紫金山天文台讲座

光干涉观测时代

超大质量黑洞、宇宙学和低频引力波探测

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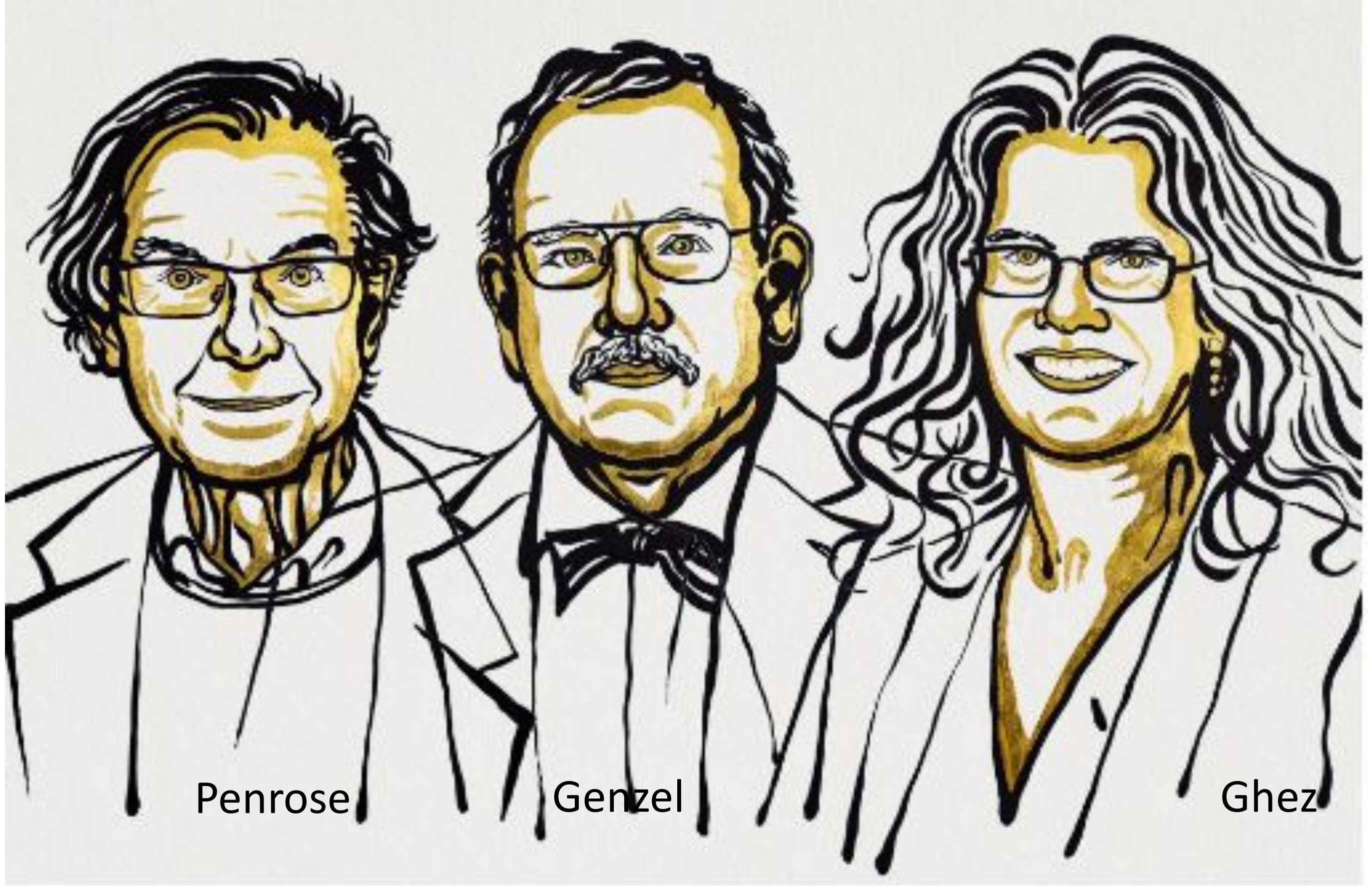
2021/05/20

