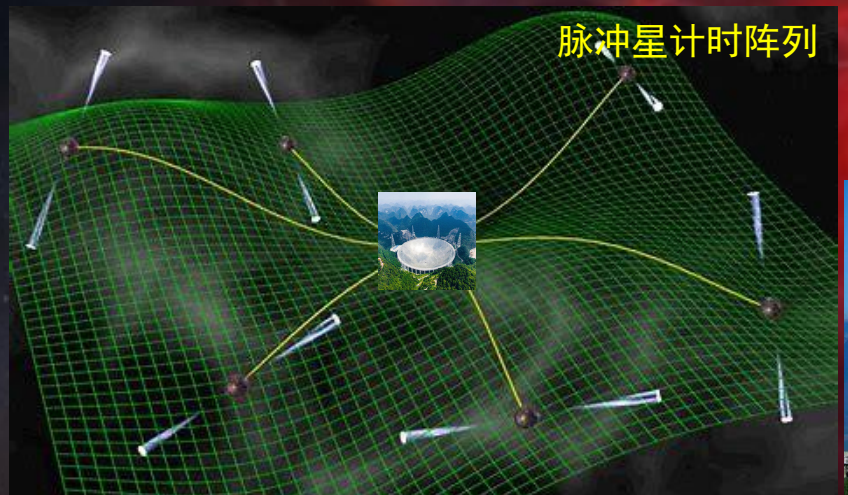
极端宇宙：黑洞与炼丹炉

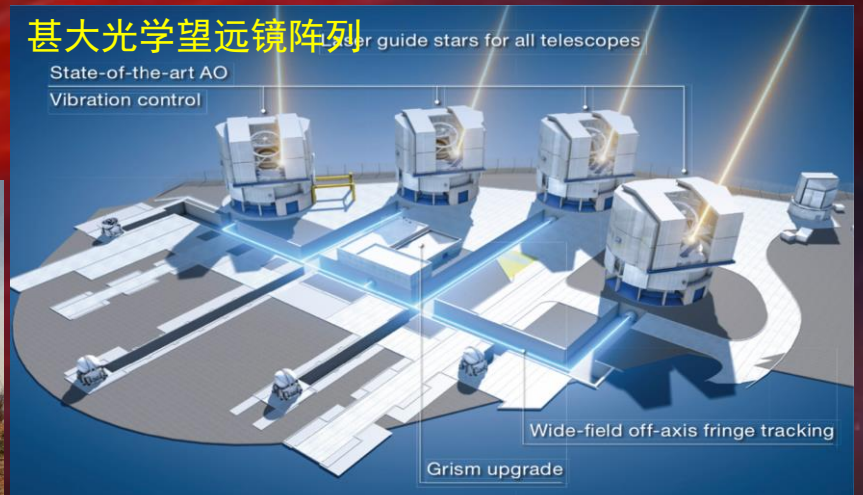
从超新星爆发、银河系中心、大质量黑洞、宇宙膨胀历史、引力波辐射

王建民

中国科学院高能物理研究所

2023/08/25，西南交大@成都

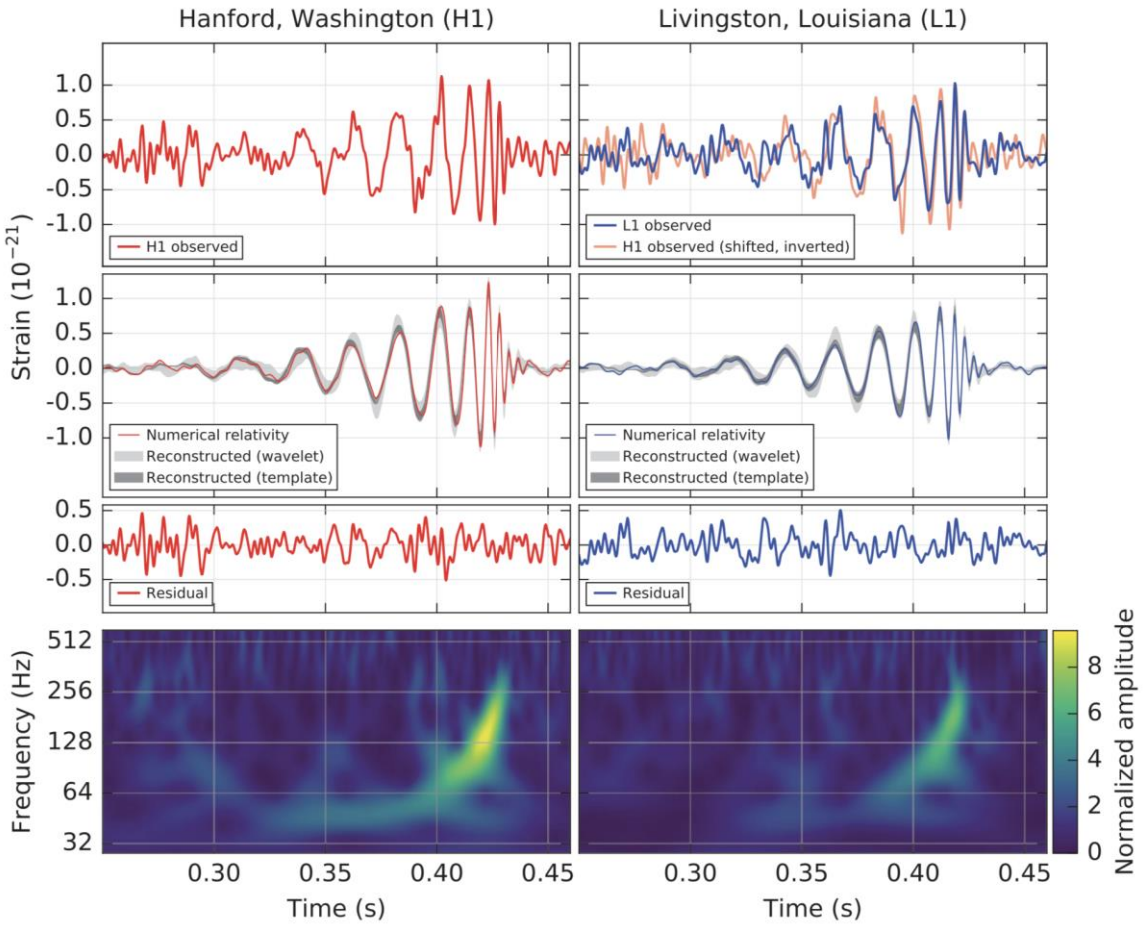




PRL 116, 061102 (2016)
Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS
week ending
12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)



双黑洞：

$36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$

GRB: 引力波辐射、中微子辐射

（多信使）

"For the greatest benefit to mankind"
Alfred Nobel

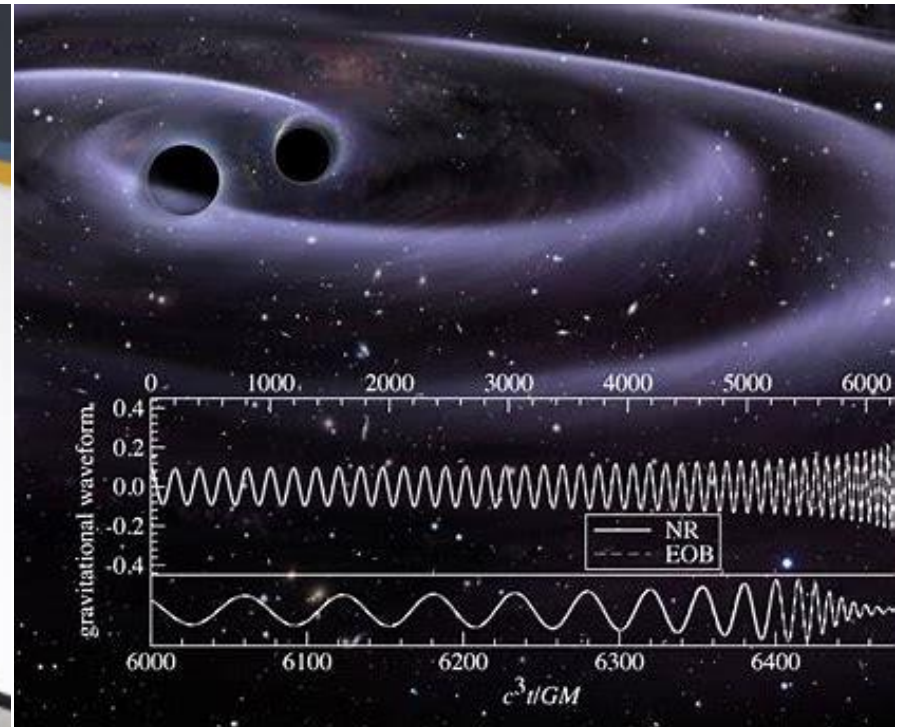
The Royal Swedish Academy of Sciences has decided to award the

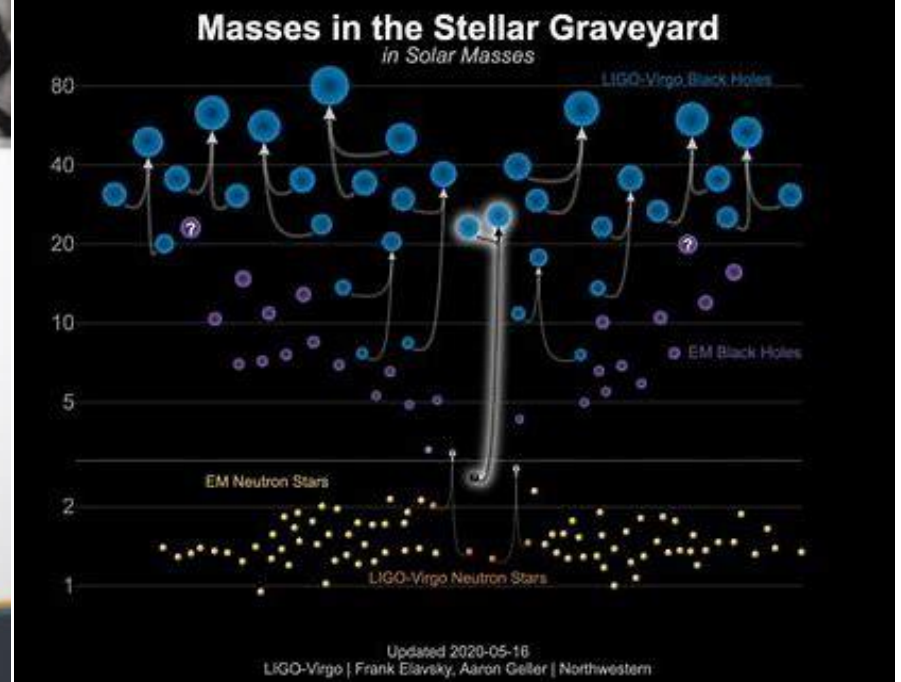
2017 NOBEL PRIZE IN PHYSICS

Rainer Weiss
Barry C. Barish
Kip S. Thorne

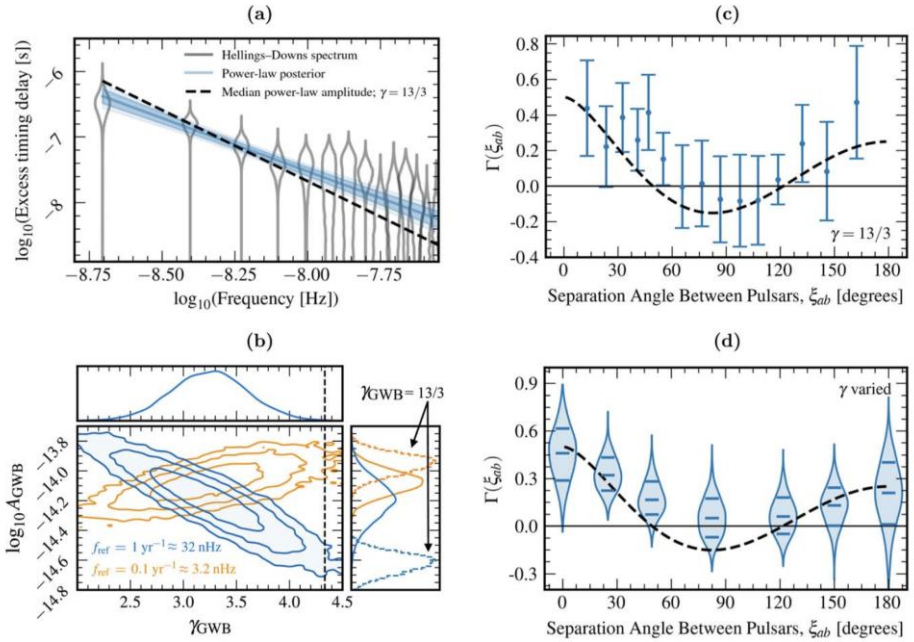
"for decisive contributions to the LIGO detector and the observation of gravitational waves"

Nobelprize.org



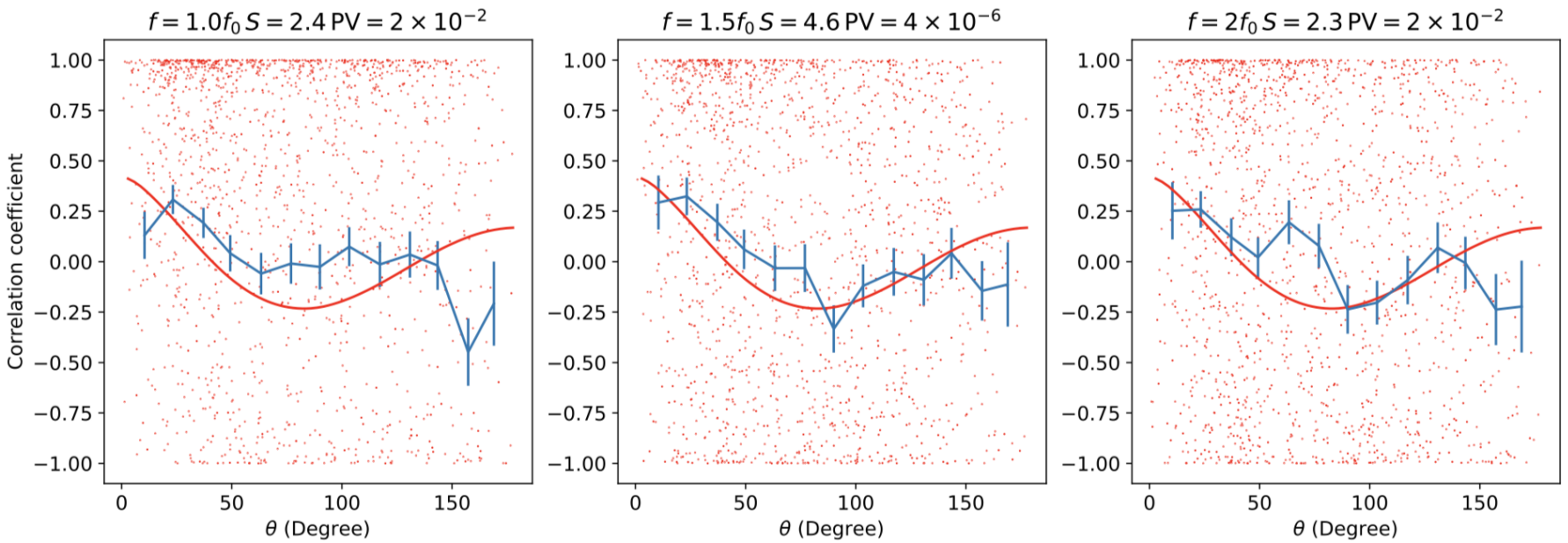


Agazie+2023



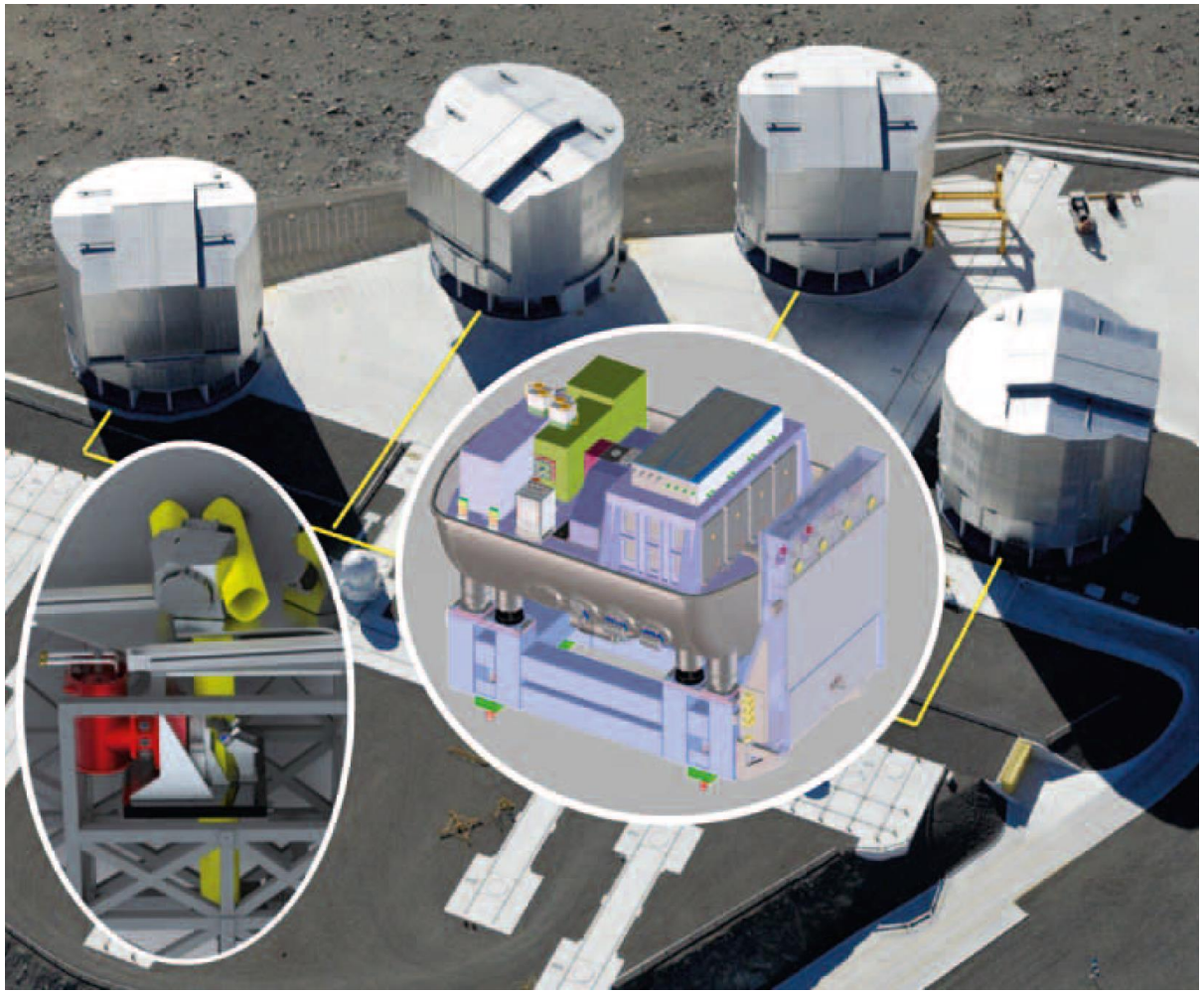
Xu+2023

CPTA



光干涉时代（始于2018）：欧洲南方天文台

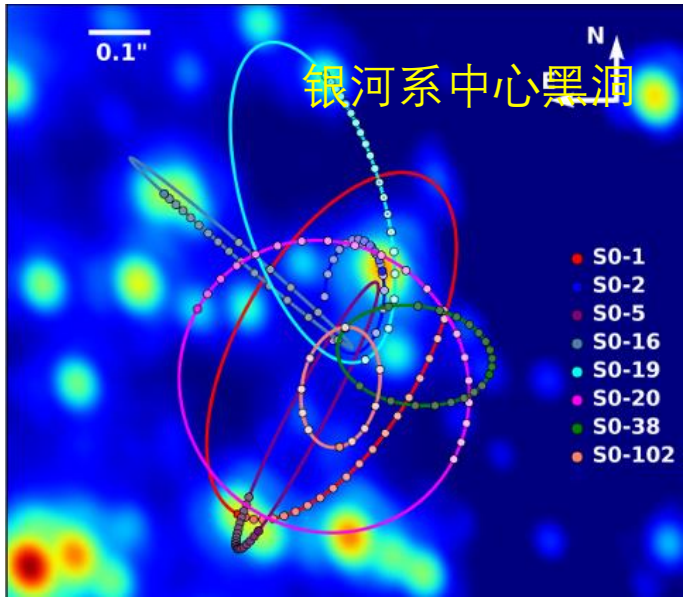
（GRAVITY/VLTI）



4台 ⊗ 8米望远镜

最高空间分辨率：

10微角秒

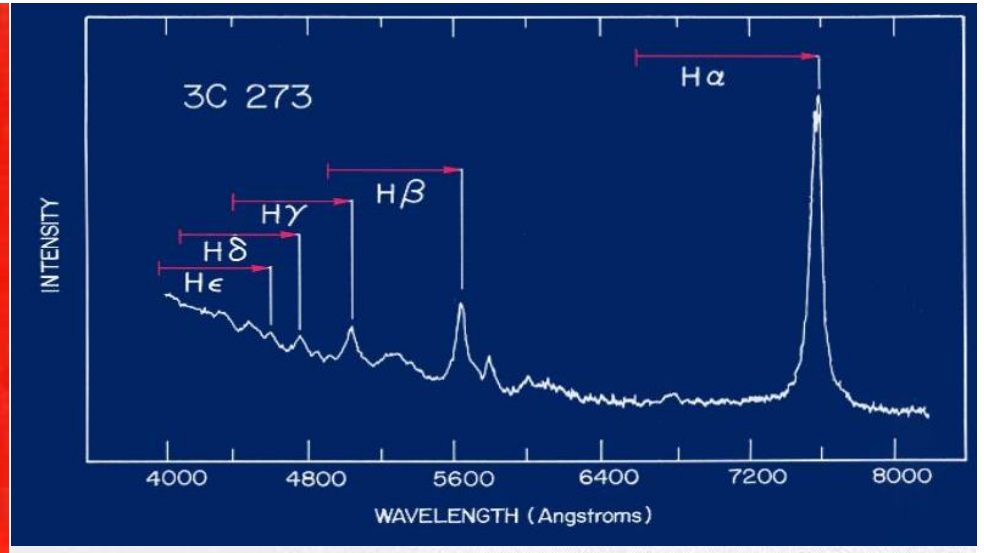


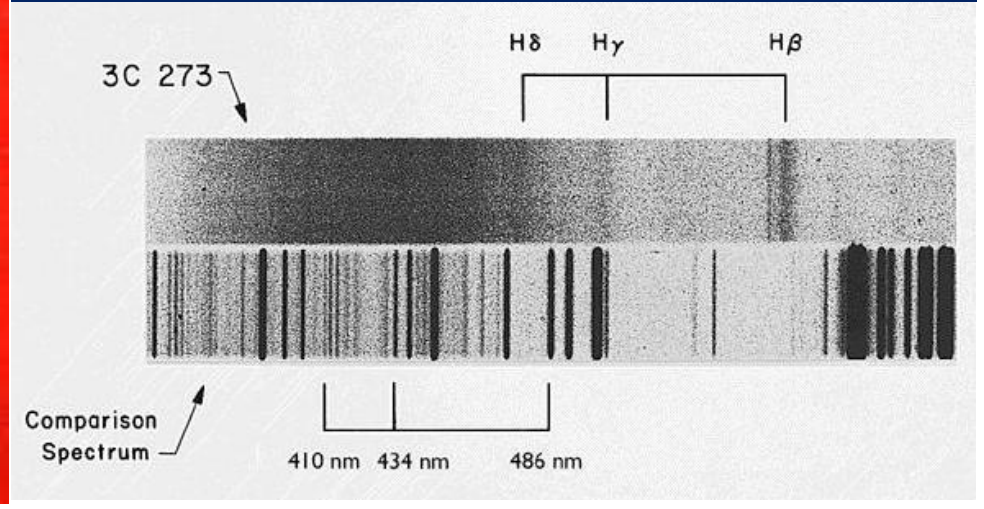
Physics in 2020

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

类星体发现六十周年





Galactic Nuclei as Collapsed Old Quasars

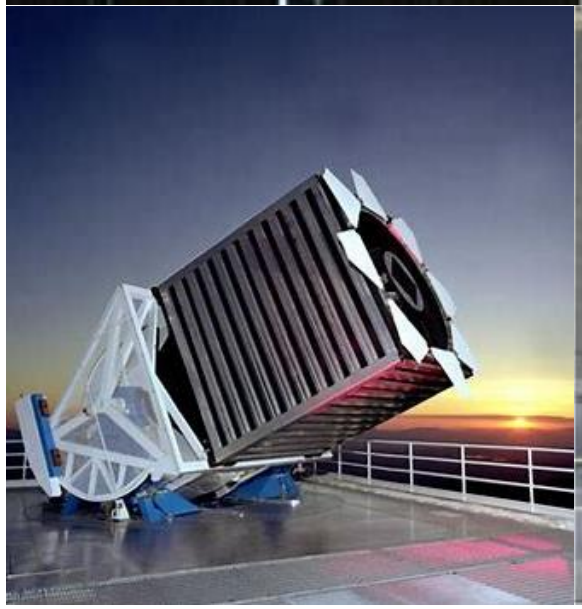
by

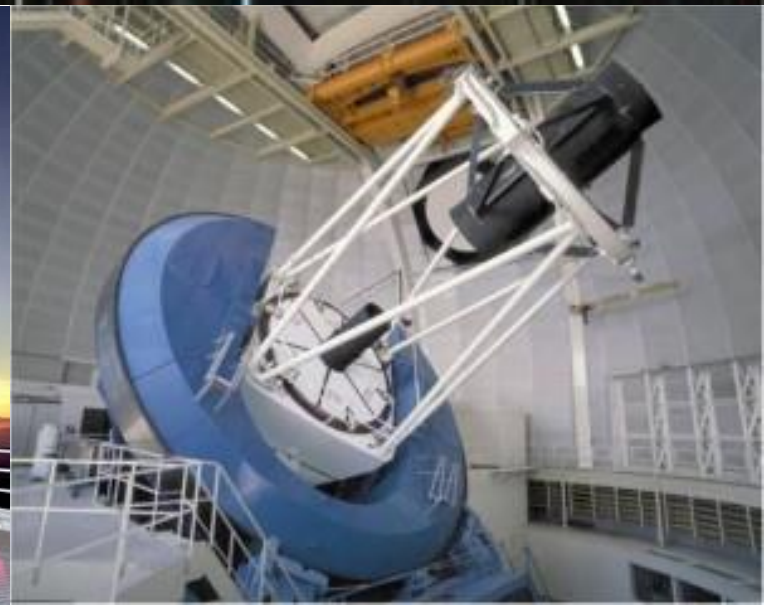
D. LYNDEN-BELL

Royal Greenwich Observatory,
Herstmonceux Castle, Sussex

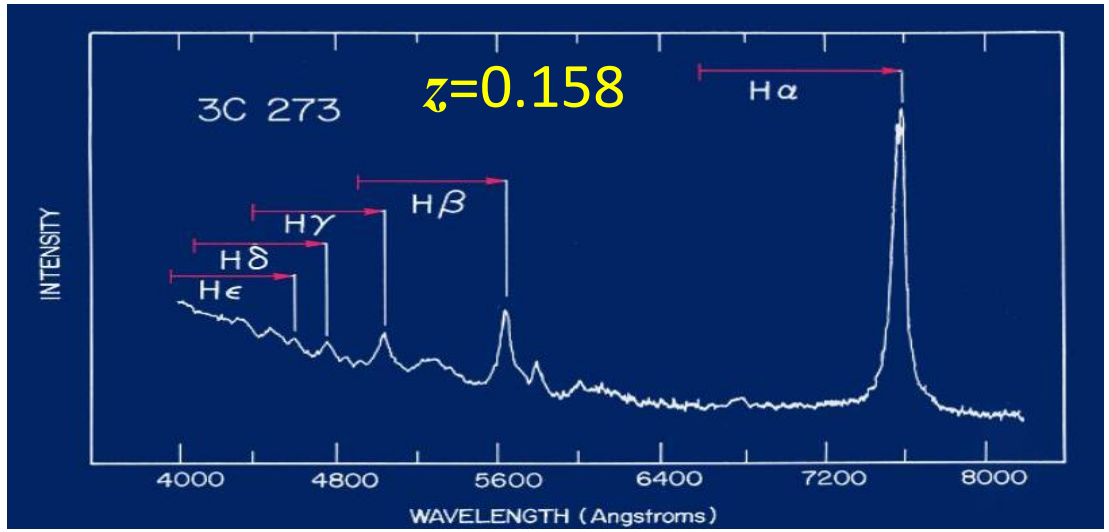
Powerful emissions from the centres of nearby galaxies may represent dead quasars.

