (2011) doi:10.1111/j.1745-3933.2011.01132.x

On rapid migration and accretion within discs around supermassive black holes

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Monthly Notices of the Royal Astronomical Society

Mon. Not. R. Astron. Soc. **425,** 460–469 (2012) doi:10.1111/j.1365-2966.2012.21486.x

Intermediate mass black holes in AGN discs – I. Production and growth

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The Astrophysical Journal, 835:165 (9pp), 2017 February 1 doi:10.3847/1538-4357/835/2/165

CrossMark

Rapid and Bright Stellar-mass Binary Black Hole Mergers in Active Galactic Nuclei

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Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **498,** 4088–4094 (2020) doi:10.1093/mnras/staa2681
Advance Access publication 2020 September 07

Black hole, neutron star, and white dwarf merger rates in AGN discs

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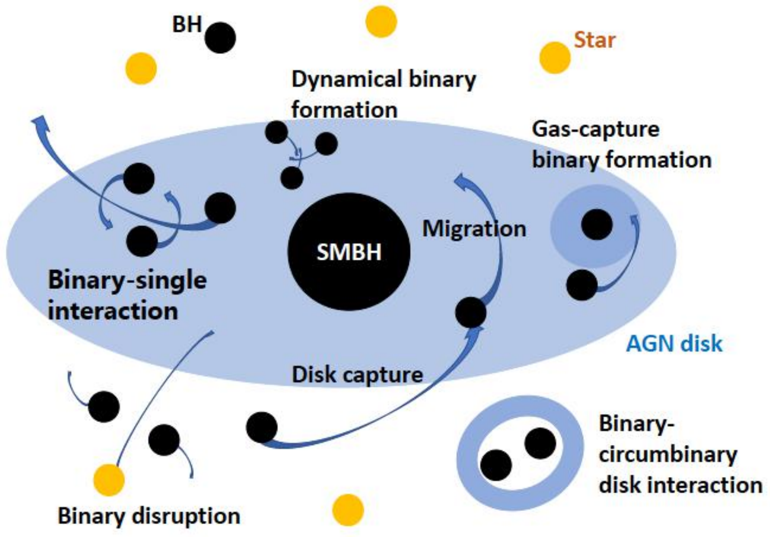

ABSTRACT

Advanced LIGO and Advanced Virgo are detecting a large number of binary stellar origin black hole (BH) mergers. A promising channel for accelerated BH merger lies in active galactic nucleus (AGN) discs of gas around supermasssive BHs. Here, we investigate the relative number of compact object (CO) mergers in AGN disc models, including BH, neutron stars (NS), and white dwarfs, via Monte Carlo simulations. We find the number of all merger types in the bulk disc grows $\propto t^{1/3}$ which is driven by the Hill sphere of the more massive merger component. Median mass ratios of NS–BH mergers in AGN discs are $\tilde{q} = 0.07 \pm 0.06(0.14 \pm 0.07)$ for mass functions (MF) $M^{-1(-2)}$. If a fraction $f_{\rm AGN}$ of the observed rate of BH–BH mergers ($R_{\rm BH-BH}$) come from AGN, the rate of NS–BH (NS–NS) mergers in the AGN channel is $R_{\rm BH-NS} \sim f_{\rm AGN}[10, 300]\,{\rm Gpc}^{-3}\,{\rm yr}^{-1}$, ($R_{\rm NS-NS} \leq f_{\rm AGN}400\,{\rm Gpc}^{-3}\,{\rm yr}^{-1}$). Given the ratio of NS–NS/BH–BH LIGO search volumes, from preliminary O3 results the AGN channel is not the dominant contribution to observed NS–NS mergers. The number of lower mass gap events expected is a strong function of the nuclear MF and mass segregation efficiency. CO merger ratios derived from LIGO can restrict models of MF, mass segregation, and populations embedded in AGN discs. The expected number of electromagnetic (EM) counterparts to NS–BH mergers in AGN discs at $z < 1$ is $\sim [30, 900]\,{\rm yr}^{-1}(f_{\rm AGN}/0.1)$. EM searches for flaring events in large AGN surveys will complement LIGO constraints on AGN models and the embedded populations that must live in them.

ophysical Journal Letters, 719:L148–L152, 2010 August 20 doi:10.1088/2041-8205/719/2/L148

The Astrophysical Journal, 739:3 (11pp), 2011 September 20 doi:10.1088/0004-637X/739/1/3

The Astrophysical Journal, 746:137 (27pp), 2012 February 20 doi:10.1088/0004-637X/746/2/137

STAR FORMATION IN SELF-GRAVITATING DISKS IN ACTIVE GALACTIC NUCLEI. II. EPISODIC FORMATION OF BROAD-LINE REGIONS

The Astrophysical Journal, 954:84 (33pp), 2023 September 1 https://doi.org/10.3847/1538-4357/acdf48

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Star Formation in Self-gravitating Disks in Active Galactic Nuclei. III. Efficient Production of Iron and Infrared Spectral Energy Distributions

Jian-Min Wang[1,2,3], Shuo Zhai[1,4], Yan-Rong Li[1], Yu-Yang Songsheng[1], Luis C. Ho[5,6], Yong-Jie Chen[1,4], Jun-Rong Liu[1,4], Pu Du[1], and Ye-Fei Yuan[7]

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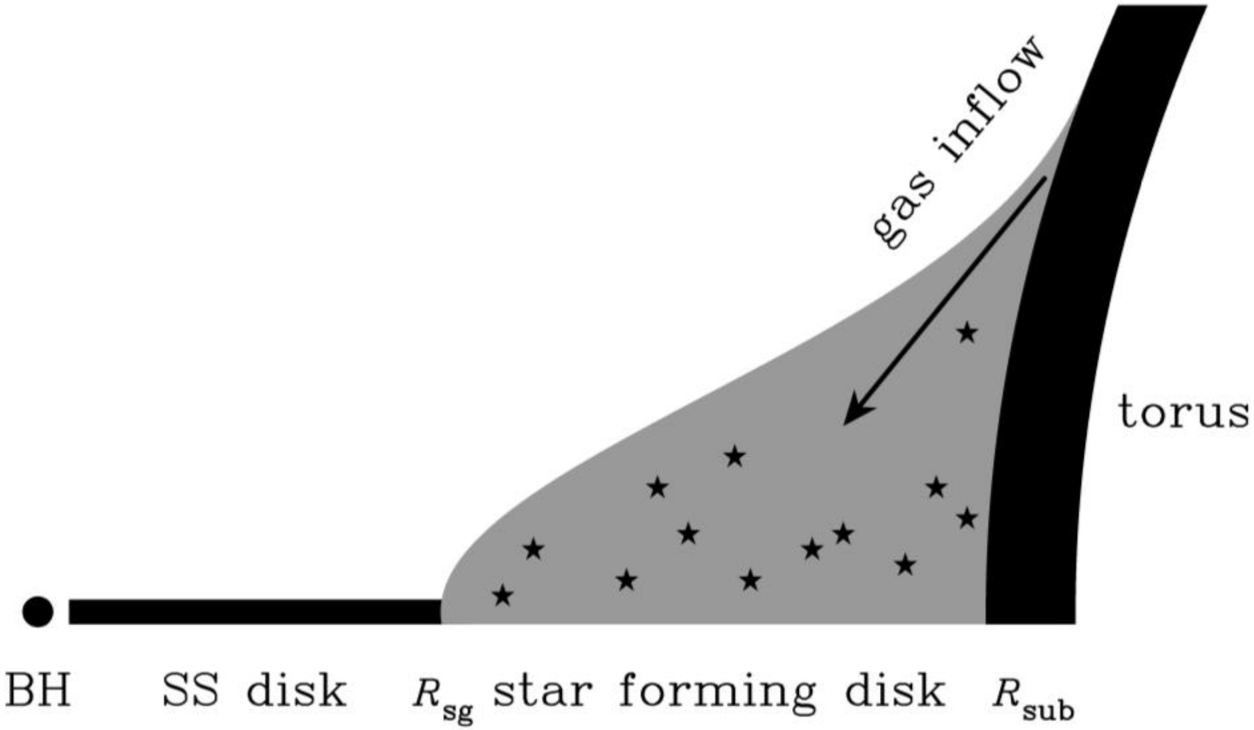
Received 2023 January 31; revised 2023 May 25; accepted 2023 June 15; published 2023 August 24

Accretion rates: nuclear starburst

(Wang+2010, ApJ, 719, L48)



Continuity equation:

$$\frac{\partial \Sigma_{gas}}{\partial t} = \frac{1}{2\pi R}\frac{\partial}{\partial R}\left\{\left[\frac{d\left(R^2\Omega\right)}{dR}\right]^{-1}\frac{\partial \mathcal{G}}{\partial R}\right\} - \dot{\Sigma}_* + \dot{\Sigma}_{SN},$$

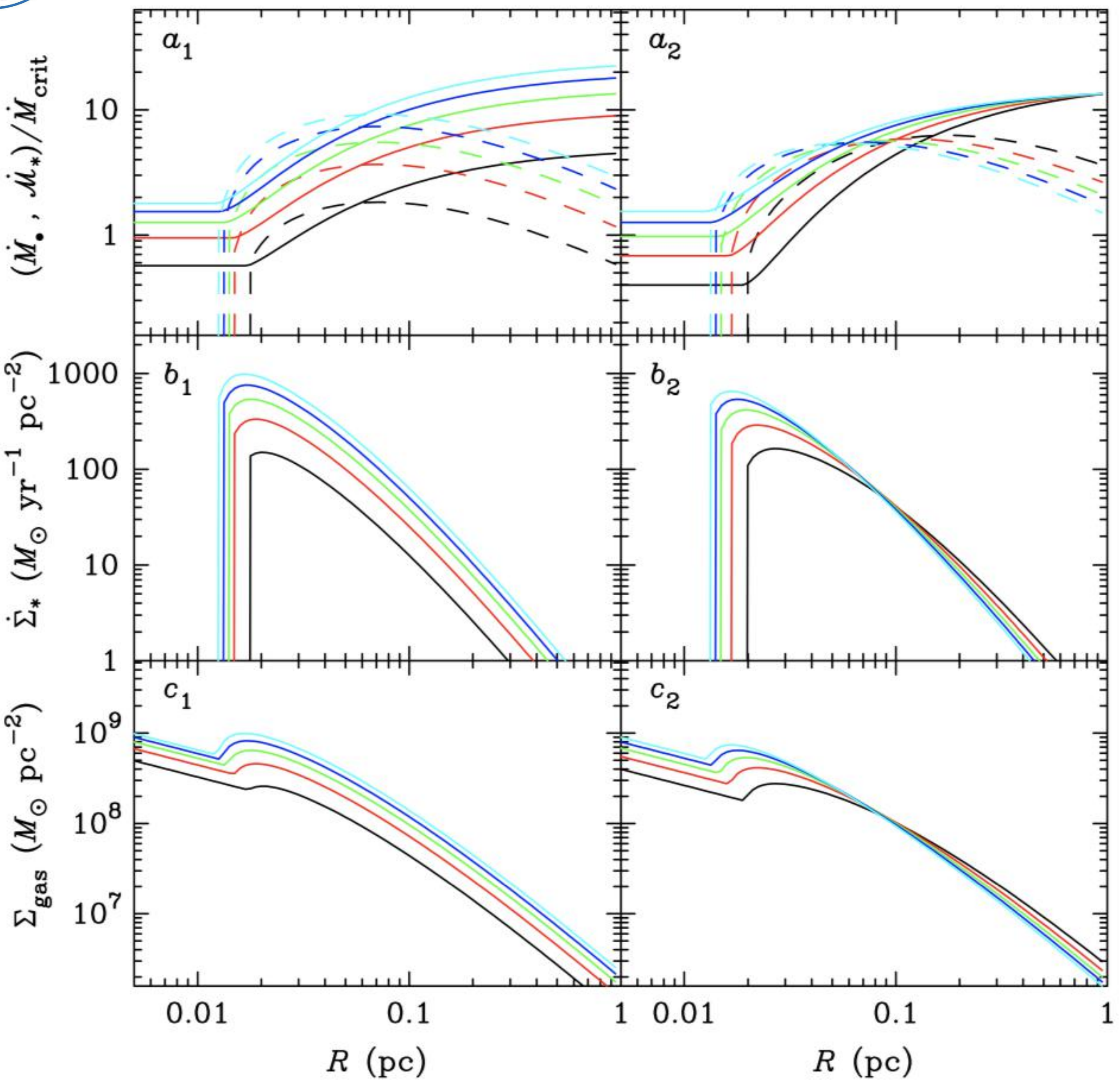
Vertical equilibrium:

$$\frac{P_{tur}}{H} = \left(\frac{GM_\bullet}{R^3}H + 2\pi G\Sigma_{gas}\right)\rho_{gas} \approx \Omega_K^2 H\rho_{gas}.$$

Energy equation:

$$\frac{\rho_{gas}V_{tur}^2}{t_{dis}} = \frac{\rho_{gas}V_{tur}^3}{H} = \epsilon f_* \dot{\rho}_* E_{SN},$$

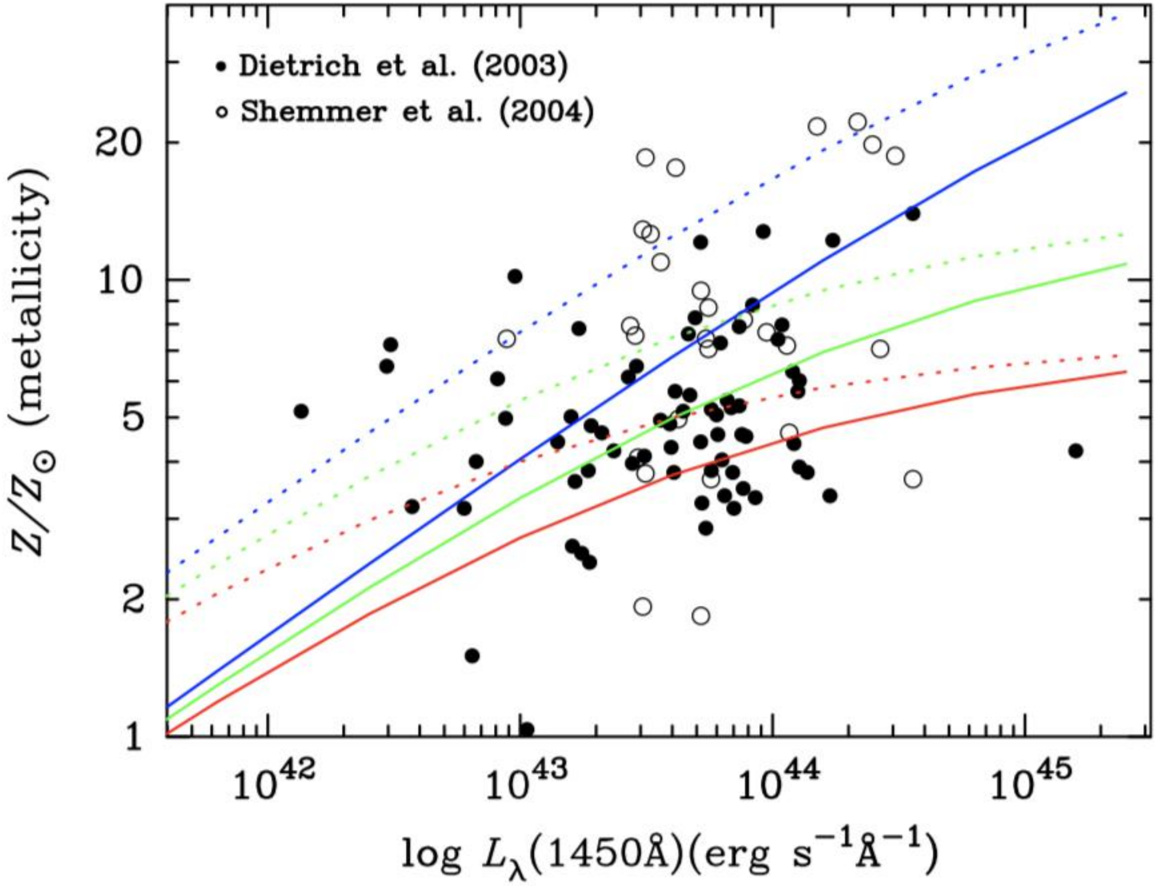
Analytical solution



$$\dot{M}_{\rm gas} \sim \dot{M}_{\rm star} \sim 10\ M_\odot\ {\rm yr}^{-1}$$

$$\dot{M}_{\rm SMBH} \sim 1\ M_\odot\ {\rm yr}^{-1}$$

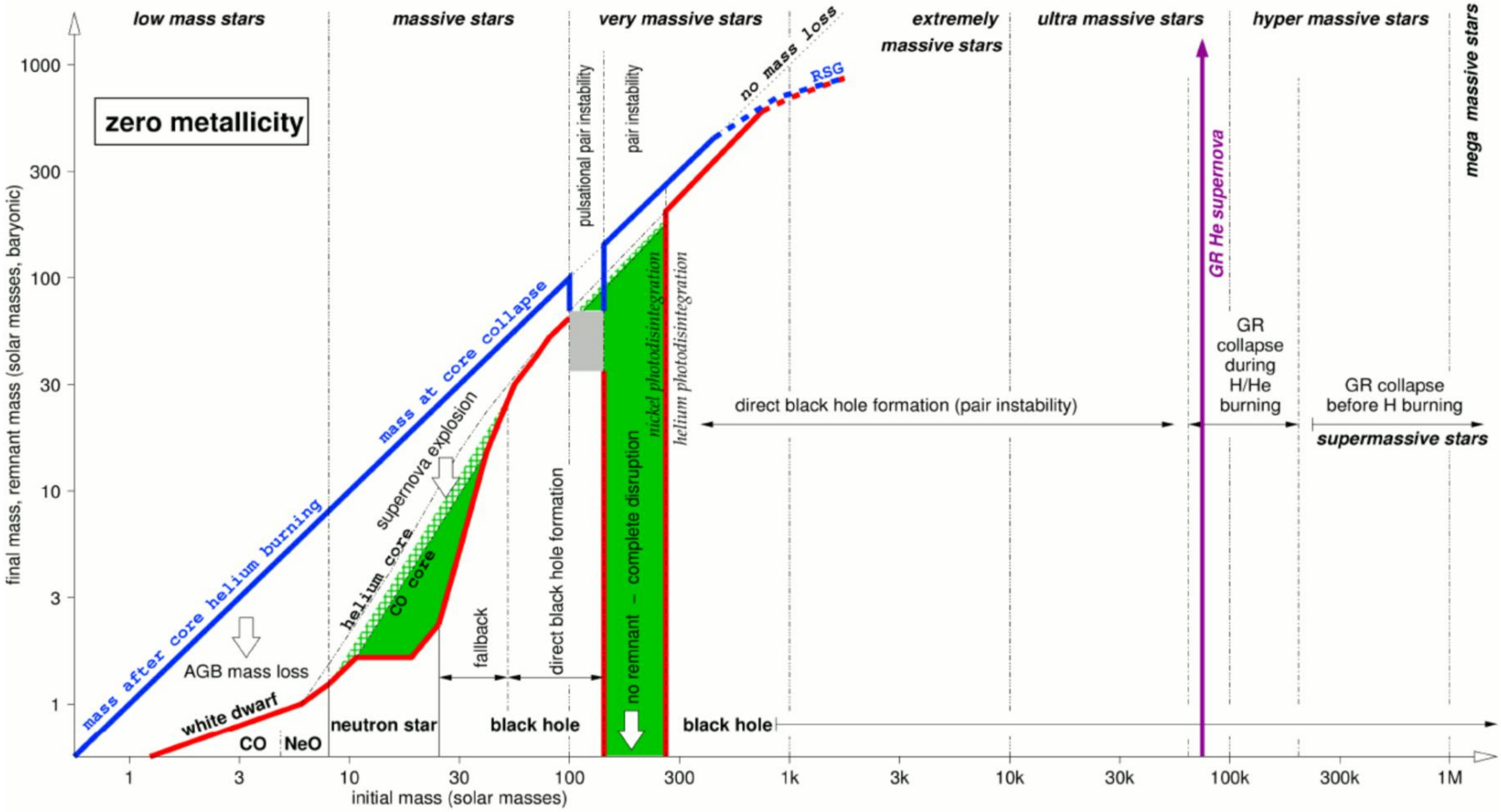
Metallicity and accretion rates



$$Z(t)M_{\rm gas}(t) = \int_0^t (Z_0\dot{M}_{\rm out} + f_c\dot{\mathcal{R}}_* m_Z - \varepsilon_1 Z\dot{M}_\bullet - \varepsilon_2 Z\dot{\mathcal{R}}_*)d\tau.$$

$$Z_{\rm max} = Z_0(1-\Lambda) + f_c(m_Z - Z_0)\Lambda \approx \frac{c_0 f_c m_Z}{\varepsilon_1 + \varepsilon_2 c_0 \dot{M}_\bullet^{0.4}}\dot{M}_\bullet^{0.4},$$

Where are compact objects?