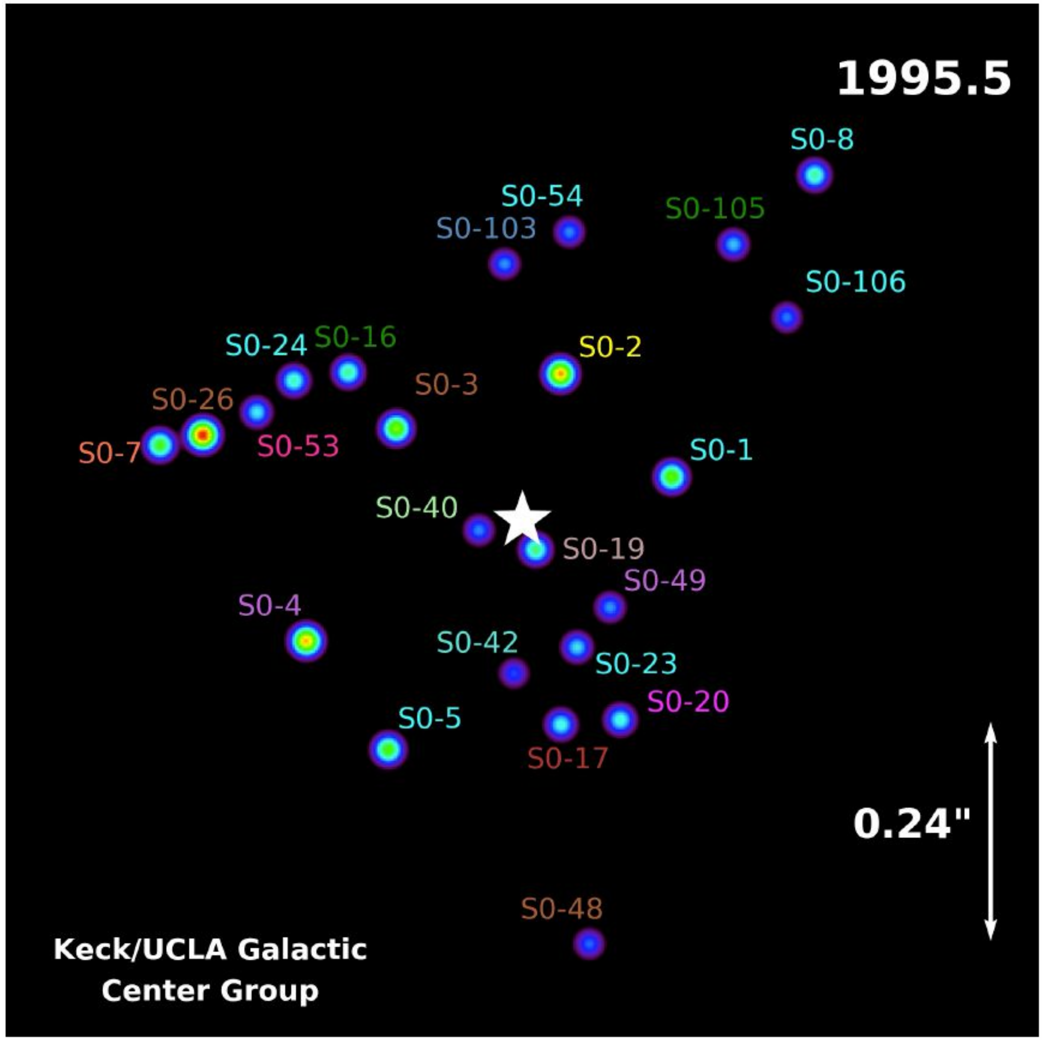
the discovery that black hole formation is a robust prediction of the general theory of relativity” and “for the discovery of a supermassive compact object at the centre of our galaxy”