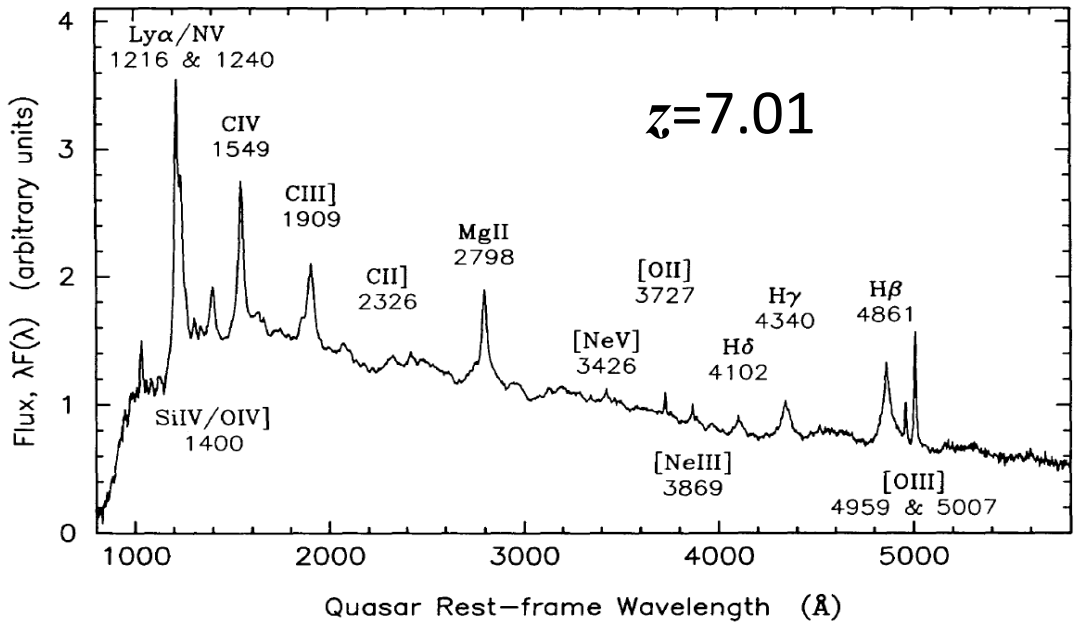

• ～100万类星体





从第一颗类星体到今天100万颗(SDSS)





令人吃惊：

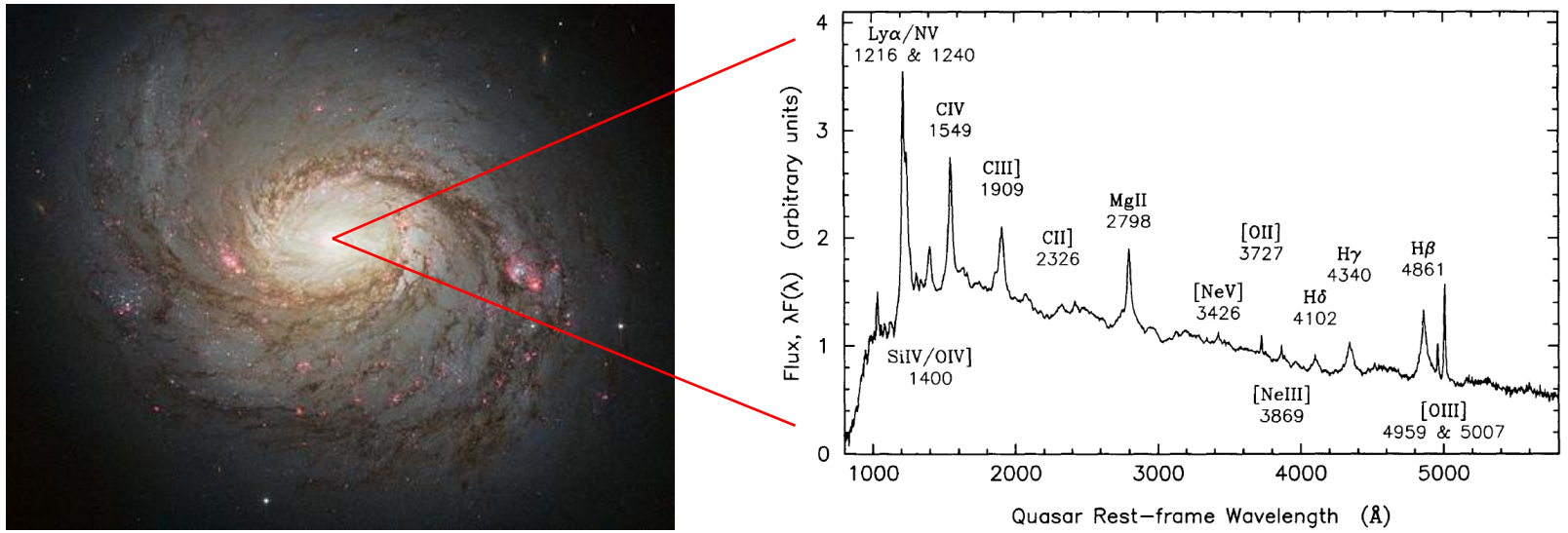
1) 光度之高？

2) 光谱非常相似!?（高低红移）

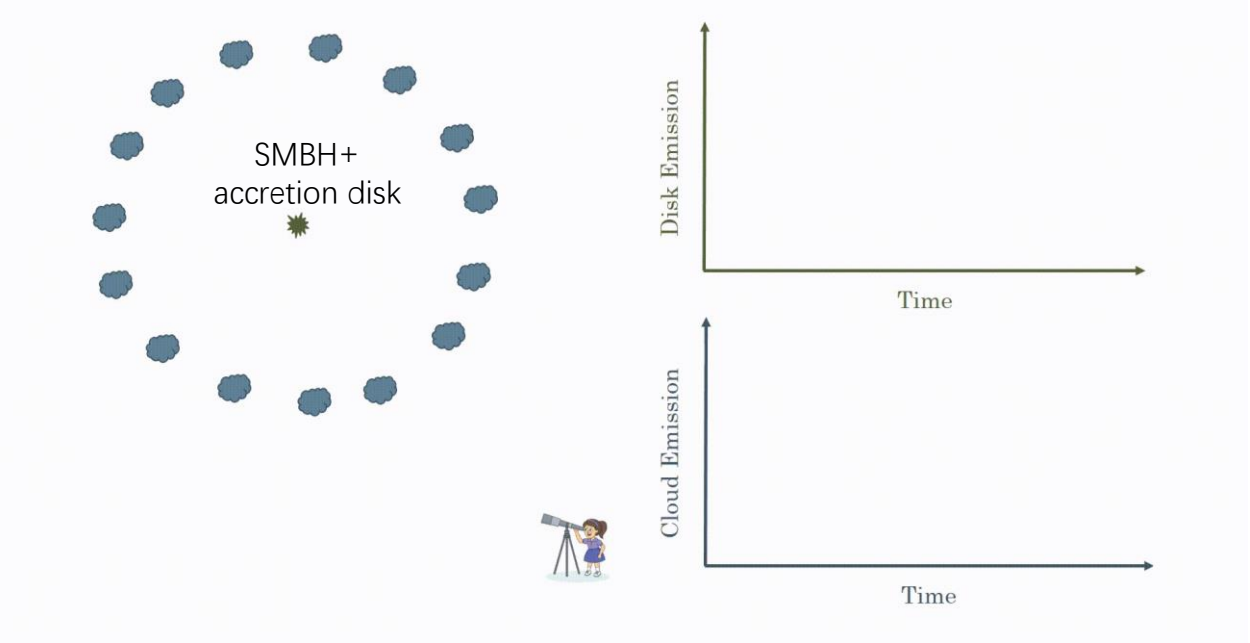
3) 超大质量黑洞（？）与吸积

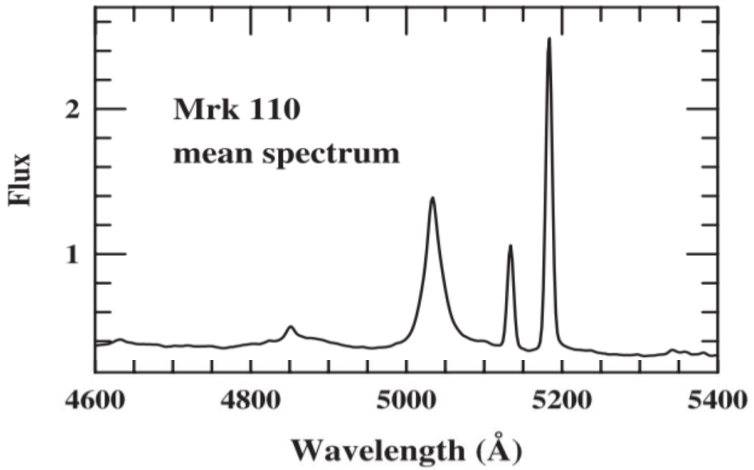
$\sim 10^8$太阳质量

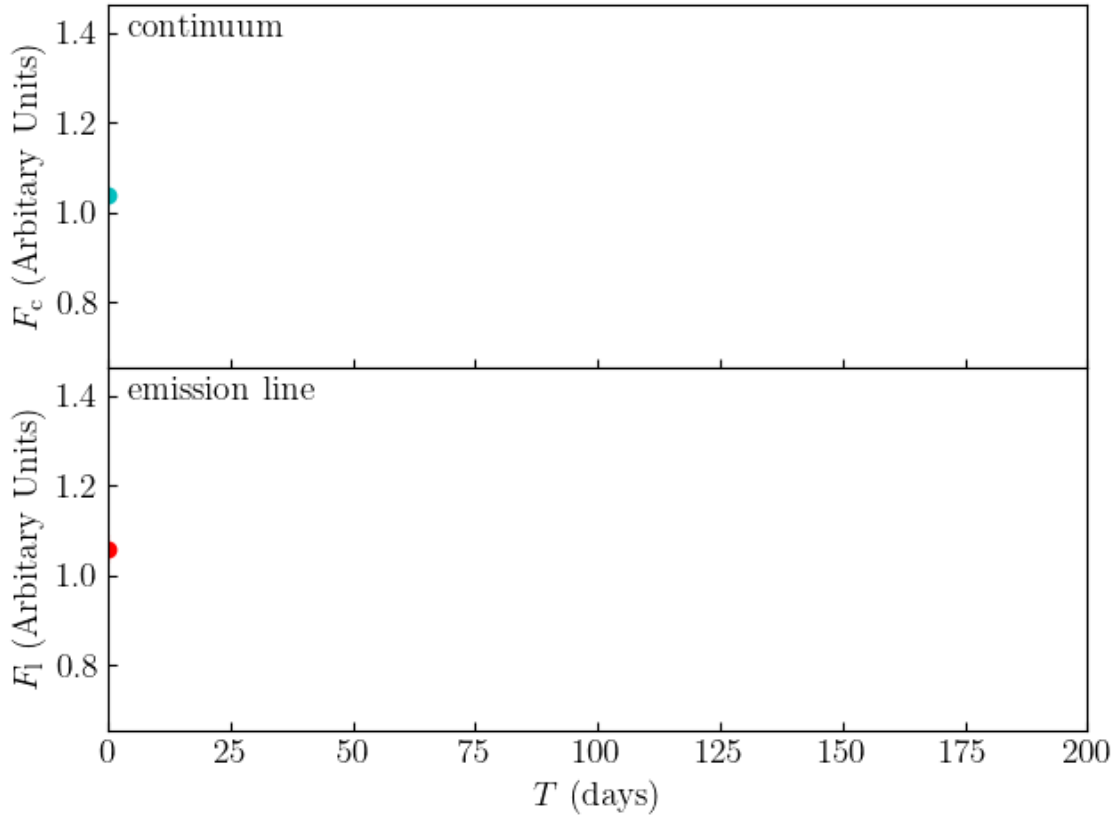
超大质量黑洞：三个里程碑



Classical tool: reverberation mapping



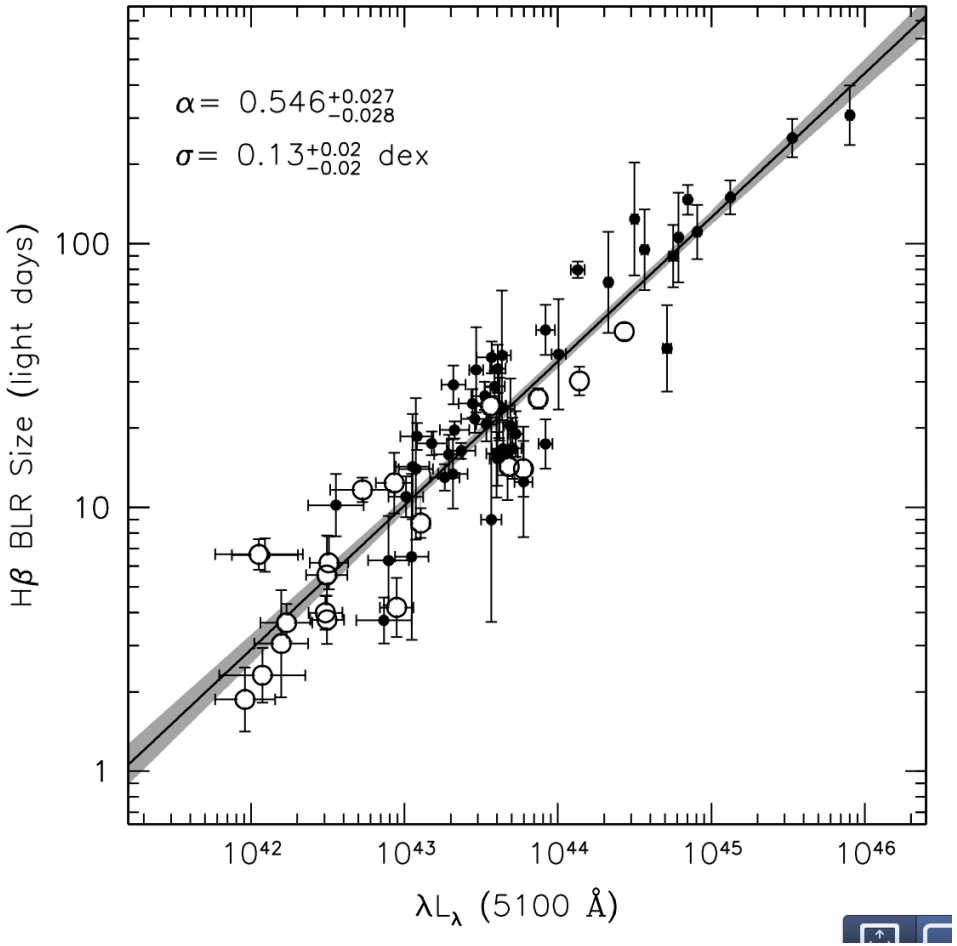


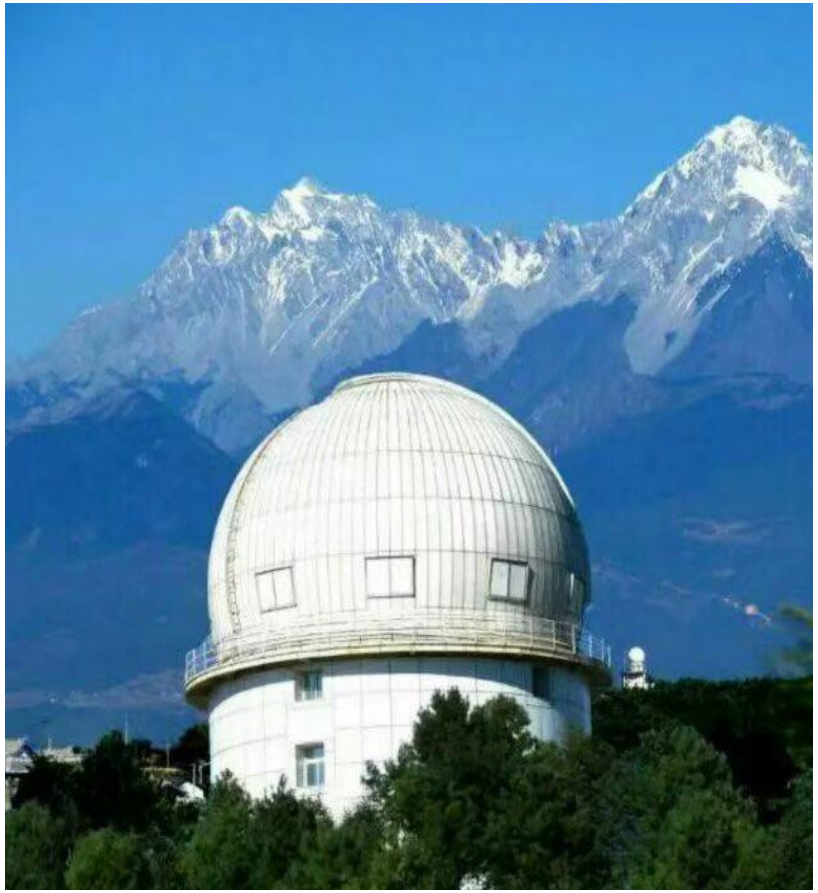


第一个里程碑

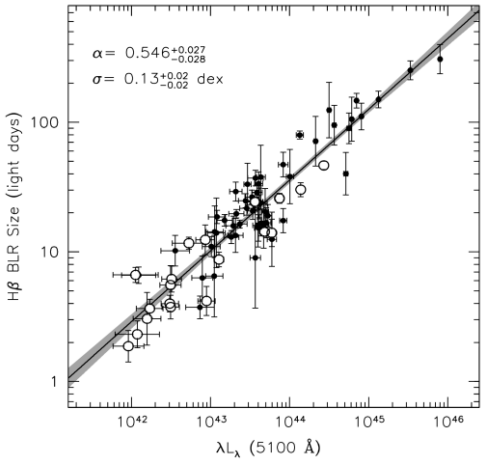
（Bahcall et al. 1972; Blandford & McKee 1982）

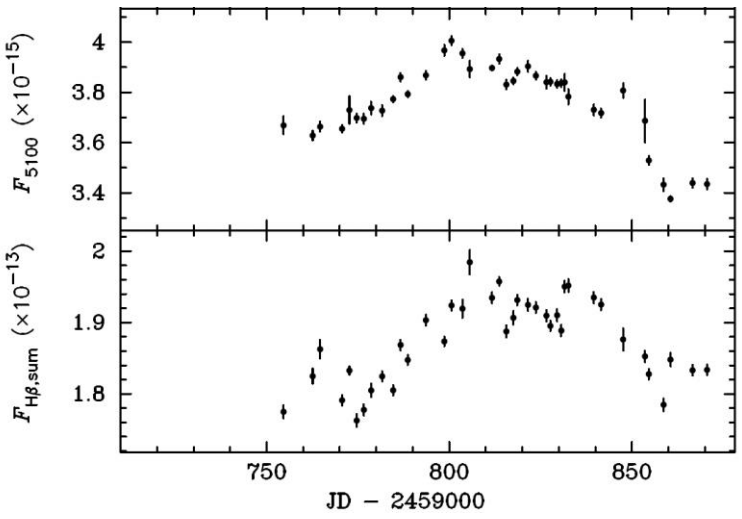
- *R-L*关系 (Peterson et al. 1998; Kaspi et al. 2000; Bentz et al. 2013)



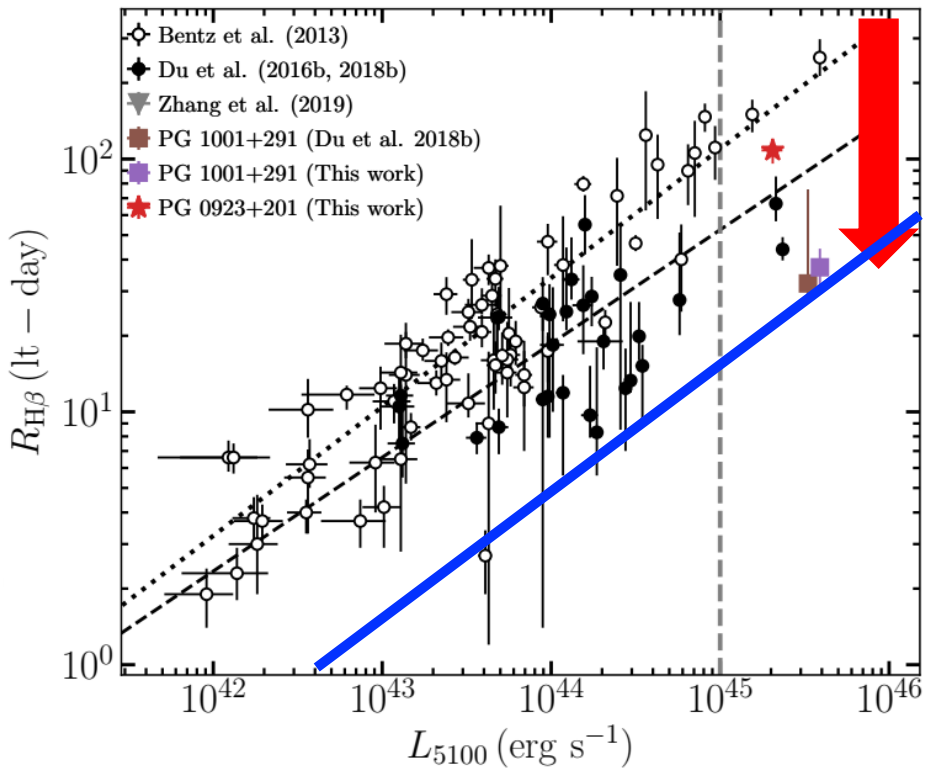


宽线区：礼崩乐坏 → 新关系

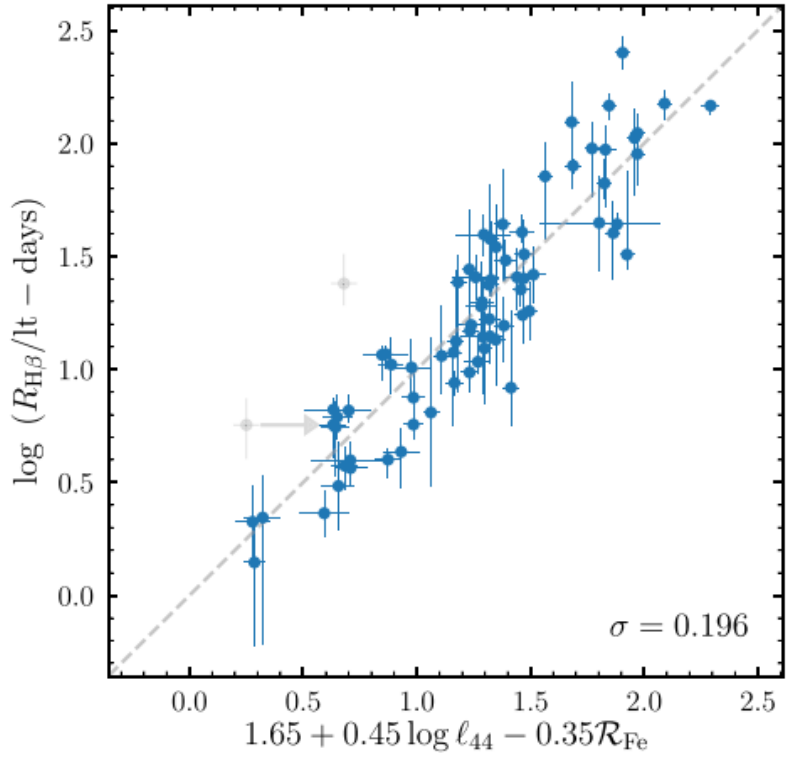




预计51天延迟；但短于10天



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



Du & Wang (2019)

最高吸积率：$2000L_{\rm Edd}/c^2$ 可以相差一个量级

Implications: SMBH formation

Heavy seed BHs: super-Eddington accretion

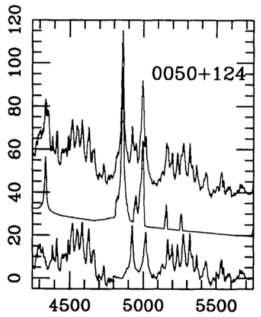
$$\dot{\mathscr{M}} = \dot{M}_\bullet / \dot{M}_{\rm Edd} \sim 10^3 \qquad M_\bullet = M_{\rm seed} \exp\left(\frac{1-\epsilon}{\epsilon}\frac{\dot{\mathscr{M}} t}{t_{\rm Salp}}\right)$$

Mon. Not. R. Astron. Soc. **314**, L17–L20 (2000)

Narrow-line Seyfert 1 galaxies and the evolution of galaxies and active galaxies

Smita Mathur
Astronomy Department, The Ohio State University, Columbus, OH 43210, USA

Accepted 2000 March 6. Received 2000 March 6; in original form 2000 January 4

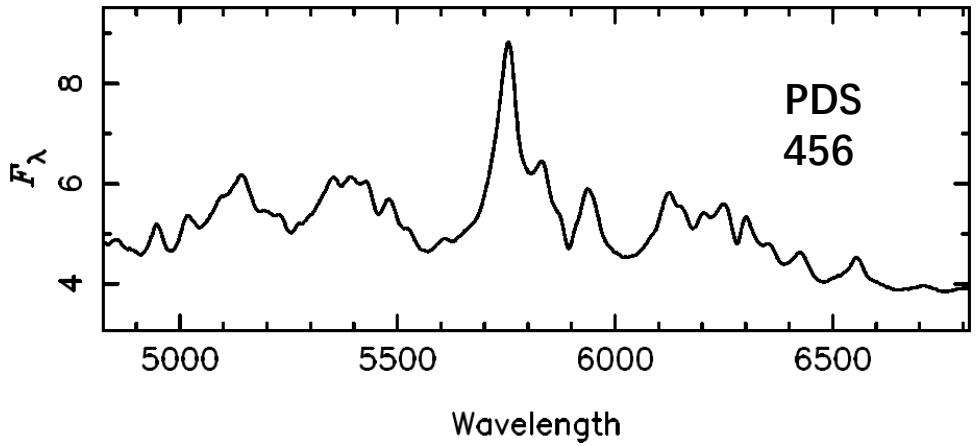


I Zw1

ABSTRACT

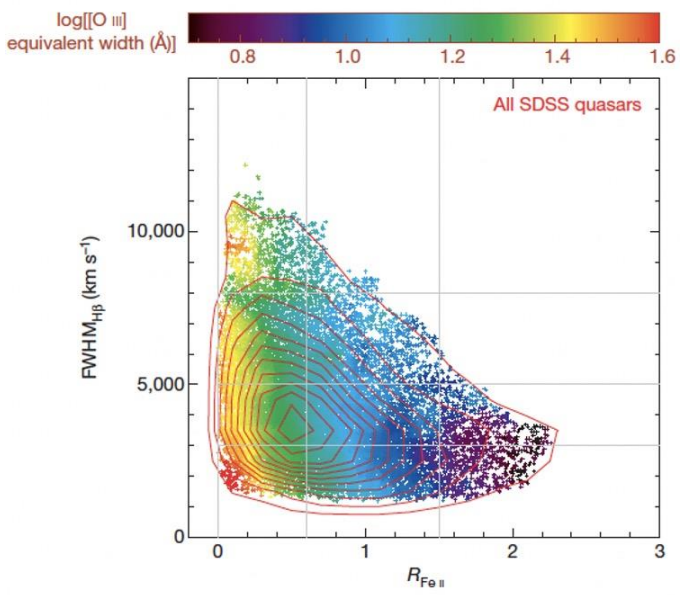
Narrow Line Seyfert 1 galaxies (NLS1s) are intriguing owing to their continuum as well as emission-line properties. The observed peculiar properties of the NLS1s are believed to be as a result of an accretion rate close to the Eddington limit. As a consequence of this, for a given luminosity, NLS1s have smaller black hole (BH) masses compared with normal Seyfert galaxies. Here we argue that NLS1s might be Seyfert galaxies in their early stage of evolution and as such may be low-redshift, low-luminosity analogues of high-redshift quasars. We propose that NLS1s may reside in rejuvenated, gas-rich galaxies. We also argue in favour of collisional ionization for production of Fe II in active galactic nuclei.