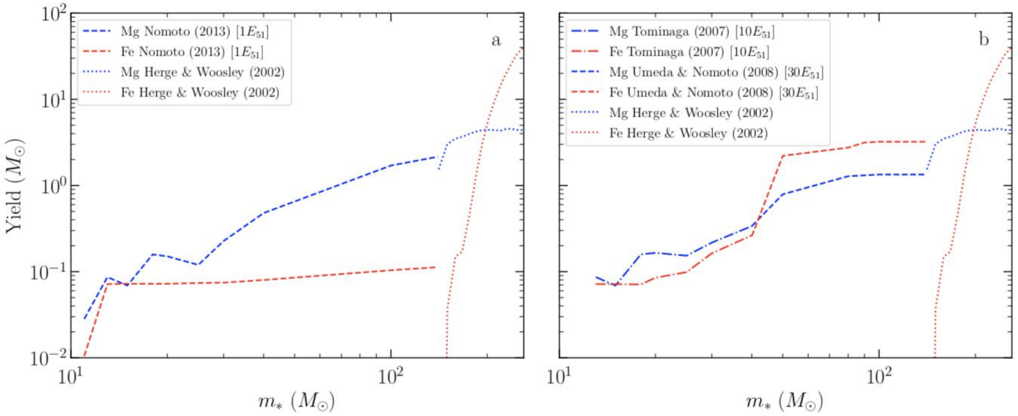

zero metallicity
low mass stars
massive stars
very massive stars
extremely massive stars
ultra massive stars
hyper massive stars
mega massive stars
supermassive stars
final mass, remnant mass (solar masses, baryonic)
initial mass (solar masses)
1000
300
100
30
10
3
1
1
3
10
30
100
300
1k
3k
10k
30k
100k
300k
1M
no mass loss
RSG
mass after core helium burning
mass at core collapse
supernova explosion
helium core
CO core
AGB mass loss
white dwarf
CO
NeO
neutron star
black hole
fallback
direct black hole formation
pulsational pair instability
pair instability
no remnant – complete disruption
nickel photodisintegration
helium photodisintegration
direct black hole formation (pair instability)
GR He supernova
GR collapse during H/He burning
GR collapse before H burning
black hole

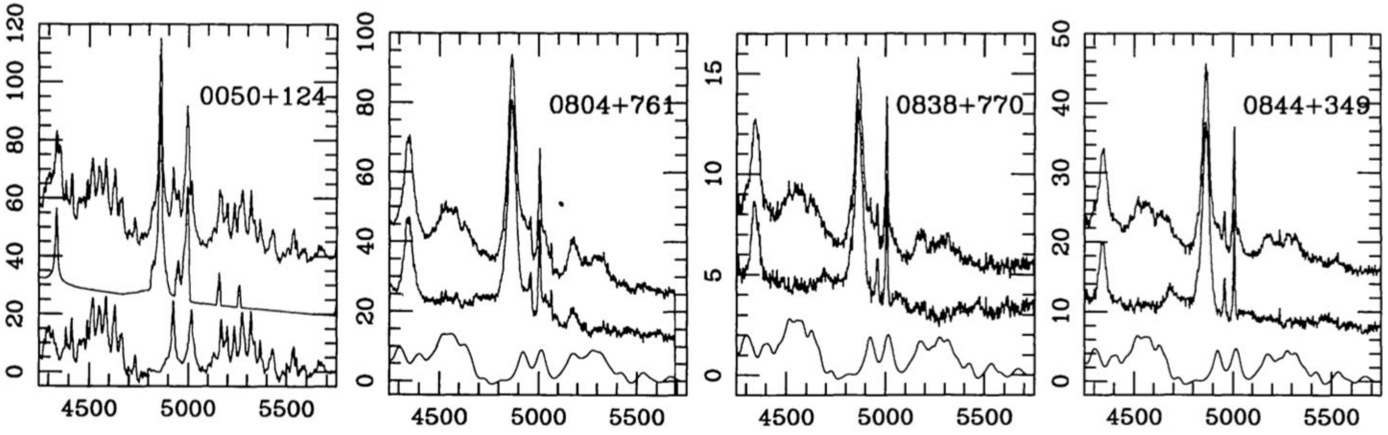
The Astrophysical Journal, 954:84 (33pp), 2023 September 1
https://doi.org/10.3847/1538-4357/acdf48

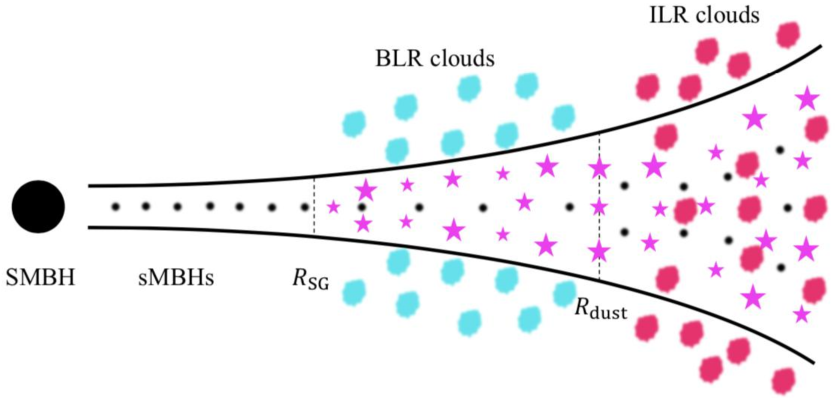
Star Formation in Self-gravitating Disks in Active Galactic Nuclei. III. Efficient Production of Iron and Infrared Spectral Energy Distributions

Jian-Min Wang[1,2,3], Shuo Zhai[1,4], Yan-Rong Li[1], Yu-Yang Songsheng[1], Luis C. Ho[5,6], Yong-Jie Chen[1,4], Jun-Rong Liu[1,4], Pu Du[1], and Ye-Fei Yuan[7]

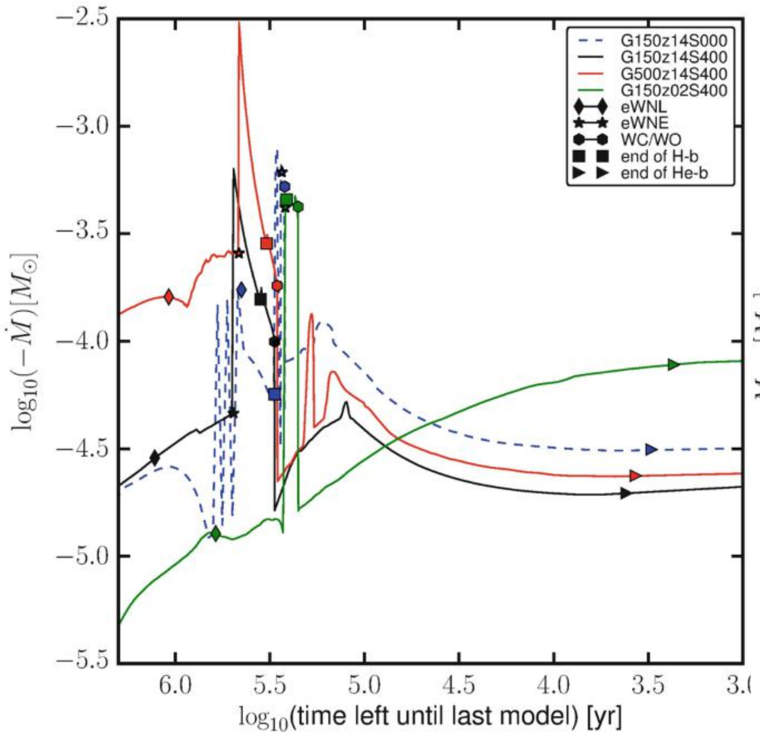
Iron production

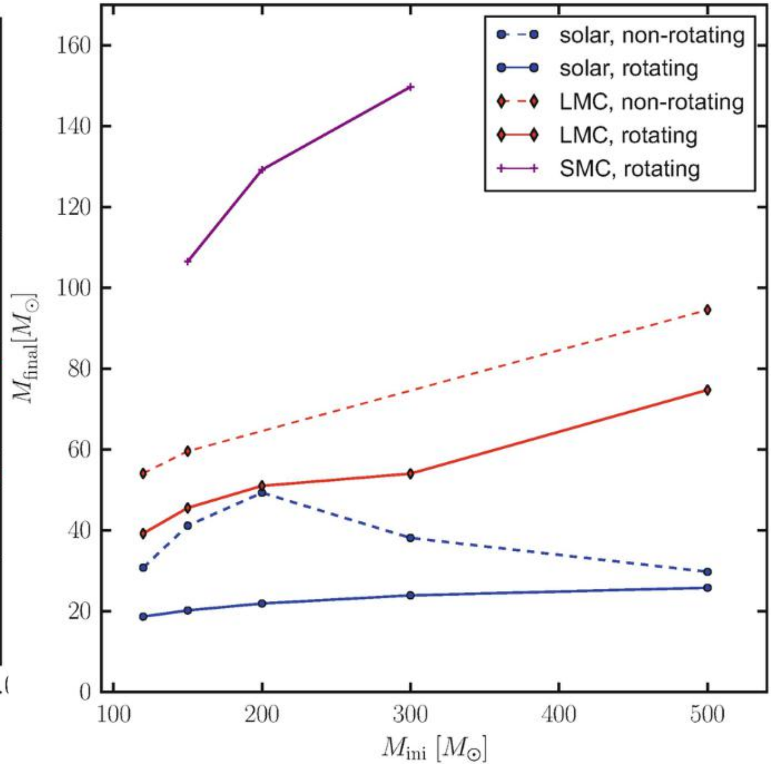


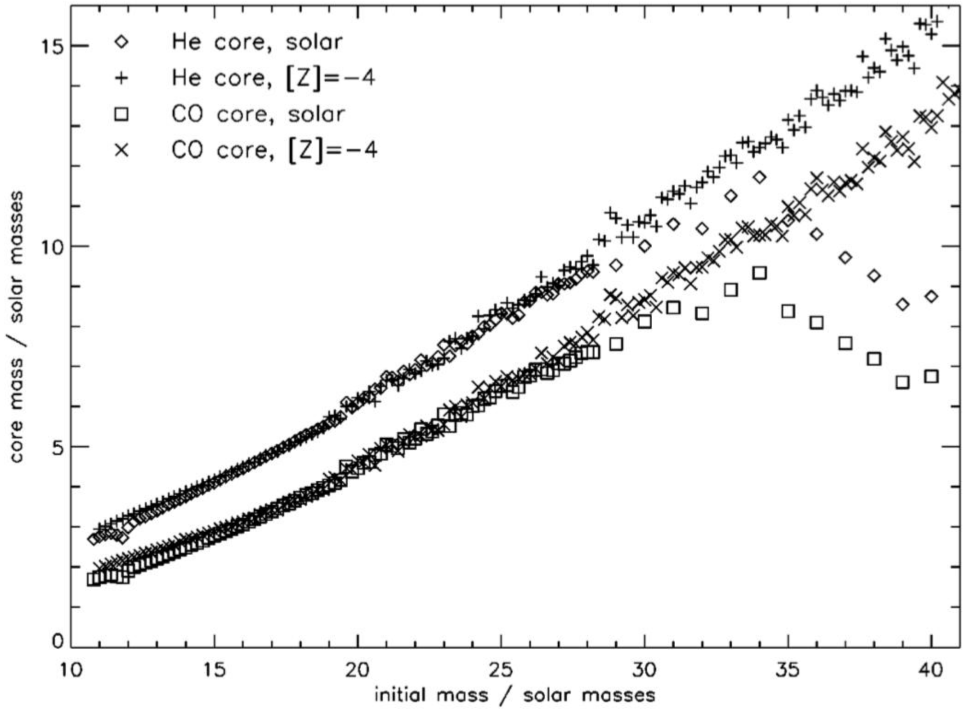




大质量恒星星风与演化：金属丰度







Hirschi(2017)； Yusolf+(2022) Woosley& Heger (2002)

如何描述星族演化？

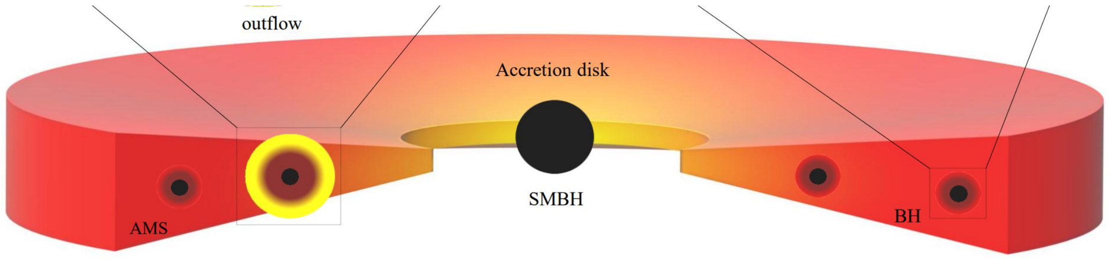
质量分布函数

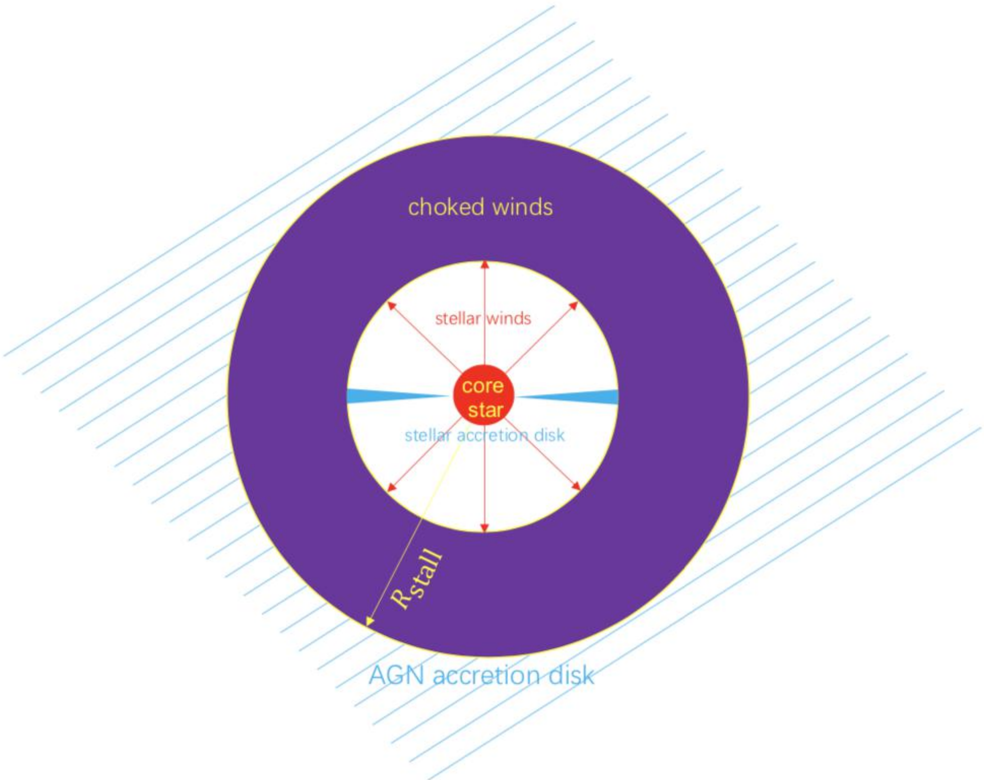
$$\frac{\partial}{\partial t}\Psi(m_*,t) + \frac{\partial}{\partial m_*}\left[\dot{m}_*\Psi(m_*,t)\right] = -\dot{\mathcal{R}}_{\rm SN}(m_*,t) + \dot{\mathcal{S}}_{\rm AD}(m_*,t)$$

$$\dot{m}_* = \dot{m}_{\rm ac} - \dot{m}_{\rm w}$$

恒星：吸积与星风

吸积盘中：恒星演化（accretion-modified stars: AMS）





$$\rho_{\rm d} = 0.92 \times 10^{-12}\ (\alpha_{0.1} M_8)^{-7/10}\ \dot{\mathscr{M}}^{11/20} r_5^{-15/8}\ {\rm g\,cm^{-3}},$$

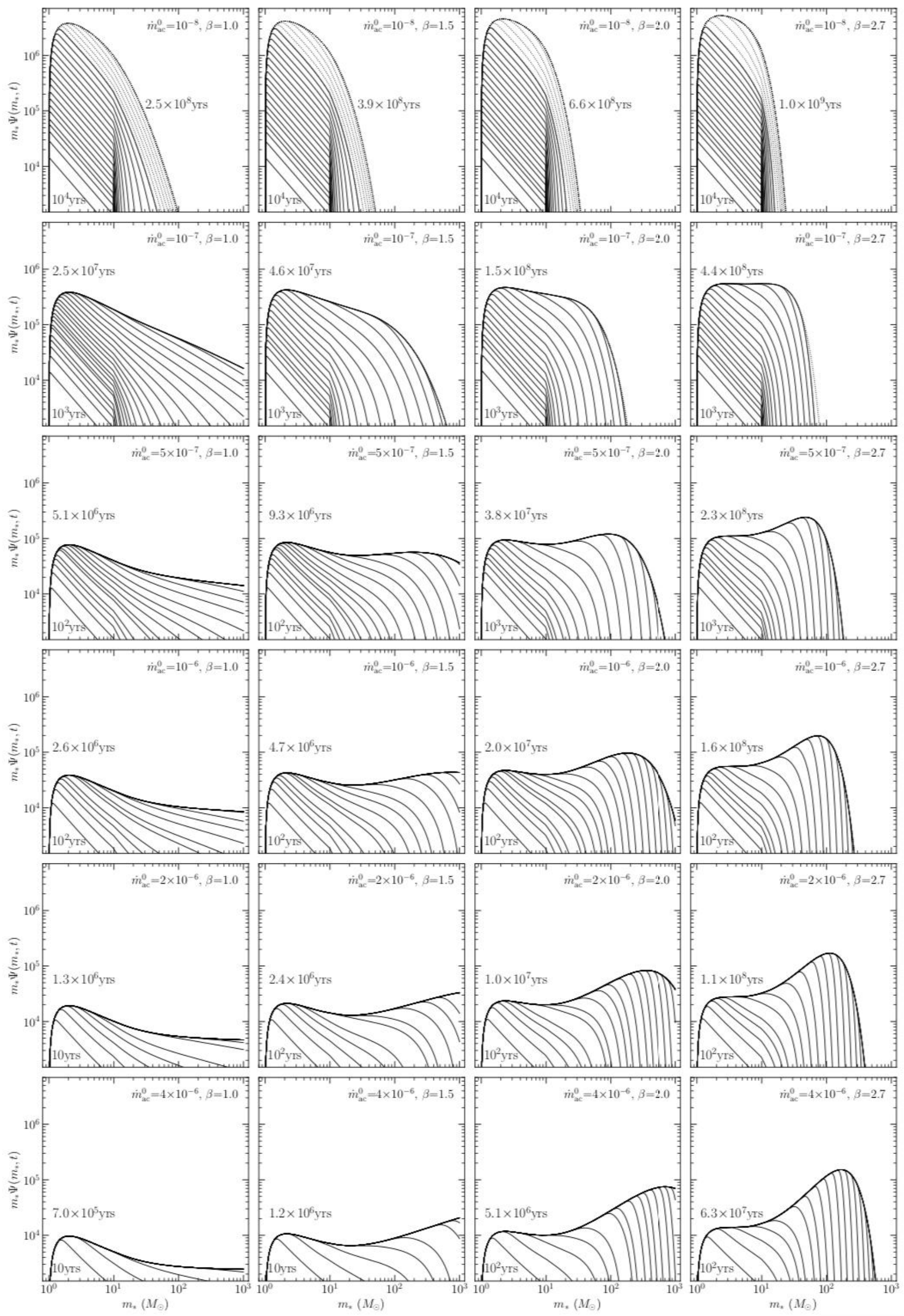
$$T_c = 0.82 \times 10^3\ (\alpha_{0.1} M_8)^{-1/5}\ \dot{\mathscr{M}}^{3/10} r_5^{-3/4}\ {\rm K},$$

$$t_{\rm stall} = 2.4\, L_{37}^{3/2} T_3^{-3/4} \rho_{\bar{1}2}^{-3/2} \left(\frac{m_*}{10^2\, M_\odot}\right)^{-2} {\rm yr},$$

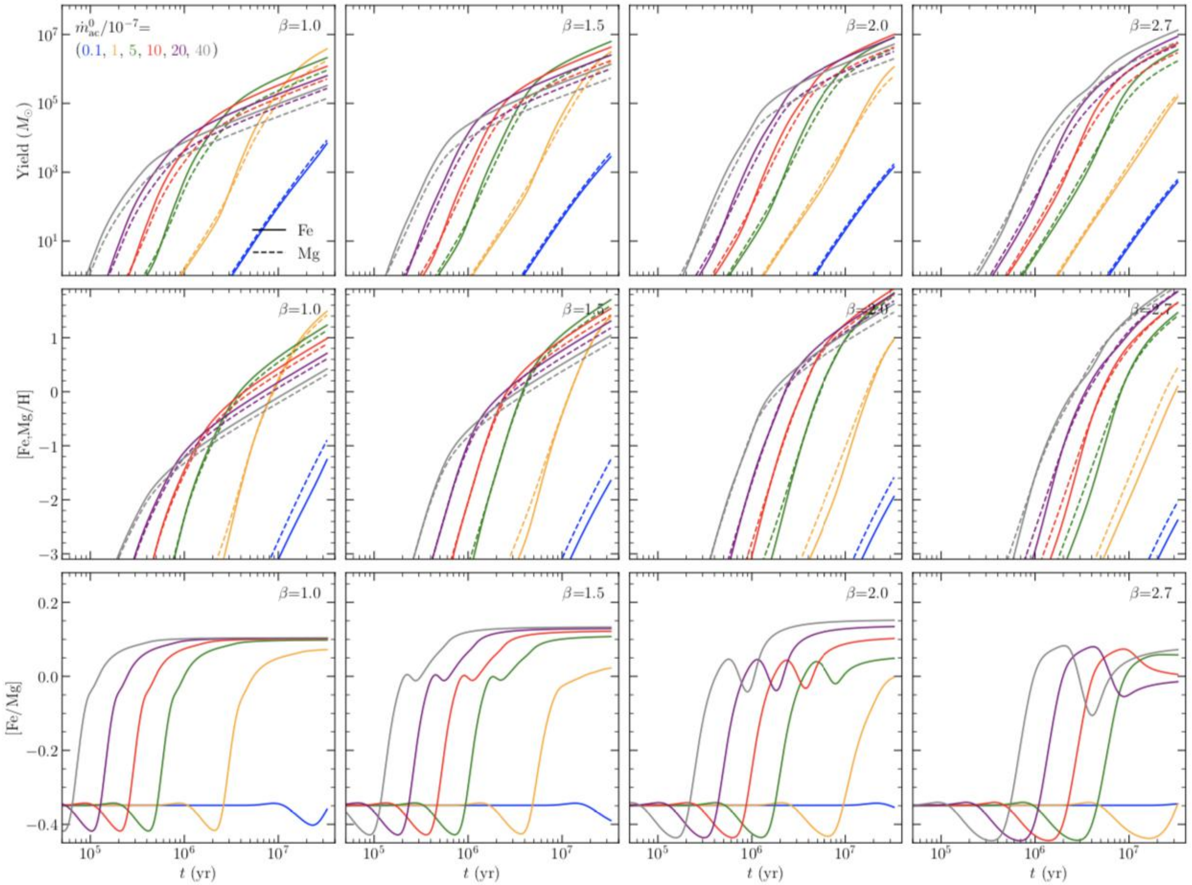
质量分布函数：

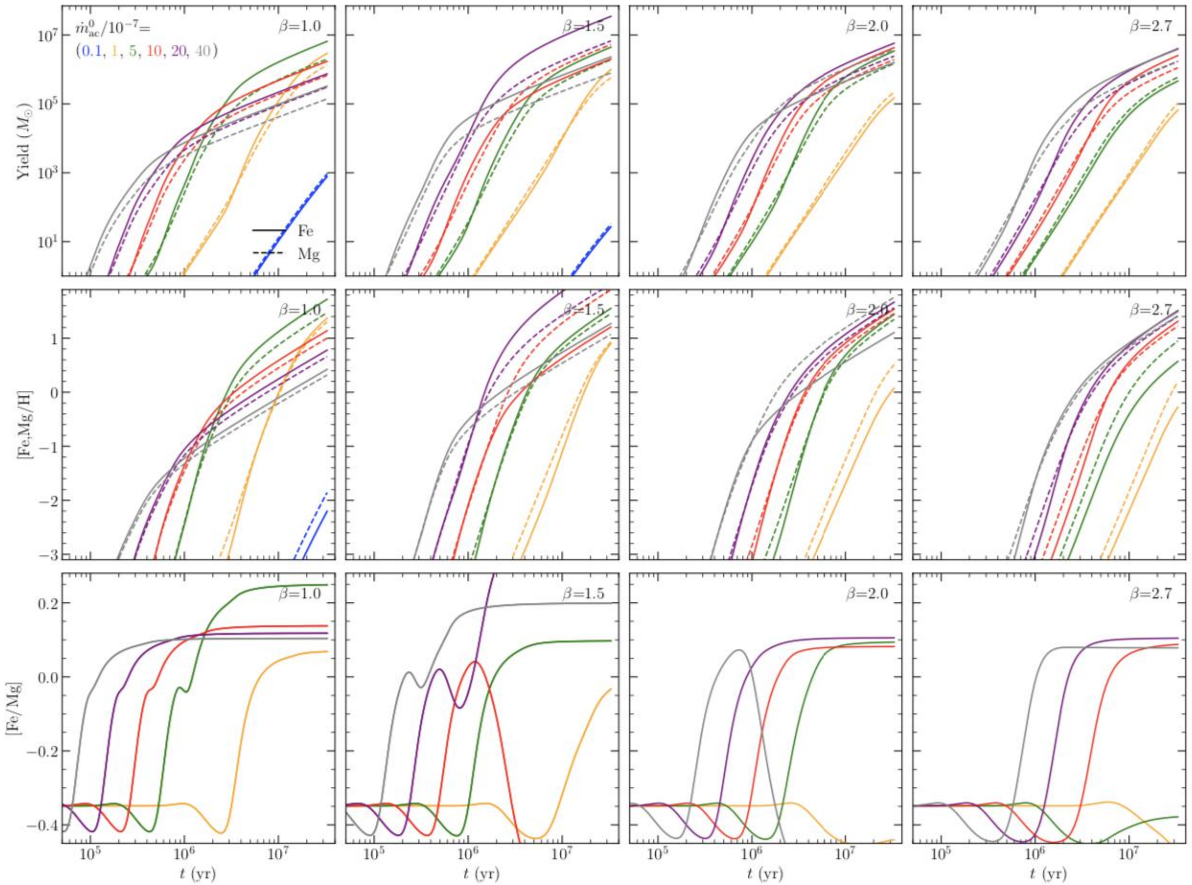
堆积分布

$$\dot{m}_* = \dot{m}_{\rm ac} - \dot{m}_{\rm w}$$



Iron abundance





Strong Irons!