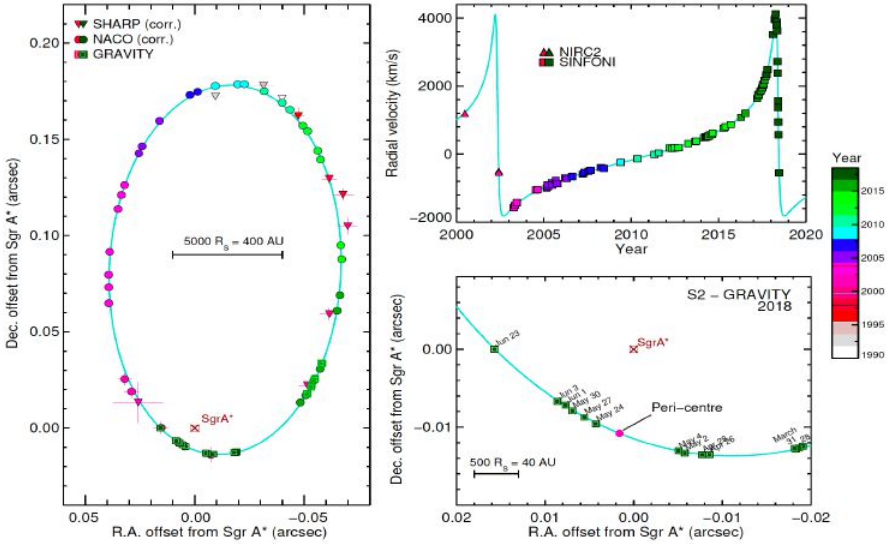
Physics in 2020



- 黑洞宇宙学：测距及膨胀历史
- 低频引力波：大质量双黑洞

银河系中心黑洞





$$z = \Delta\lambda/\lambda \approx 200\,\mathrm{km\,s^{-1}}/c$$

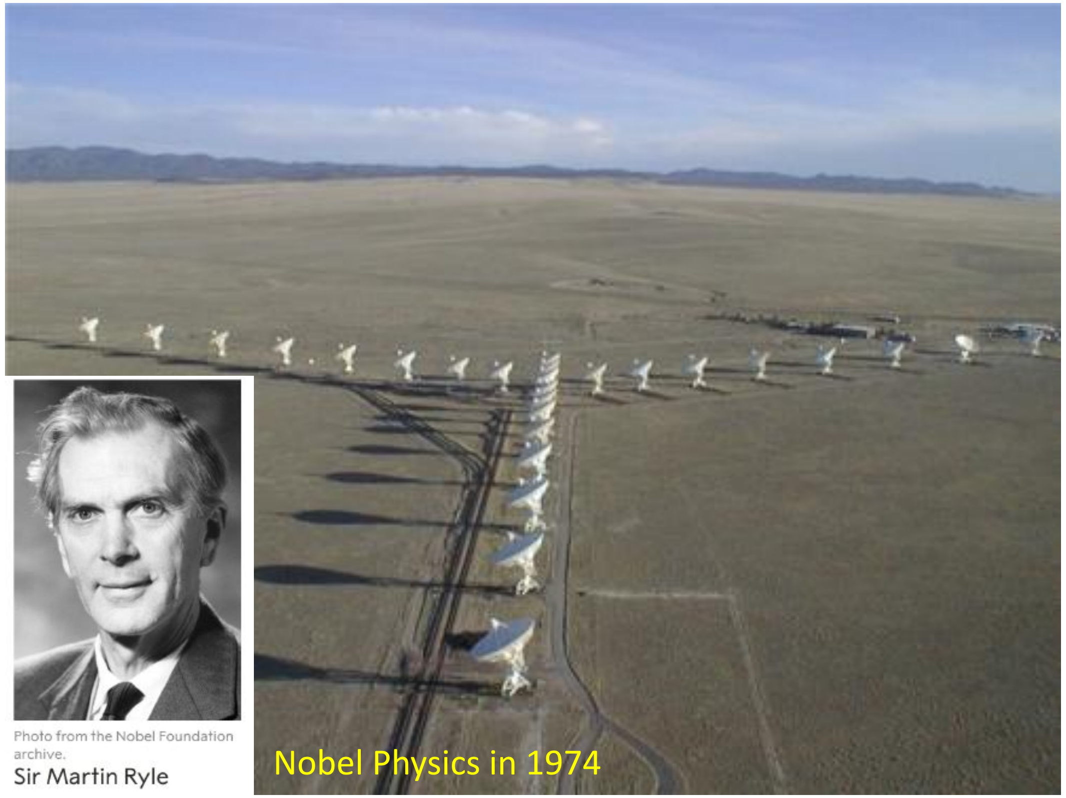
Gravity Collaboration+(2018,2019)