Key words: galaxies: active – galaxies: evolution – quasars: general – galaxies: Seyfert.

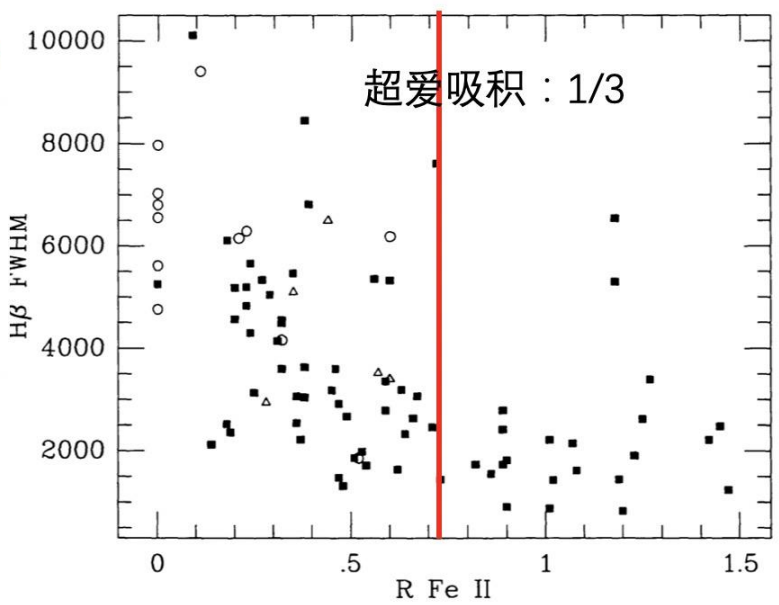


R_{FeII}: 吸积率的指示器

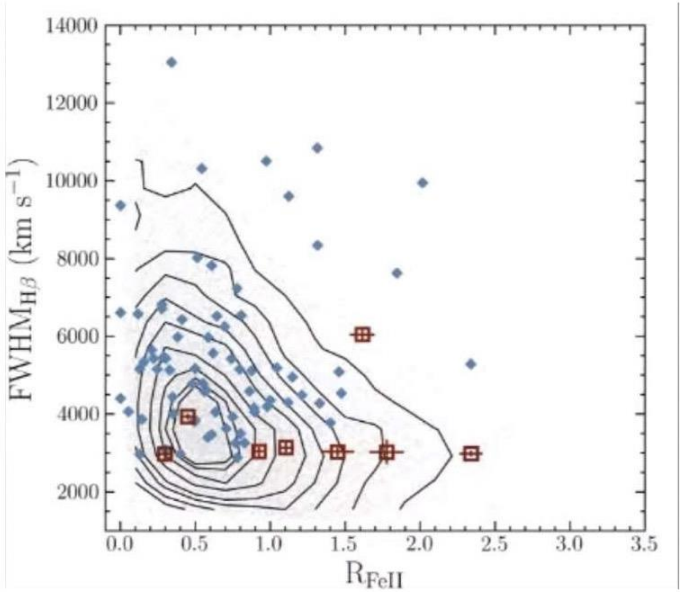
SDSS大样本类星体（Shen & Ho 2014）



标准的低红移类星体（Borosn & Green 1992）



JWST观测z~6红移类星体（Yang+2022/12/15视频会议）

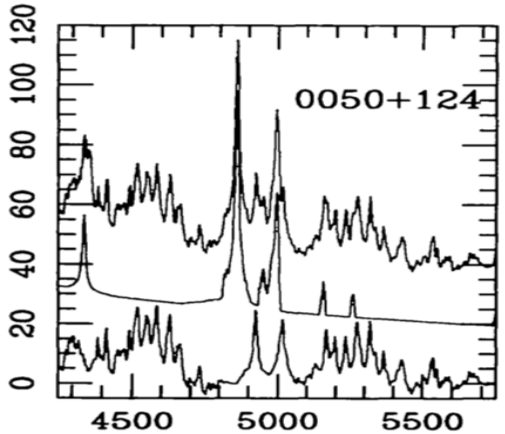


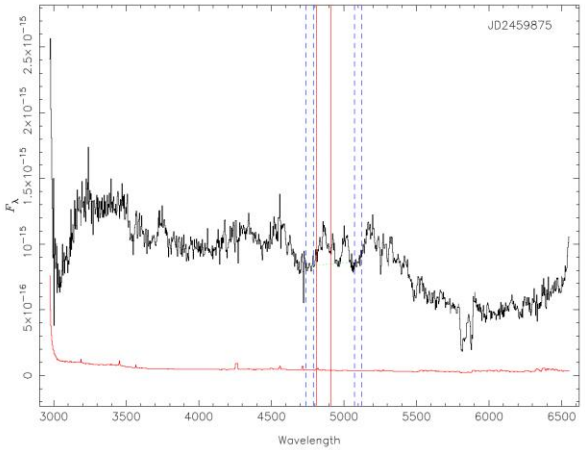
1）JWST最新观测：R_{FeII}竟然达到2.5

2）超爱黑洞是普遍现象

3）超爱吸积是超大质量黑洞一种途径

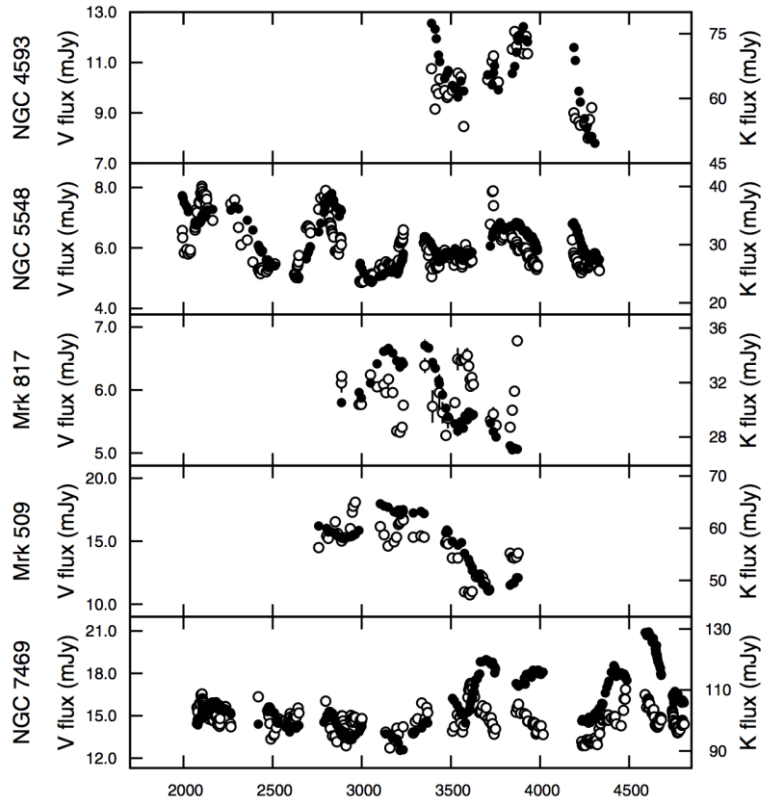
4）吸积率越高金属丰度越高

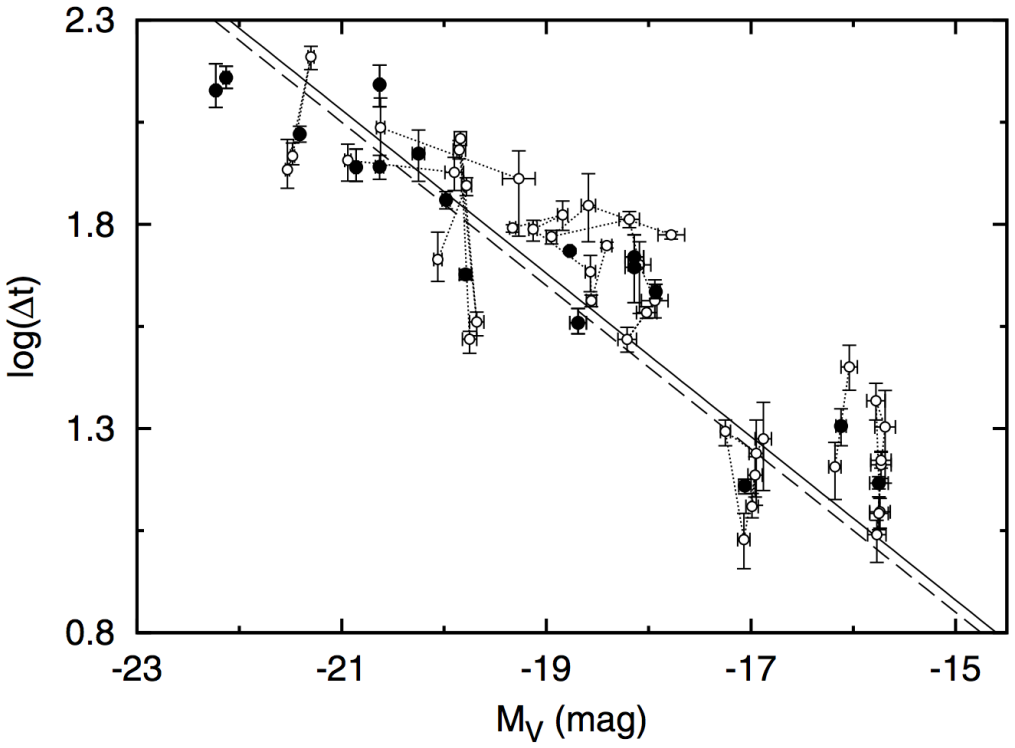




第二个里程碑

- 尘埃辐射响应 (Suganuma et al. 2006; Koshida et al. 2014)





第三个里程碑

(Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000; Kormendy & Ho 2013)

- M-σ/M_K关系：维里化运动→1) 大质量黑洞(Lynden-Bell 1969)

  2) 吸积增长(Yu & Tremaine 2002)

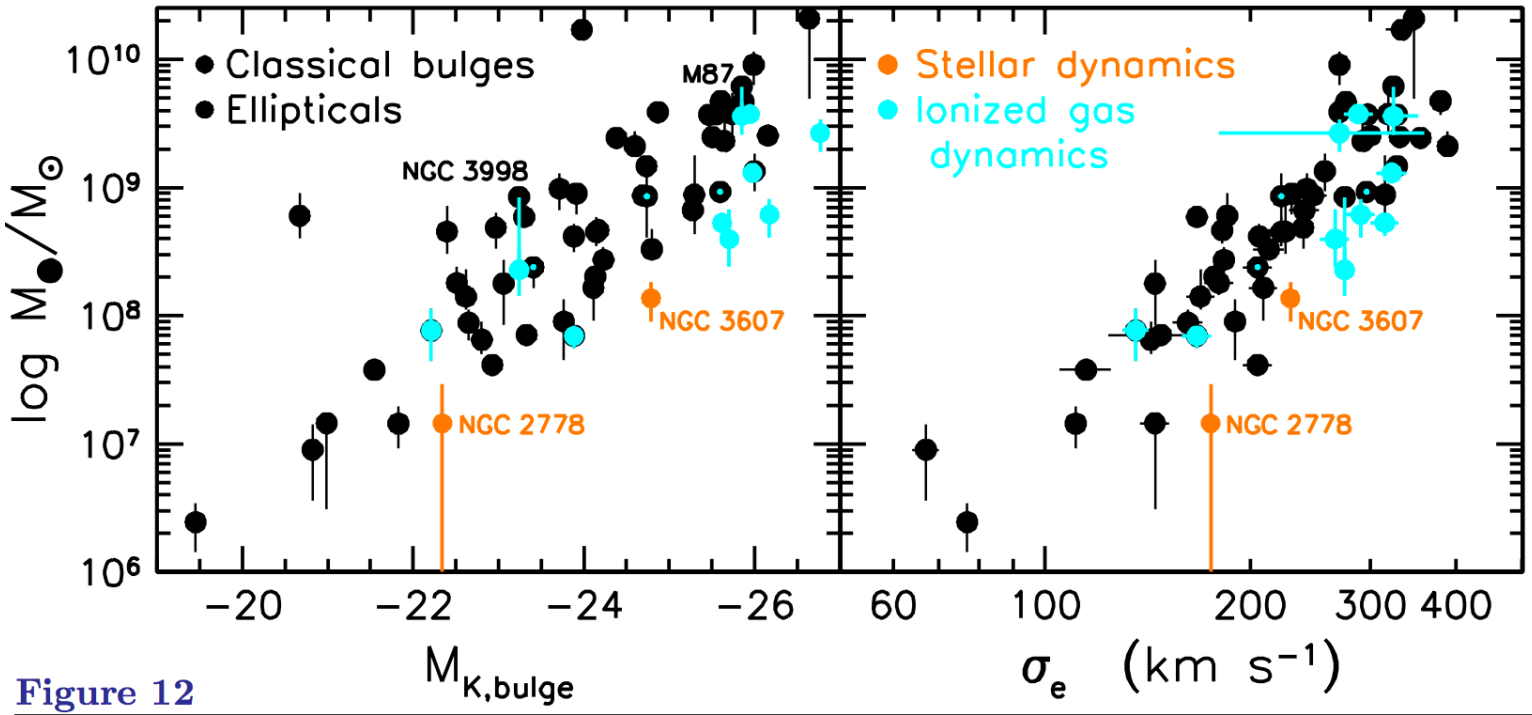
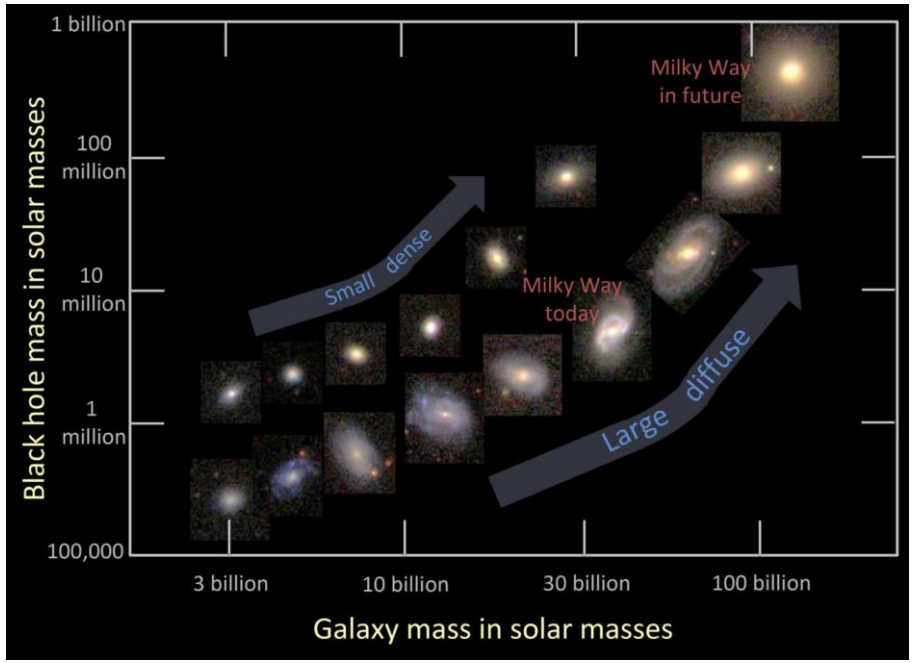
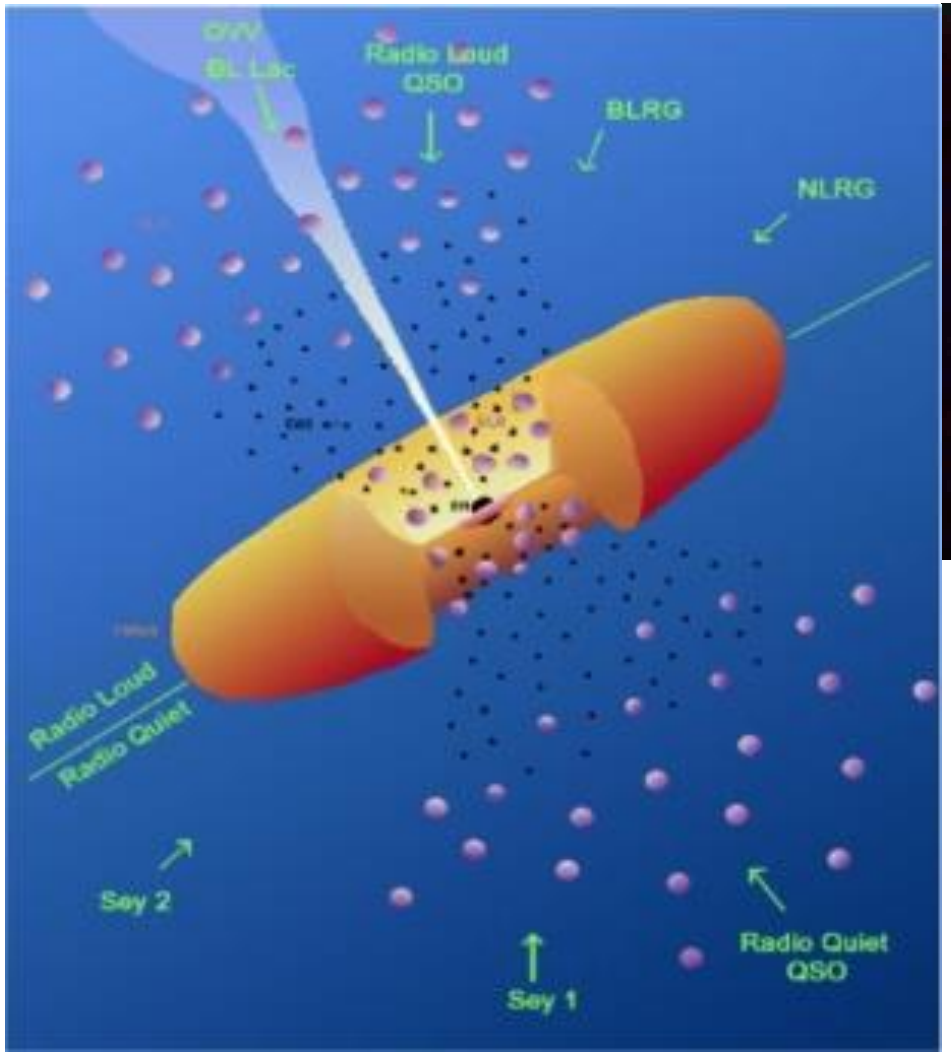
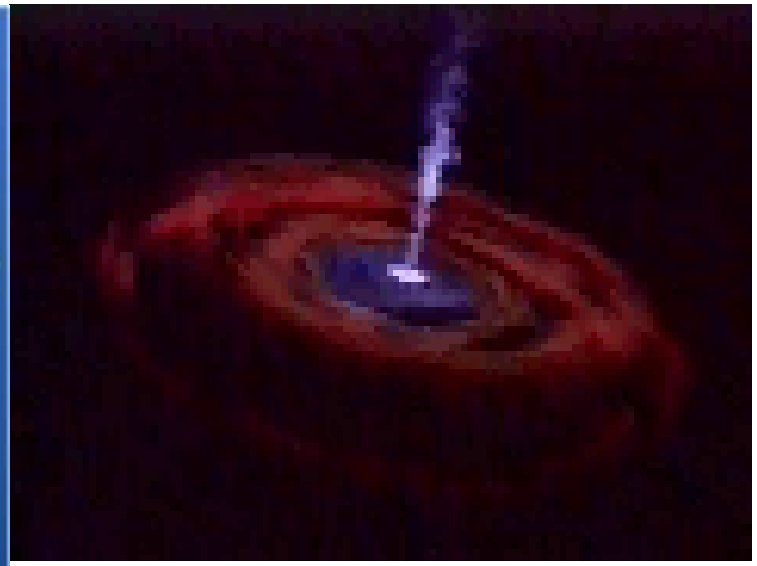