JWST's observations（Yang+2023）

OURNAL SUPPLEMENT SERIES, 80:109–135, 1992 May

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

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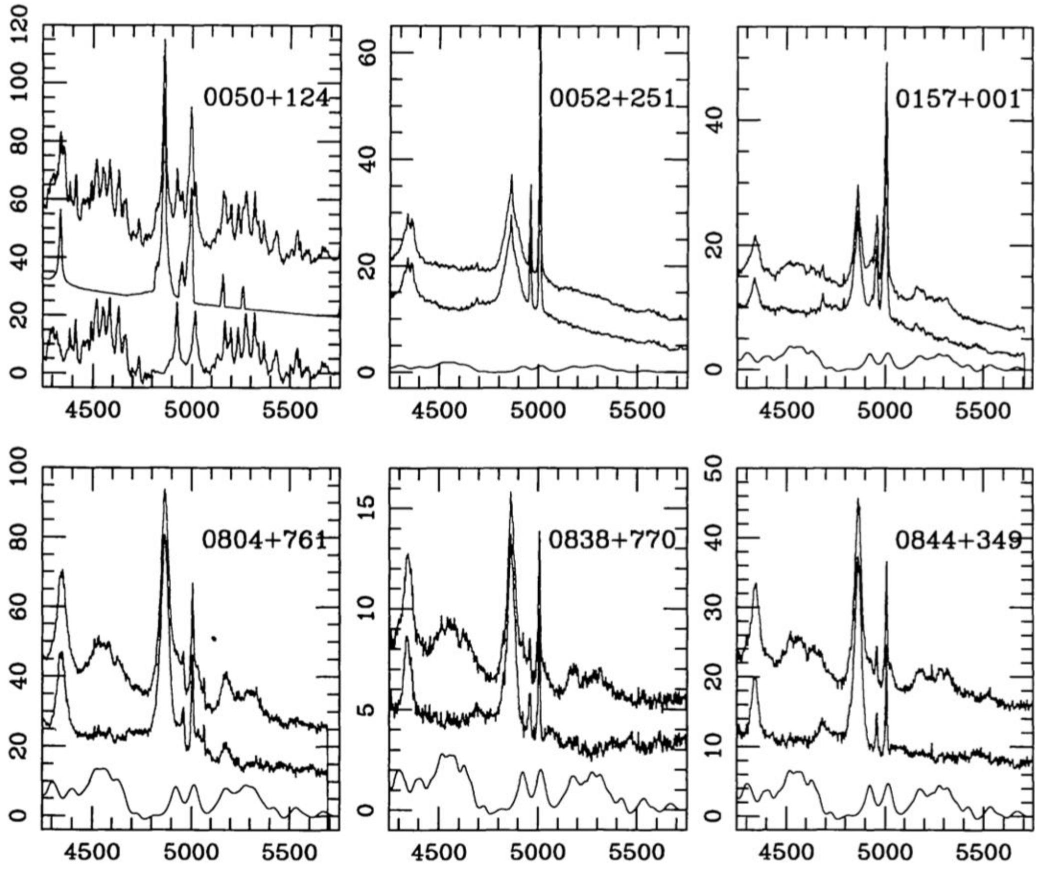
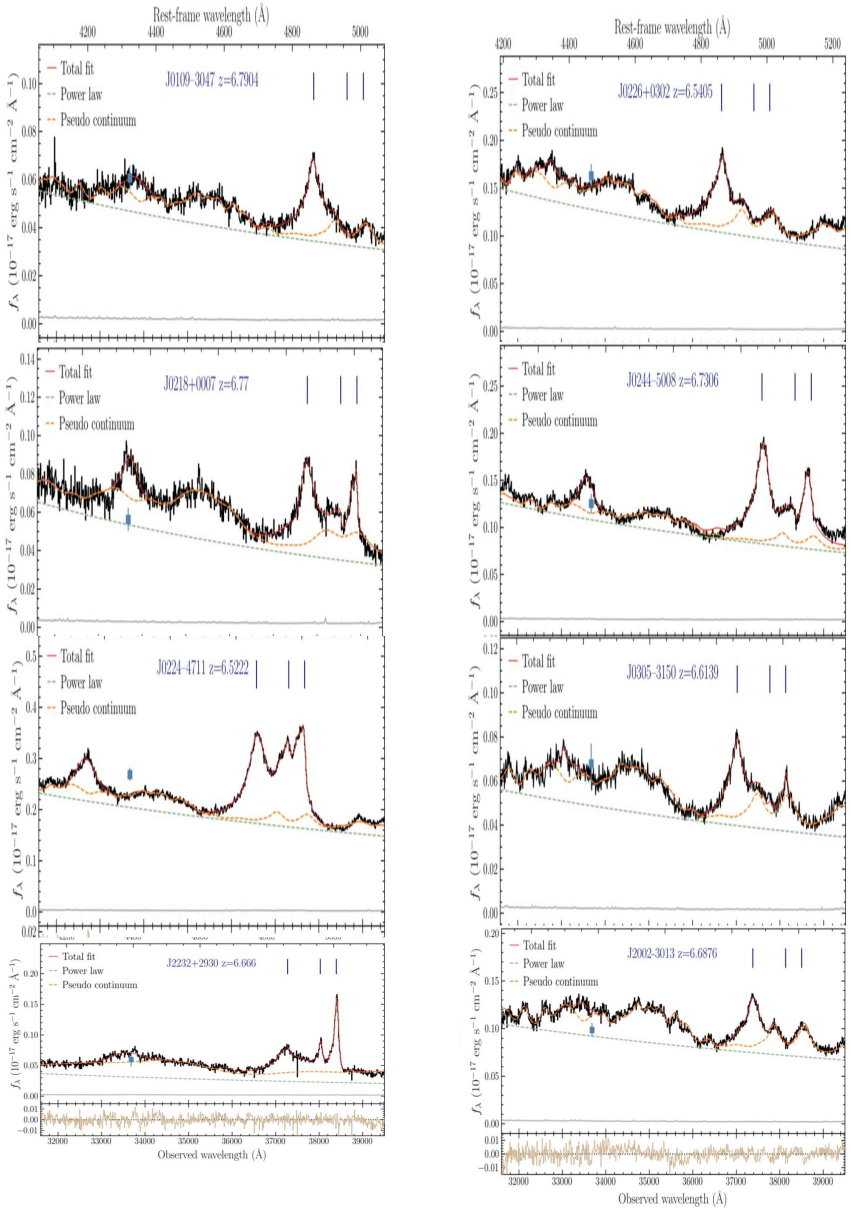
Kitt Peak National Observatory, National Optical Astronomy Observatories,[1] P.O. Box 26732, Tucson, AZ 85726
Received 1991 August 2; accepted 1991 October 14



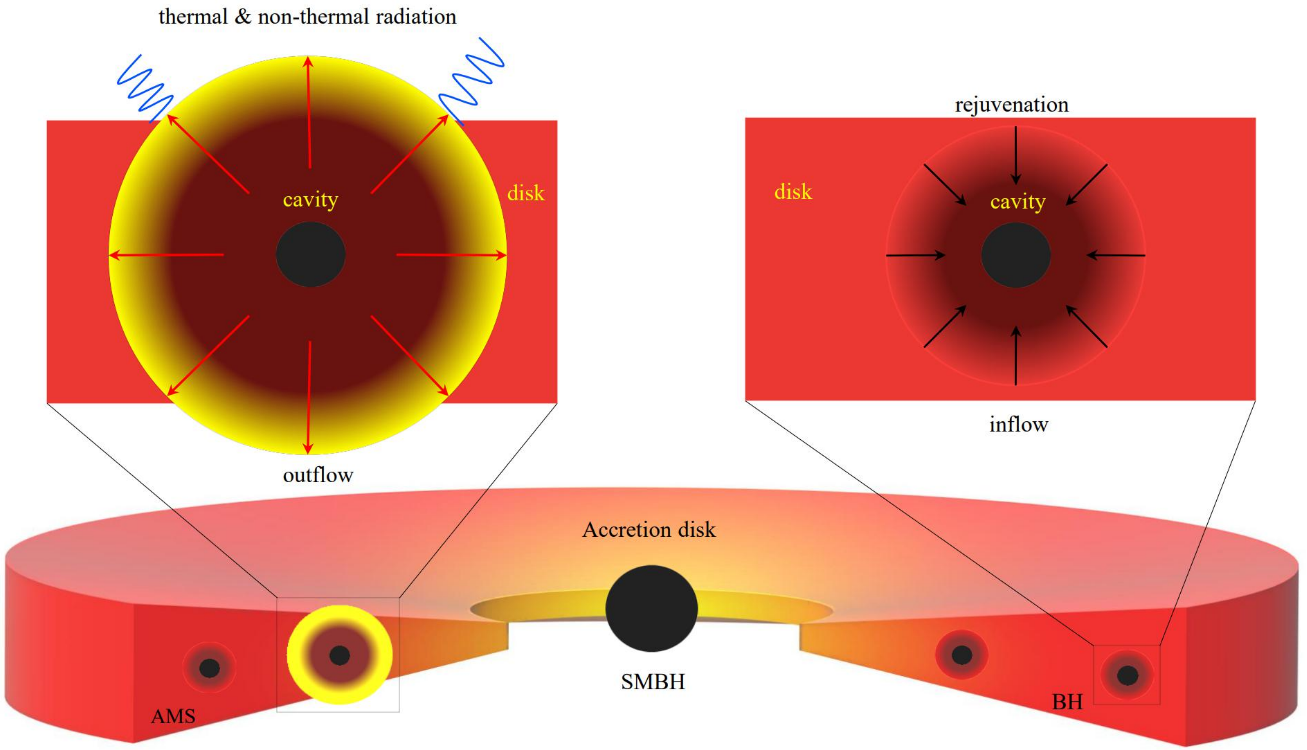


Compact objects：outburst and GWs

Accretion-modified Stars (AMS)

Wang et al. 2021a, b

Chen, K.+(2023)



AMS

↓

Hyper-Eddington accretion

↓

Bondi explosion

↓

AMS rejuvenation

$$\dot{m}_{\rm Bon} = \frac{\dot{M}_{\rm Bon}}{\dot{M}_{\rm Edd}}$$

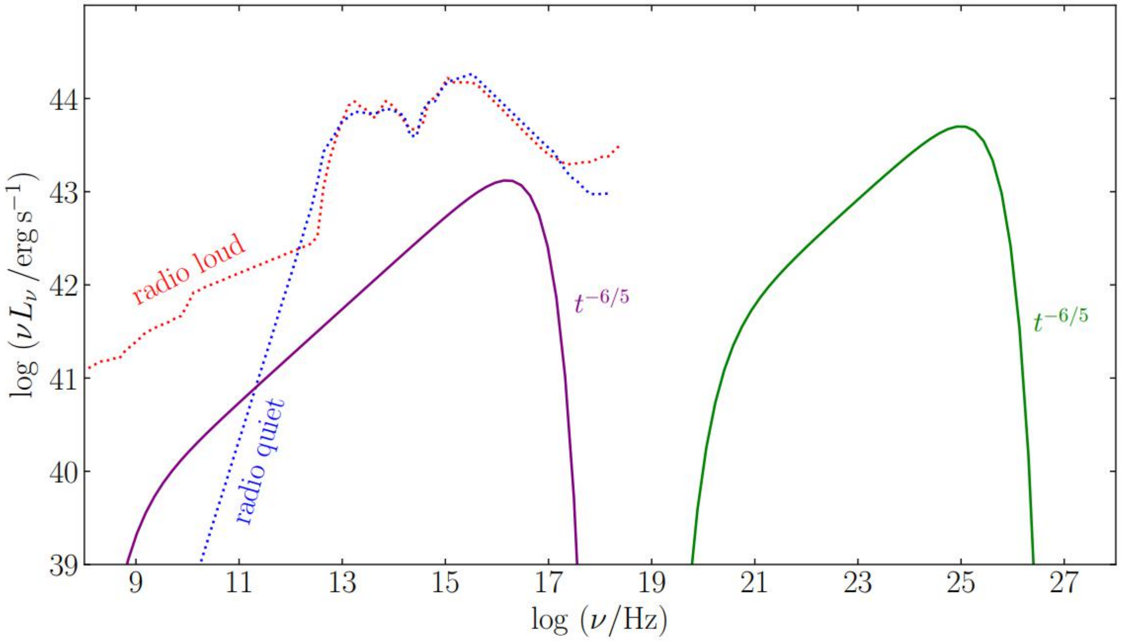
$$\approx \begin{cases} 8.9 \times 10^8\, m_1(\alpha_{0.1}M_8)^{-2/5}\dot{\mathscr{M}}^{1/10} r_4^{-3/4} & \text{(for corotation),} \\ 5.1\, m_1(\alpha_{0.1}M_8)^{-7/10}\dot{\mathscr{M}}^{11/20} r_4^{-3/8} & \text{(for counter rotation)} \end{cases}$$

$$_{\rm rej} = \frac{R_{\rm exp}}{c_s} = 268.9\,\alpha_{0.1}^{3/10} M_8^{11/20} \dot{\mathscr{M}}^{-13/40} r_4^{21/16} E_{52}^{1/4}\ \text{yr.}$$

THE ASTROPHYSICAL JOURNAL LETTERS, 911:L14 (8pp), 2021 April 10 https://doi.org/10.3847/2041-8213/abee81

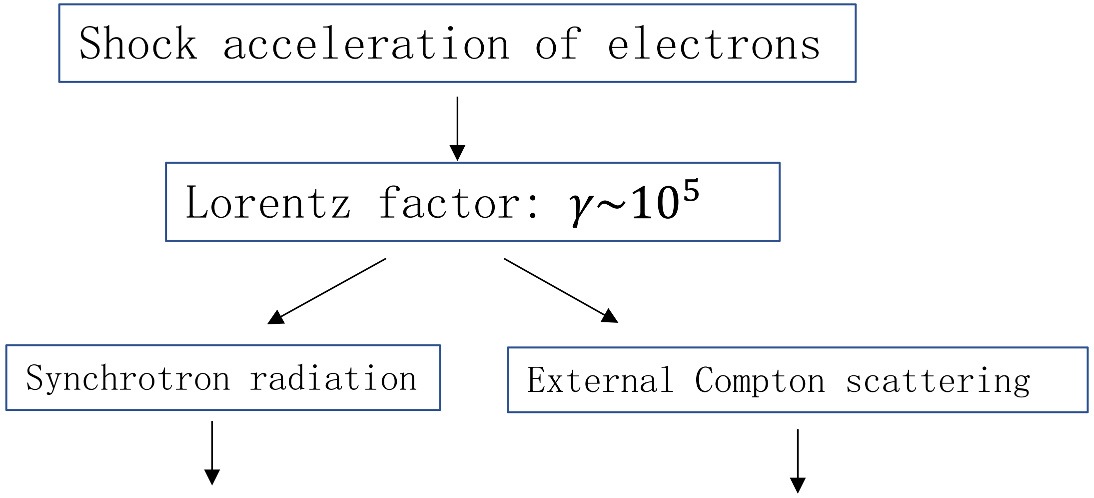
Accretion-modified Stars in Accretion Disks of Active Galactic Nuclei: Slowly Transient Appearance

Jian-Min Wang[1,2,3], Jun-Rong Liu[1,2], Luis C. Ho[4,5], and Pu Du[1]



Bondi explosion SED

Observable properties



$\nu_{\rm syn}^{\max} \approx 0.17\, B_0 \gamma_{\max,5}^2\,\mathrm{keV}$

$\nu_{\rm IC}^{\max} \approx \gamma_{\max}^2 \nu_{\rm UV} \approx 41.7\, \gamma_{\max,5}^2 \nu_{15}^{\rm UV}\,\mathrm{GeV}$

- Bondi accretion rates $\sim 10^9 L_{\rm Edd}/c^2$.
- Accretion timescale: $t_{\rm a} \sim 10^5 m_1 s$.
- Powerful outflows: 10 times of SNe

- Bondi explosion: radio-quiet to intermediate.
- EIC: peaks≈40 GeV *Fermi*-LAT detectable.

. Journal Letters, 916:L17 (11pp), 2021 August 1 https://doi.org/10.3847/2041-8213/ac0b46

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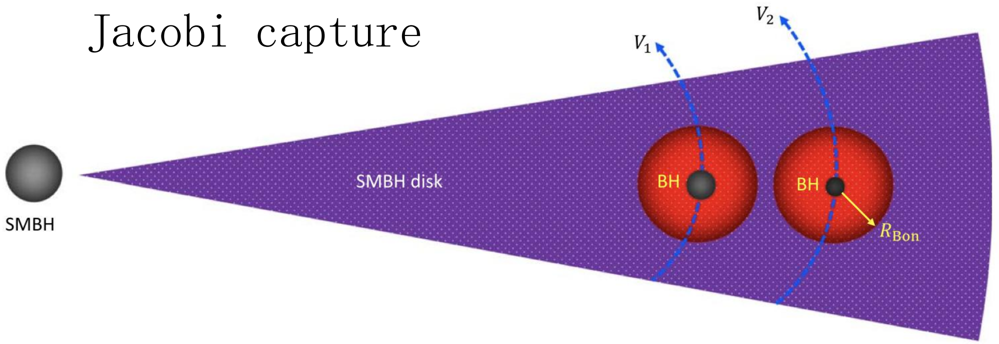
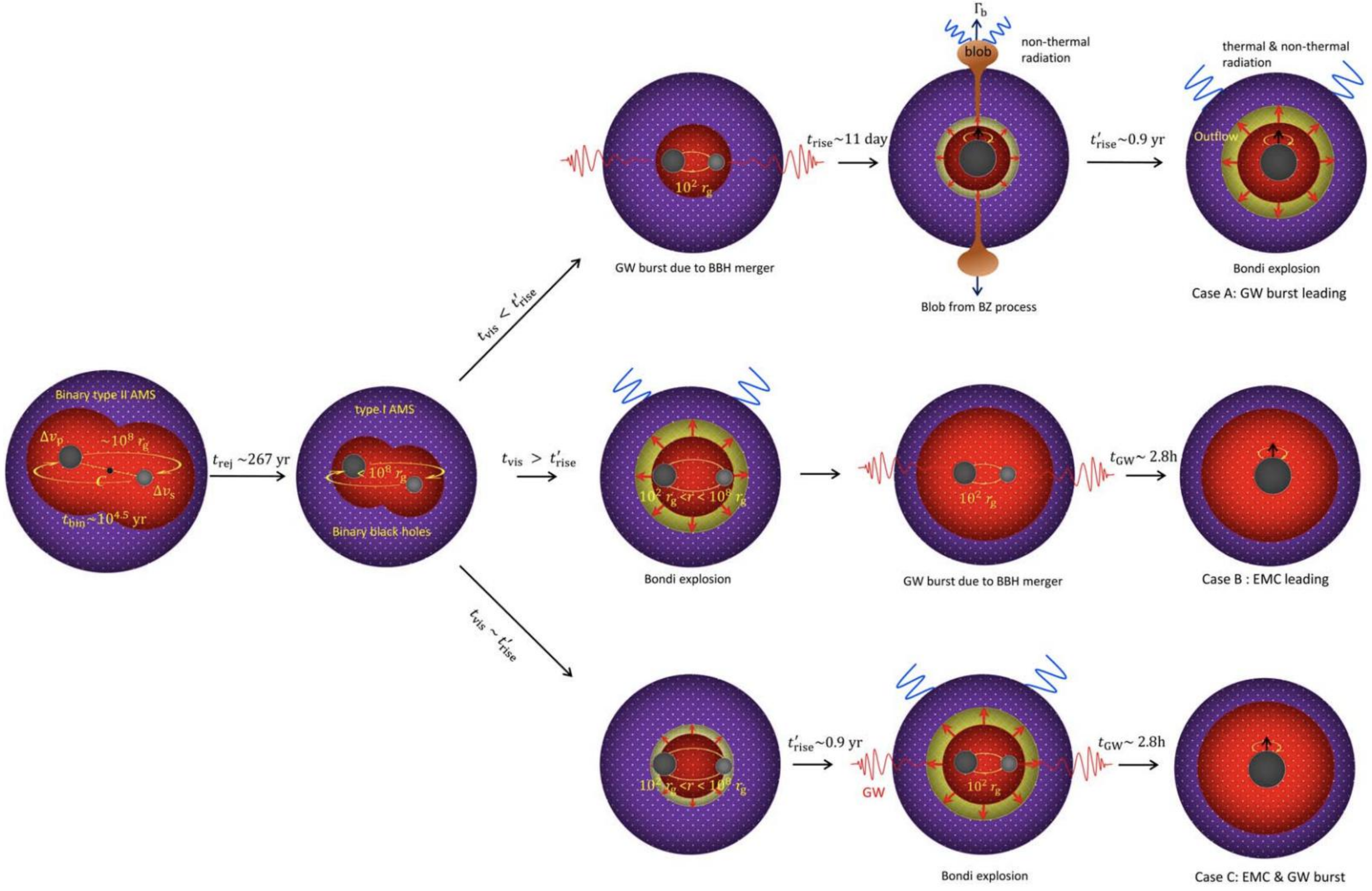
Accretion-modified Stars in Accretion Disks of Active Galactic Nuclei: Gravitational-wave Bursts and Electromagnetic Counterparts from Merging Stellar Black Hole Binaries

Jian-Min Wang[1,2,3], Jun-Rong Liu[1,2], Luis C. Ho[4,5], Yan-Rong Li[1], and Pu Du[1]