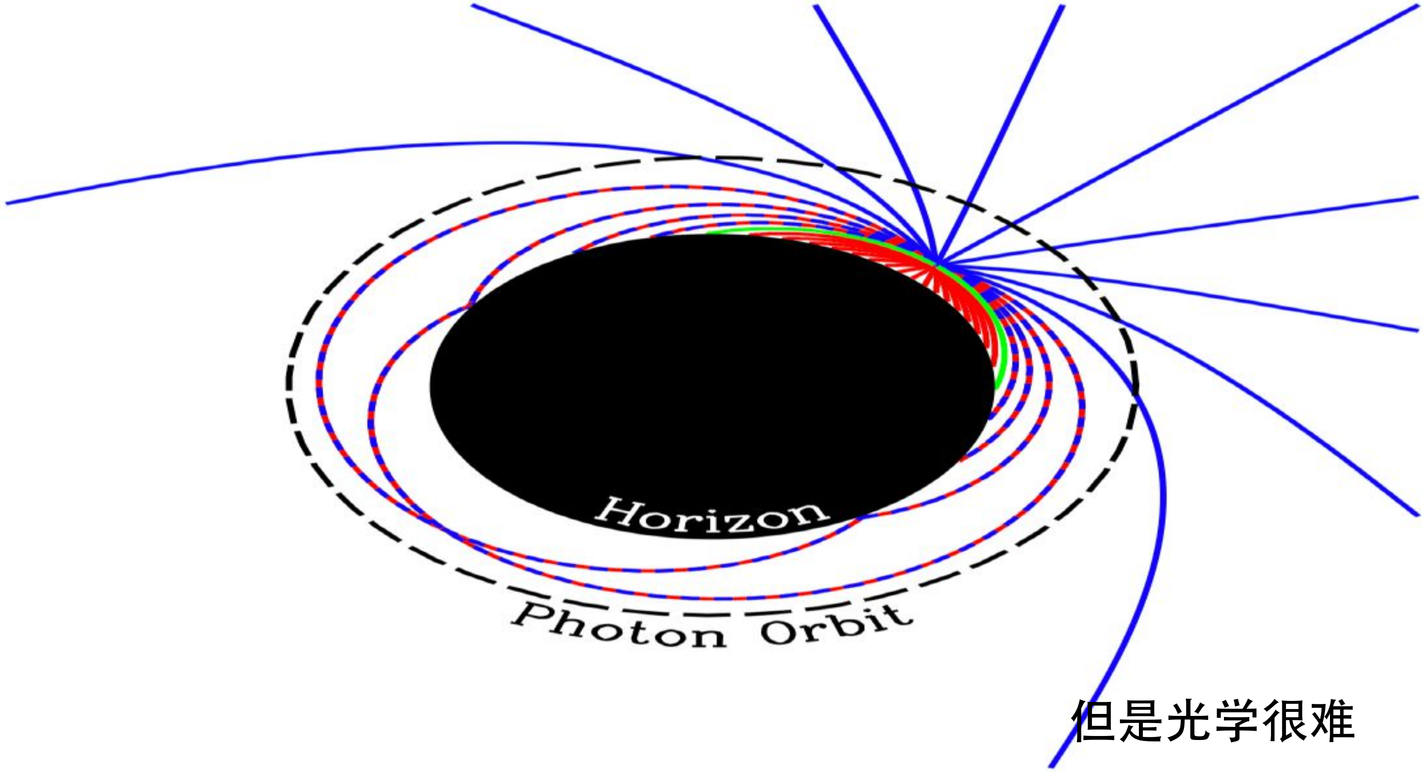
黑洞真实存在

GRAVITY/VLT干涉时代(>2017)

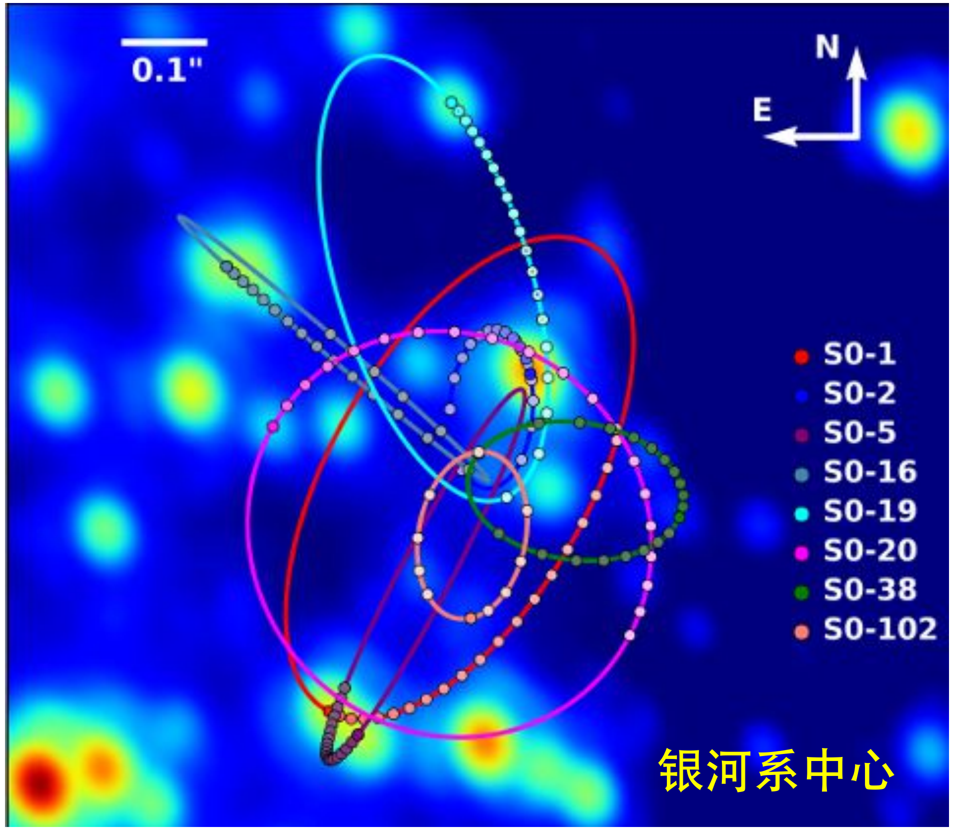
2018年突破：10μas@GRAVITY

高空间分解率：永恒的追求





但是光学很难



VLT干涉： 4 ⊗ 8 米 (2017)