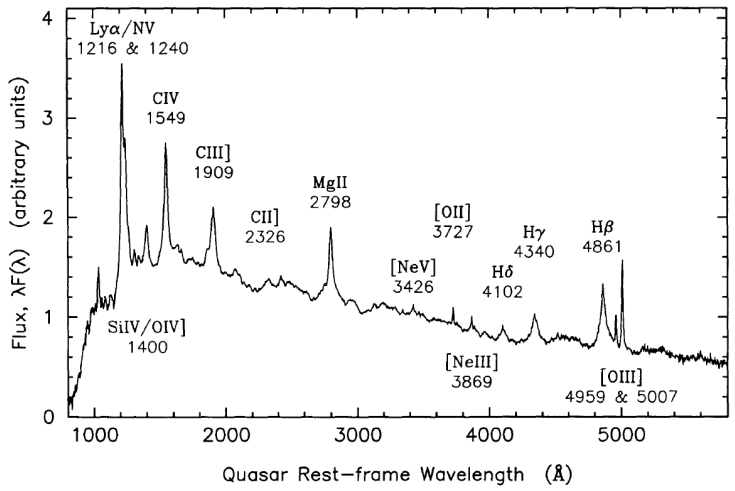
Figure 12



大质量黑洞吸积：引力能释放





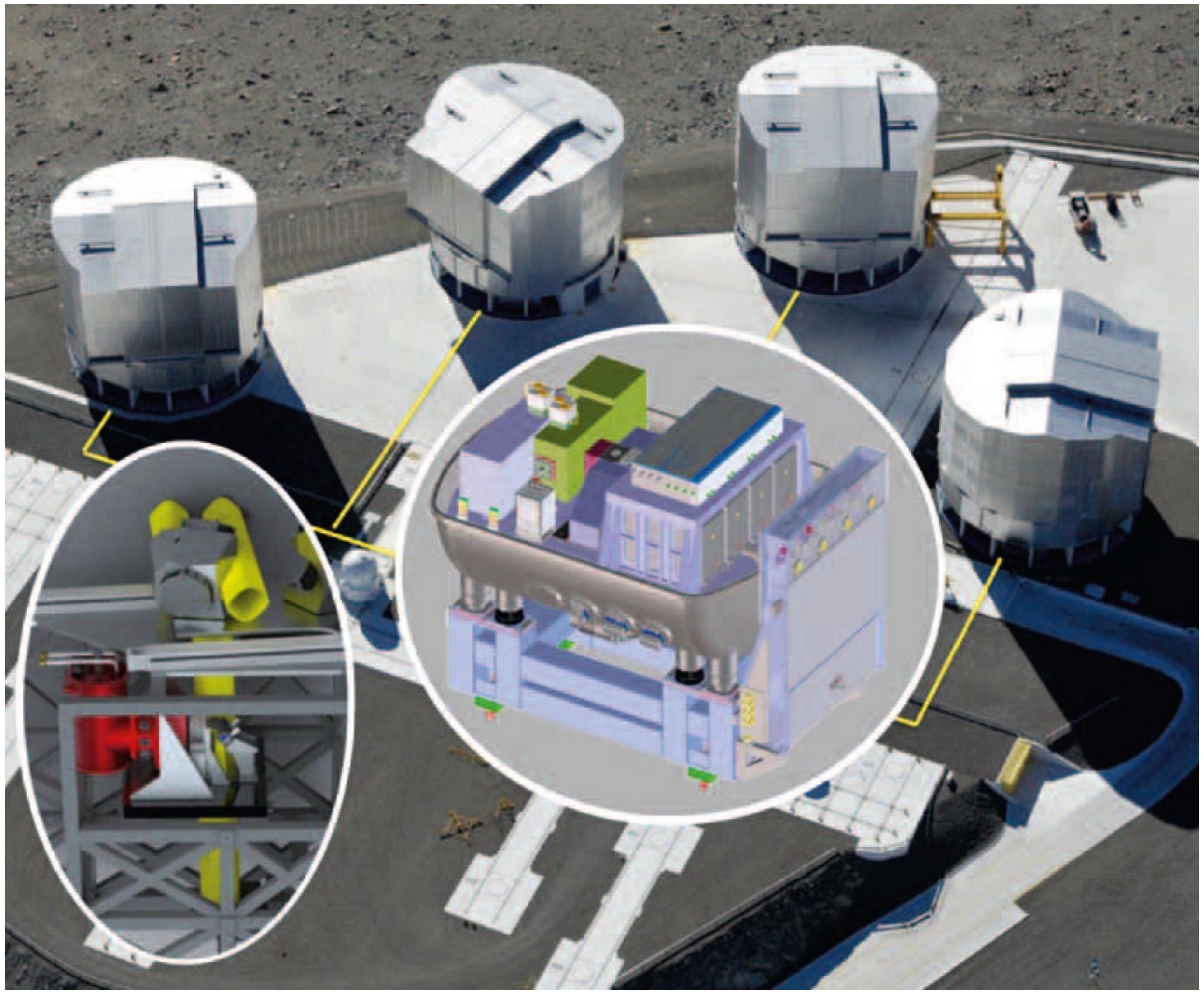


故事结束？

- 黑洞周围的小黑洞
- 超大质量双黑洞
- 宇宙学

光干涉时代（始于2018）：欧洲南方天文台

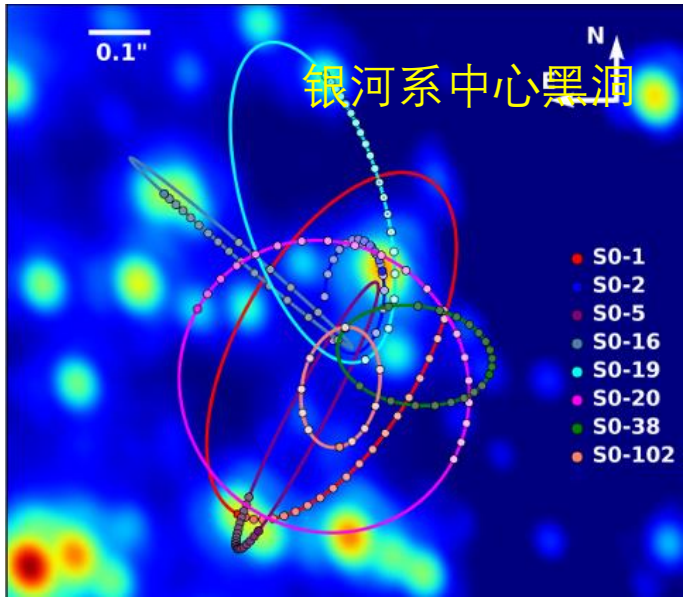
（GRAVITY/VLTI）



4台 ⊗ 8米望远镜

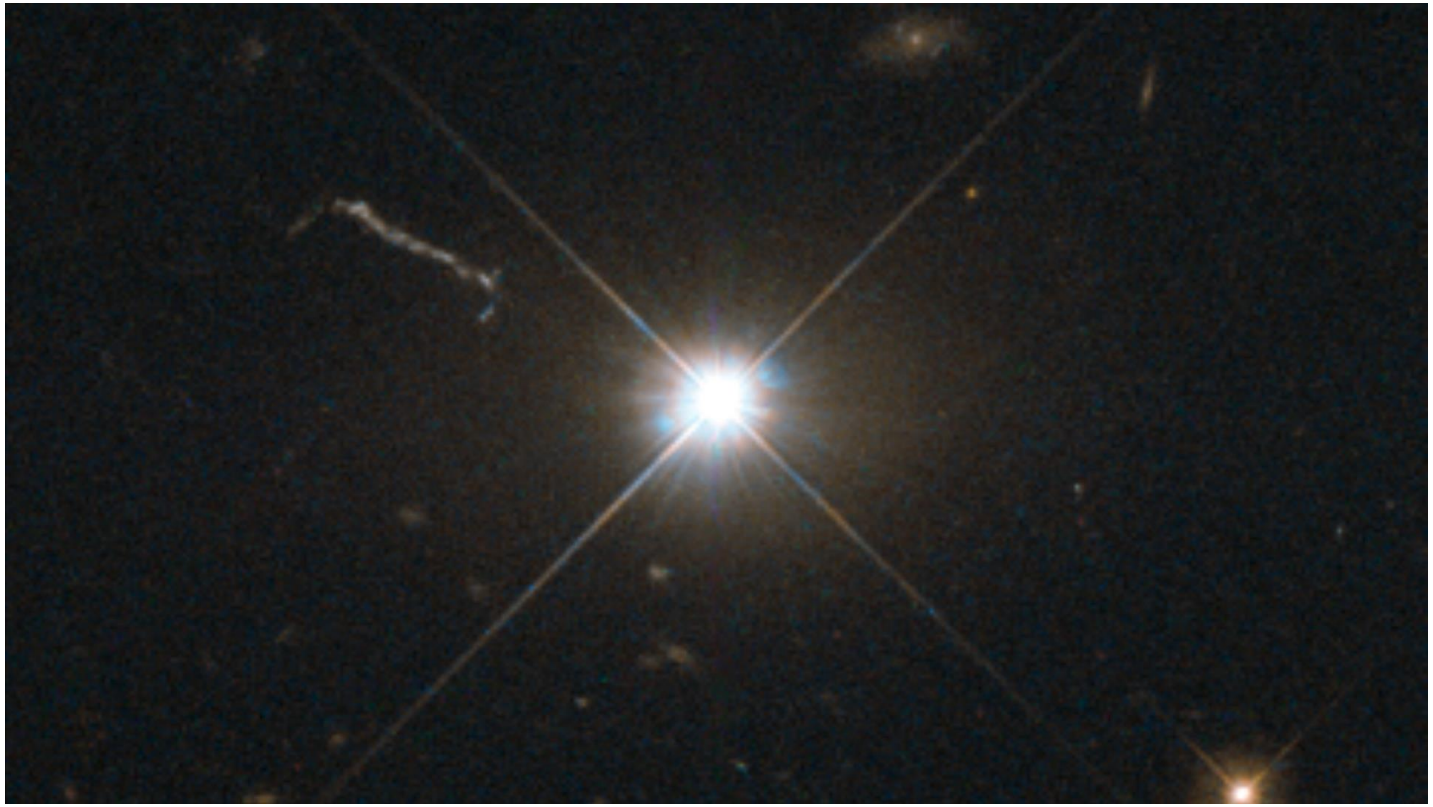
最高空间分辨率：

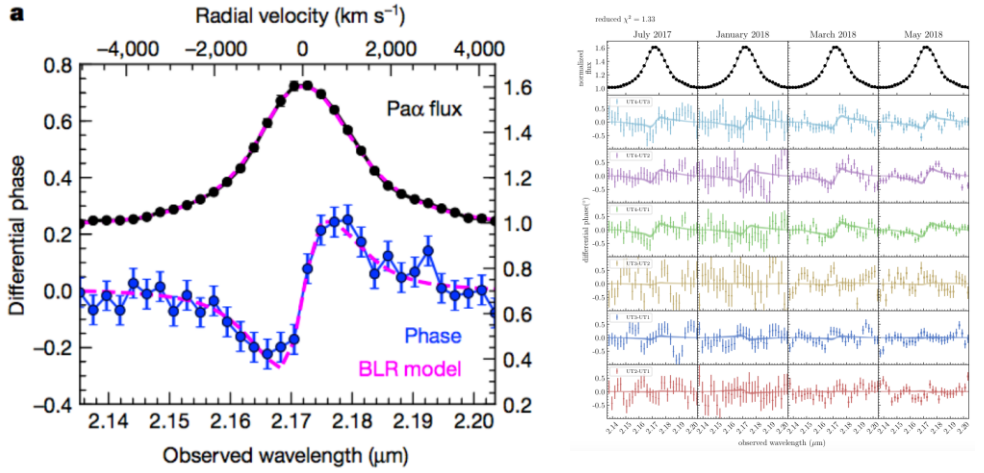
10微角秒

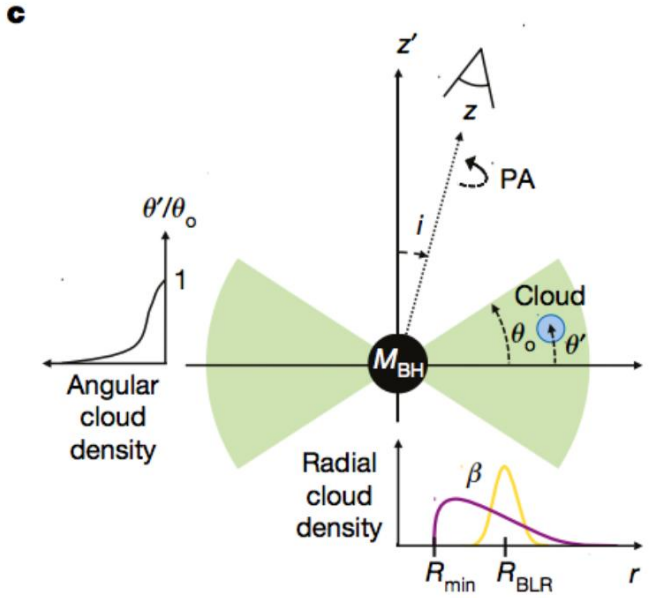


Physics in 2020

3C 273: A breakthrough







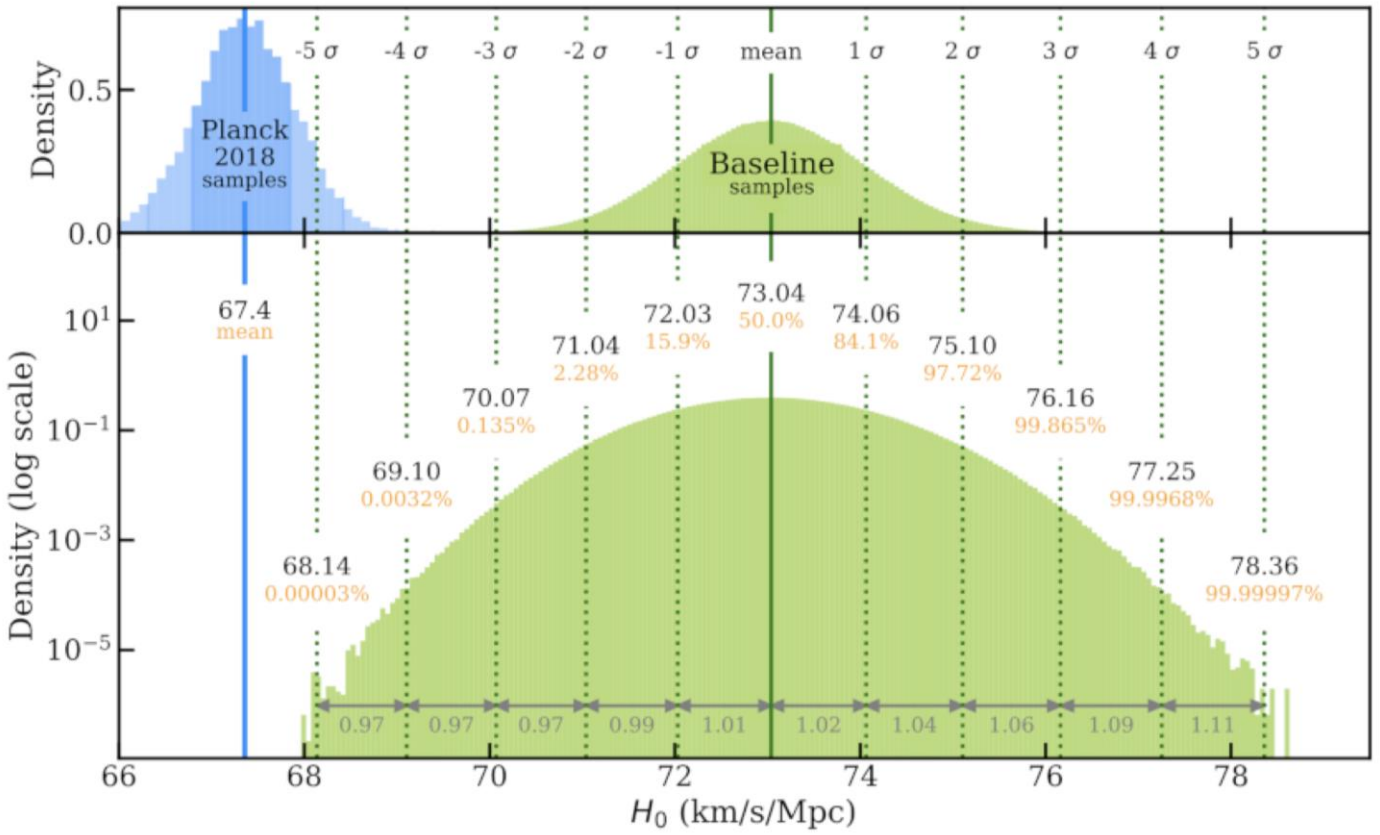
SMBH masses:

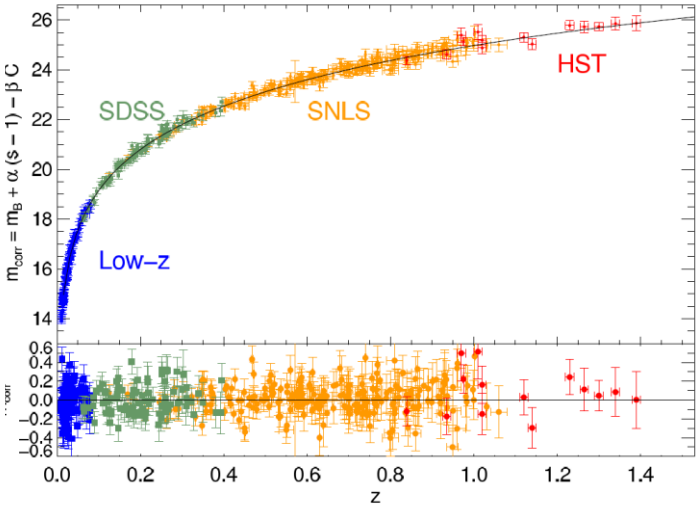
$(2.6 \pm 1.1) \times 10^8 M_\odot$

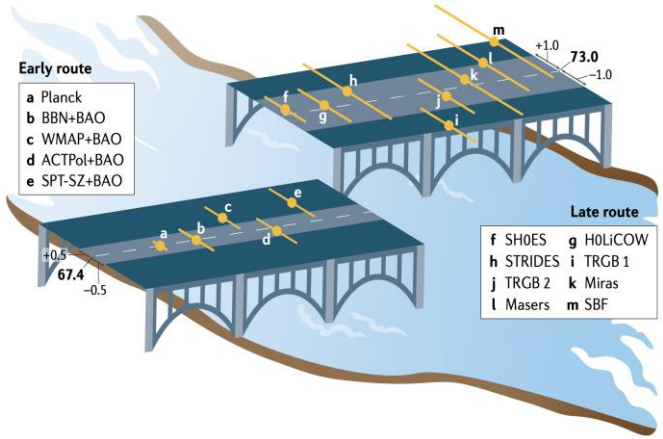
Gravity collaboration, 2018, Nature, 563, 567

哈勃常数与宇宙加速膨胀

2010年诺奖







Riess+2021

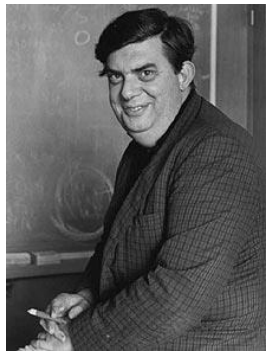
呼唤宇宙距离测量工具

Sandage (1965)

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

Quasar as cosmic probe

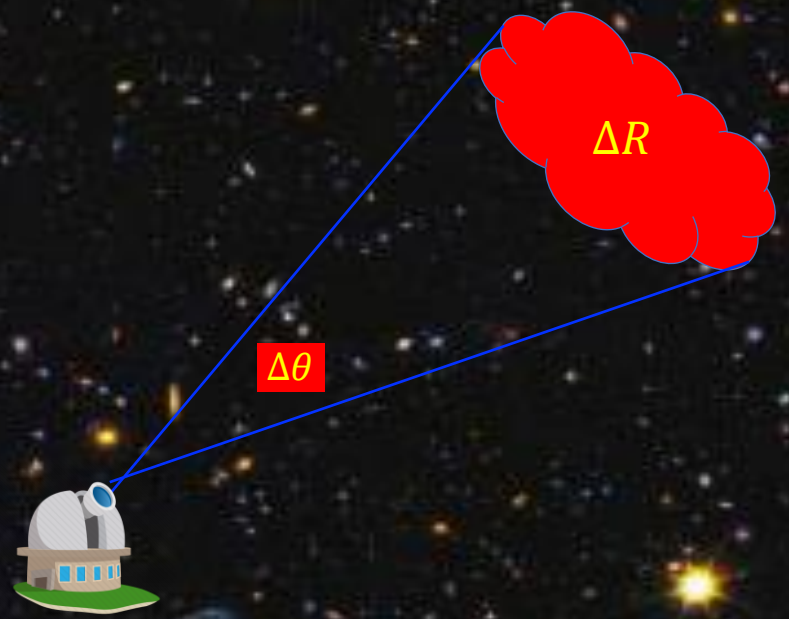







Giant difficulties of Geometric measurement

- Angular size, but the physical hard;
- Physical sizes, but the angular hard



$$D = \frac{\Delta R}{\Delta \theta} \rightarrow z\text{-}D \text{ relation}$$

Hubble constant and expansion history

SARM : SpectroAstrometry + Reverberation Mapping

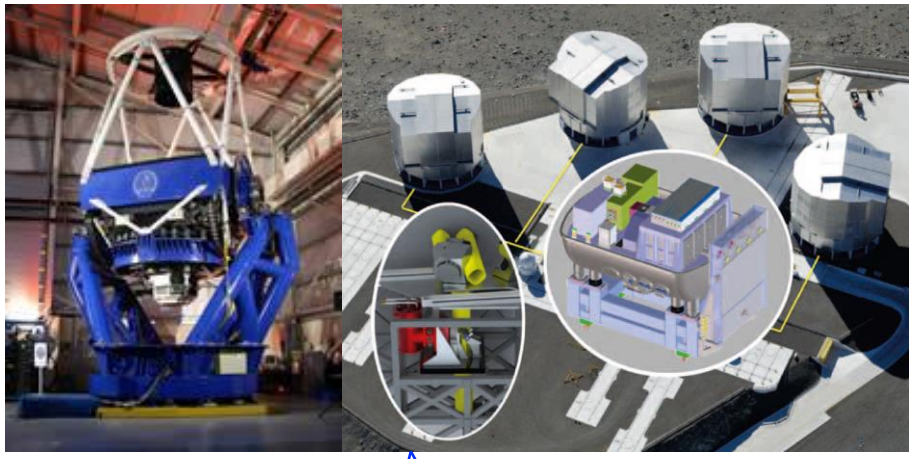
nature astronomy

LETTERS

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

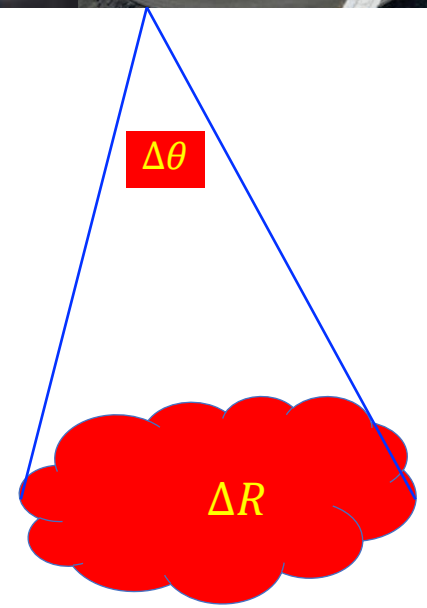
A parallax distance to 3C 273 through spectroastrometry and reverberation mapping

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



Cosmic distance and SMBH masses

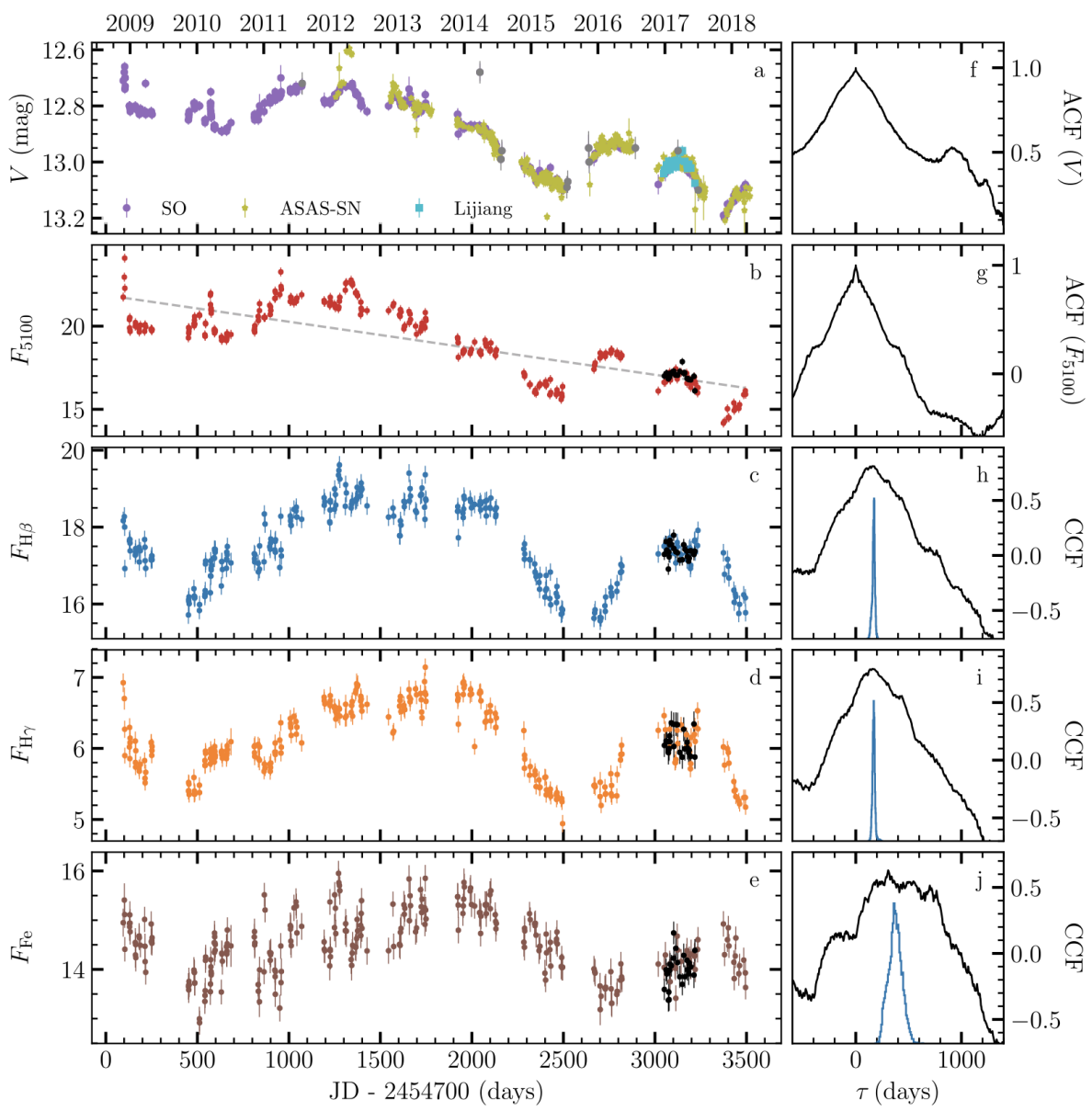
$$d = \frac{\Delta R}{\Delta \theta}; \qquad M_{\rm BH}$$

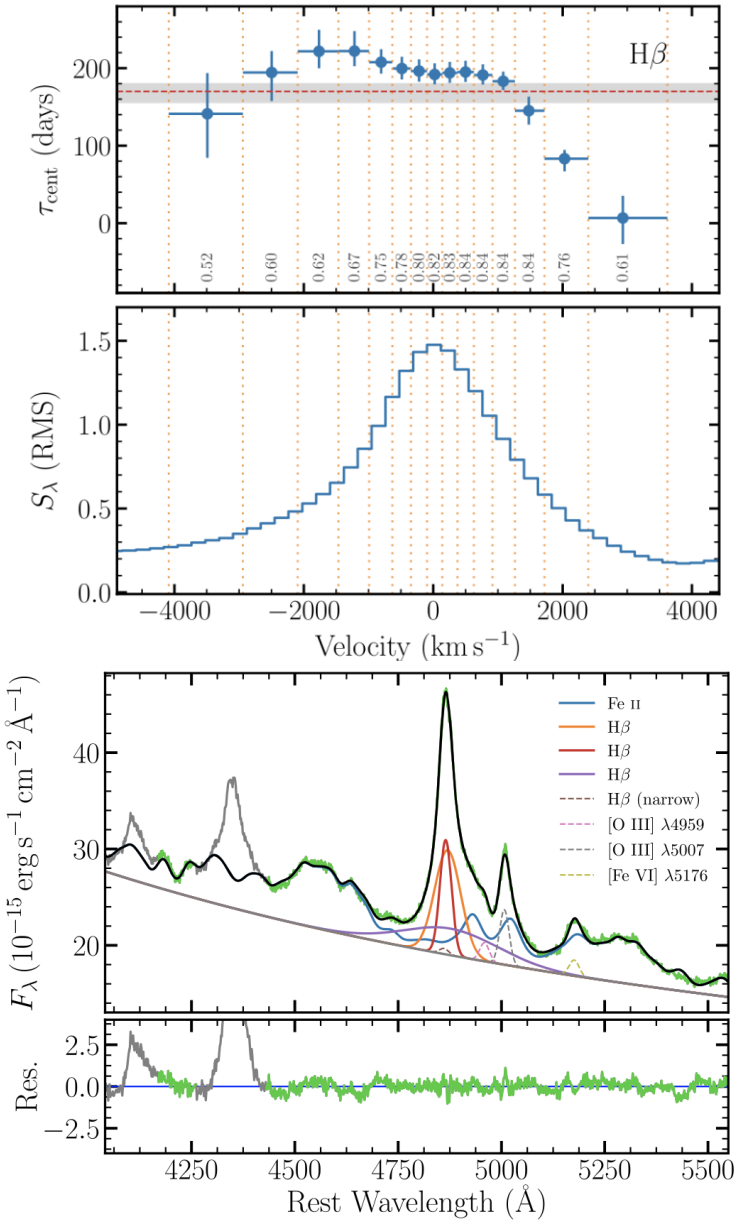


Scientific values of 2m and VLTI data are equal:

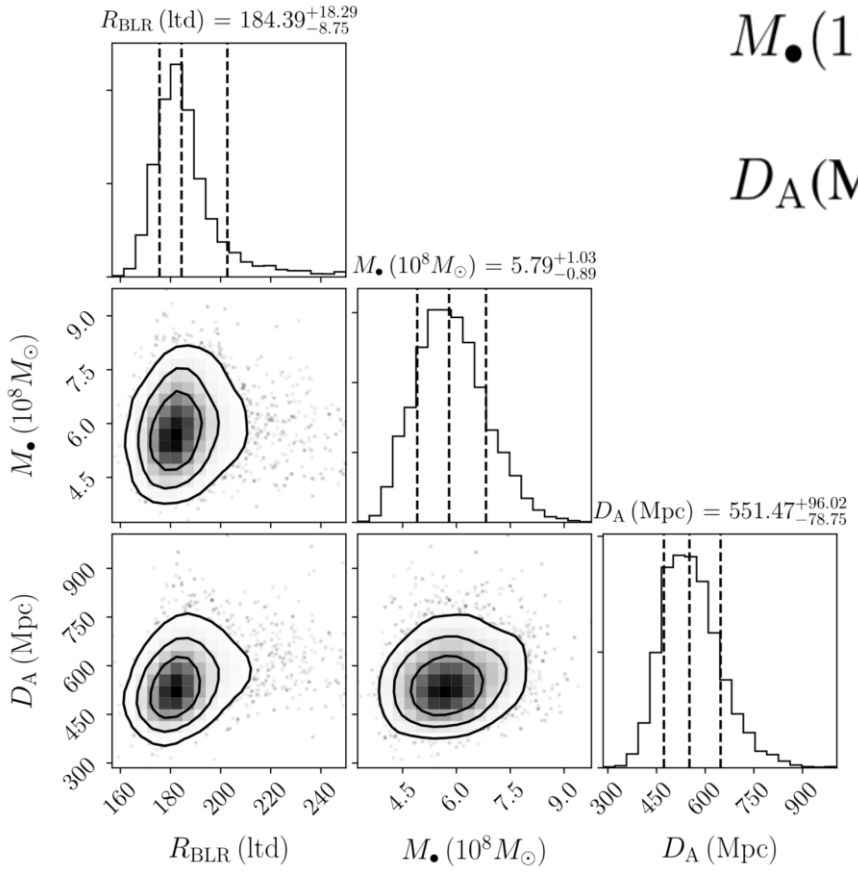
a chance in a million （千载难逢）

RM: 3C273 (Zhang et al. 2019)





Cosmic distances of quasars：SARM results



$M_\bullet(10^8 M_\odot)$ $5.78^{+1.11}_{-0.88}$ $H_0 = 71.5^{+11.9}_{-10.6}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$

$D_{\rm A}$(Mpc) $551.50^{+97.31}_{-78.71}$ $\frac{\Delta D}{D} \sim 15\%$

Purely geometric measurements, independent of：

- 👍 extinction/reddening
- 👍 standardization
- 👍 cosmic ladders (Cepheids, SNIa)
- 👍 examinations of systematic errors

SARM is expected to expand sample

THE ASTROPHYSICAL JOURNAL, 182:L85–L88, 1973 June 1

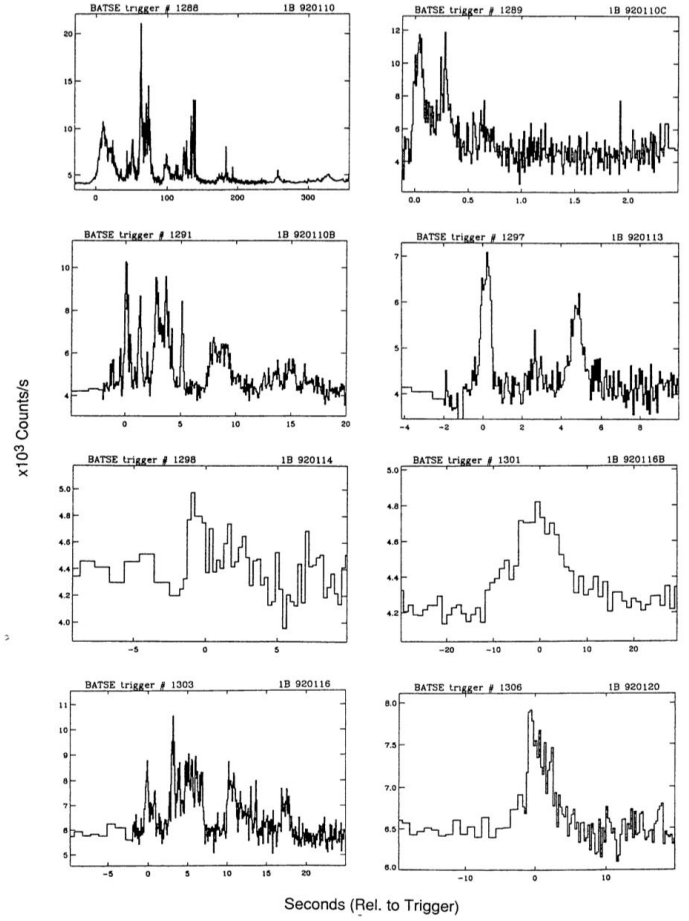
伽马射线暴发现

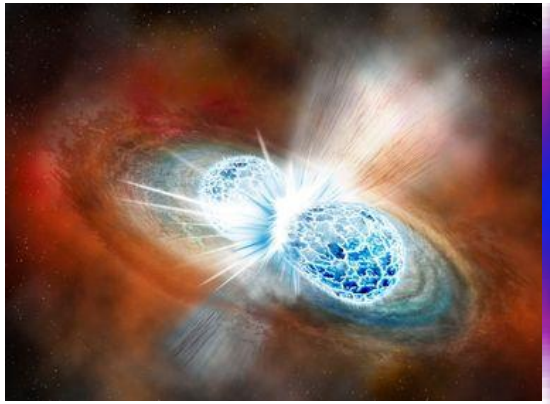
OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

RAY W. KLEBESADEL, IAN B. STRONG, AND ROY A. OLSON

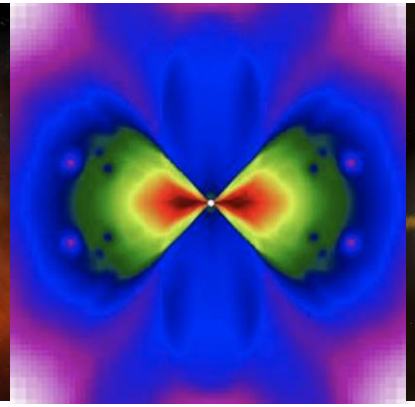
University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico
Received 1973 March 16; revised 1973 April 2

光变曲线

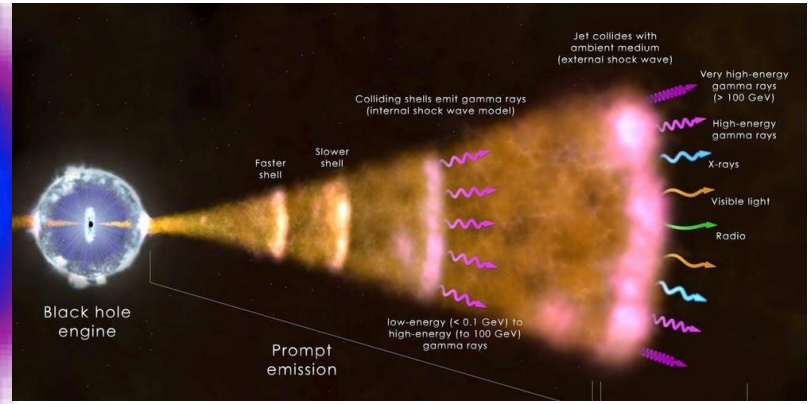




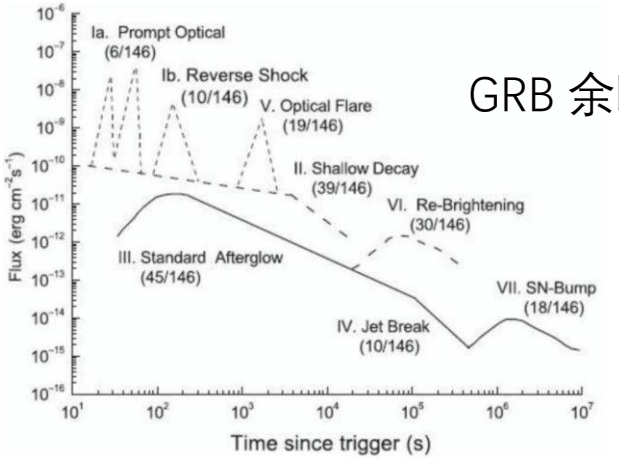
中子星并合 (Paczynski 1986);



大质量恒星塌缩 (Woosley 1993)

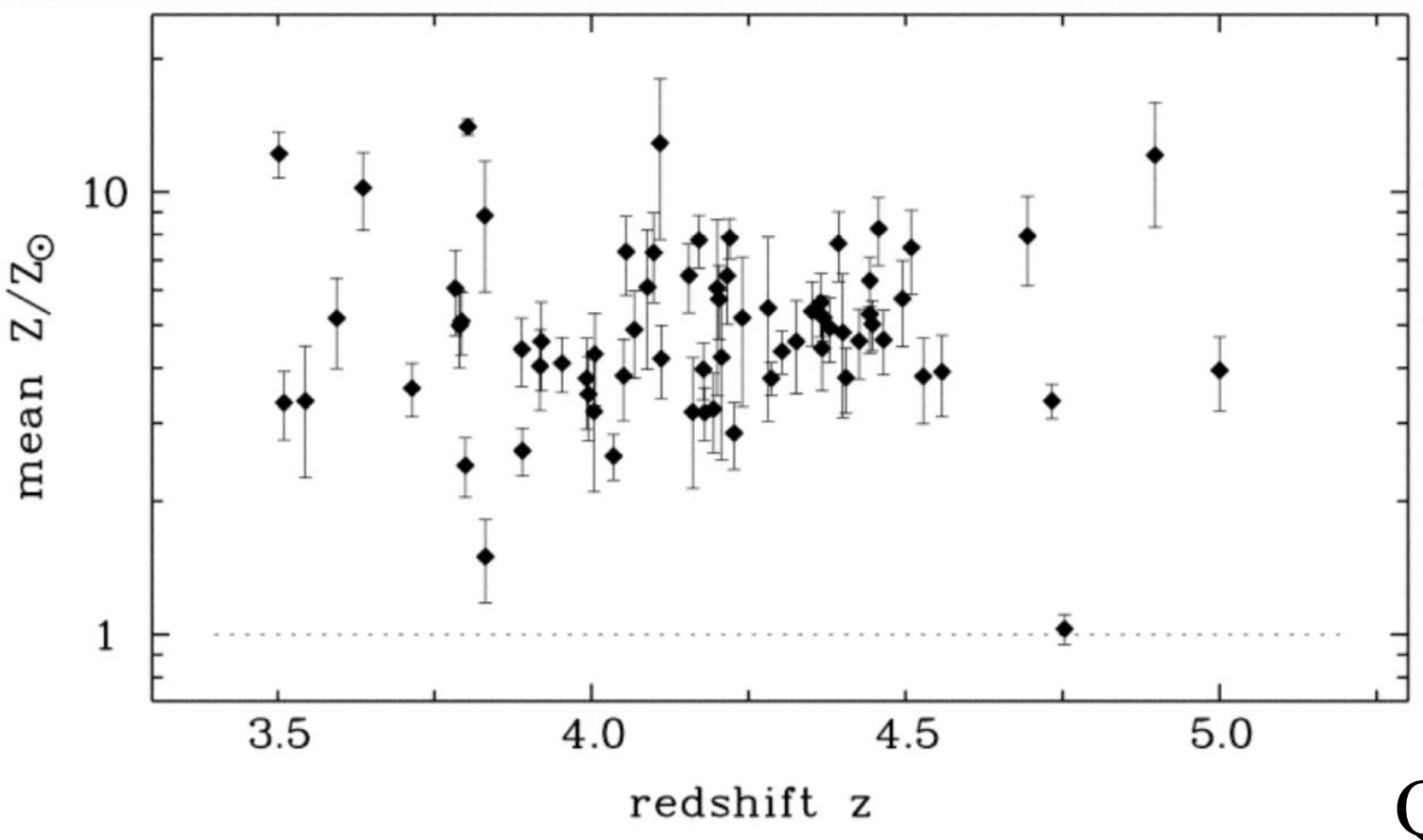


GRB 火球



GRB 余晖

金属丰度：炼丹炉



Quasars: metal-rich

(Hamann, Dietrich & Ferland 2007)

问题：GRB与类星体成协？

Idea: 致密天体与金属丰度？

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

JIAN-MIN WANG
Astronomy Department, Beijing Normal University, Beijing 100875; Astronomy Department, Nanjing University, Nanjing 210008; and Chinese Academy of Sciences-Peking University Joint Beijing Astrophysical Center (CAS-PKU.BAC), Beijing 100871, People's Republic of China
Received 1998 October 7; accepted 1999 April 1

AGN标准模型: GW190521 打破

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

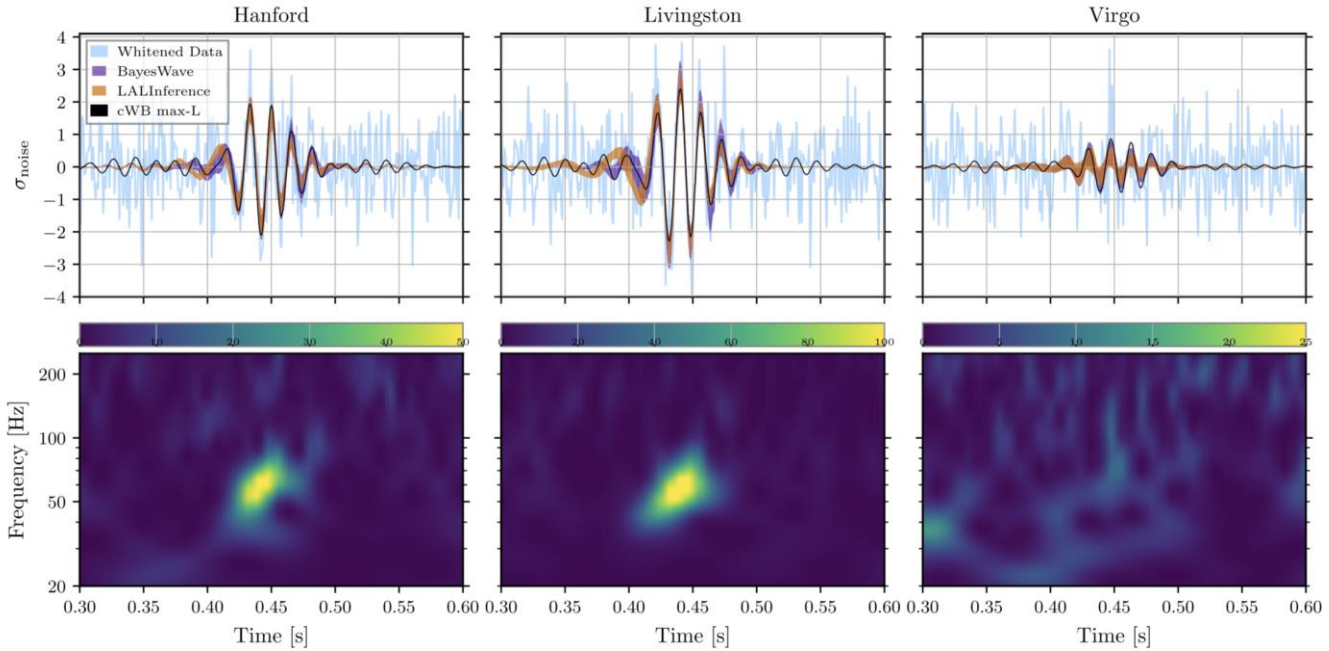
Editors' Suggestion | Featured in Physics

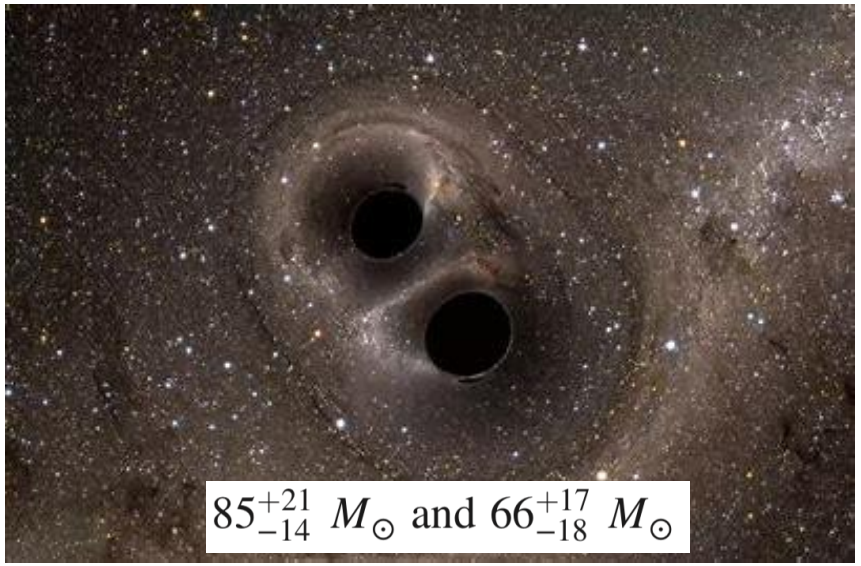
GW190521: A Binary Black Hole Merger with a Total Mass of 150 $M_\odot$

R. Abbott *et al.*[*]

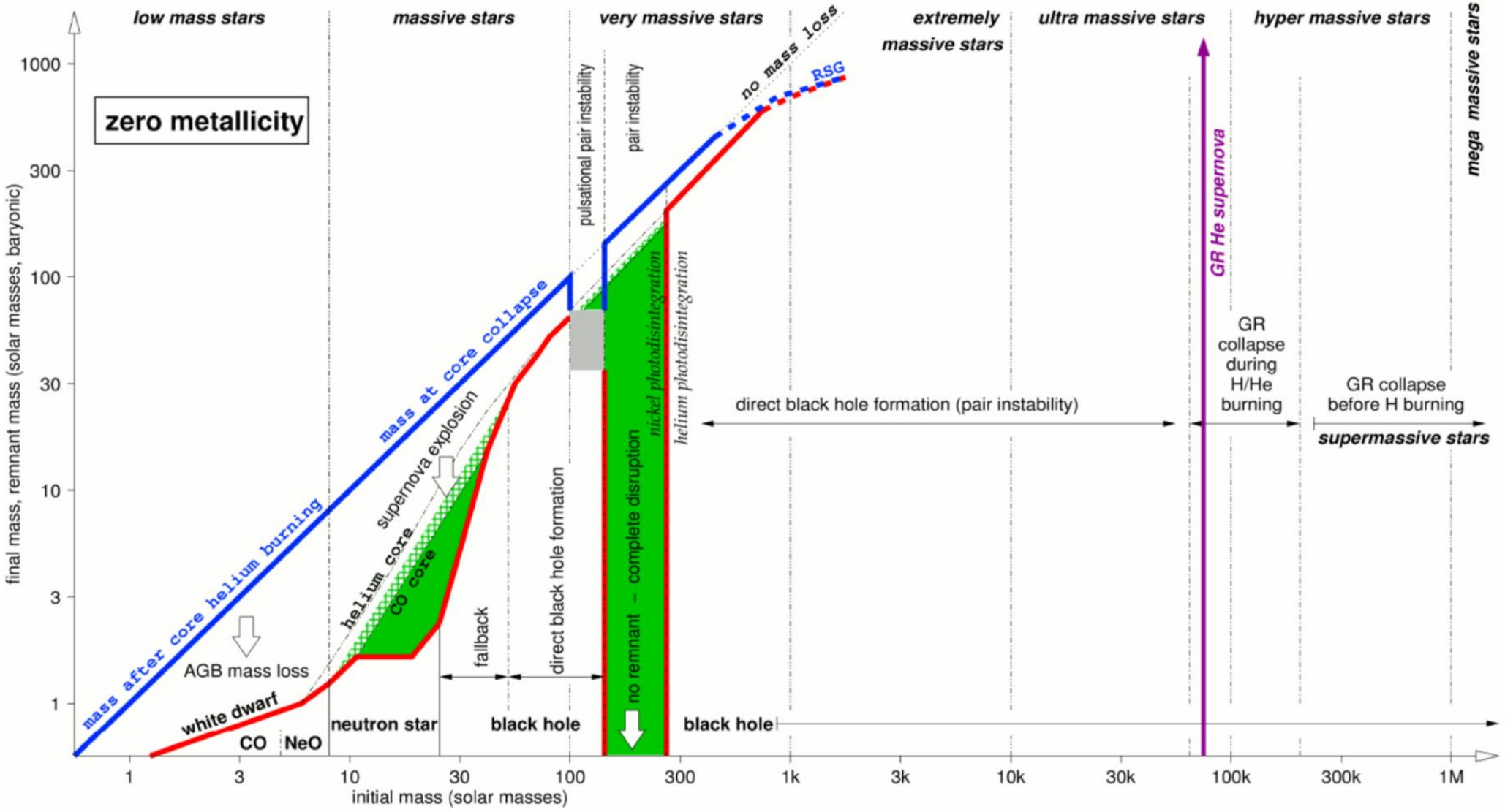
(LIGO Scientific Collaboration and Virgo Collaboration)

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





恒星演化与黑洞形成

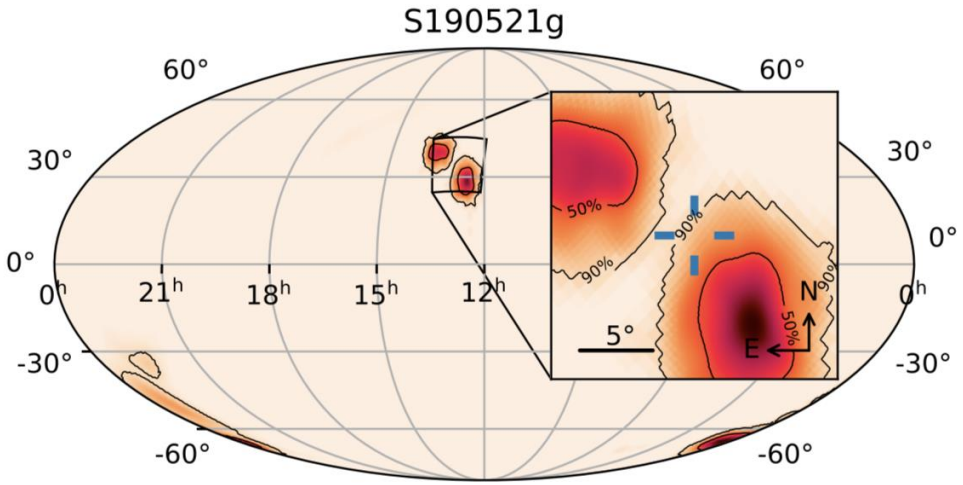

low mass stars
massive stars
very massive stars
extremely massive stars
ultra massive stars
hyper massive stars
mega massive stars
zero metallicity
final mass, remnant mass (solar masses, baryonic)
initial mass (solar masses)
1000
300
100
30
10
3
1
1
3
10
30
100
300
1k
3k
10k
30k
100k
300k
1M
mass after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

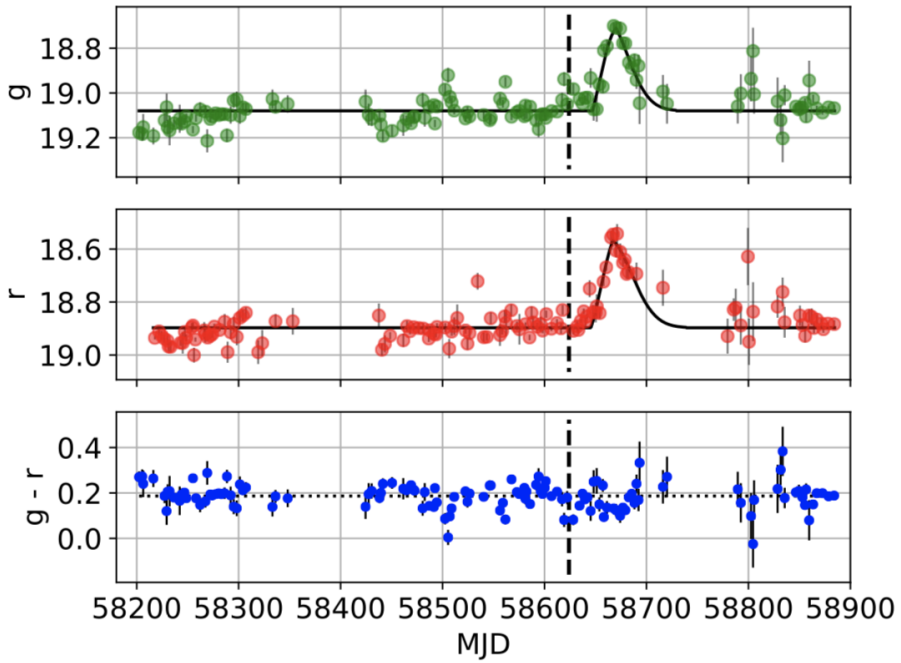
PHYSICAL REVIEW LETTERS **124,** 251102 (2020)

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 80$M_\odot$?

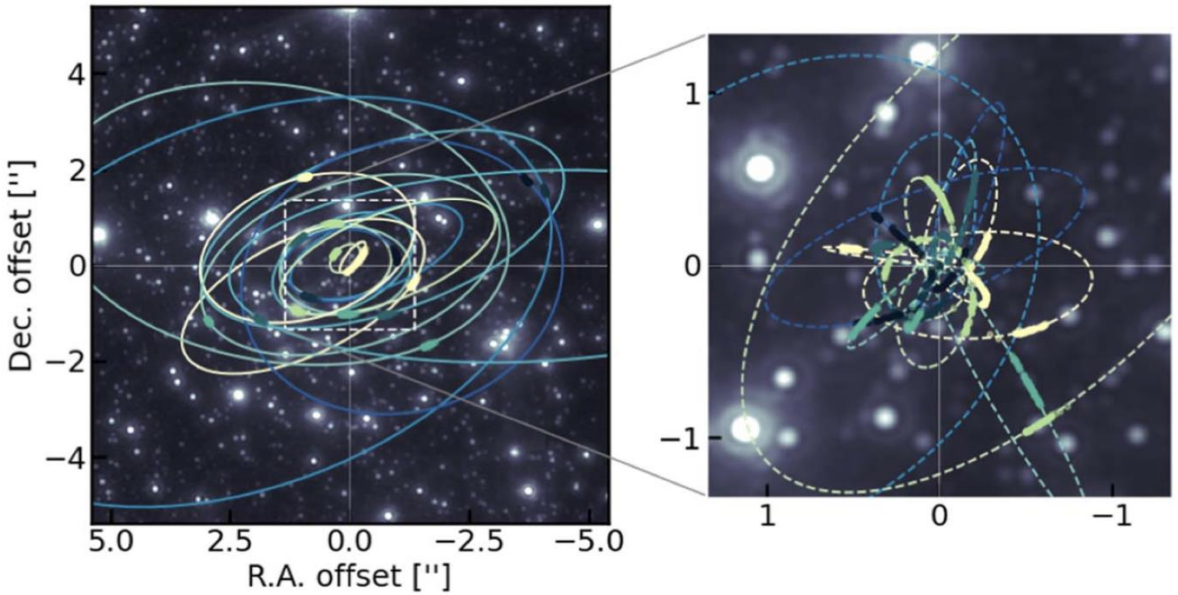
2) host galaxy?