Jacobi capture



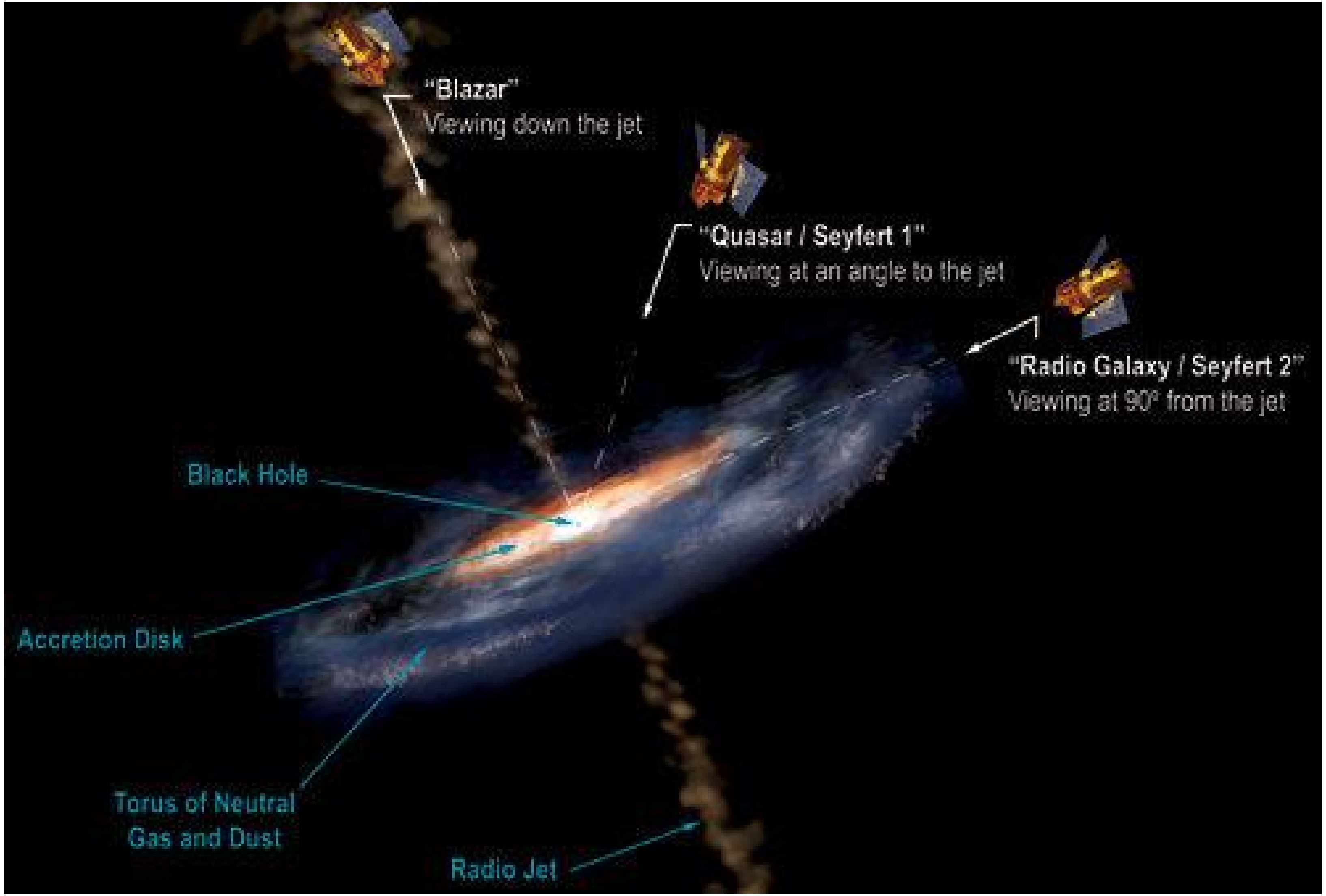


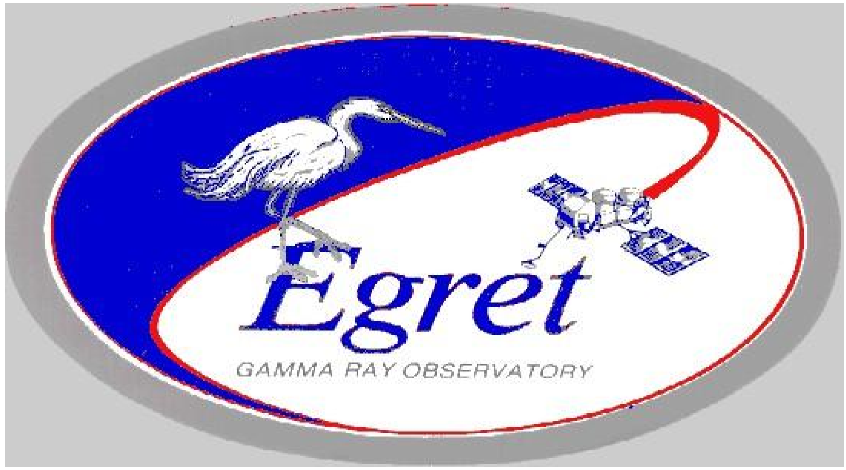
AMS: **radio**、γ-rays

slow transients

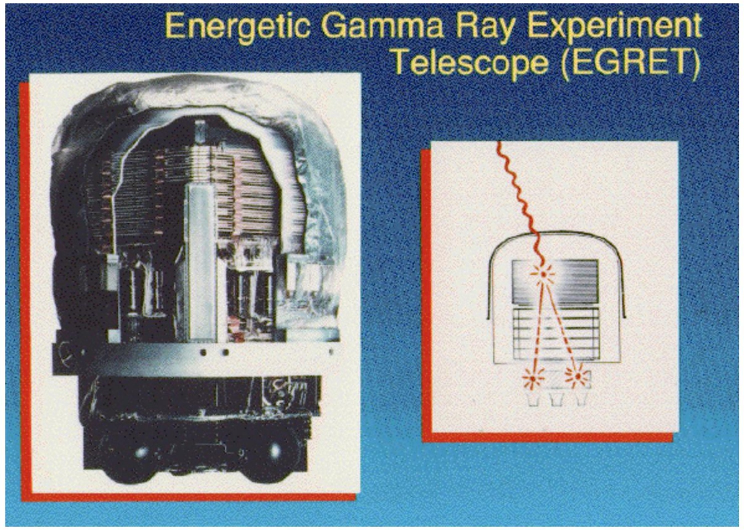
Merger rates: a few per year

Blazar-AGN: standard model





The Energetic Gamma Ray Experiment Telescope (EGRET)



THE ASTROPHYSICAL JOURNAL, 416:L53–L56, 1993 October 20

EGRET LIMITS ON HIGH-ENERGY GAMMA-RAY EMISSION FROM X-RAY– AND LOW-ENERGY GAMMA-RAY–SELECTED SEYFERT GALAXIES

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Received 1993 February 24; accepted 1993 August 4

ABSTRACT

A sample of 22 Seyfert galaxies, 11 type 1 and two type 2 galaxies selected according to their X-ray fluxes in the AGN survey catalogs of *EXOSAT* and *Ginga*, two additional type 1 galaxies for which detections in low-energy gamma rays have been reported in the past, plus six more type 1 galaxies and one unclassified Seyfert that have been studied by the OSSE collaboration, have been examined for high-energy gamma ray emission in observations by the EGRET telescope on the *Compton Observatory*. No high-energy gamma-ray emission has been detected from any of them. The 2 σ upper limits of the gamma-ray fluxes above 100 MeV for these 22 Seyfert galaxies are given here. The significance of these negative results is discussed. Implications of the EGRET result for NGC 4151 are discussed in more detail.

Subject headings: galaxies: Seyfert — gamma rays: observations

TABLE 1

PHOTON FLUX UPPER LIMITS FOR ENERGY >100 MeV

Source	Observation Periods	2σ Upper Limit (10^{-7} photons cm^{-2} s^{-1})
Mrk 335	92/Apr/23-Apr/28,May/07-May/14,Aug/20-Aug/27	0.9
Mrk 348	92/Apr/23-Apr/28,May/07-May/14,Aug/20-Aug/27	1.0
Mrk 590	92/Feb/20-Mar/05	0.7
NGC 1068	92/Feb/20-Mar/05	0.8
NGC 1275	91/Nov/28-Dec/12	0.9
3C 111	91/Nov/28-Dec/12,92/Jun/11-Jun/25	0.9
3C 120	91/May/16-May/30,92/Feb/20-Mar/05,May/14-Jun/04	0.9
MCG +8-11-11	92/Jun/11-Jun/25	1.1
NGC 3783	91/Oct/17-Oct/31	1.2
NGC 4051	91/Jun/28-Jul/12	0.5
NGC 4151	91/Jun/28-Jul/12	0.5
NGC 4593	91/Jun/15-Jun/28,Oct/03-Oct/17	1.2
MCG -6-30-15	91/Oct/17-Oct/31	1.0
Mrk 279	92/Mar/15-Mar/29	0.7
NGC 5548	92/Apr/02-Apr/09,Apr/09-Apr/16	1.0
Mrk 841	92/Apr/02-Apr/09,Apr/09-Apr/16,Apr/16-Apr/23	0.9
3C 390.3	92/Jan/10-Jan/23,/Mar/05-Mar/19	0.7
ESO 141-55	92/Aug/06-Aug/11,Aug/27-Sep/01	1.5
Mrk 509	91/Aug/15-Aug/22,Jan/23-Feb/06	0.8
NGC 7213	92/Oct/15-Oct/29	1.0
NGC 7469	92/Apr/23-Apr/28,May/07-May/14,Aug/20-Aug/27	1.1
MCG -2-58-22	92/Jan/23-Feb/06	0.9

The Astrophysical Journal, 601:142–150, 2004 January 20

STACKING SEARCHES FOR GAMMA-RAY EMISSION ABOVE 100 MeV FROM RADIO AND SEYFERT GALAXIES

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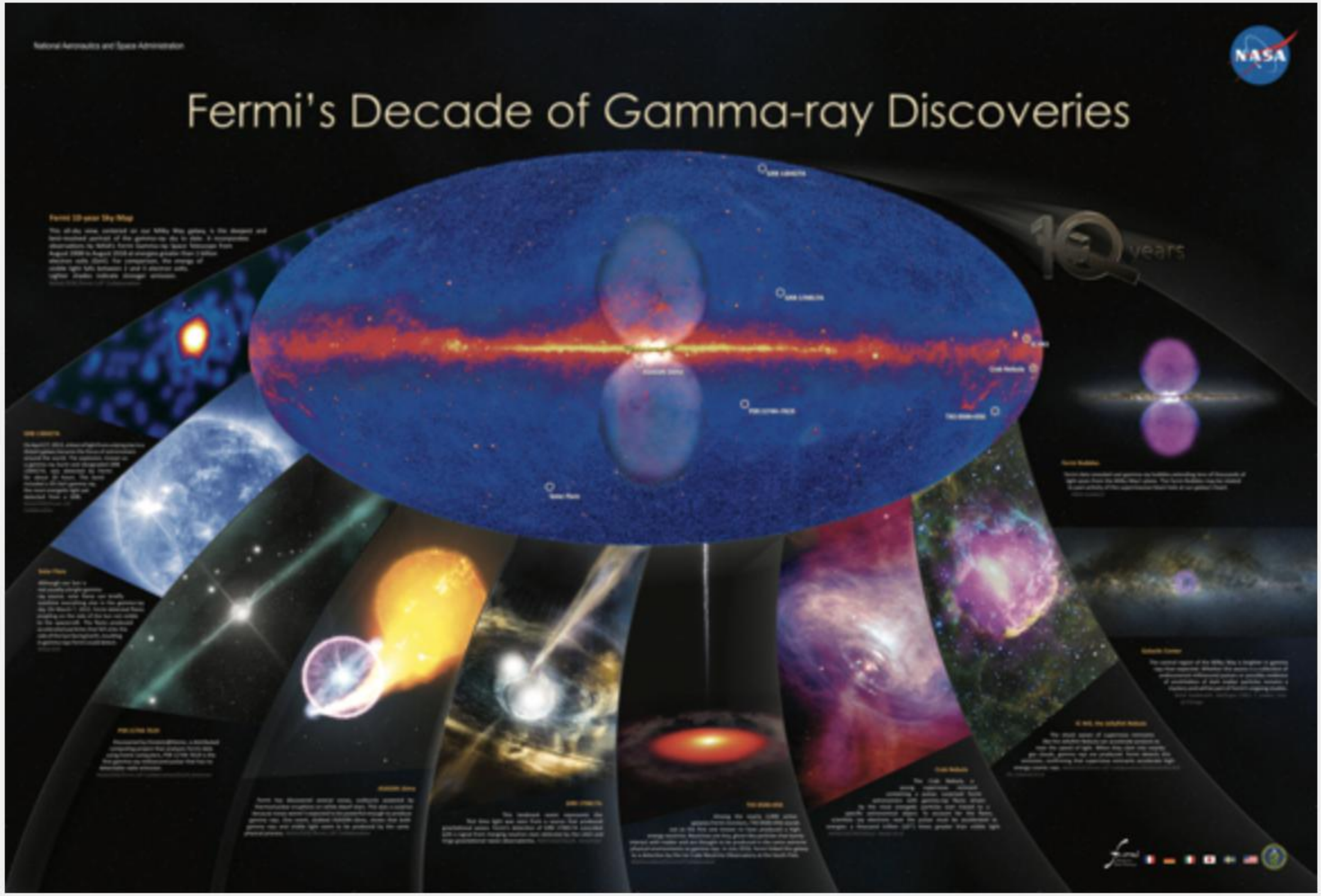
Received 2003 July 16; accepted 2003 October 6

ABSTRACT

The EGRET telescope on board *Compton Gamma Ray Observatory* detected more than 60 sources of high-energy gamma radiation associated with active galactic nuclei (AGNs). All but one of those belong to the blazar subclass; the only exception is the nearby radio galaxy Centaurus A. Since there is no obvious reason other than proximity to expect Cen A to be the only nonblazar AGN emitting in high-energy gamma rays, we have utilized the "stacking" technique to search for emission above 100 MeV from two nonblazar AGN subclasses, radio galaxies and Seyfert galaxies. Maps of gamma-ray counts, exposure, and diffuse background have been created, then co-added in varying numbers based on sorts by redshift, 5 GHz flux density, and optical brightness, and finally tested for gamma-ray emission. No detection significance greater than 2 σ has been found for any subclass, sorting parameter, or number of objects co-added. Monte Carlo simulations have also been performed to validate the technique and estimate the significance of the results.

Subject headings: galaxies: active — galaxies: Seyfert — gamma rays: observations

Fermi's Decade of Gamma-ray Discoveries



Fermi
Gamma-ray
Space Telescope

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

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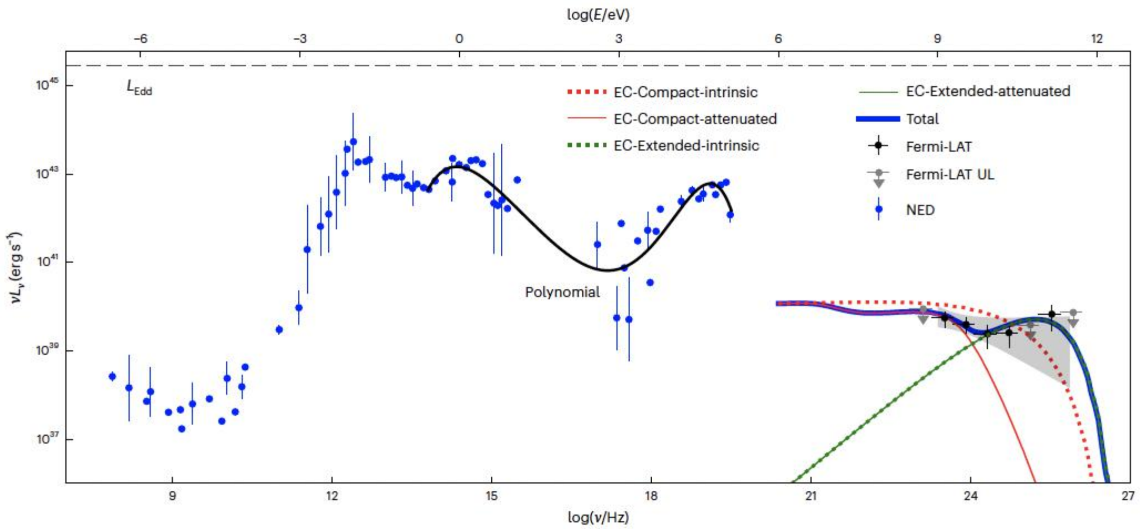
Check for updates

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 nuclei, how the supermassive black holes work in γ-ray bands is still unknown despite great observational efforts in the past three decades. Here, considering the previous efforts, we carefully select an active galactic nucleus sample composed of 37 nearby Seyfert galaxies with ultrahard X-rays for γ-ray detection by excluding all potential contamination in this band. Adopting a stacking technique, we report the significant γ-ray detection (test statistic 30.6, or 5.2σ) from the sample using 15-year Fermi-LAT observations. We find the average γ-ray luminosity of the sample to be $(1.5 \pm 1.0) \times 10^{40}$ erg s^{-1} at energies of 1–300 GeV. Limited by the well-known pair production from the interaction of γ-rays with low-energy photons, γ-rays of more than several giga-electronvolts are found to originate from an extended corona (~2.7×10^6 gravitational radii), whereas the canonical much more compact X-ray corona (~10 gravitational radii) is responsible for γ-rays of one to several giga-electronvolts. The finding of the compact region lends strong support to the long-time theoretical expectations, but the extended corona is an unexpected finding. One promising scenario is that the electron–positron pairs produced in the compact X-ray corona would expand as a fireball, similar to that in γ-ray bursts, forming the structure of extended corona.



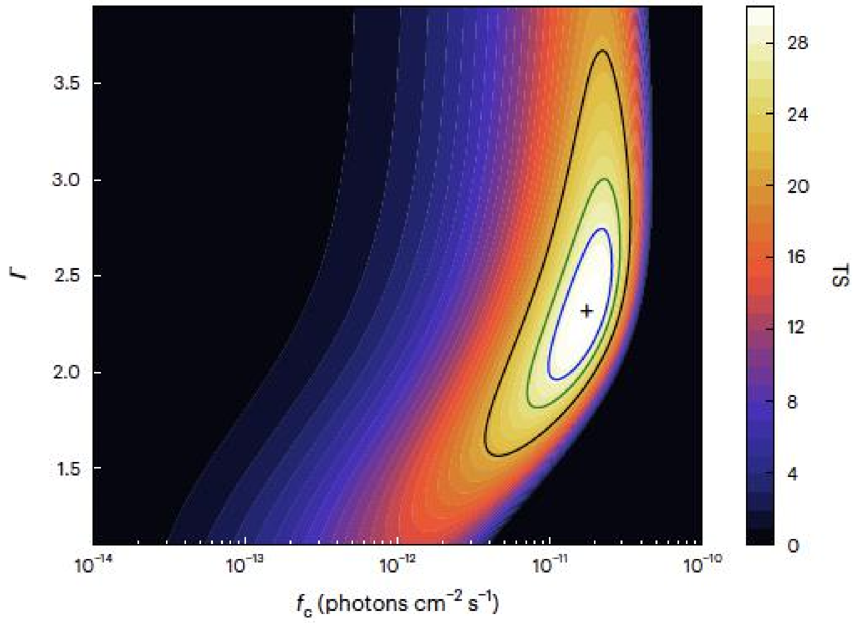


Fig. 1 | Stacked TS profile for FGR sample containing 37 sources. The TS value is colour-coded for each flux and index combination. The maximum TS value is 30.6 (5.2σ), corresponding to the best-fit result of $f_c = 1.8^{+0.8}_{-0.8} \times 10^{-11}$ photons s^{-1} cm^{-2} and $\Gamma = 2.32^{+0.40}_{-0.35}$, marked by the black cross. The three solid contours represent the 68%, 90% and 99% confidence level.

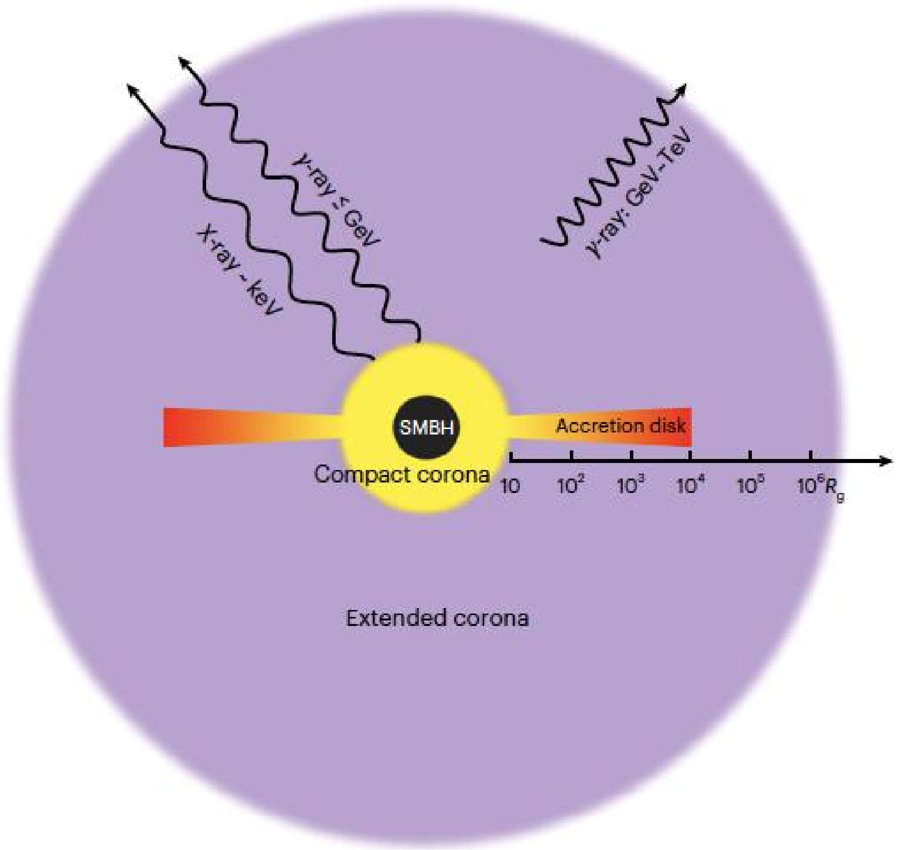
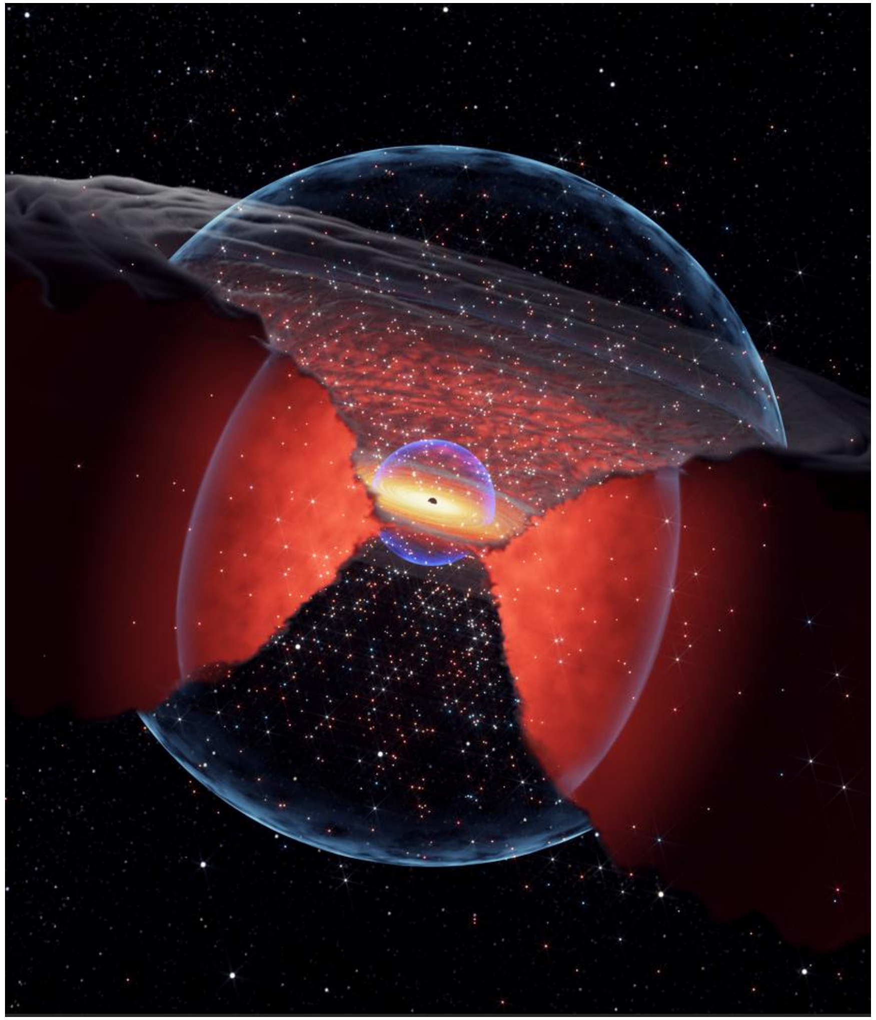


Fig. 3 | Illustration of the AGN corona scenario used to explain the γ-ray emission from the FGR sample. The extended corona ($\geq 2.7 \times 10^6 R_g$ or 2.8 pc) is responsible for the emission of photons of more than several giga-electronvolts, and the compact corona ($10R_g$) for that of photons of fewer than several giga-electronvolts.