高空间分辨率： 解析宽线区

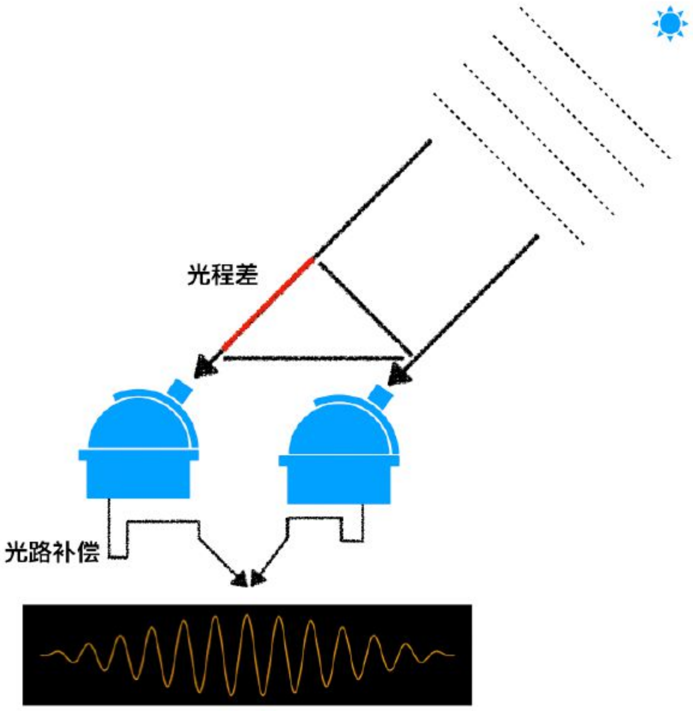
(分辨率:10μas)