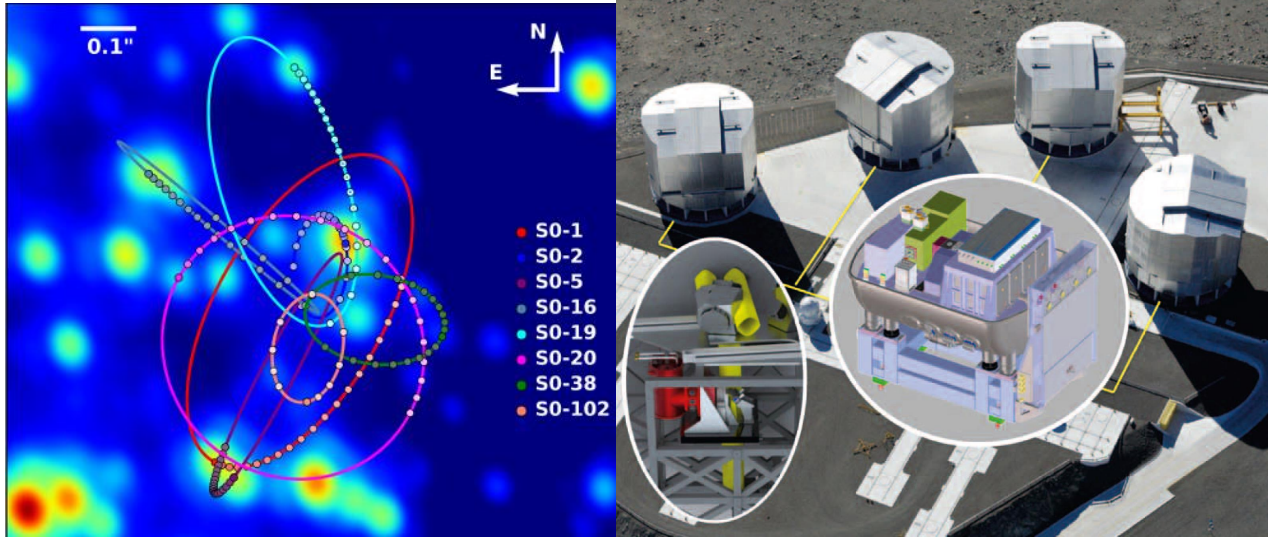
银河系中心：启发

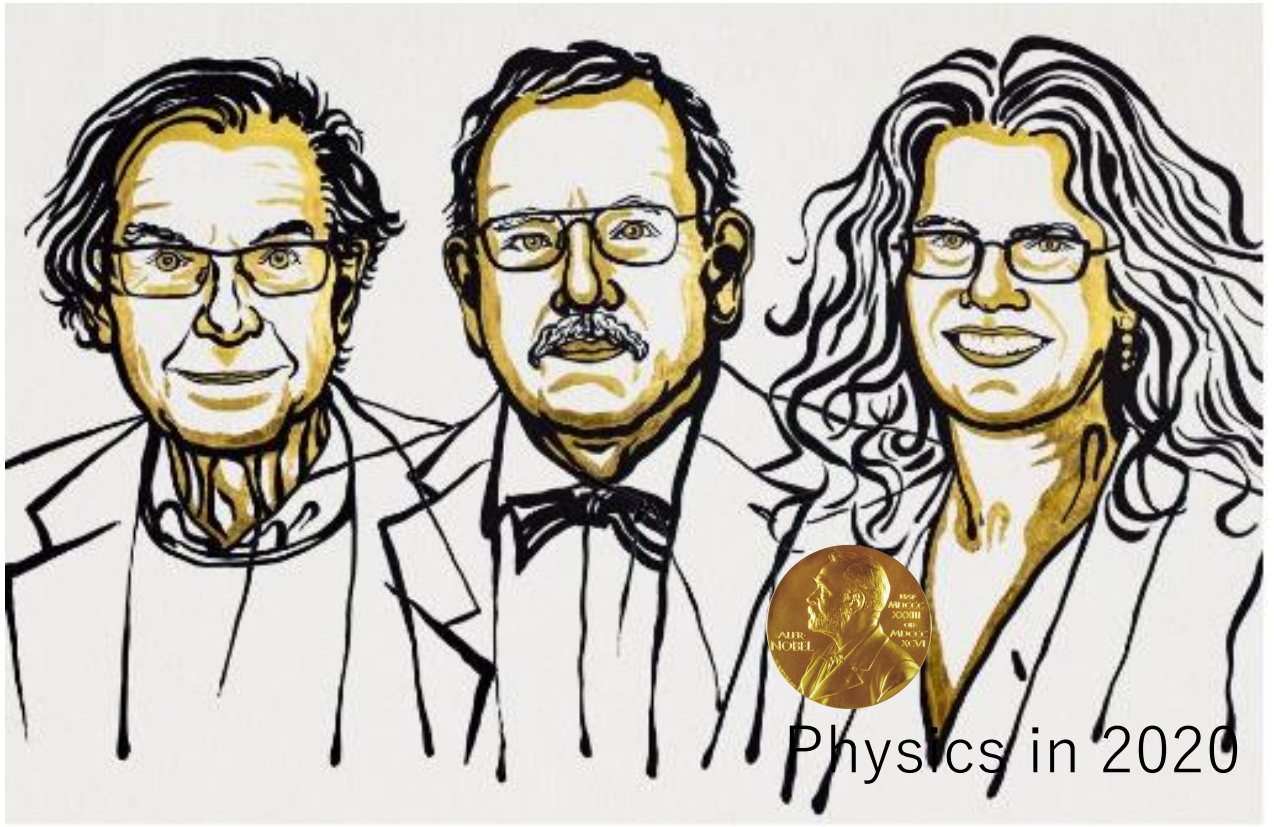
The Astrophysical Journal Letters, 932:L6 (29pp), 2022 June 10 https://doi.org/10.3847/2041-8213/ac68ef

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]



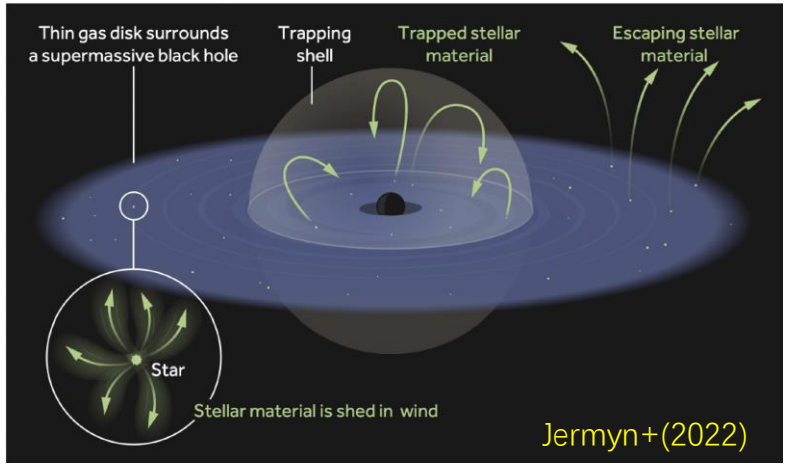




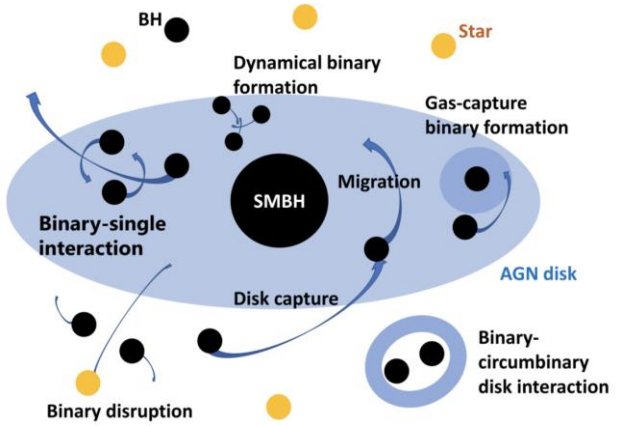
随机吸积：角动量随时间减小

银河系中心：暗物质？

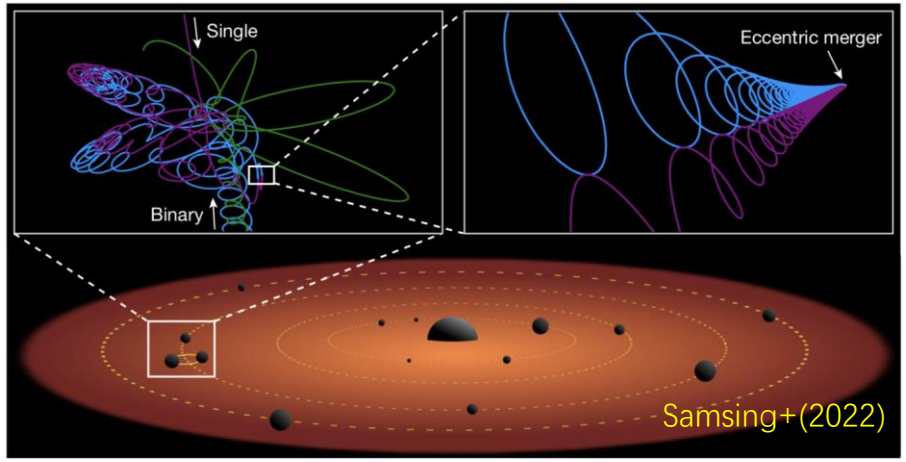
evolutions of massive stars



binaries of compact objects

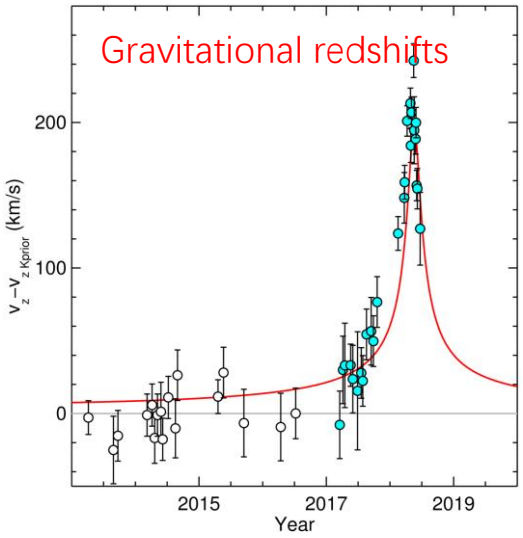


Tagawa+(2021)

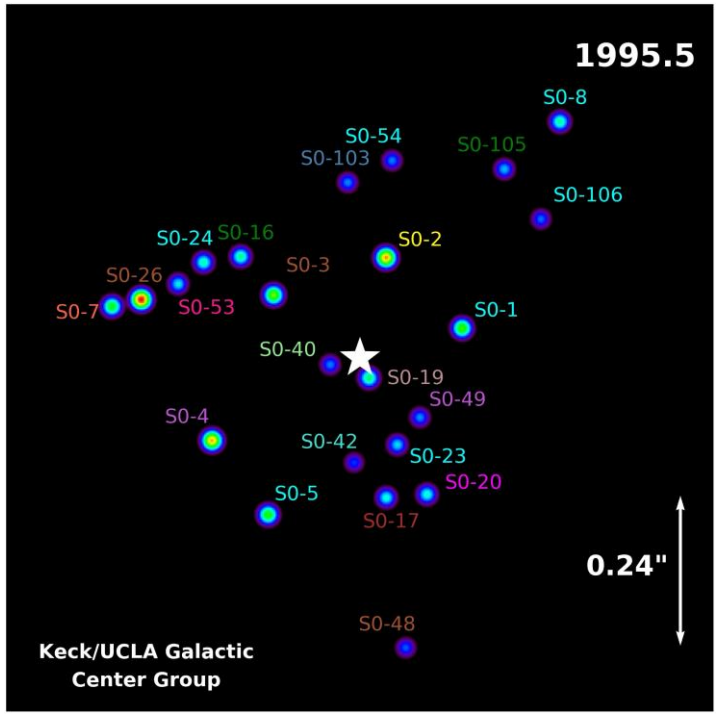


许多问题: 挑战与机遇

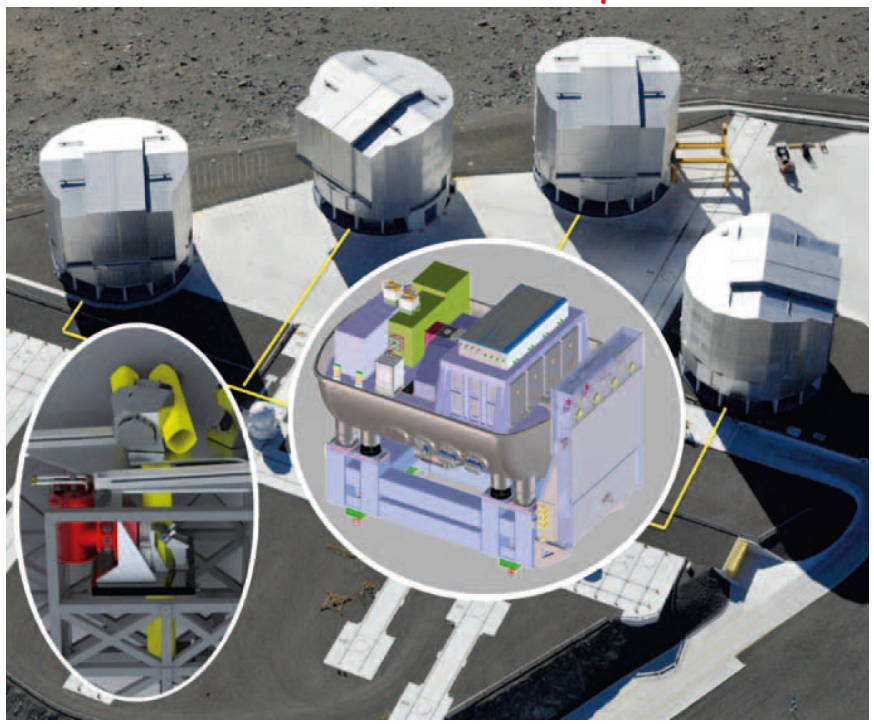
Physics in 2020

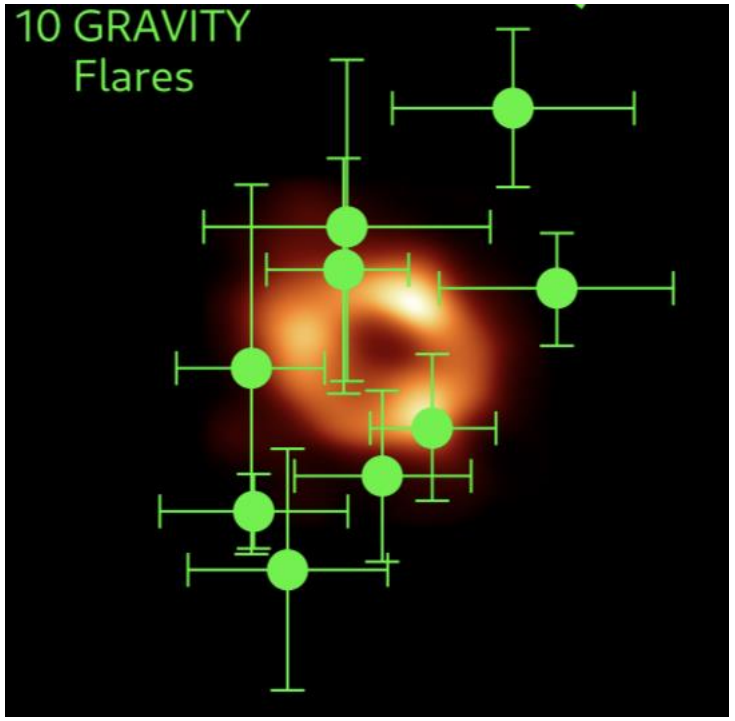


Galactic center



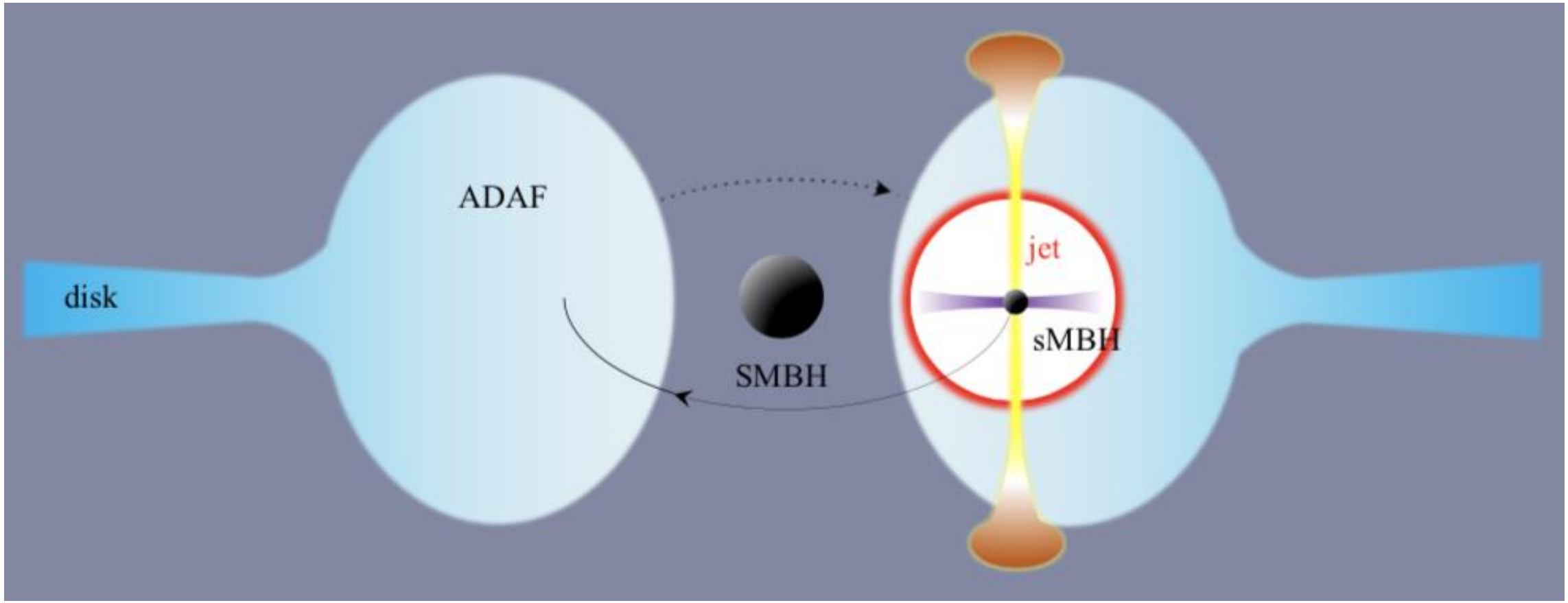
VLTI/ESO: 10μas





银河系中心中心：极端质量比旋进天体

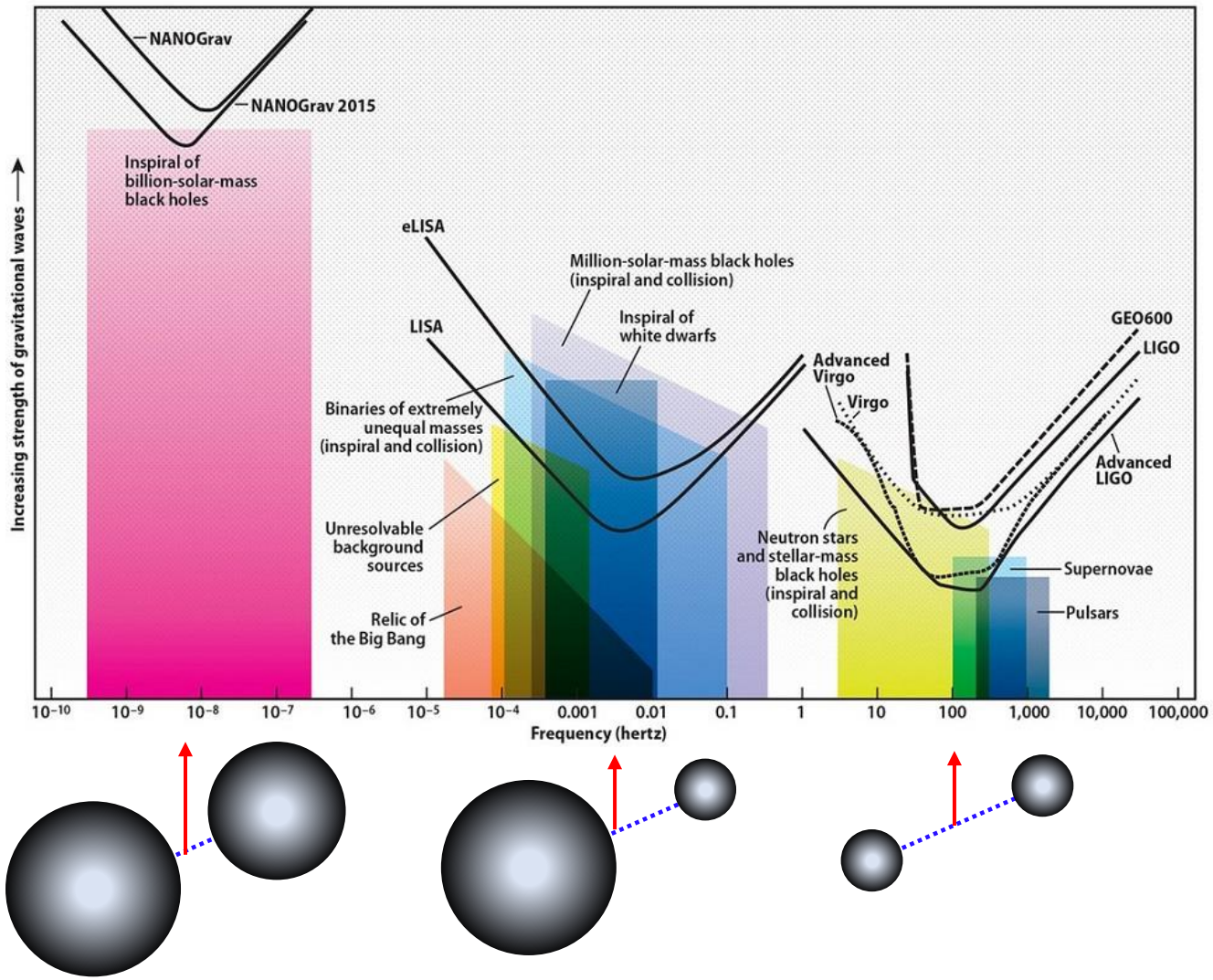
(Wang+2023)



问题：动力学和辐射

- 吸积盘上恒星演化：黑洞、中子星、白矮星?
- 动力学：恒星与气体相互作用？
- 双星演化：致密天体双星
- 吸积恒星（Accretion-modified stars）：
  - 外流Outflow-driven cavity
  - 双黑洞演化
  - 引力波辐射
- 超大质量+恒星双黑洞：EMRI

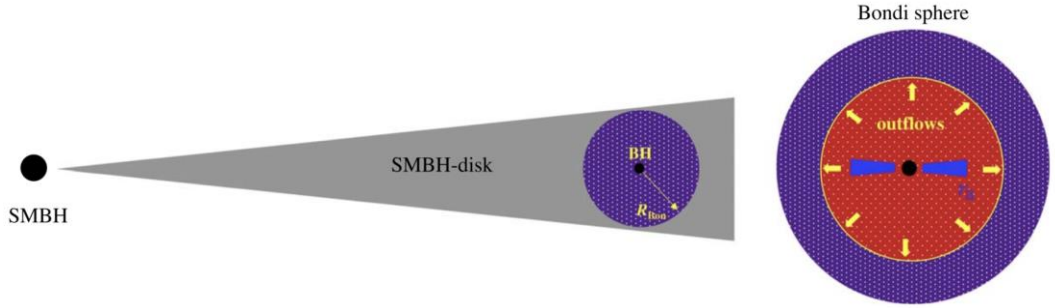
双黑洞与引力波波谱

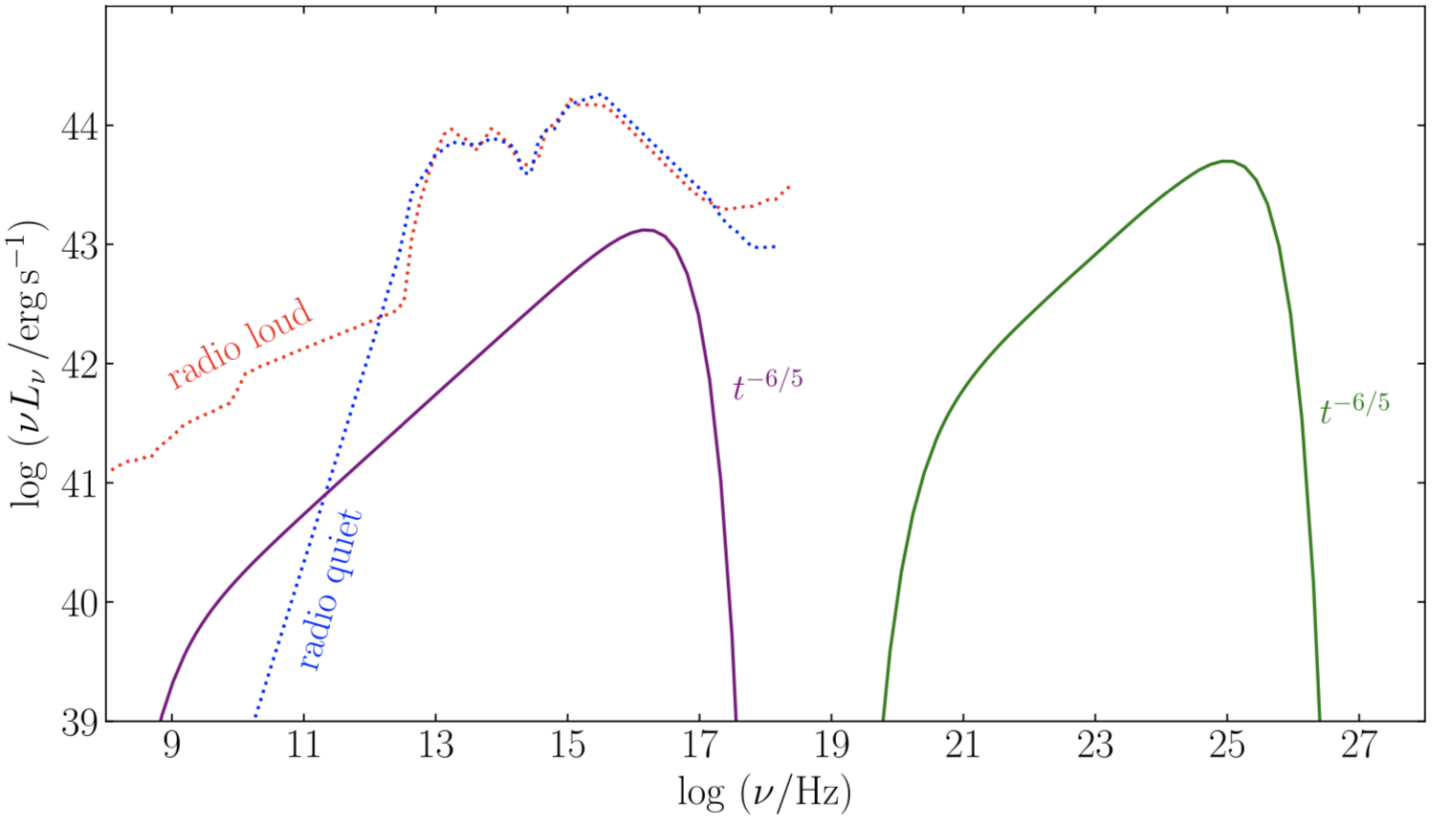

NANOGrav
NANOGrav 2015
Inspiral of billion-solar-mass black holes
eLISA
LISA
Million-solar-mass black holes (inspiral and collision)
Inspiral of white dwarfs
Binaries of extremely unequal masses (inspiral and collision)
Unresolvable background sources
Relic of the Big Bang
Advanced Virgo
Virgo
GEO600
LIGO
Advanced LIGO
Neutron stars and stellar-mass black holes (inspiral and collision)
Supernovae
Pulsars
Increasing strength of gravitational waves
10⁻¹⁰ 10⁻⁹ 10⁻⁸ 10⁻⁷ 10⁻⁶ 10⁻⁵ 10⁻⁴ 0.001 0.01 0.1 1 10 100 1,000 10,000 100,000
Frequency (hertz)