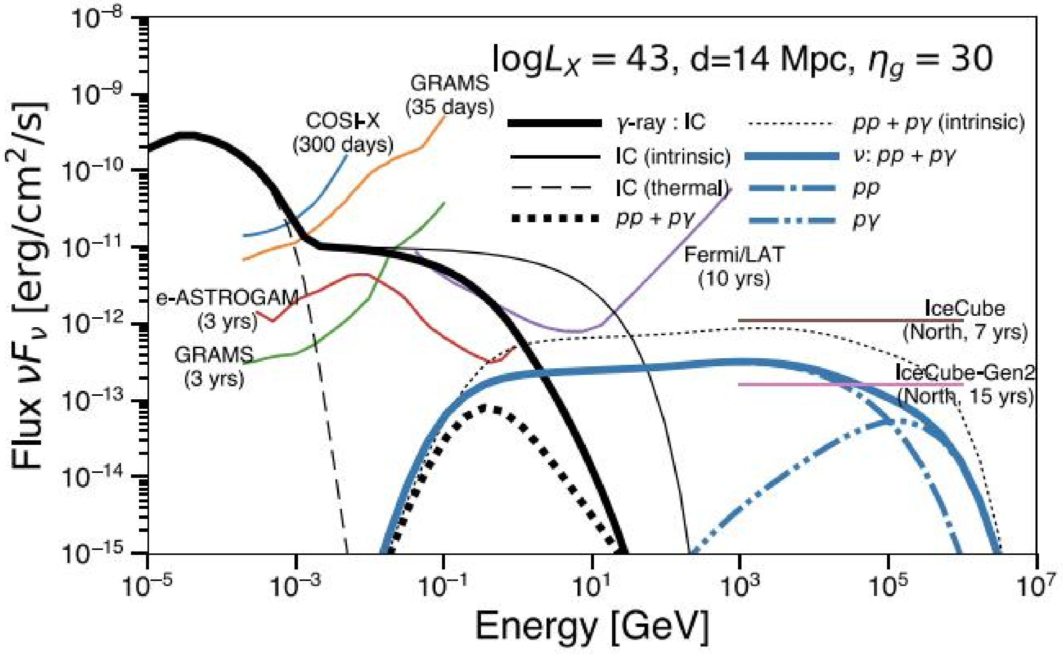
Radiation mechanism: AMS explosion?

Consequence: sMBHs exit around central SMBH

The Astrophysical Journal, 880:40 (17pp), 2019 July 20
https://doi.org/10.3847/1538-4357/ab2715

On High-energy Particles in Accretion Disk Coronae of Supermassive Black Holes: Implications for MeV Gamma-rays and High-energy Neutrinos from AGN Cores

Yoshiyuki Inoue[1,2], Dmitry Khangulyan[3], Susumu Inoue[1], and Akihiro Doi[4,5]



The Astrophysical Journal, 319:643–661, 1987 August 15

PAIR PRODUCTION AND COMPTON SCATTERING IN COMPACT SOURCES AND COMPARISON TO OBSERVATIONS OF ACTIVE GALACTIC NUCLEI

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California Institute of Technology, and Harvard-Smithsonian Center for Astrophysics
Received 1986 November 14; accepted 1987 February 3

$$l = \frac{L\sigma_T}{Rm_e c^3} = 2\pi\left(\frac{m_p}{m_e}\right)\left(\frac{L}{L_E}\right)\left(\frac{R_S}{R}\right)$$

$$l_x \equiv \frac{L_x \sigma_T}{Rm_e c^3}$$

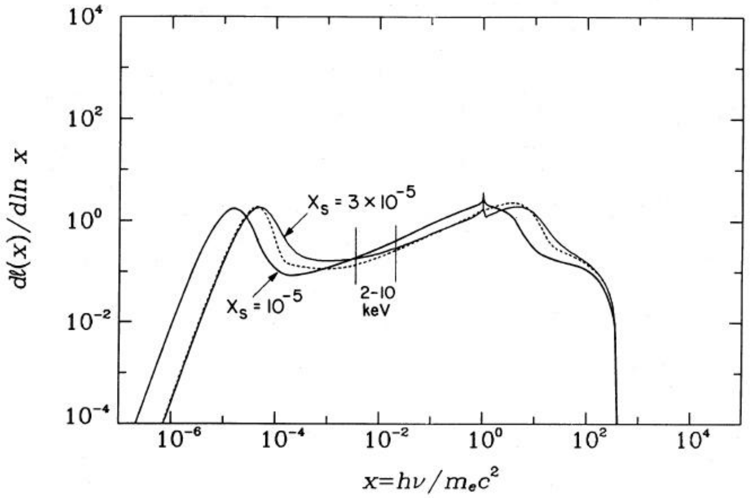
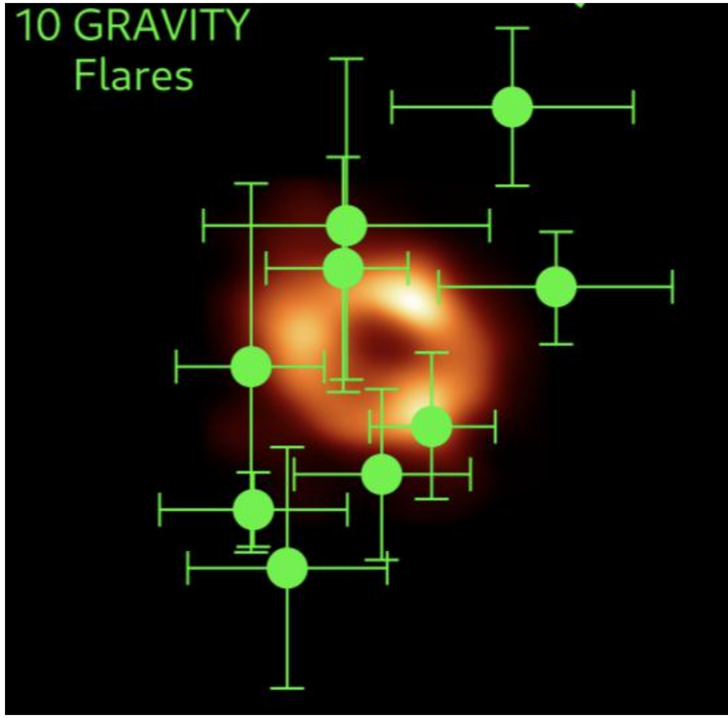


Fig. 7.—Emerging spectra for monoenergetic injections at $\gamma_{max} = 400$, $l_e = 10$, and $l_s/l_e = 0.25$, showing the effect of varying x_s. Dotted curve is the $x_s = 3 \times 10^{-5}$ model without thermal Comptonization included. Vertical lines show the 2–10 keV X-ray energy range. See Table 1, models L and M.

Milky Way Center: Sgr A*

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

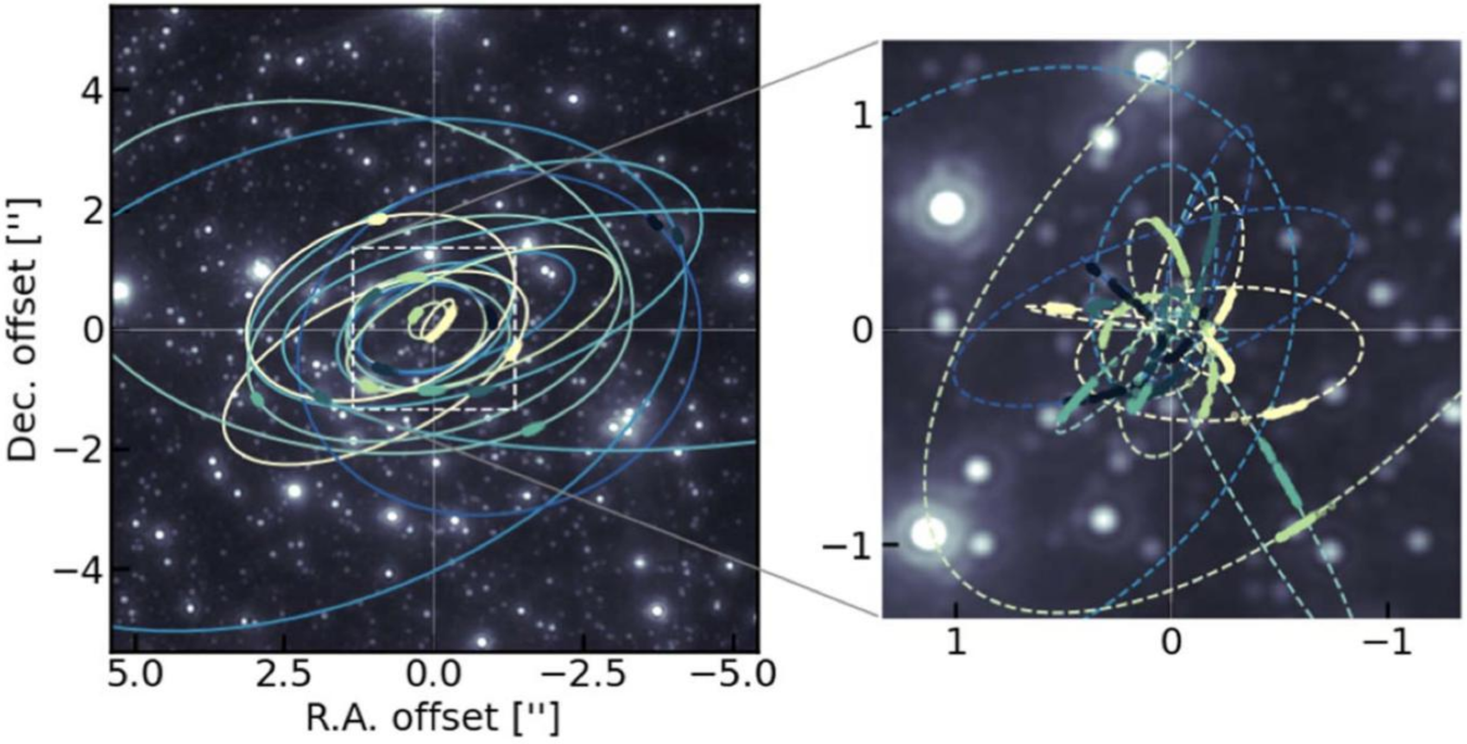
The Galactic Center

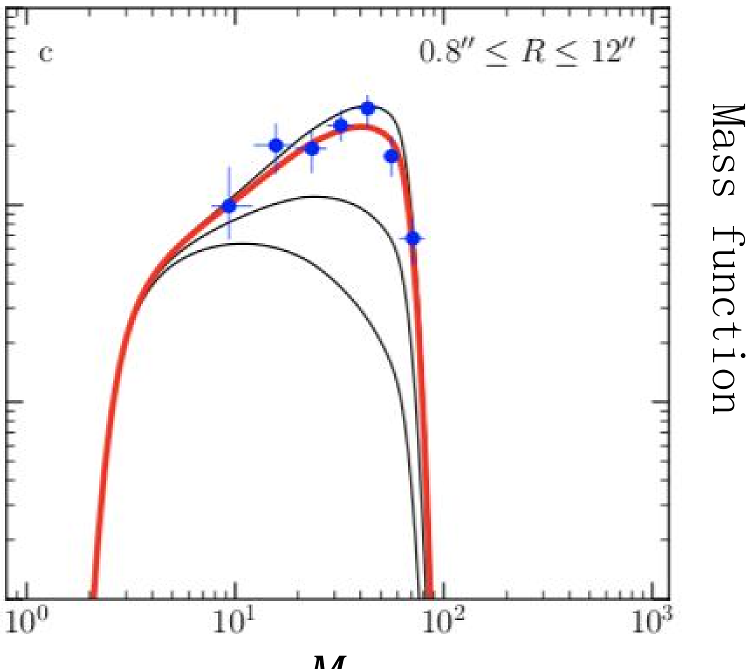
- Why are there no neutron stars?
- Are there stellar mass BHs?
- How to form the stellar disks

The Astrophysical Journal Letters, 932:L6 (29pp), 2022 June 10
https://doi.org/10.3847/2041-8213/ac68ef

The Young Stars in the Galactic Center

Sebastiano D. von Fellenberg[1,2], Stefan Gillessen[2], Julia Stadler[3], Michi Bauböck[4], Reinhard Genzel[2,5], Tim de Zeeuw[2,6], Oliver Pfuhl[7], Pau Amaro Seoane[2,8,9,10], Antonia Drescher[2], Frank Eisenhauer[2], Maryam Habibi[2], Thomas Ott[2], Felix Widmann[2], and Alice Young[2]





Wang+2023

A&A 672, A63 (2023)
https://doi.org/10.1051/0004-6361/202245132

Astronomy & Astrophysics

Where intermediate-mass black holes could hide in the Galactic Centre

A full parameter study with the S2 orbit

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

(Affiliations can be found after the references)

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Three-body problem:

$4*10^6 M_\odot$ + $M_\odot$ 10^3

$M_\odot$

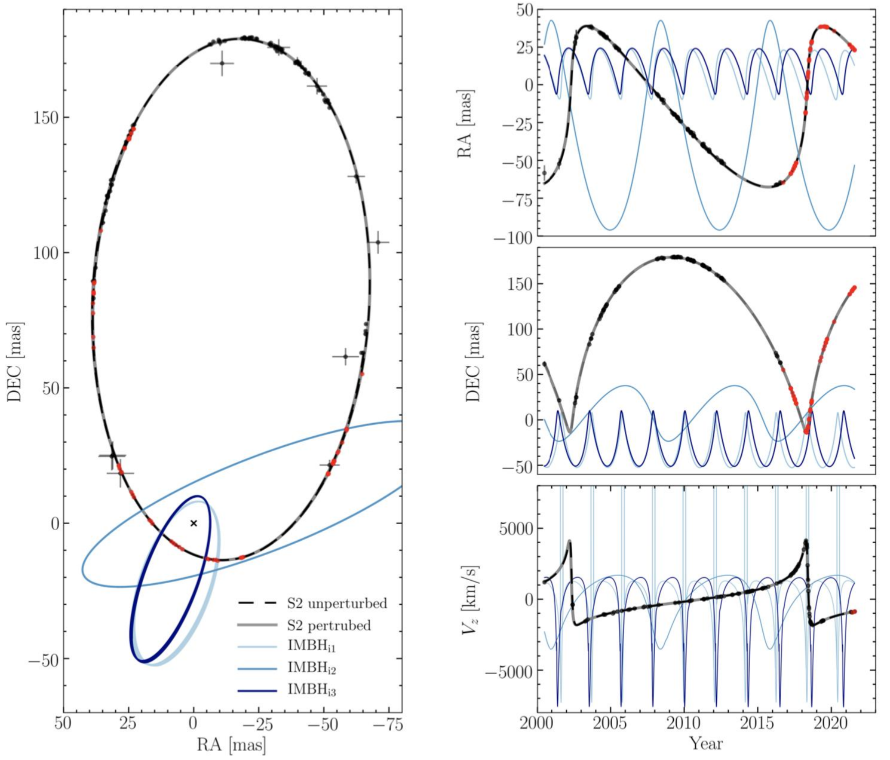
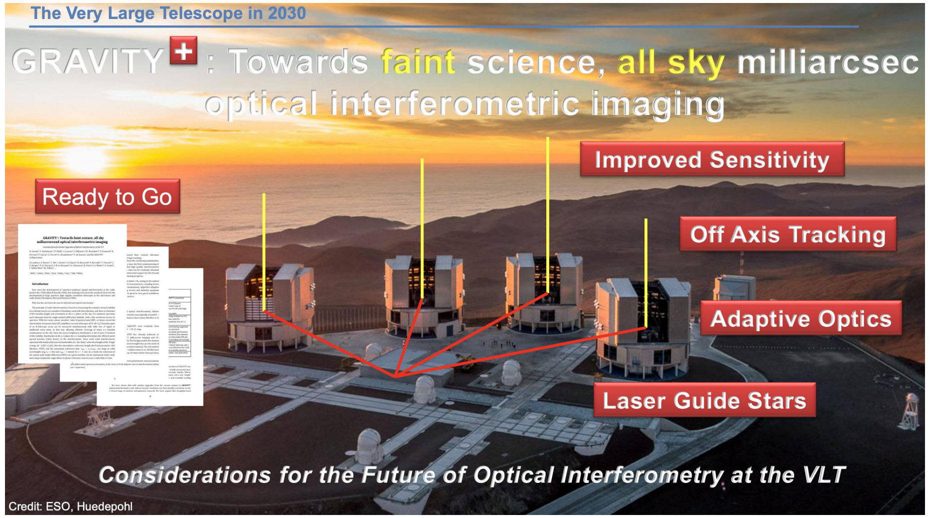


Fig. 3. Example orbits of allowed IMBHs in the Galactic Centre. The left panel shows the on-sky orbits of S2 and three IMBH solutions around Sgr A* (indicated by the cross). The right panels show the time evolution of the RA, Dec, and radial velocity. The solid grey and dashed black curves show the orbit of S2 with and without an IMBH, respectively. The IMBHs are shown in blue and correspond to the parameters given in Table 2. The data points show the last 30 years of observations of S2. The black points correspond to adaptive optics measurements with NACO and early speckle imagery with SHARP. The red points correspond to GRAVITY interferometric measurements. The black and red radial velocity observations correspond, respectively, to SINFONI – KECK and GNIRS spectral measurements of the line-of-sight velocity.



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

Astronomy & Astrophysics

Magnetic field reconnection?

It should randomly happen

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. Wiezorek[1], and J. Woillez[4]

(Affiliations can be found after the references)

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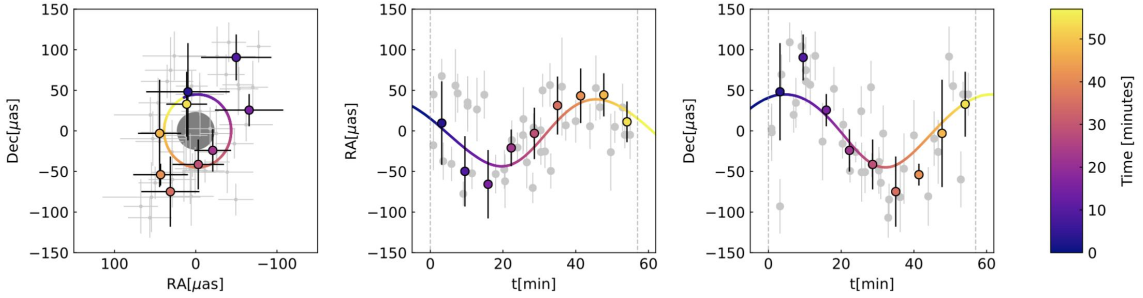
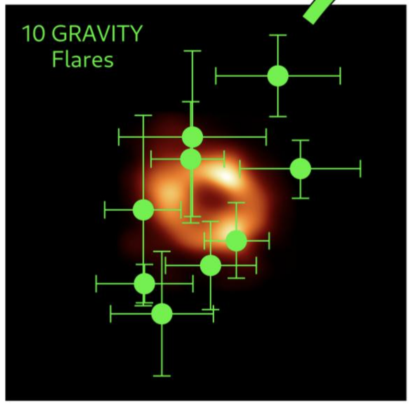
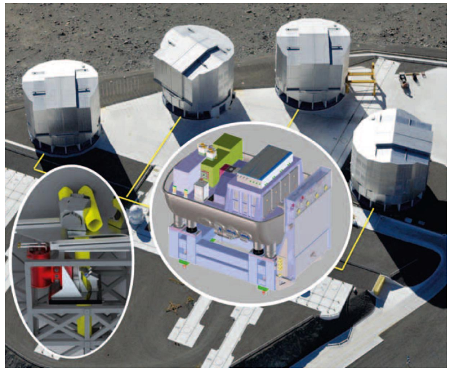
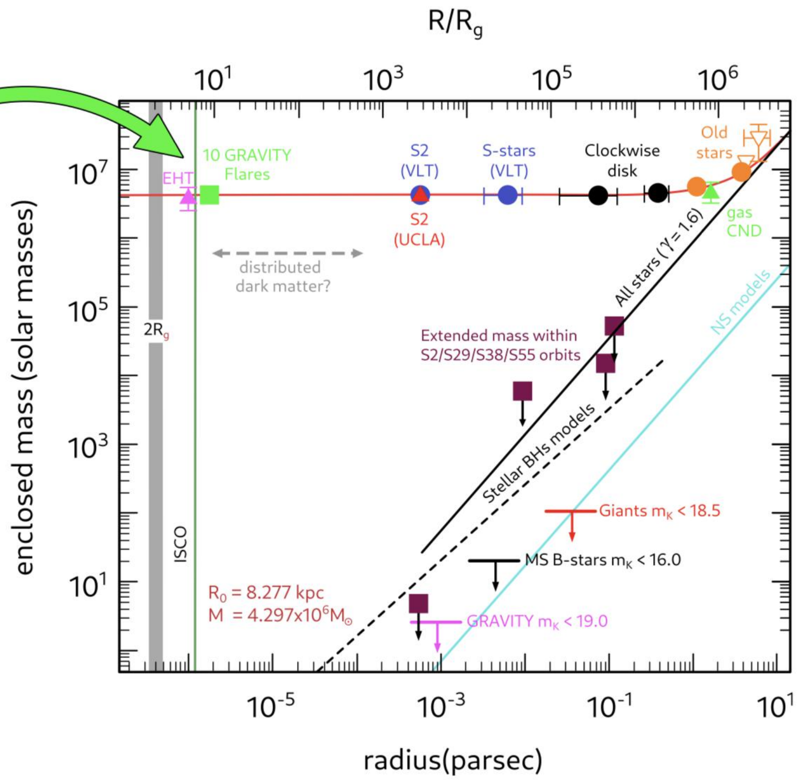


Parameter	Posterior mean
Radius	$R = 8.9^{+1.5}_{-1.3}\,R_g$
Inclination	$i = 154.9^{+4.6°}_{-4.6°}$
Position angle	$\Omega = 177.3^{+24°}_{-23°}$
Enclosed mass	$M_{enc} = 4.2^{+1.2}_{-0.9} \times 10^6\,M_\odot$