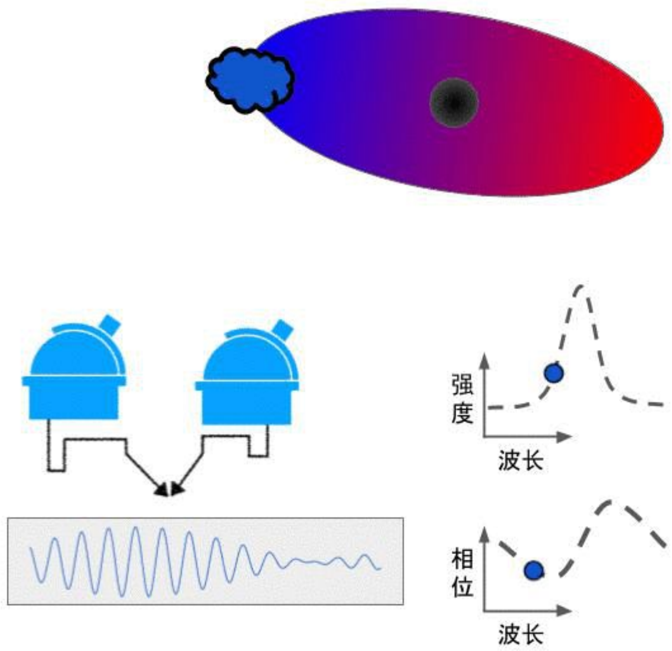
→

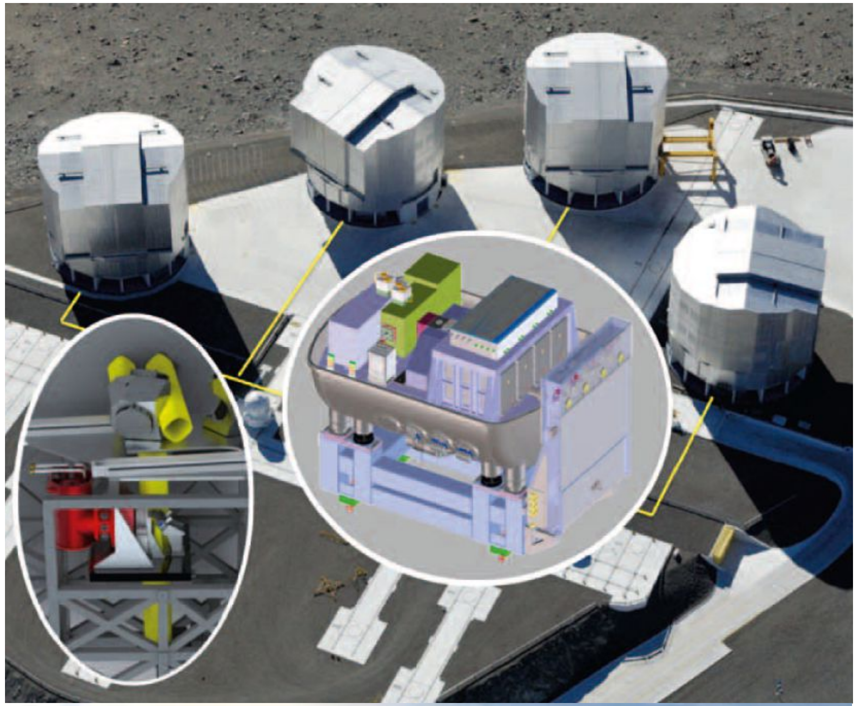
河外天体

类星体

AO+干涉+光谱定位：分辨率$10\mu as$







可见光波段：相干时标一般短于10毫秒，

近红外波段：一般短于百毫秒。

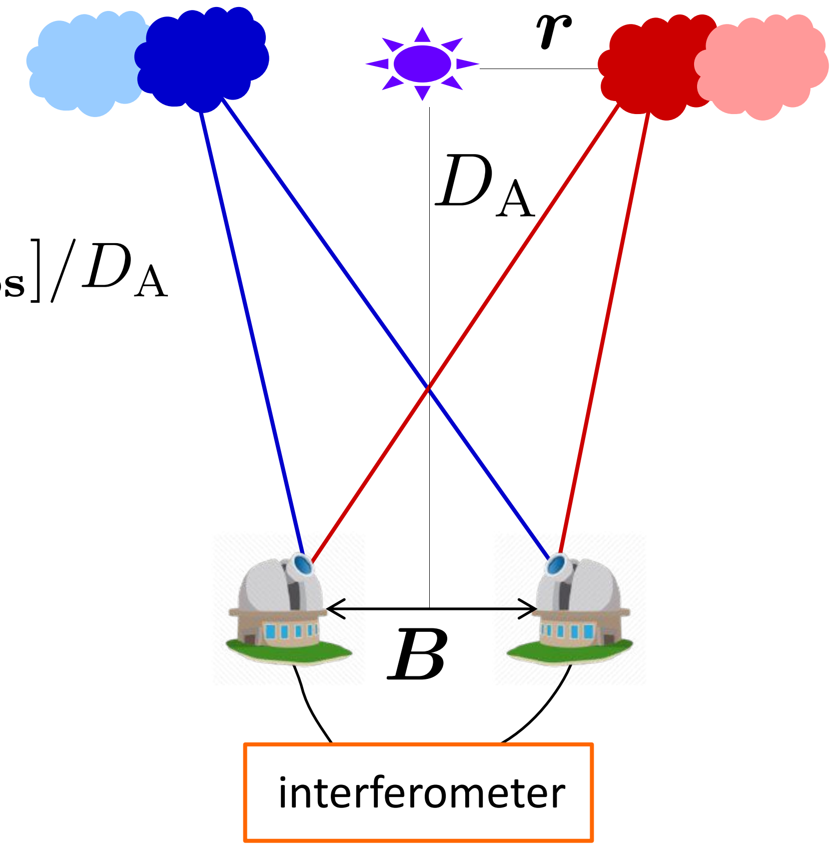
干涉测量：高空间分辨率

$$\phi_*(\lambda, \lambda_r) = -2\pi \boldsymbol{B} \cdot [\boldsymbol{\epsilon}(\lambda) - \boldsymbol{\epsilon}(\lambda_r)]/\lambda$$

$$\boldsymbol{\epsilon}(\lambda) = \bar{\boldsymbol{\alpha}}(\lambda) \sim [\boldsymbol{r} - (\boldsymbol{r} \cdot \boldsymbol{n}_{\rm obs})\boldsymbol{n}_{\rm \bf obs}]/D_{\rm A}$$