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]





Outflows from AMS:

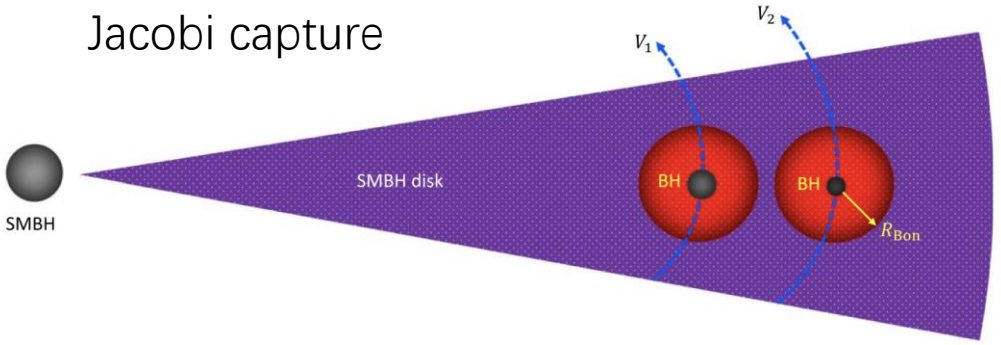
- Cavity forms
- Radiation: slow transients
- Low duty cycle
- Growth of sMBH

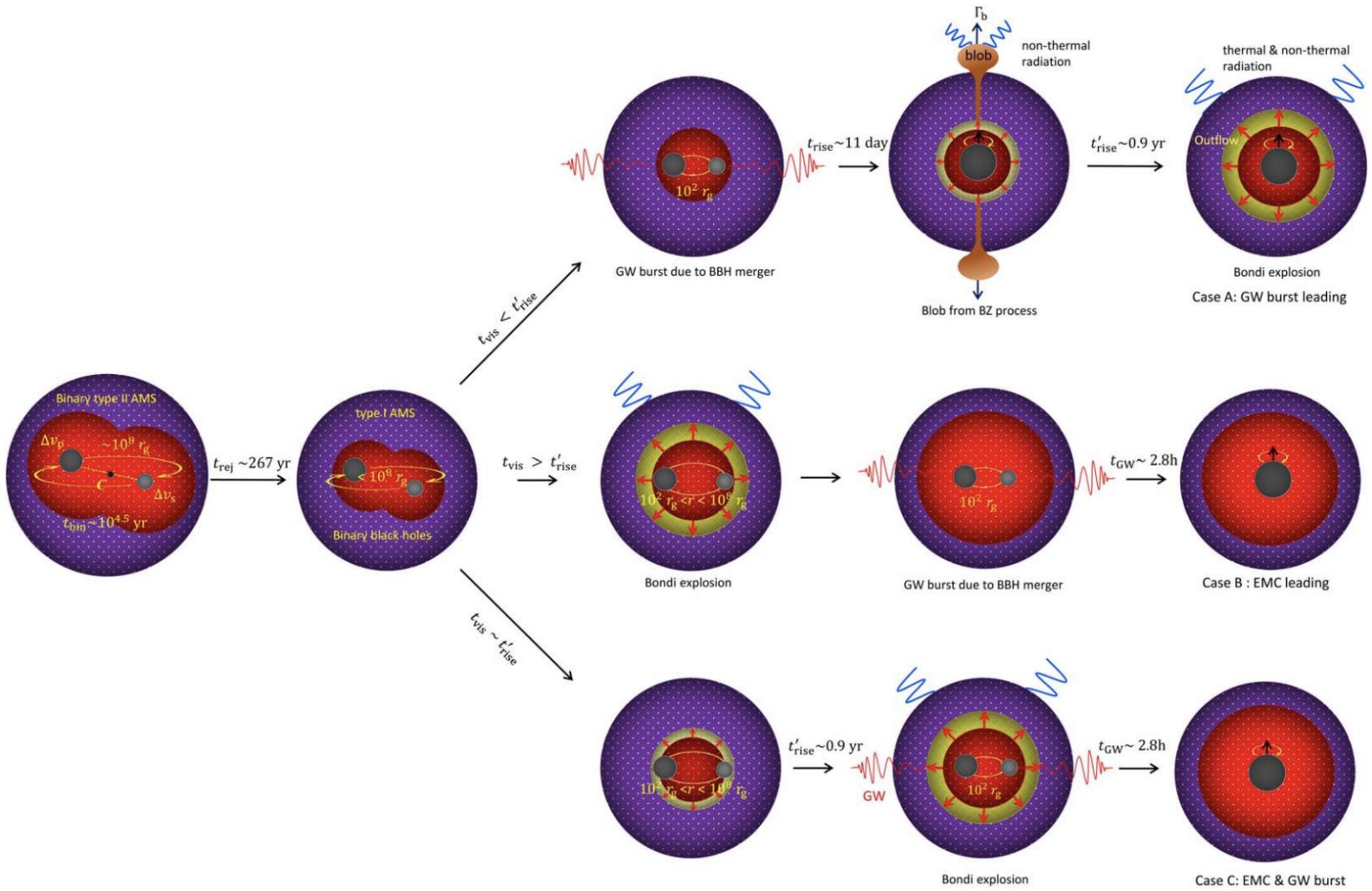
The Astrophysical Journal Letters, 916:L17 (11pp), 2021 August 1 https://doi.org/10.3847/2041-8213/ac0b46