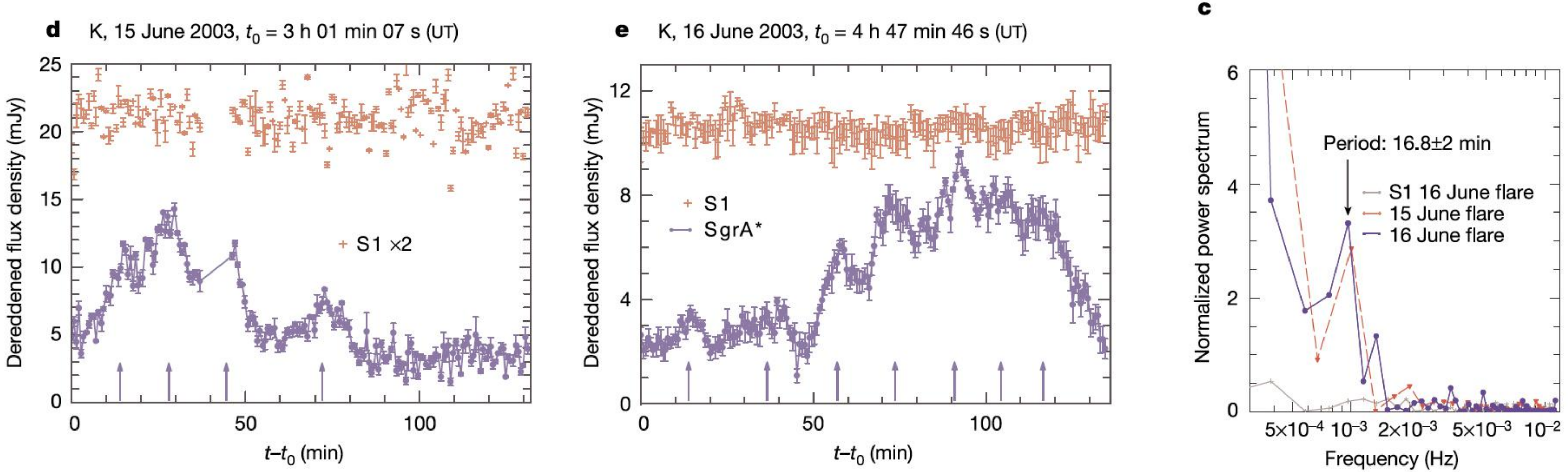


letters to nature

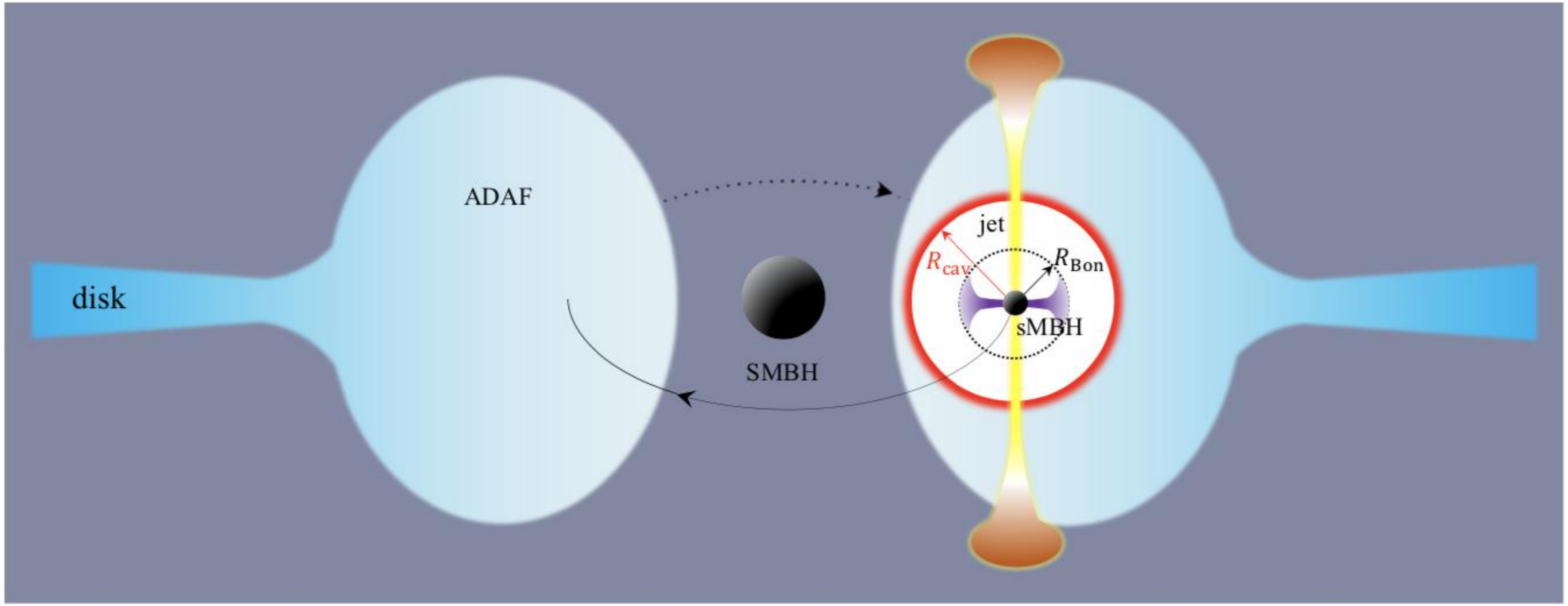
Near-infrared flares from accreting gas around the supermassive black hole at the Galactic Centre

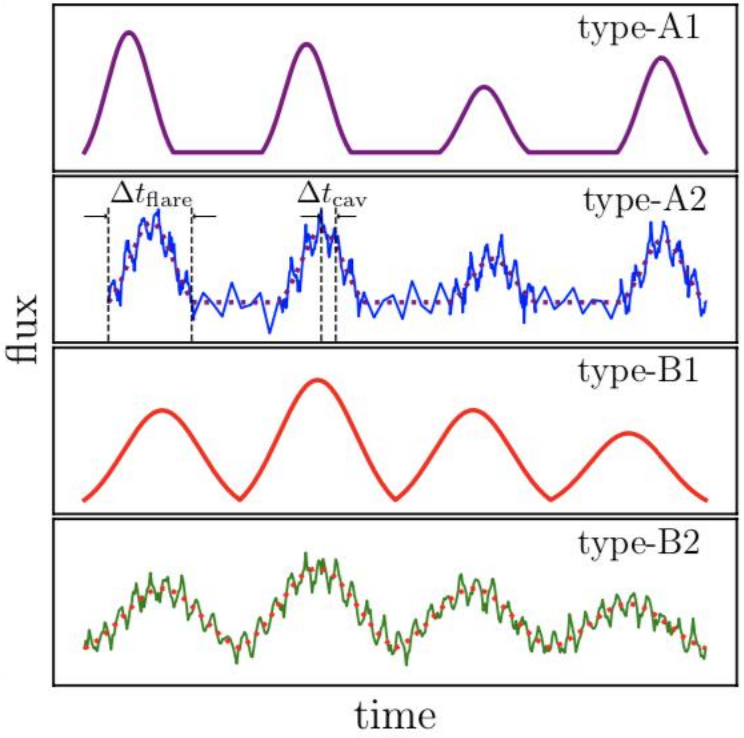
R. Genzel[1,2], R. Schödel[1], T. Ott[1], A. Eckart[3], T. Alexander[4], F. Lacombe[5], D. Rouan[5] & B. Aschenbach[1]

Quasi-periodical variability



银河心中心：Sgr A





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

$$t_{GW} = \frac{A}{dA/dt} = \frac{5a^4}{64q(1+q)} \left(\frac{R_g}{c}\right) \approx 48.8\, a_1^4 q_{\bar{5}}^{-1} \left(\frac{M_6}{4}\right) \mathrm{yr},$$

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

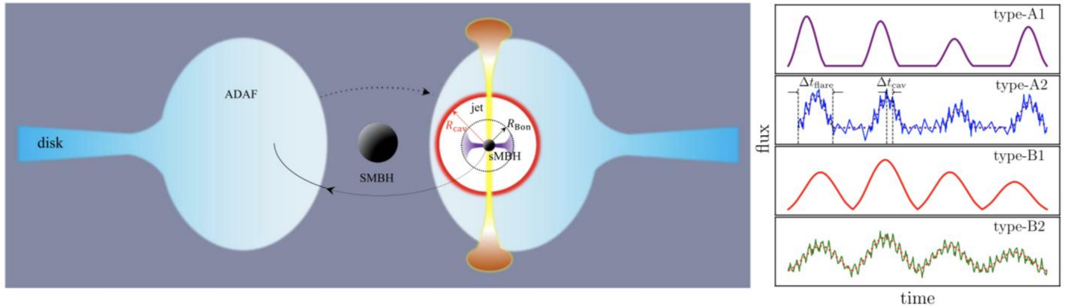
THE ASTROPHYSICAL JOURNAL LETTERS, 958:L40 (13pp), 2023 December 1 https://doi.org/10.3847/2041-8213/ad0bd9

Accretion-modified Stars in Accretion Disks of Active Galactic Nuclei: The Low-luminosity Cases and an Application to Sgr A*

Jian-Min Wang[1,2,3], Jun-Rong Liu[1,4], Yan-Rong Li[1], Yu-Yang Songsheng[1], Ye-Fei Yuan[5], and Luis C. Ho[6,7]

$$\mathscr{\dot M}_{\rm s} = \frac{\dot M_{\rm s}}{\dot M_{\rm Edd}} = 2.0 \times 10^{-6}\, \alpha_{0.1}^{-1} \mathscr{\dot M}_{{\rm p},\bar 3} q_{\bar 5},$$

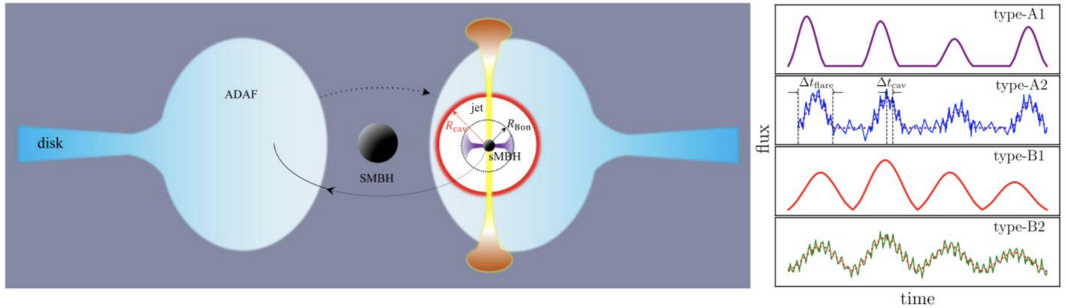
$$R_{\rm Bon} = \frac{GM_{\rm s}}{c_{\rm s,p}^2} = 2.1 \times 10^{8}\left(\frac{m_1}{4}\right) r_1 \ {\rm cm},$$



Outflows from ADAF to form a cavity $L_{\rm out}\,\Delta t_{\rm cav} = \frac{4\pi}{3} R_{\rm cav}^3 P_{\rm gas}$, $L_{\rm out}/v_{\rm out} = 4\pi R_{\rm cav}^2 P_{\rm gas}$

$$R_{\rm cav} = 1.9 \times 10^{10} \eta_{0.1}^{1/3} \alpha_{0.1}^{-1/3} r_1^{4/3} q_{\bar 5}^{2/3} \left(\frac{M_6}{4}\right) {\rm cm}, \qquad \Delta t_{\rm cav} = \frac{HP_{\rm gas}}{Q_+} = 45.9\, \alpha_{0.1}^{-1} r_1^{3/2} \left(\frac{M_6}{4}\right) {\rm minutes},$$

Rejuvenation timescale of cavity



$$\Delta t_{\rm rej} = \frac{R_{\rm cav}}{v_{\rm tur}} = 37.9\, \eta_{0.1}^{1/3} \alpha_{0.1}^{-4/3} q_{\bar{5}}^{2/3} r_1^{11/6} \left(\frac{M_6}{4}\right) {\rm s},$$

$$R_{\rm flare} \approx \left(\frac{3L_{\rm out}\Delta t_{\rm cool}}{4\pi P_{\rm gas}}\right)^{1/3}$$
$$= 3.7 \times 10^{10}\, \eta_{0.1}^{1/3} \chi_0^{-1/3} T_9^{1/6} n_{10}^{-1/3} r_1^{5/6} q_{\bar{5}}^{2/3} \left(\frac{M_6}{4}\right)^{2/3} {\rm cm},$$

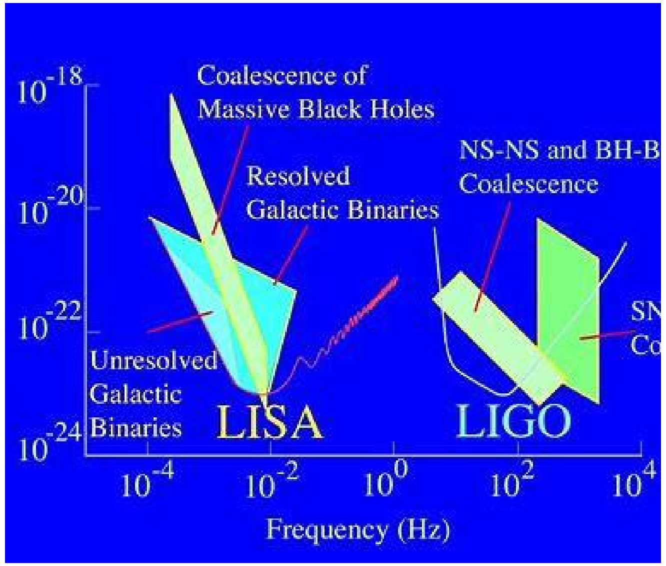
$$\Delta t_{\rm cool} = \frac{3}{2}\frac{n_{\rm e} k T_{\rm s}}{\epsilon_{\rm tot}} \approx 5.6\, \chi_0^{-1} T_9^{1/2} n_{10}^{-1}\, {\rm hr},$$

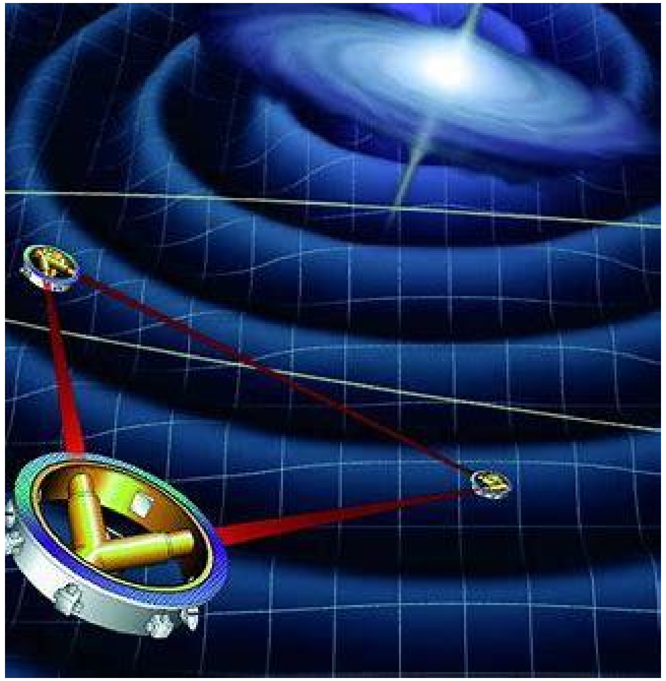
$$N_{\rm flick} = \frac{\Delta t_{\rm cool}}{\Delta t_{\rm cav}} \approx 7.4 \left(\frac{\Delta t_{\rm cool}}{5.6\ {\rm hr}}\right)\left(\frac{\Delta t_{\rm cav}}{45.9\ {\rm minutes}}\right)^{-1}.$$

GW: Extremely small mass ratio spiral

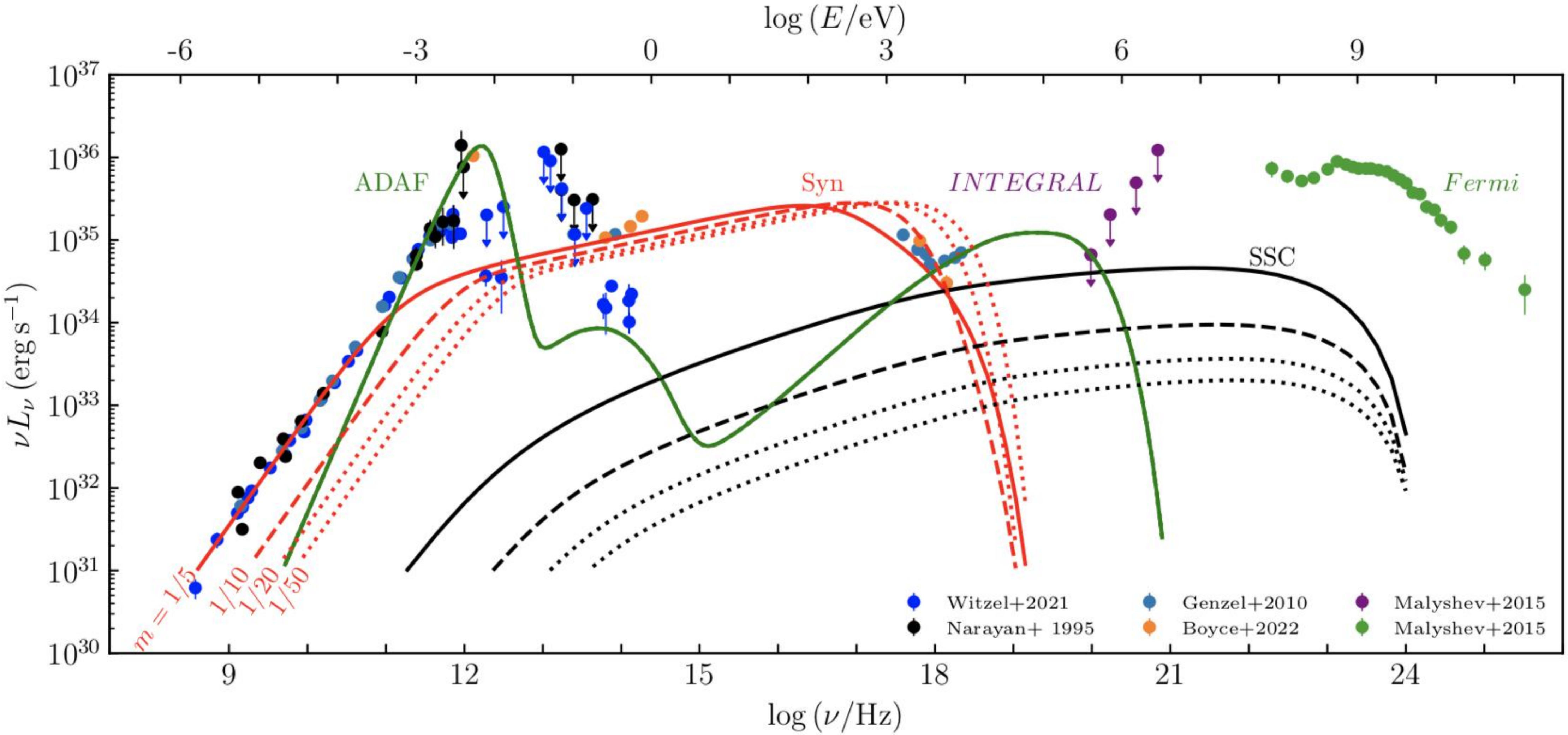
$$h_s = \left(\frac{128}{15}\right)^{1/2} \frac{(GM_c)^{5/3}}{c^4 d_L} (\pi f)^{2/3}$$
$$= 7.6 \times 10^{-17} \, d_{10\,\mathrm{kpc}}^{-1} a_1^{-1} q_{\bar{5}} \left(\frac{M_6}{4}\right),$$

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





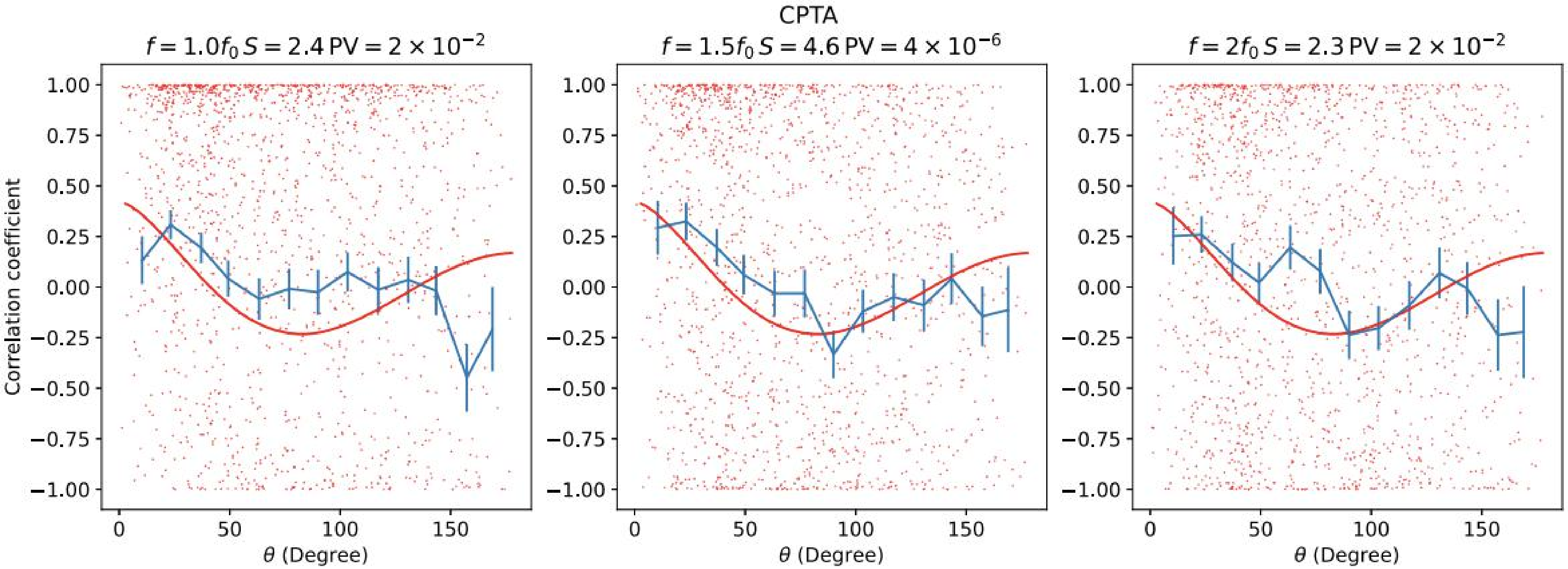
SED


log (E/eV)
-6
-3
0
3
6
9
ADAF
Syn
INTEGRAL
Fermi
SSC
m = 1/5
1/10
1/20
1/50
Witzel+2021
Narayan+ 1995
Genzel+2010
Boyce+2022
Malyshev+2015
Malyshev+2015
log (ν/Hz)
9
12
15
18
21
24

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

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]



同时检验：nHz引力波

Binary-SMBHs

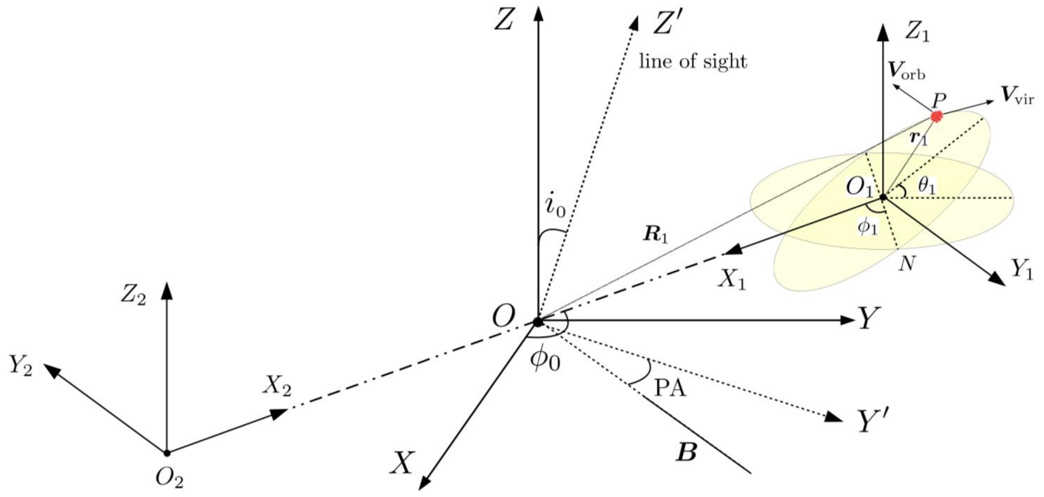
The Astrophysical Journal, 862:171 (10pp), 2018 August 1 https://doi.org/10.3847/1538-4357/aacdfa

CrossMark

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]