Angular size

Perpendicular to LOS



Assuming $D_{\rm A} \rightarrow R_{\rm BLR}$ and $M_\bullet$

光传播位相差：垂直方向

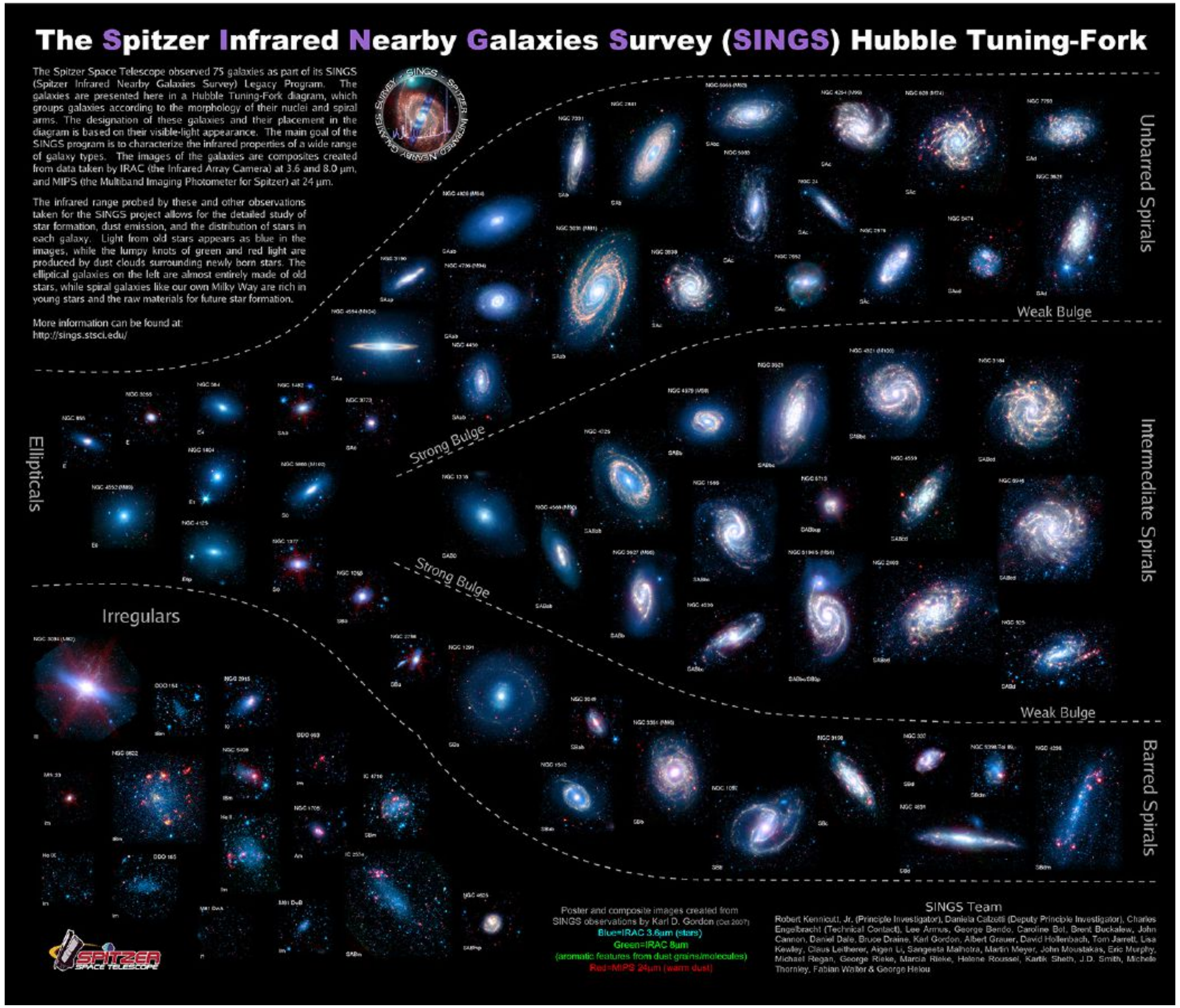
辐射区角径

光干涉时代的前沿课题

- 测量黑洞质量：与星系的共同演化
- 几何测量距离：暗能量（宇宙学）
- 超大质量双黑洞：低频引力波

河外超大质量黑洞

星系中心：黑洞?



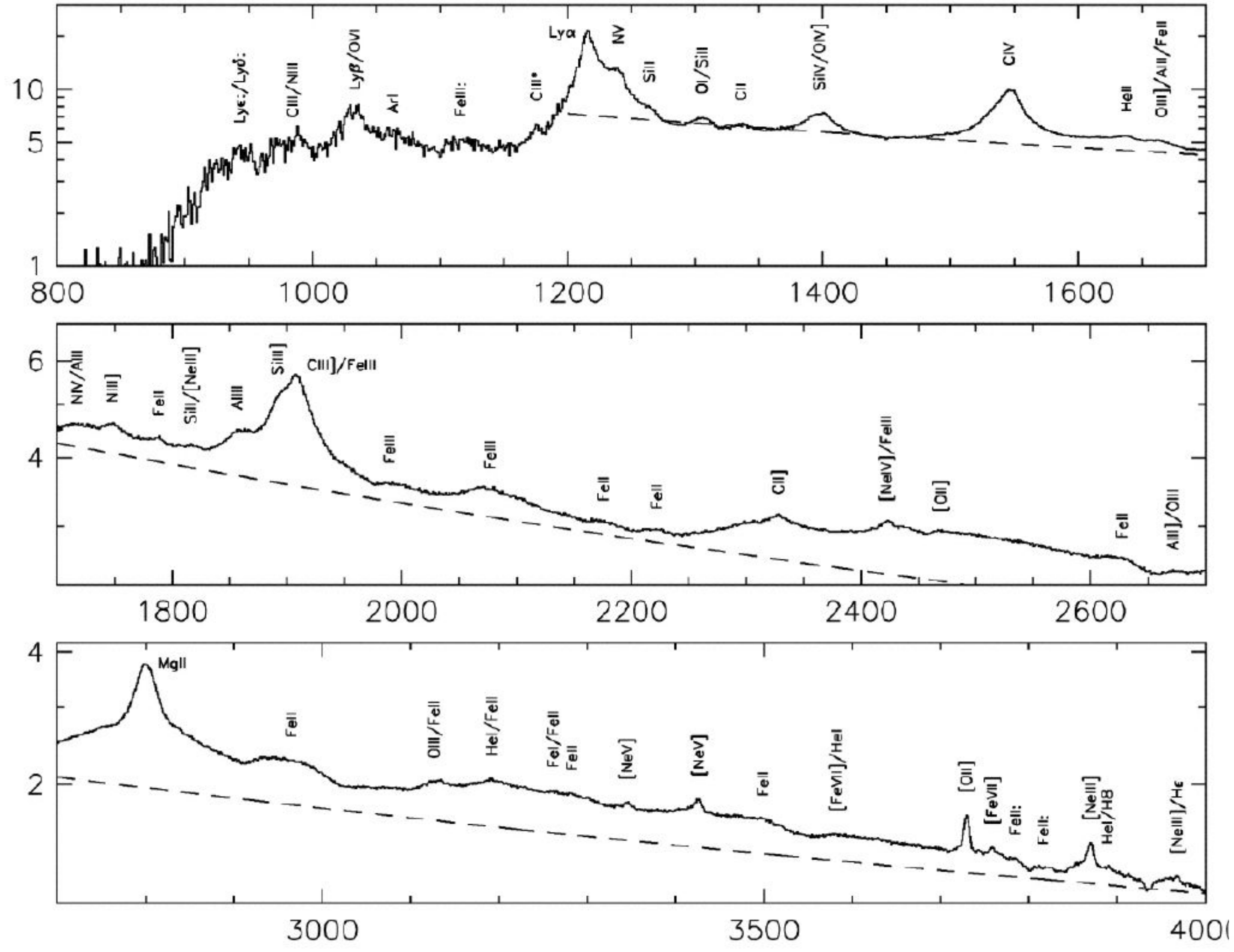
- Seyfert星系，类星体是AGNs?
- 银河系中心黑洞质量与角动量?
- 河外星系?
- 如何测量黑洞质量?
- 黑洞与星系的共同演化?