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



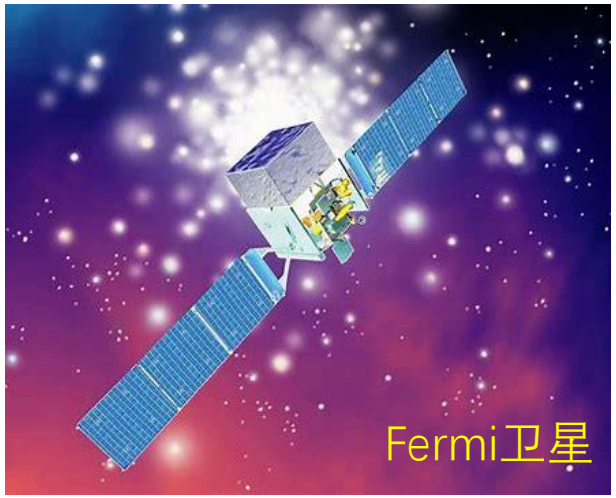


AMS: radio、γ-rays

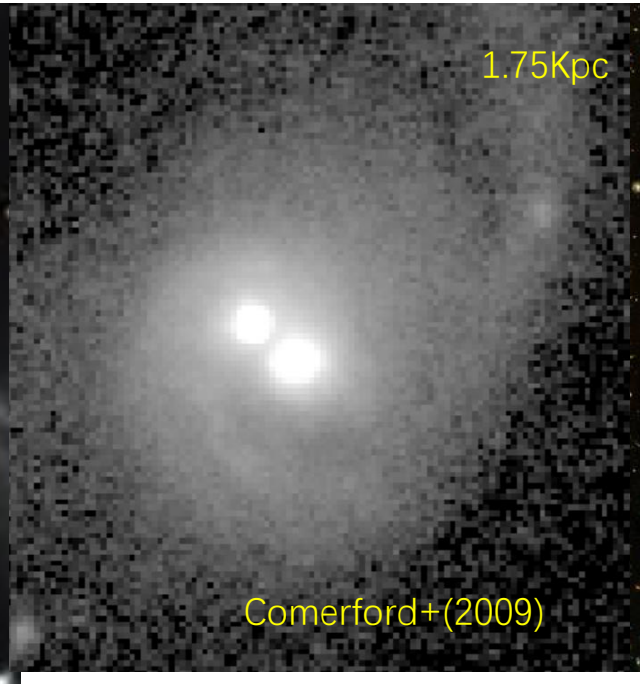
slow transients

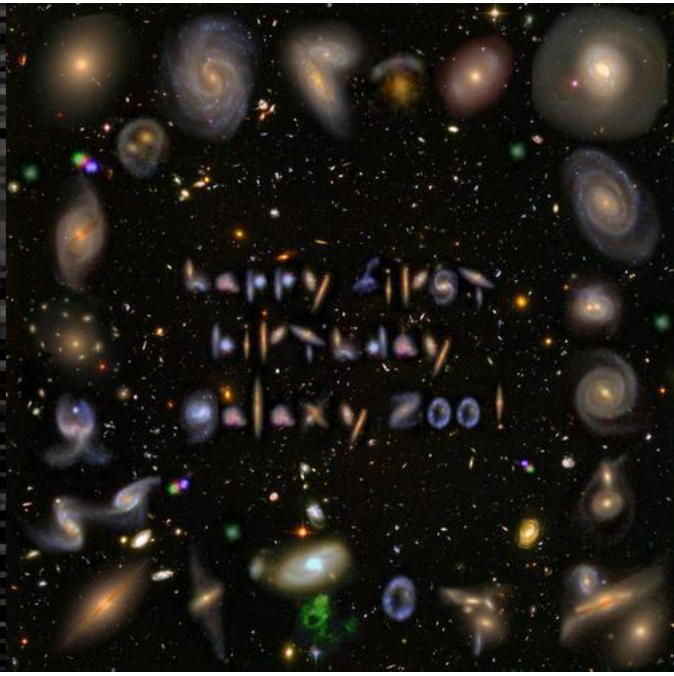
Merger rates: a few per year

LIGO: 10^2Hz GWs

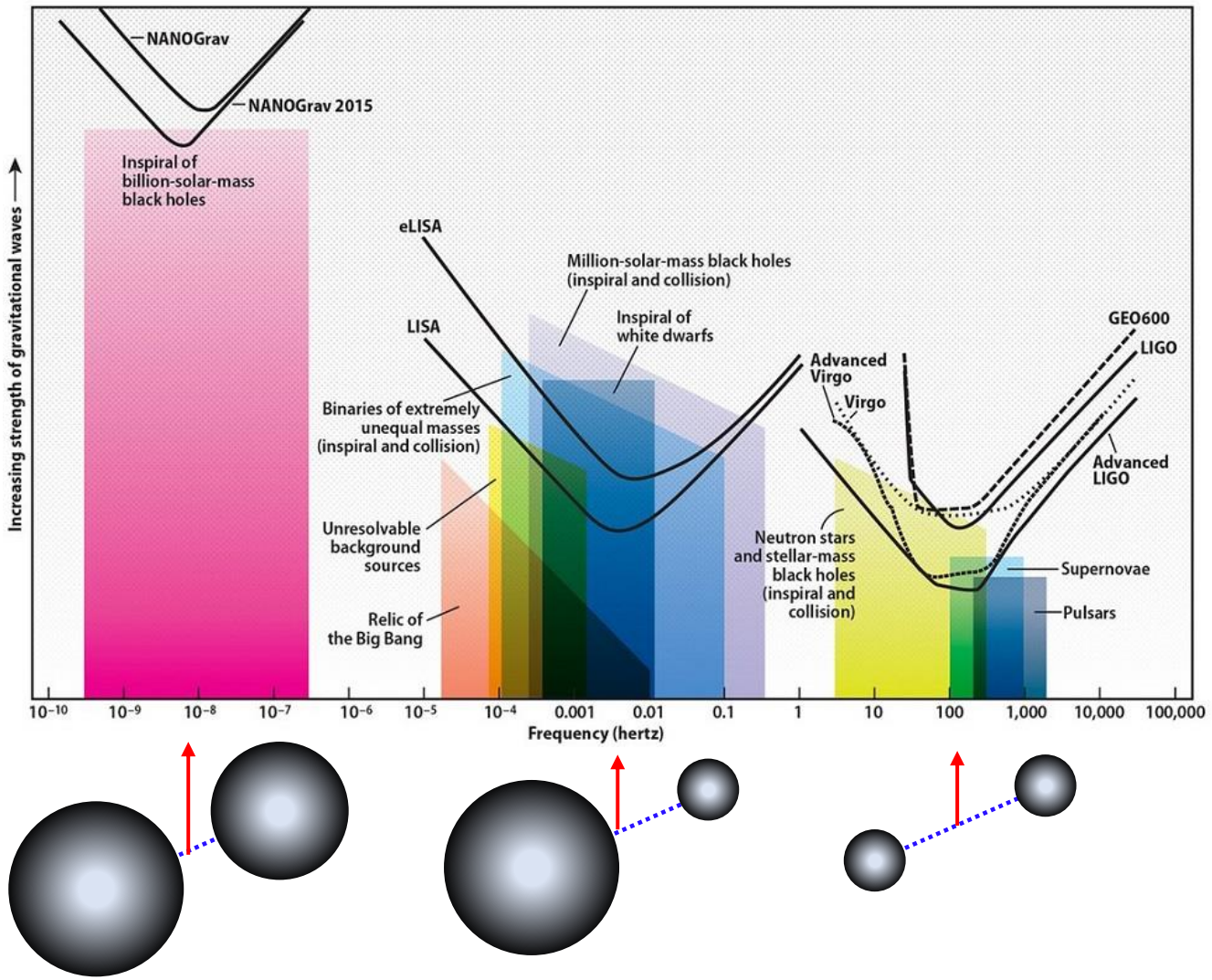


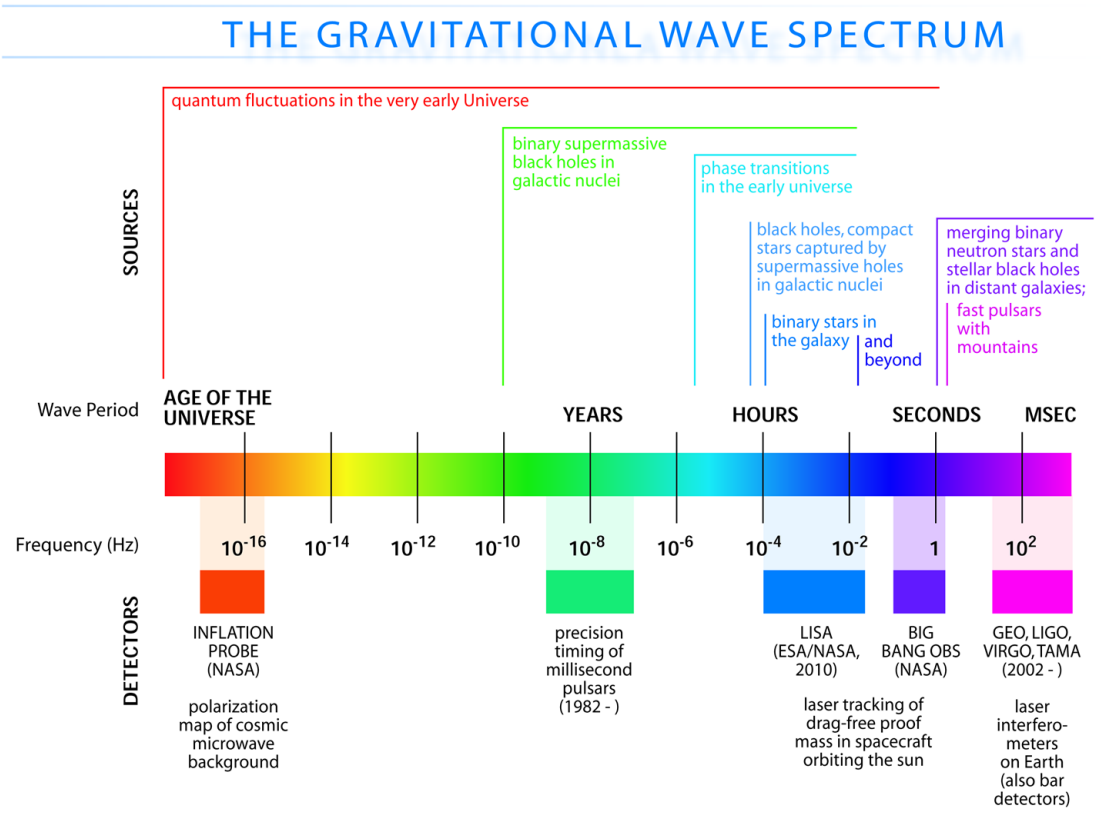
星系并合：超大质量双黑洞





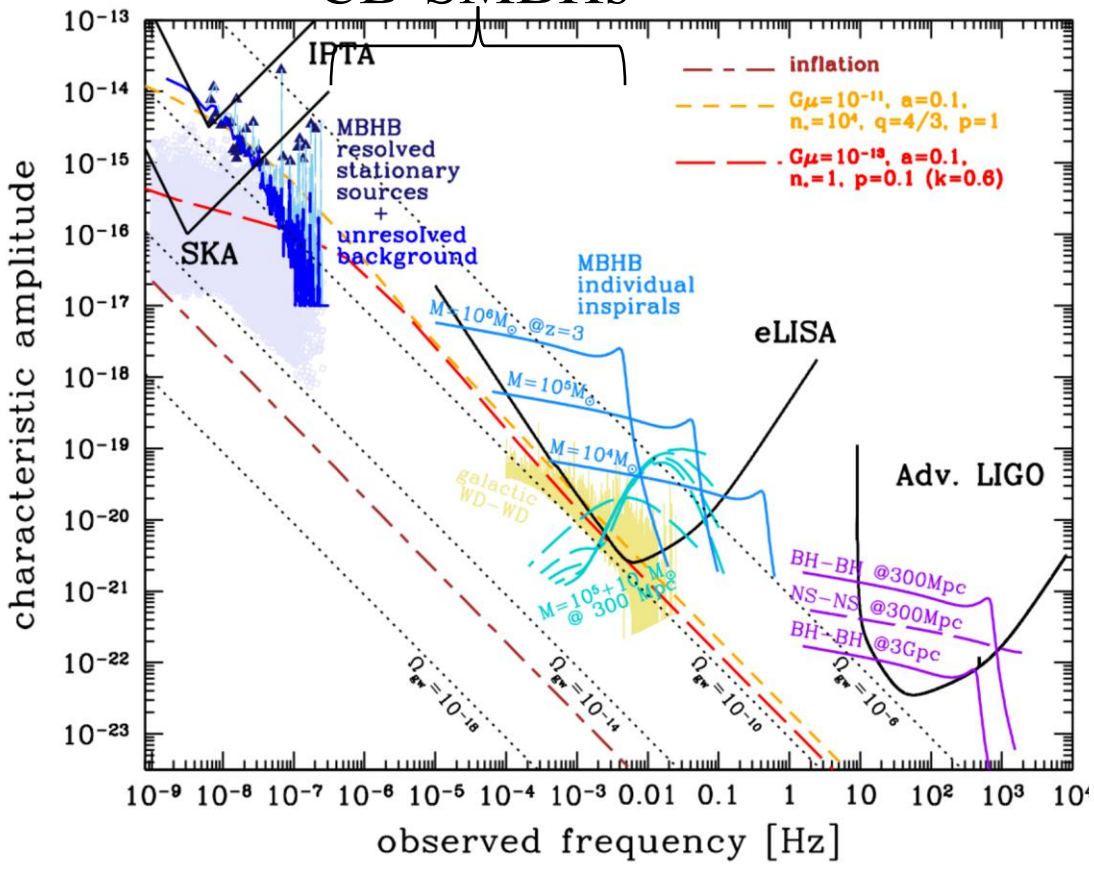
银河系中心：双星与引力波



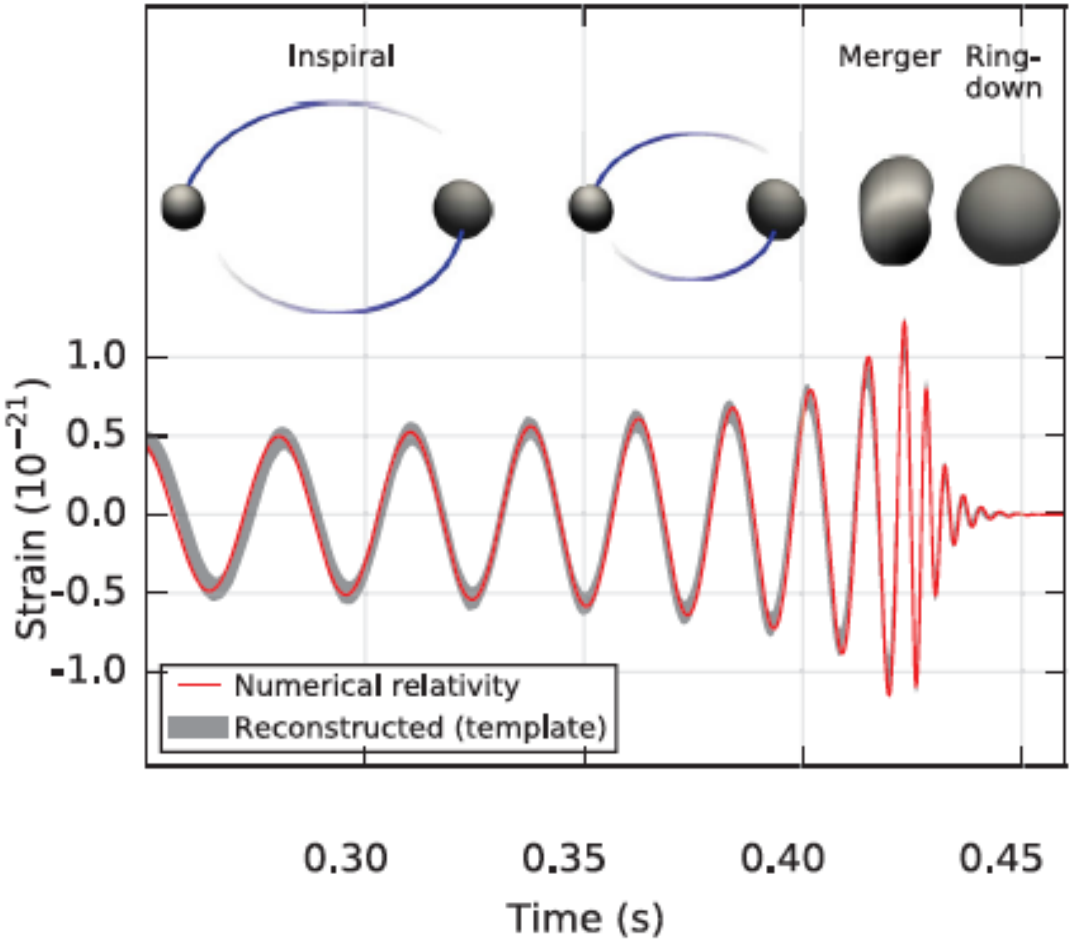


Close binaries of SMBHs：orbital parameters

CB-SMBHs

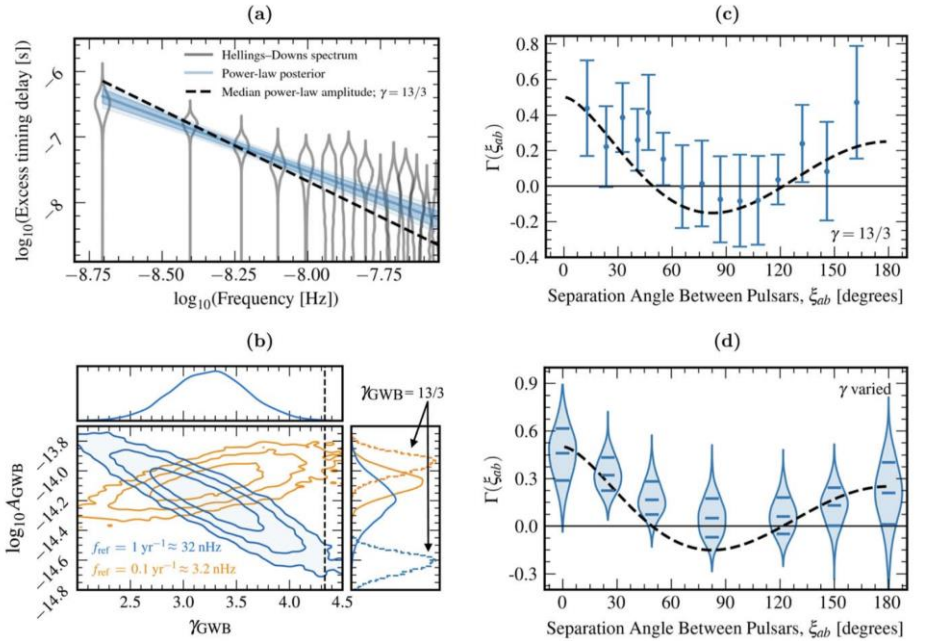


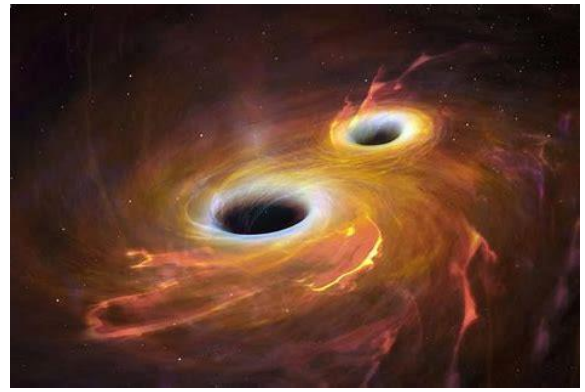
LIGO: 100Hz-GWs



Period ～ 10-100yrs： entire waveform possible，chirping impossible

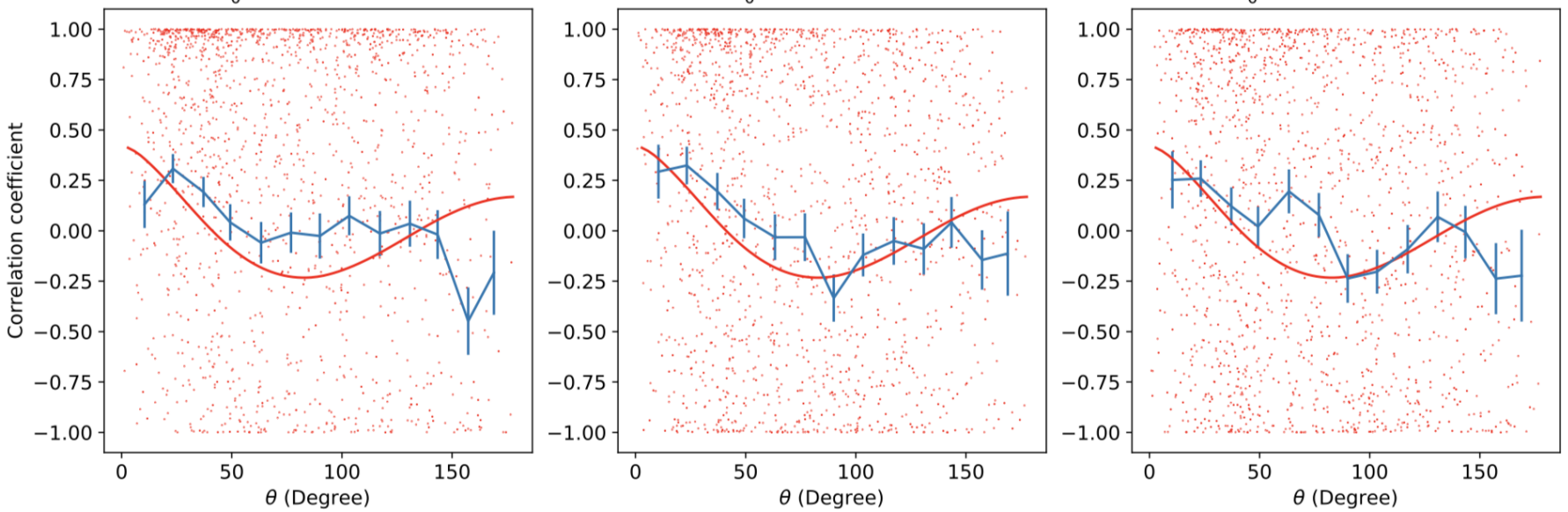
Agazie+2023



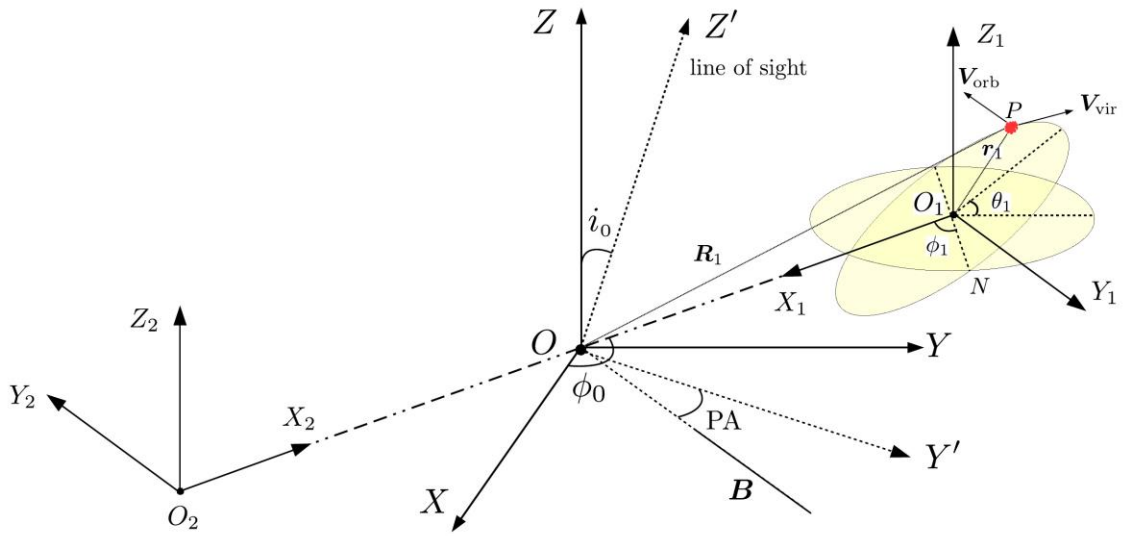


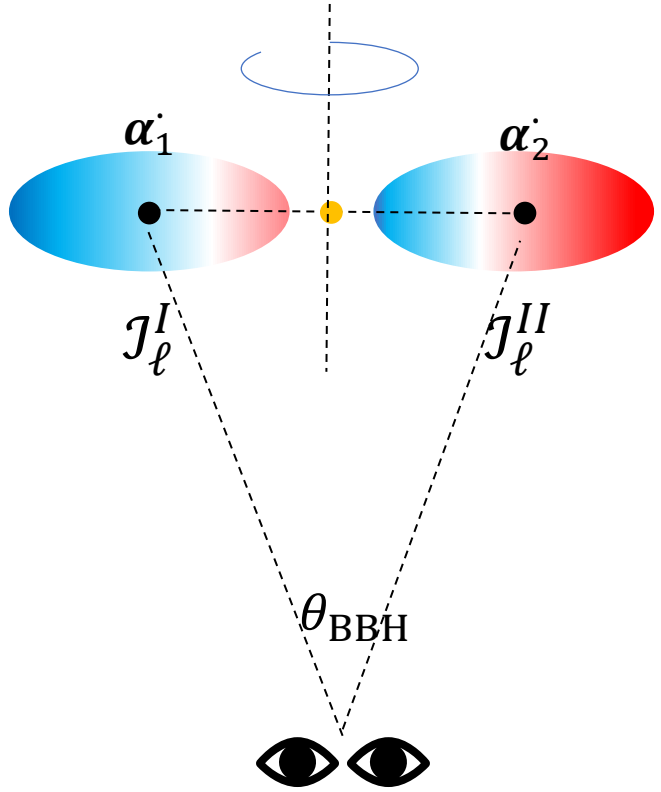
Xu+2023

CPTA



光干涉阵列: 双黑洞(Songsheng+2019)

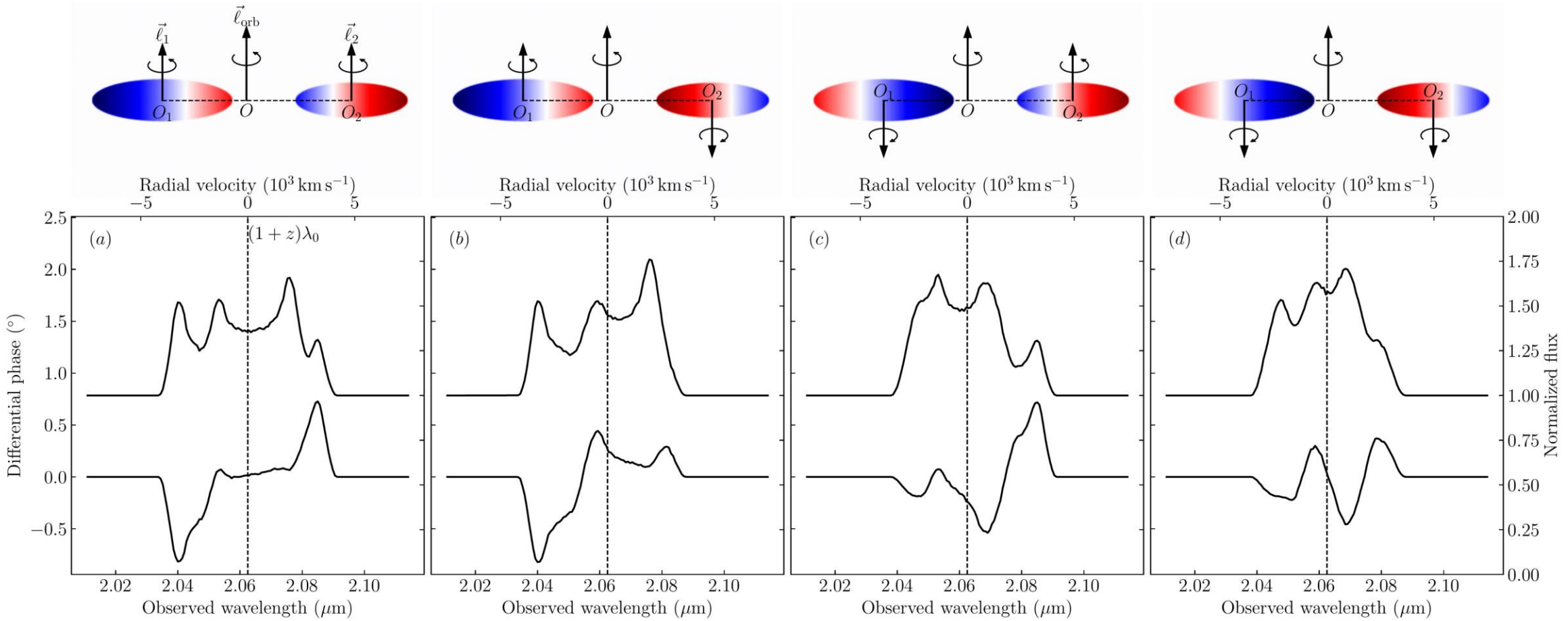




$$V_{\rm rel} = 3\times10^3 \left(\frac{M_\bullet}{10^8 M_\odot}\right)^{1/2} \left(\frac{a}{0.05\,{\rm pc}}\right)^{-1/2} {\rm km/s}$$

$$\theta_{\rm BBH} = 51.6 \left(\frac{a}{0.05\,{\rm pc}}\right) \left(\frac{D_{\rm A}}{200\,{\rm Mpc}}\right)^{-1} \mu{\rm as}$$

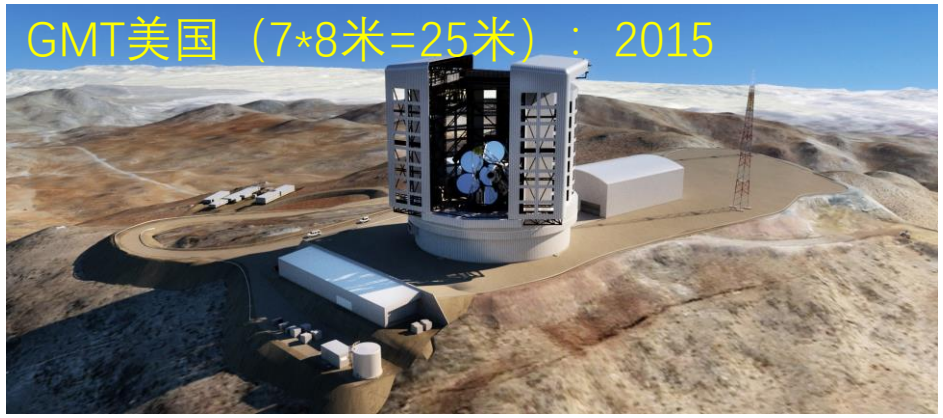
4 个最简单的构型

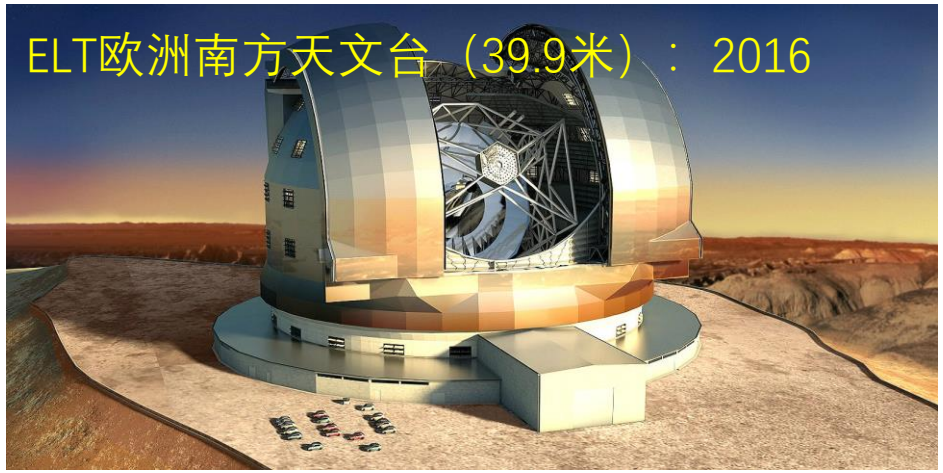


(Songsheng+2019, Kovacevic+2020)

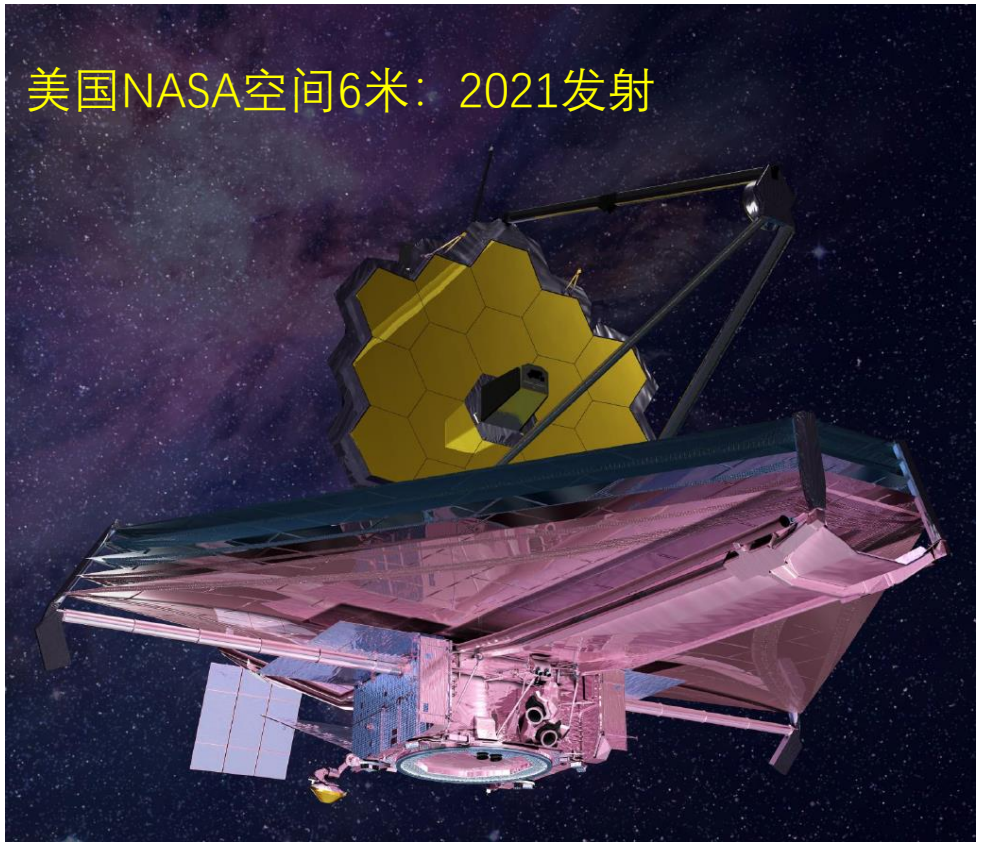
10年内：轨道参数的大规模观测

国际上大型设备投资


GMT美国（7*8米=25米）：2015


ELT欧洲南方天文台（39.9米）：2016

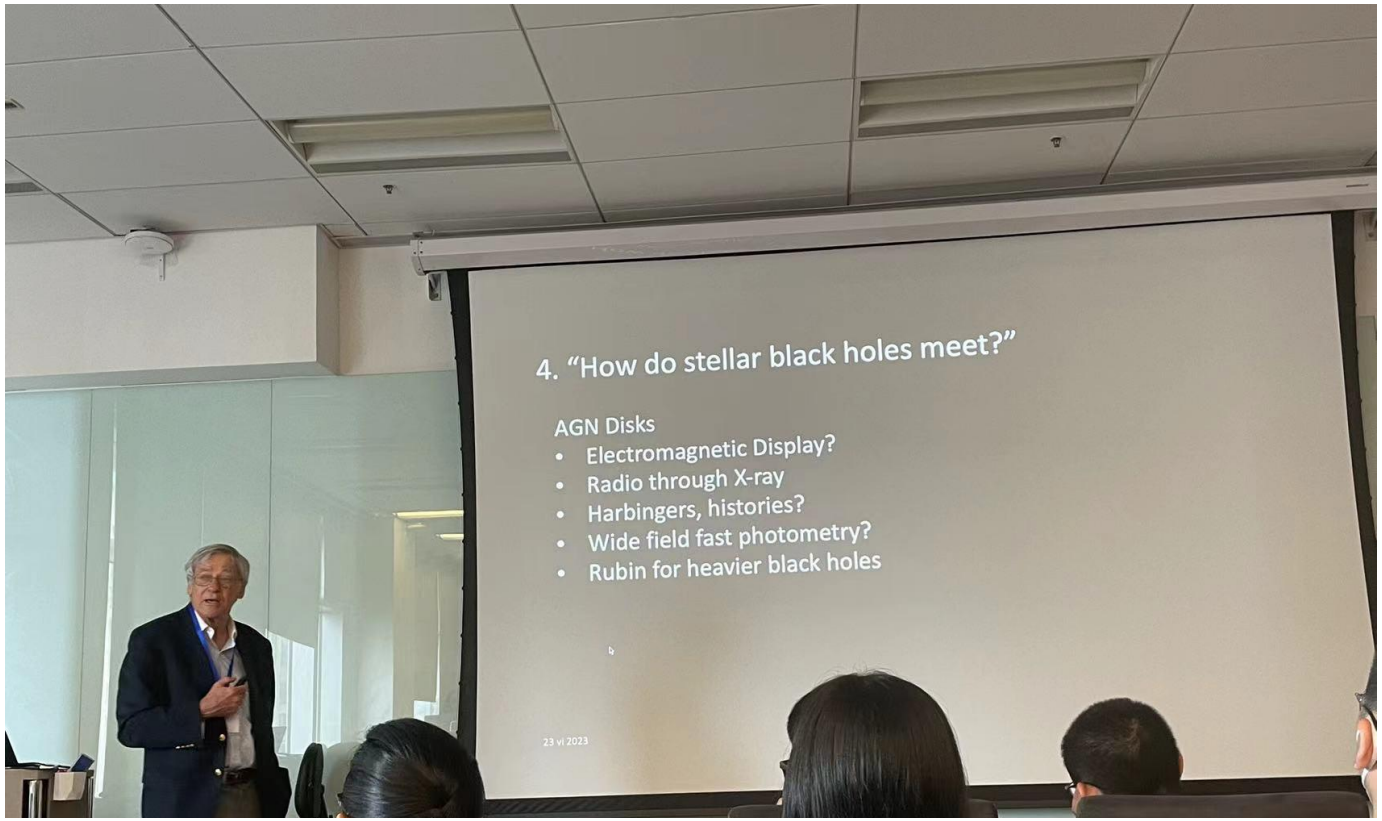

TMT美国30米：2022

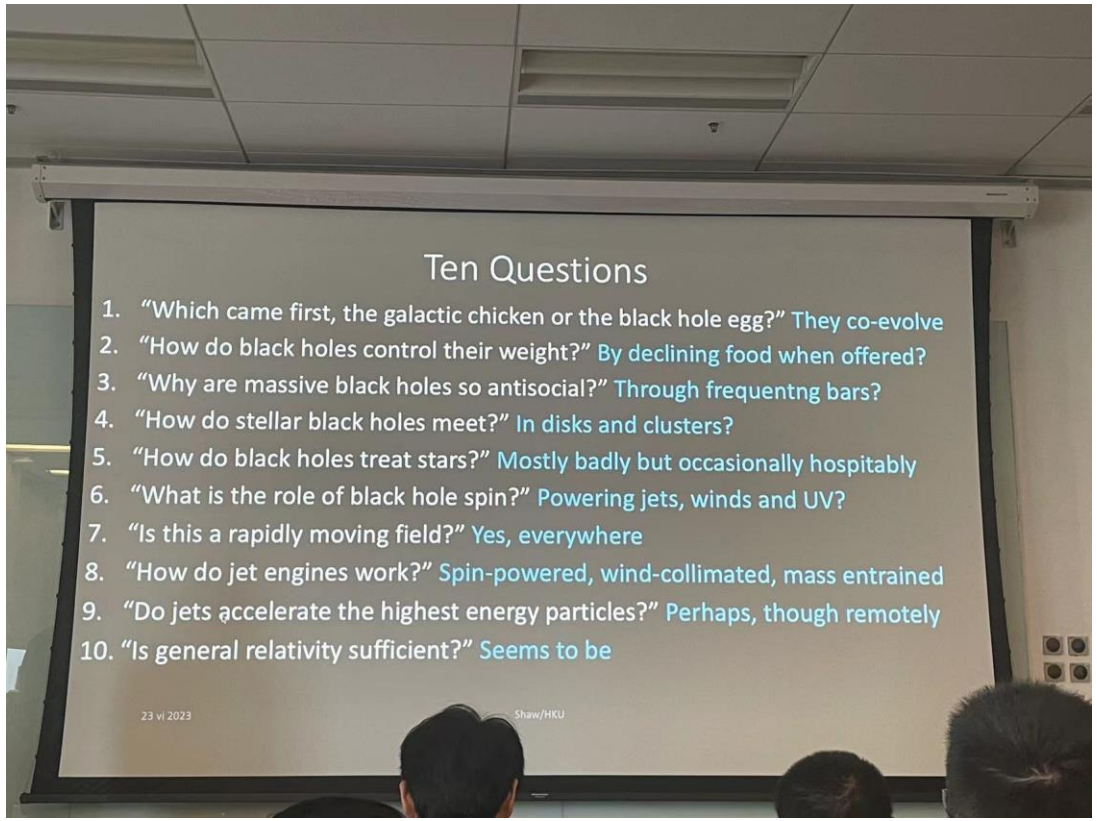

美国NASA空间6米：2021发射


欧亚：中国是创始国之一
平方公里阵列 2018

Astrophysical Black Holes: A Rapidly Moving Field

（for 邵逸夫奖获得者 Prof. R. Blandford）



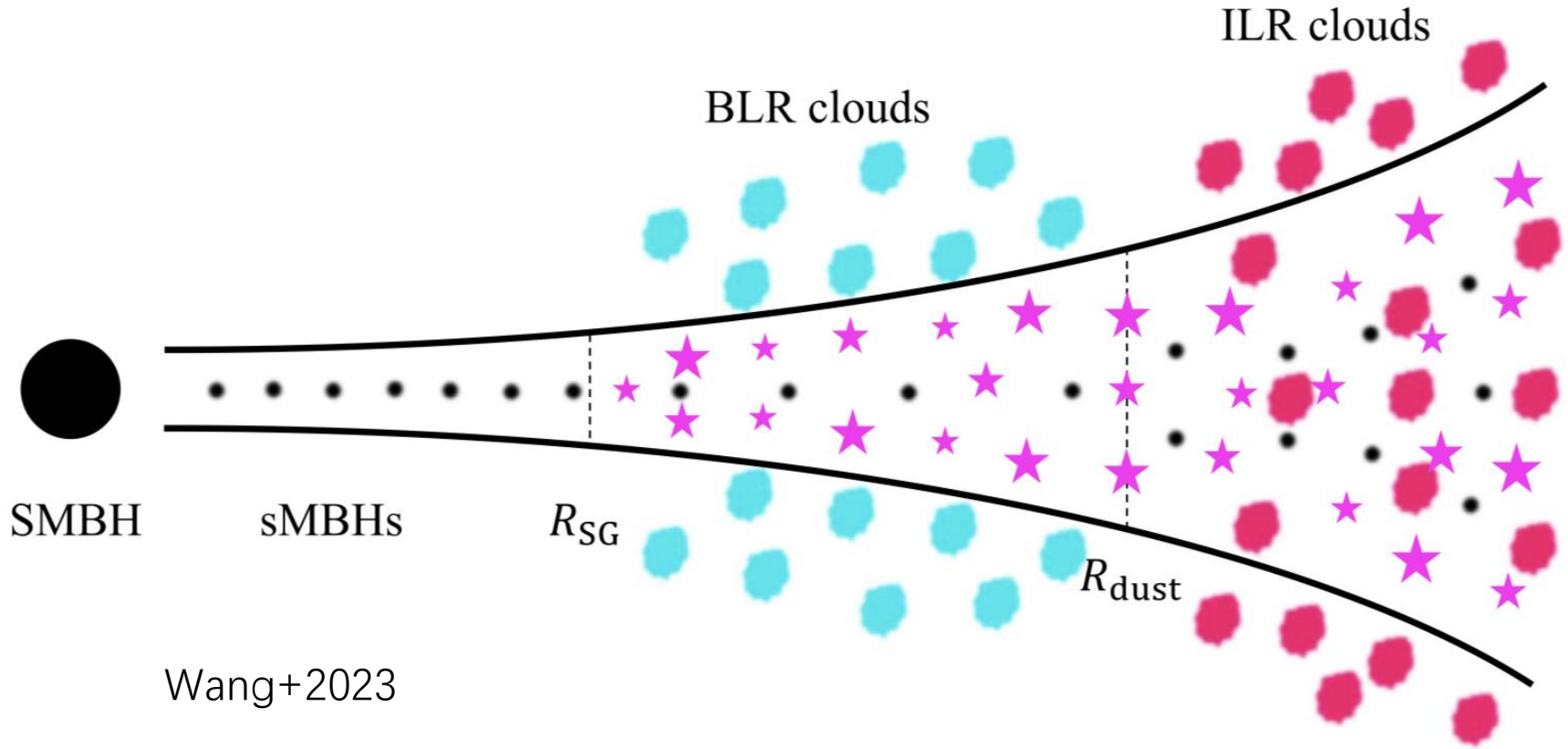


The University of Hong Kong 2023/06/23

美国天文十年**规**划**负责**人

结论

- 黑洞天体物理**观测现**象十分丰富
- 理解十分有限
- **对基础**物理的挑**战严**峻



Wang+2023