Binary-BLRs



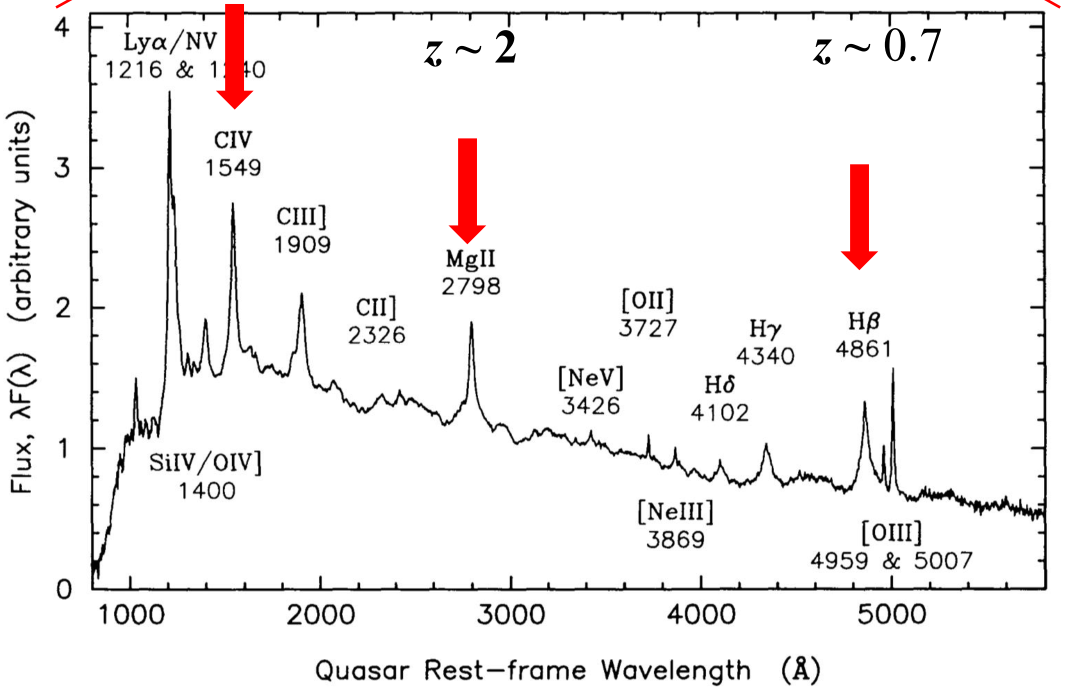
Blandford & McKee(1982): 2D-transfer function

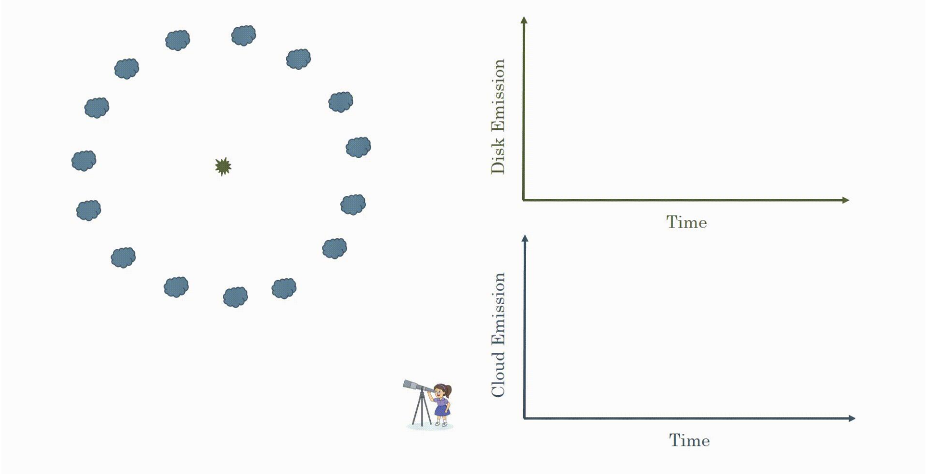
$$\Psi(v,\, t) = \frac{1}{2\pi}\mathscr{F}^{-1}\left[\frac{\tilde{L}_{\ell}(v,\, \omega)}{\tilde{L}_{\rm c}(v,\, \omega)}\right],$$

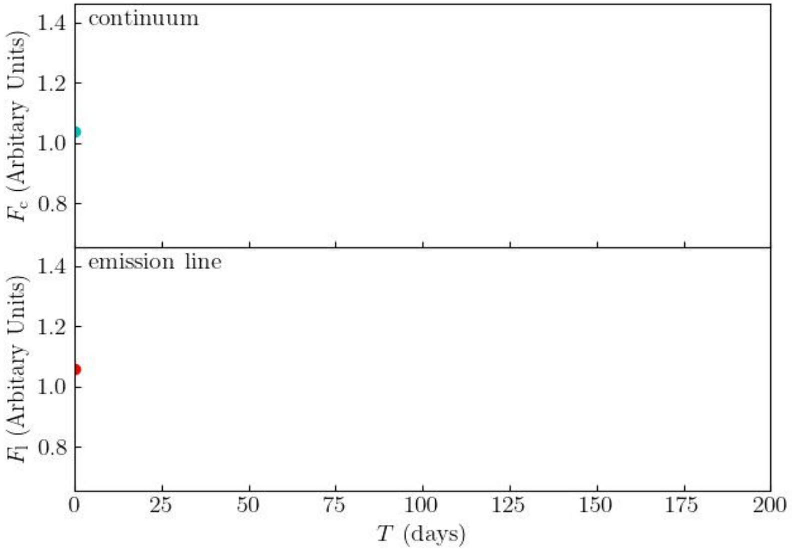
$$\tilde{L}_{\ell,{\rm c}} = \mathscr{F}[L_{\ell,{\rm c}}(v,\, t)],$$

$$\Psi_{\rm tot}(v,\, t) = \frac{\Psi_1(v,\, t)}{1 + \Gamma_0} + \frac{\Psi_2(v,\, t)}{1 + \Gamma_0^{-1}},$$

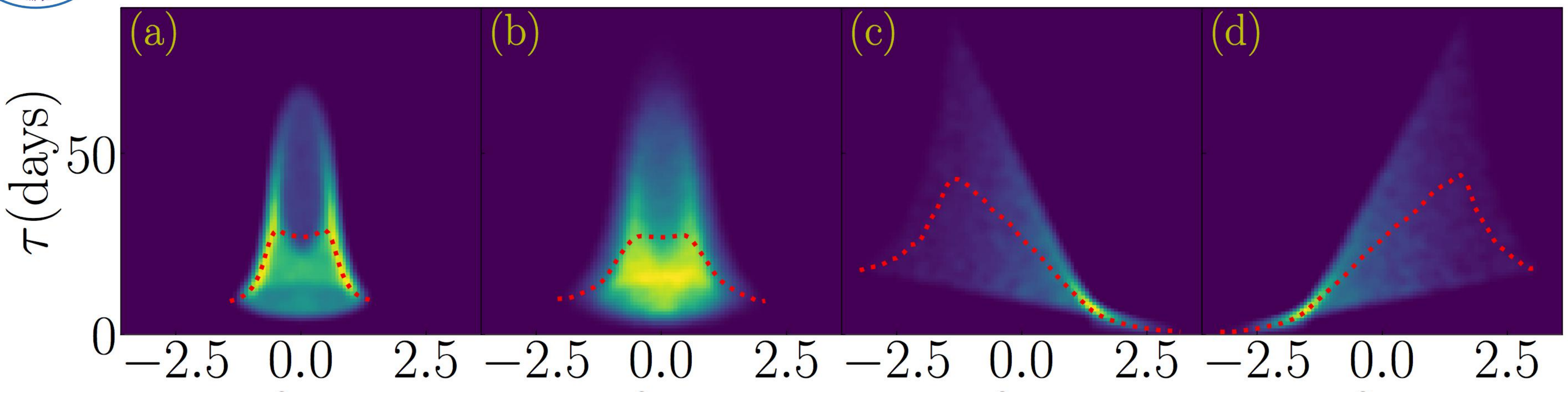
Reverberation mapping: spatial distributions and gas dynamics



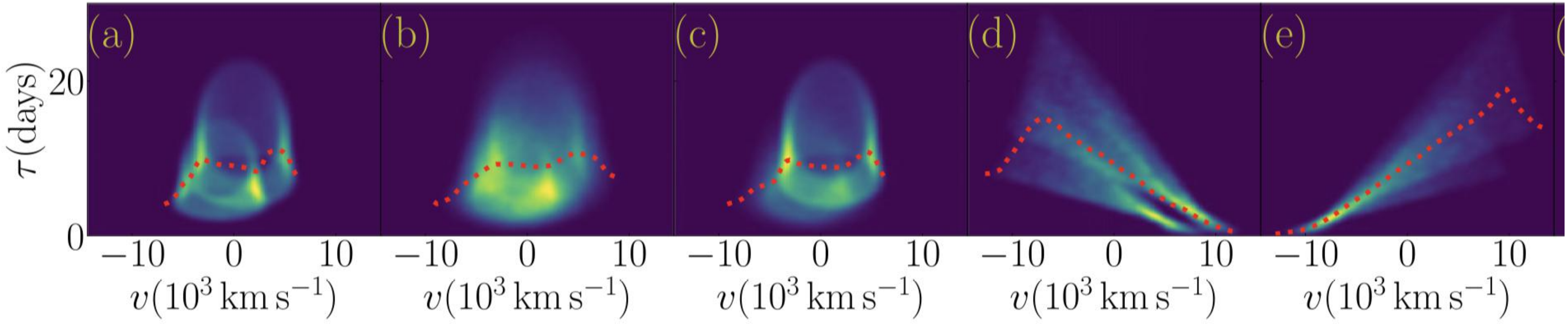




Songsheng+(2020); Kovacevic+(2020)



单一宽线区



RM: 2D transfer functions

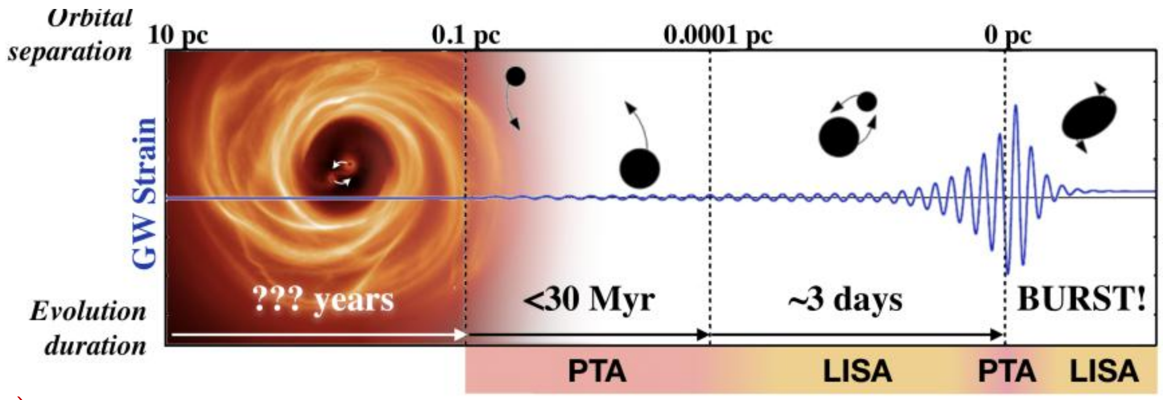
(Wang+2018; Songsheng+2019; Kovacevic+2019)

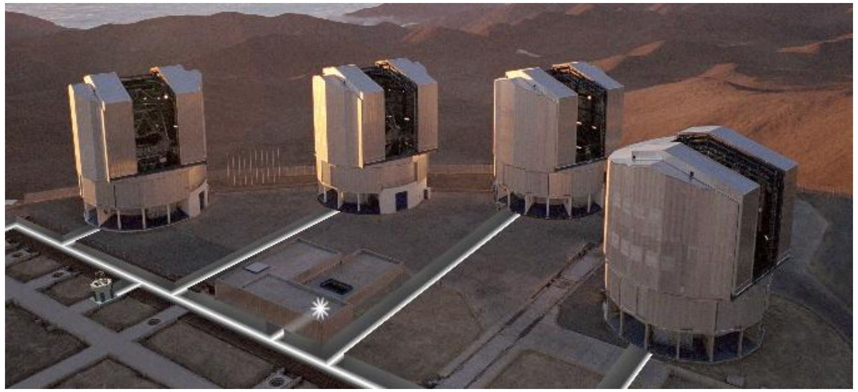
轨道运动：偏离

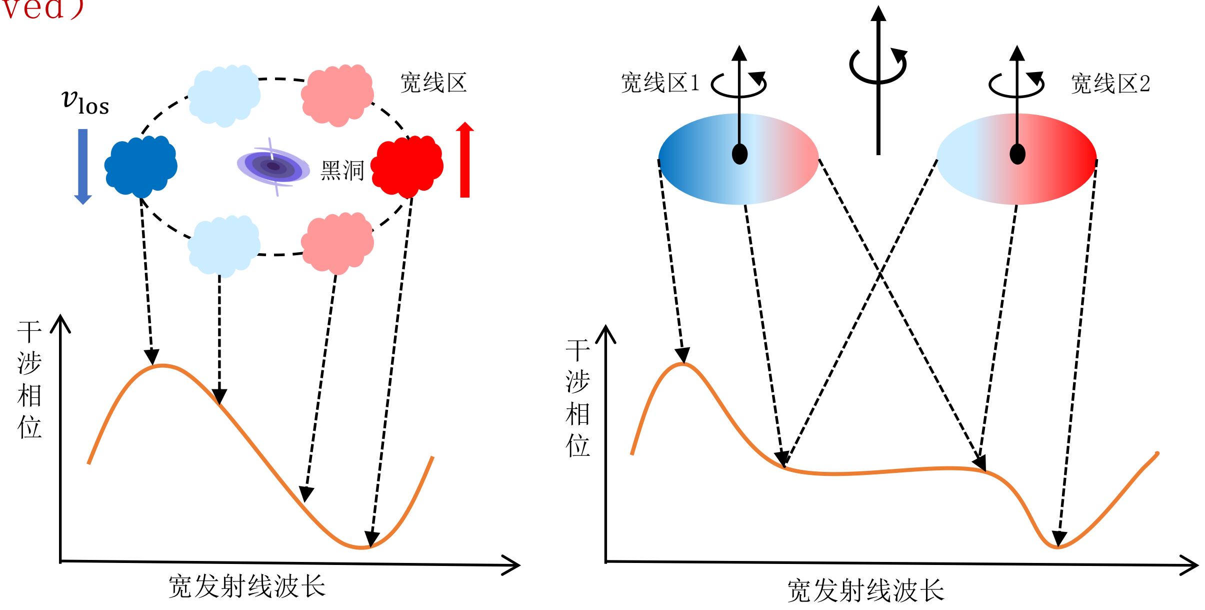
Very Large Telescope Interferometer (VLTI)

Interferometric characteristics: binary-SMBHs

- Difficulties:
  - ➢ Diameter ≲ 100μas, hardly imaged
  - ➢ Periodical, asymmetric profiles: multiple explanations
- Gas dynamics around binary-SMBHs
  - ➢ Reverberation mapping (resolved in time domain)
  - ➢ Interferometry and astrometry (spatially resolved)



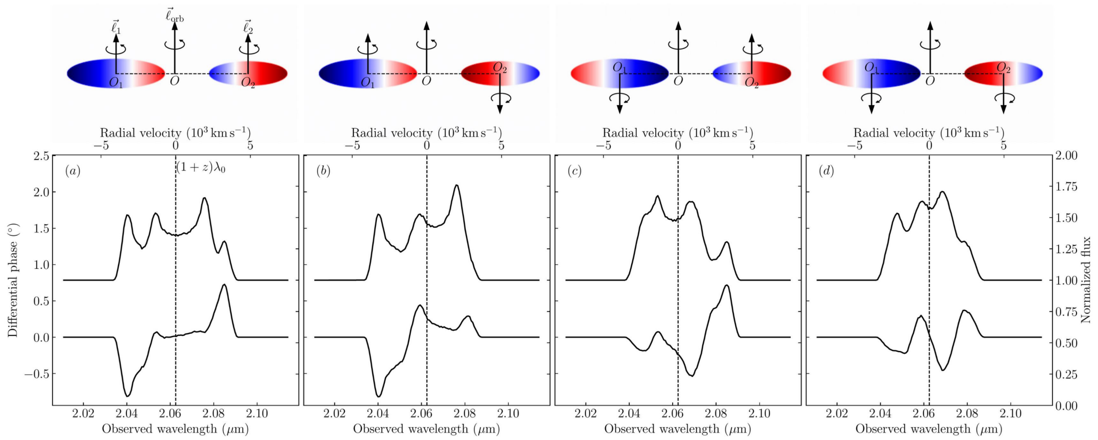




Binary-SMBHs: separate BLRs

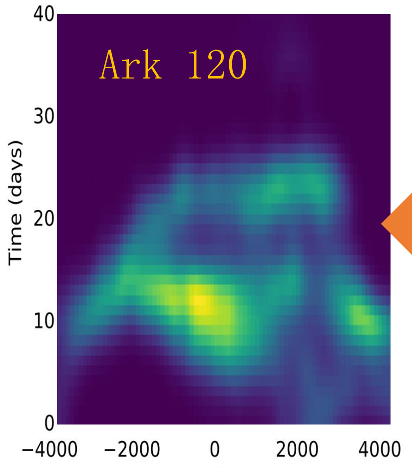
(Songsheng, Wang+2019; Kovačević, Songsheng+2020)

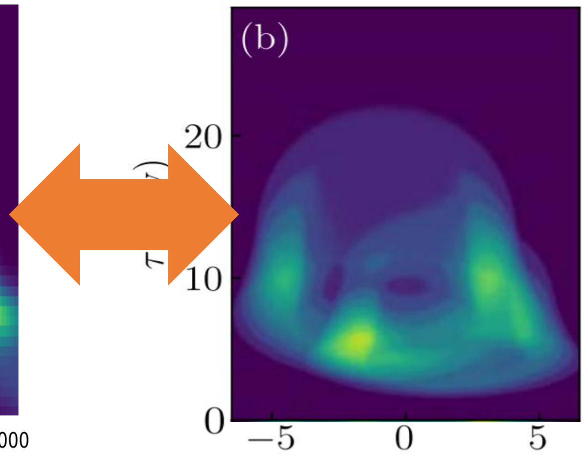
Circle orbits: different configurations



关键特征：相位平台或多峰（谷）结构

With GRAVITY+, it will be possible for the first time to probe radio-quiet parsec-scale binary SMBHs, from the local universe, through the 'peak of binarity' at z $\approx$0.6 – 1.3, and out to the cosmic peak of galaxy merging (z $\approx$ 2). GRAVITY+ can detect the tell-tale phase signatures of dual BLRs in close binary SMBHs (Songsheng et al. 2019). By providing spatial information, GRAVITY+ will be the ultimate instrument to firmly establish the binarity of candidates that are expected in the thousands from, e.g., upcoming surveys with SDSS-V and 4MOST. The infrared regime will overcome potential obscuration in these systems while removing the requirement for radio-loudness.

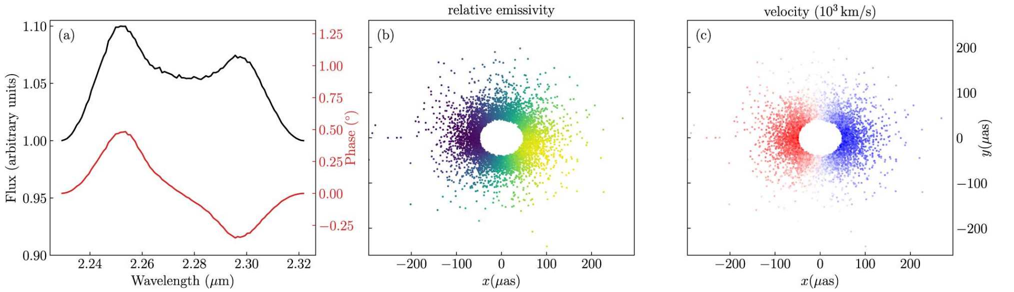




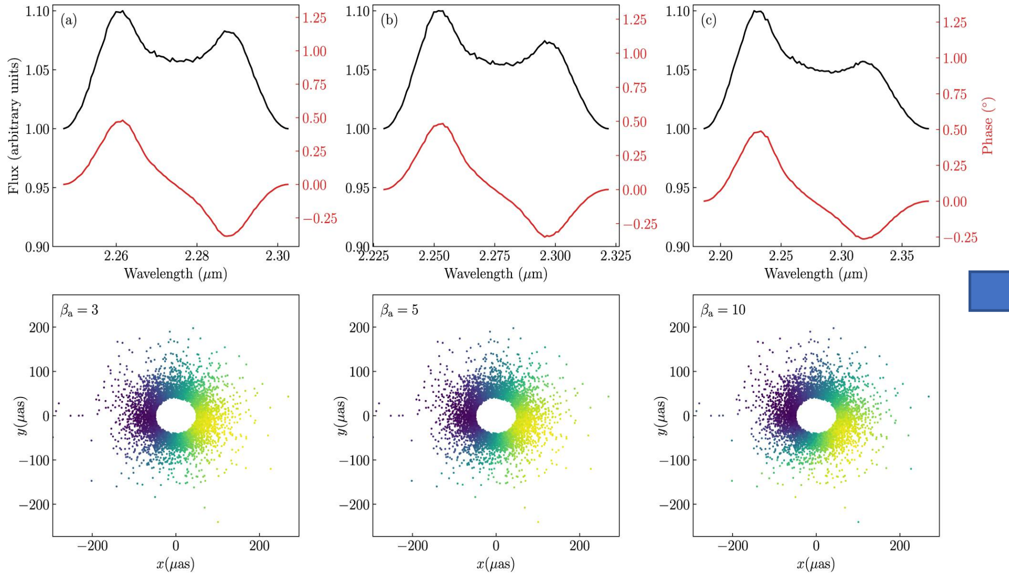
Binary-SMBHs: merged BLRs

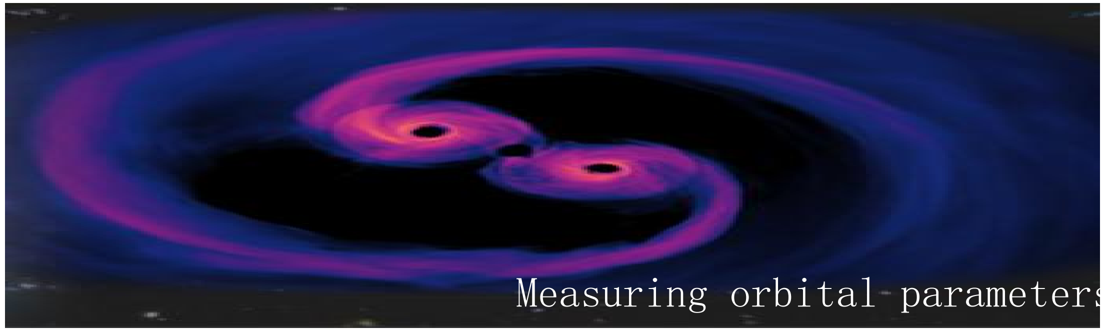
(Songsheng & Wang 2023)

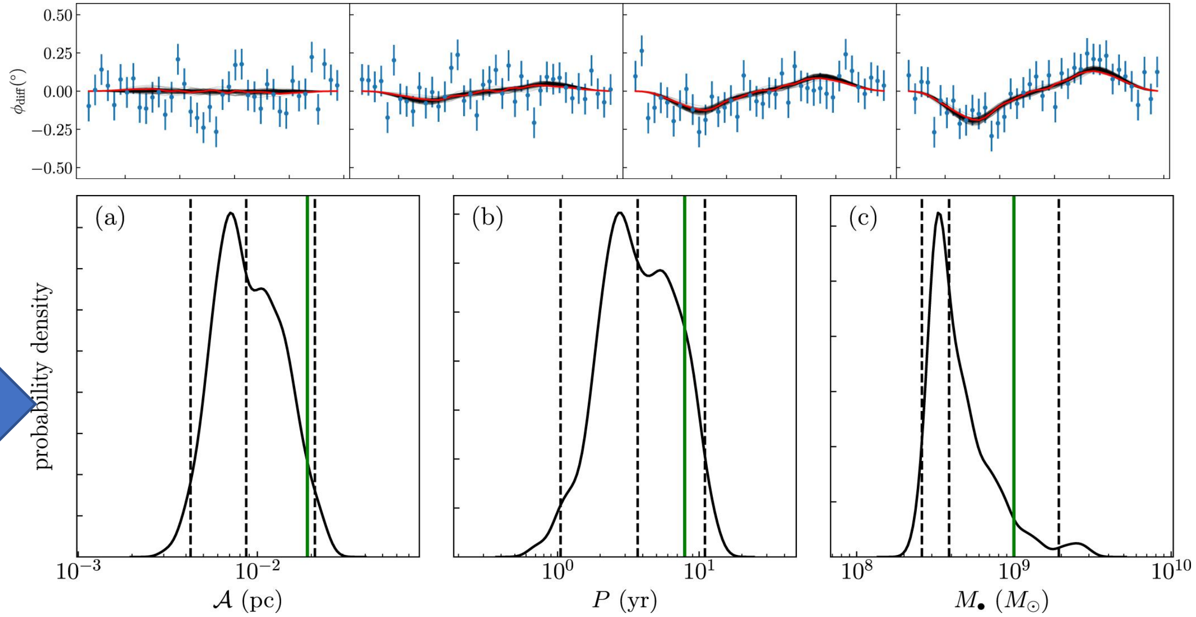
- Asymmetry: Doppler boosting effects



- Interferometric information: sensitive to orbits

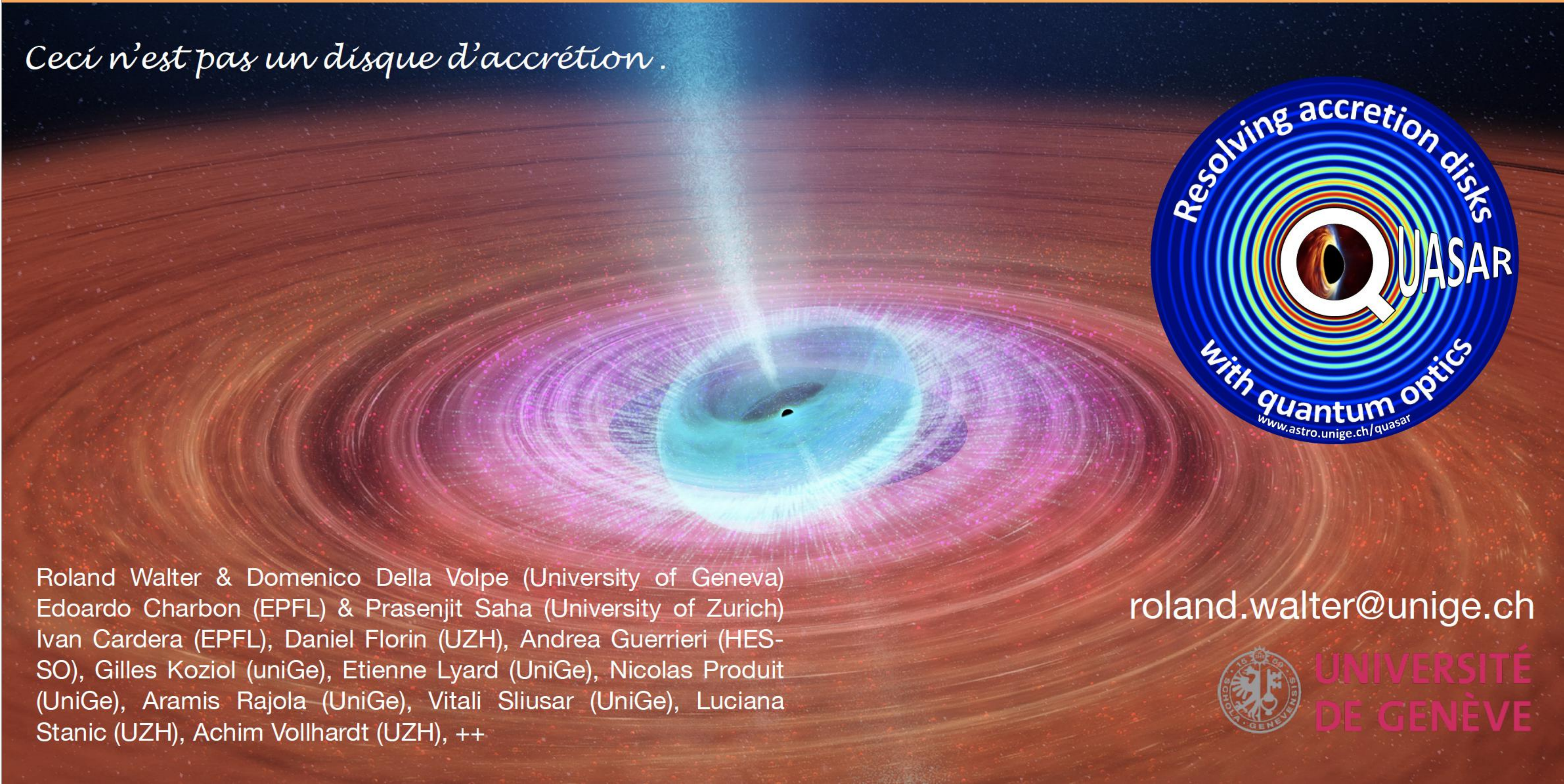






On separations On periods Total mass

Reaching 10 microarcsec in the optical to resolve accretion disks



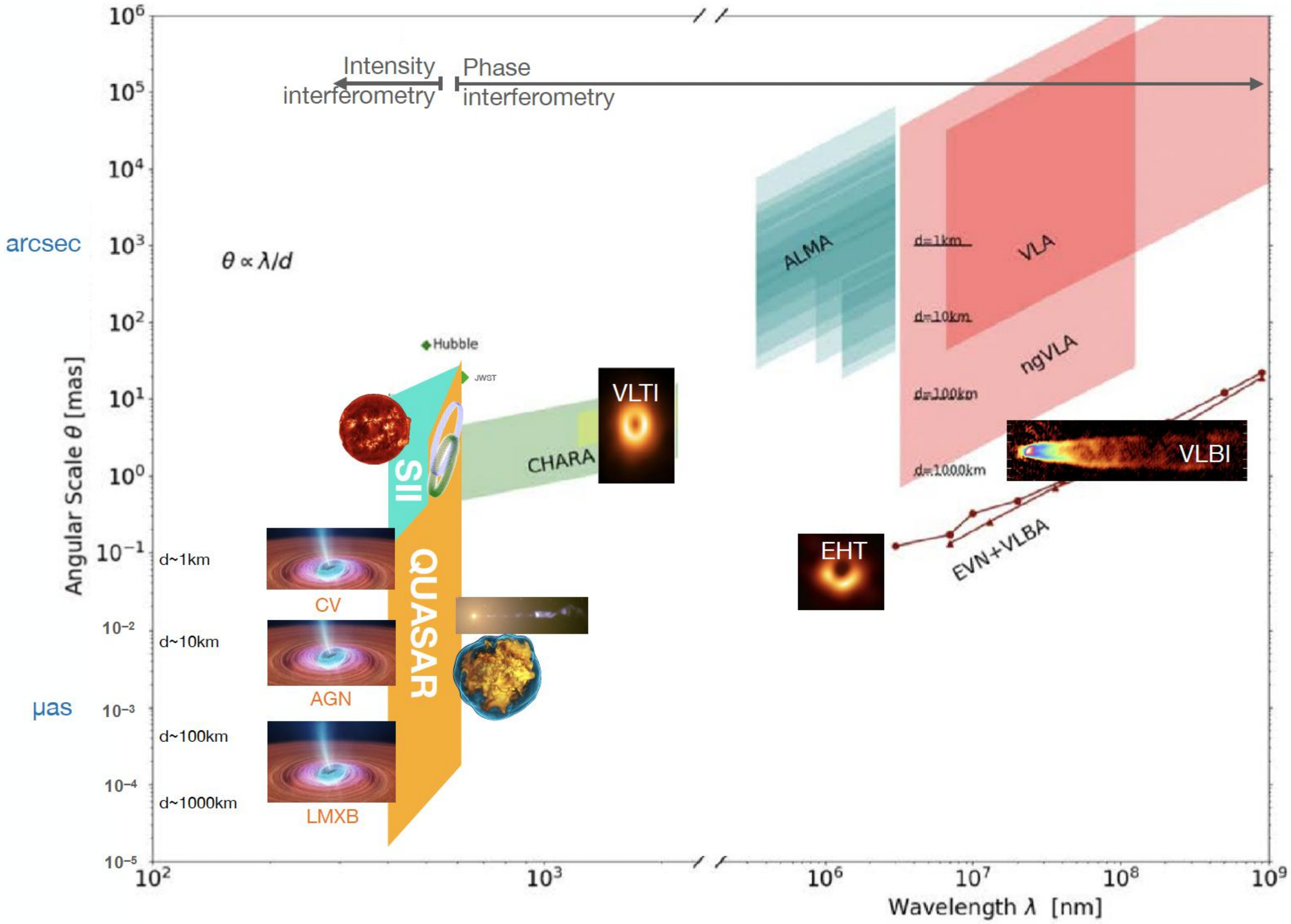
Ceci n'est pas un disque d'accrétion .

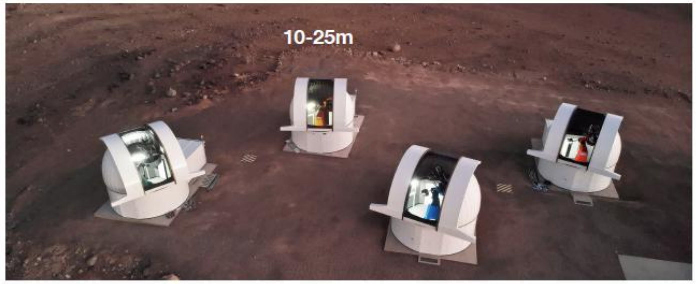
Roland Walter & Domenico Della Volpe (University of Geneva)
Edoardo Charbon (EPFL) & Prasenjit Saha (University of Zurich)
Ivan Cardera (EPFL), Daniel Florin (UZH), Andrea Guerrieri (HES-SO), Gilles Koziol (uniGe), Etienne Lyard (UniGe), Nicolas Produit (UniGe), Aramis Rajola (UniGe), Vitali Sliusar (UniGe), Luciana Stanic (UZH), Achim Vollhardt (UZH), ++

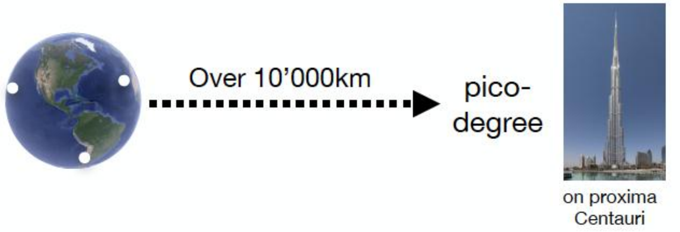
roland.walter@unige.ch

UNIVERSITÉ DE GENÈVE

In the optical, a baseline of 4km provides the same resolution as the EHT







In quantum physics we trust !

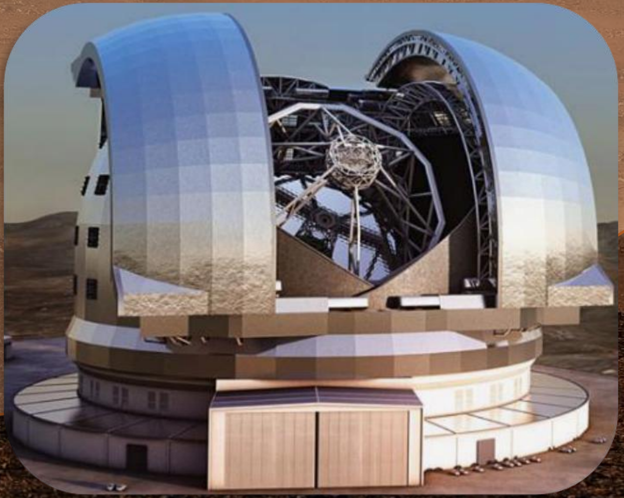
Ten-Kilometer Baselines
Thousands m^2 Collecting Area Optical / IR

Resolution ~ λ/B = 10 μas

Sensitivity ~ ELT ~ 28 (23) mag$_{AB}$

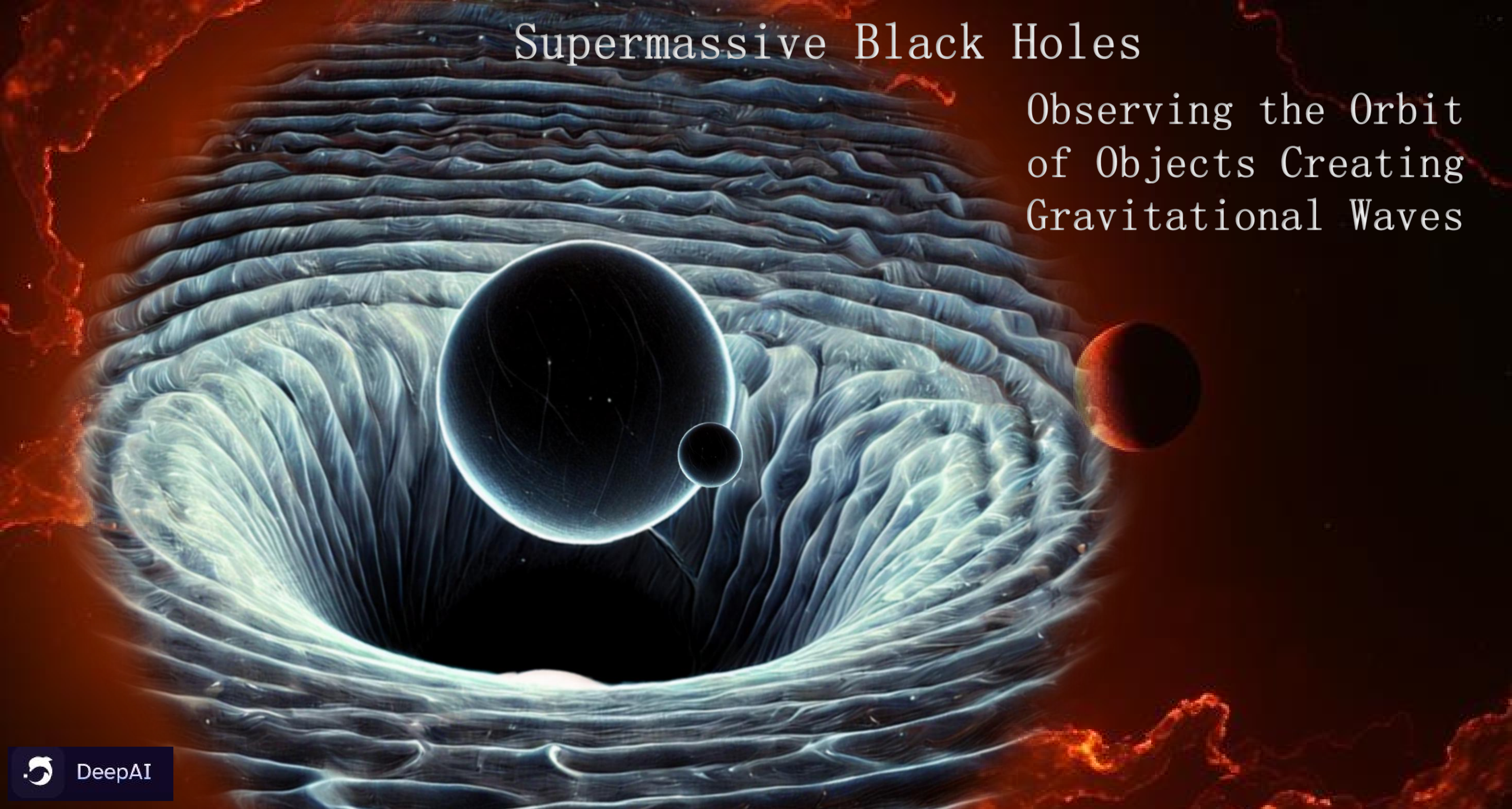
Point Source Imaging (Spectroscopy), 10ks, 10σ

Astrometry ~ 0.1 μas



Supermassive Black Holes

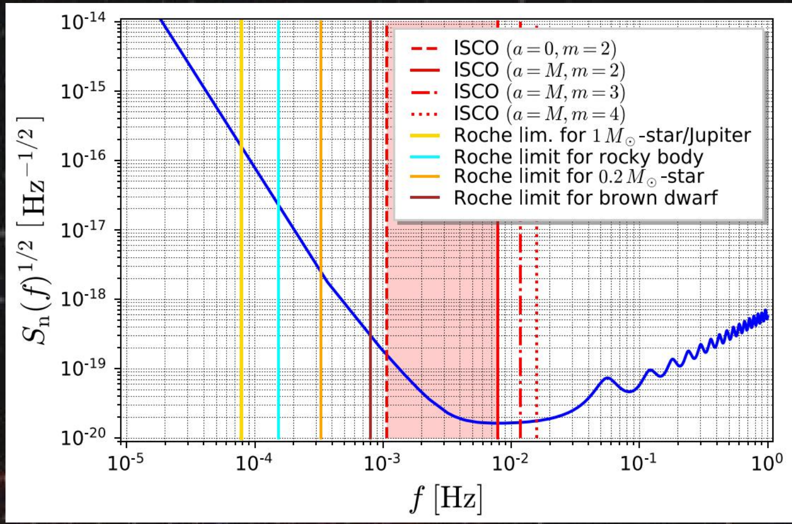
Observing the Orbit of Objects Creating Gravitational Waves



„rotating supermassive black hole with a flaring accretion disc and a neutron star on close orbit emitting gravitational waves.“

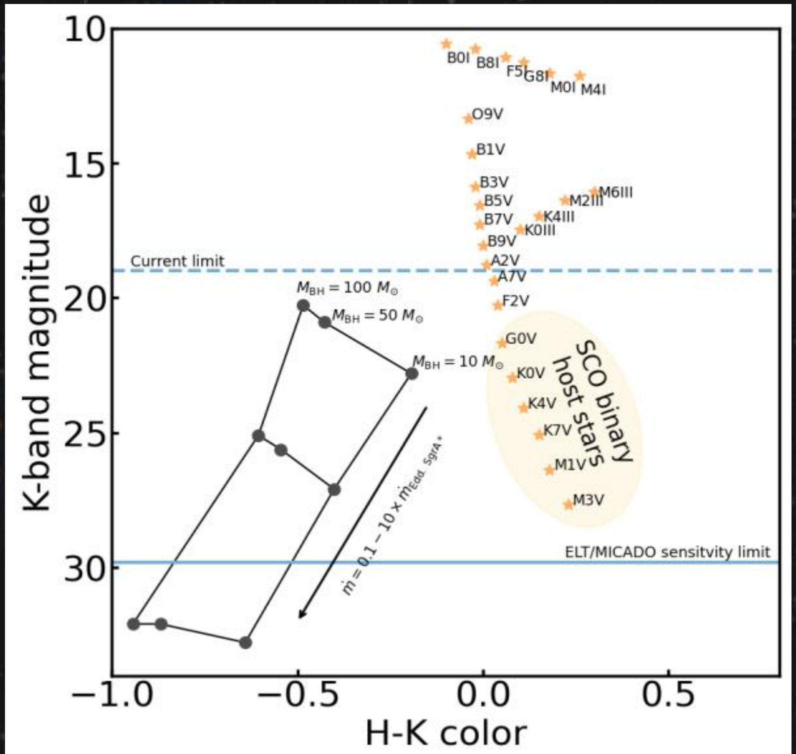
SMBHs

Observing the Orbit of Objects: Gravitational Waves



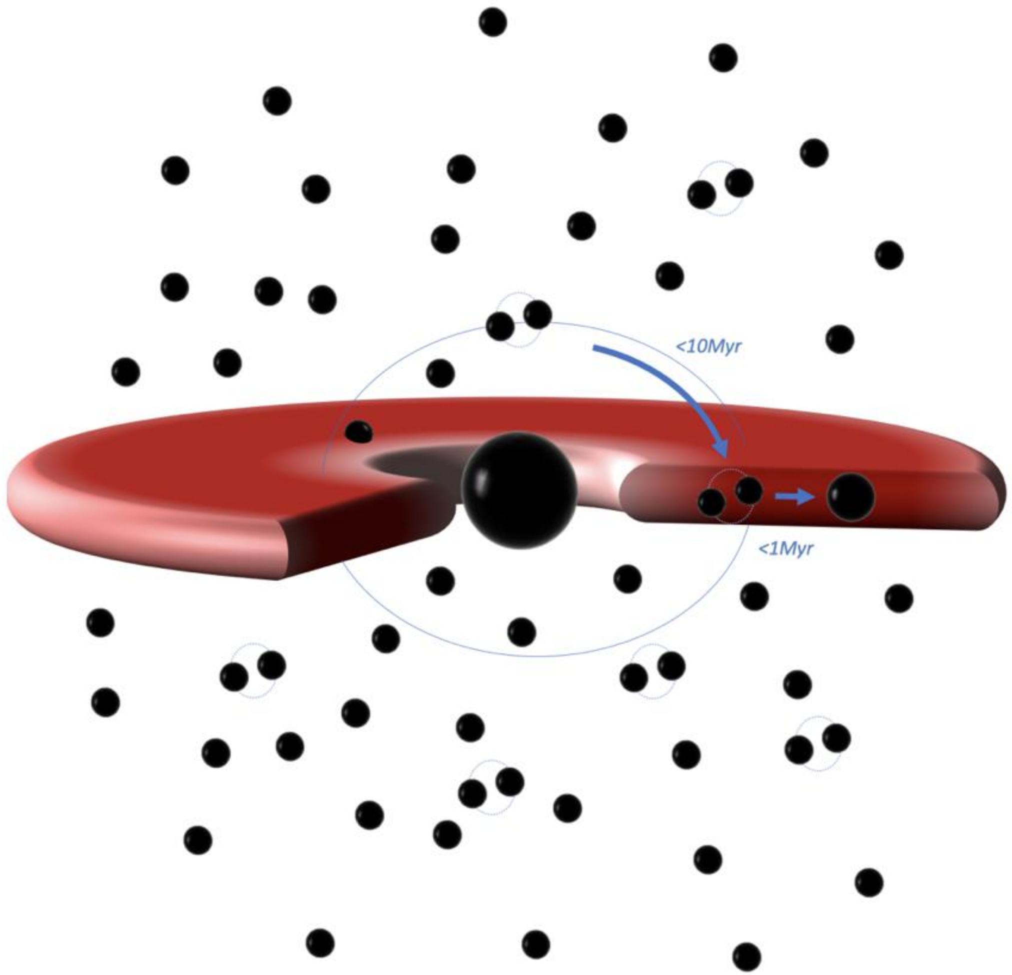
Gourgoulhon+ 19

Amaro Seoane+ 23



Von Fellenberg (2025)

Credit: NASA



2040：15years

AGN structure：

- New energy sources:

  compact objects

- Gravitational Waves？

Conclusions

- AGN-disk: stellar processes
- Accretion rates: starburst
- Metallicity: observational appearance
- Satellite sMBH: GWs and Bondi explosion

AGN: golden mine

谢谢!