  质量和角动量

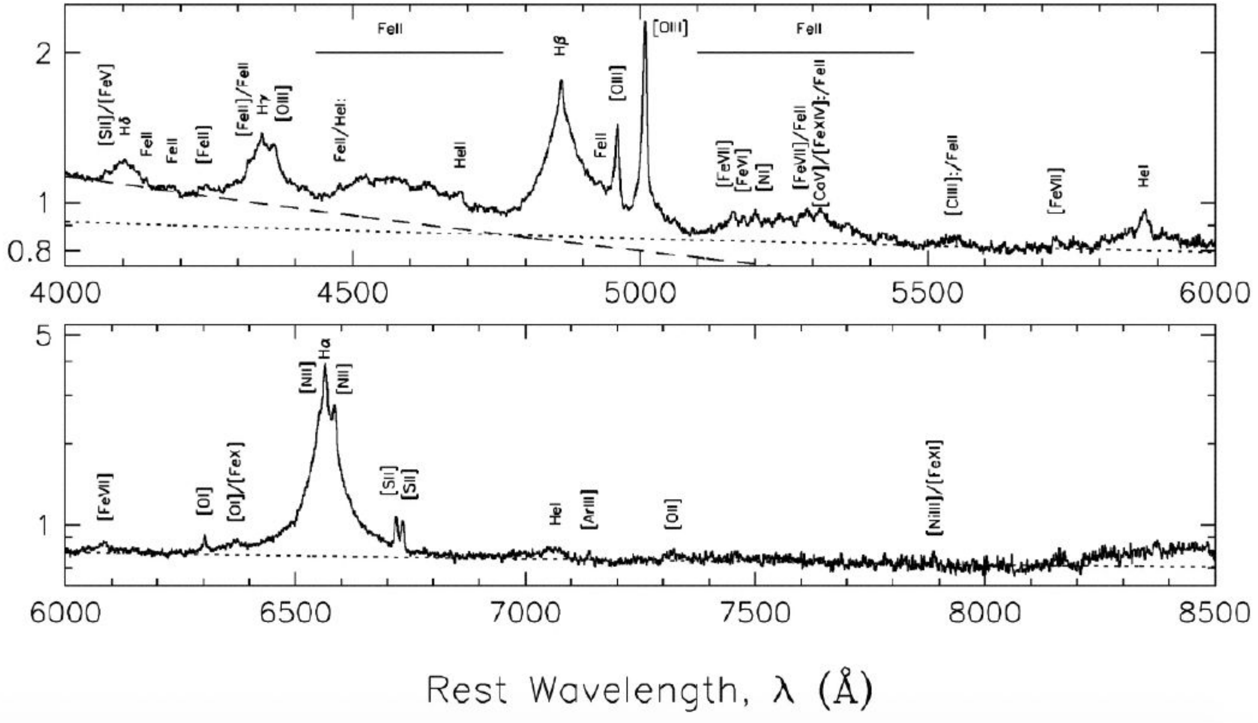
黑洞质量测量

- 正常星系：　星系动力学方法
  - 高空间分辨率（HST）：测量恒星运动的统计性质
- 活动星系：反响映射
  - 宽线区云块的动力学统计性质

类星体特征光谱



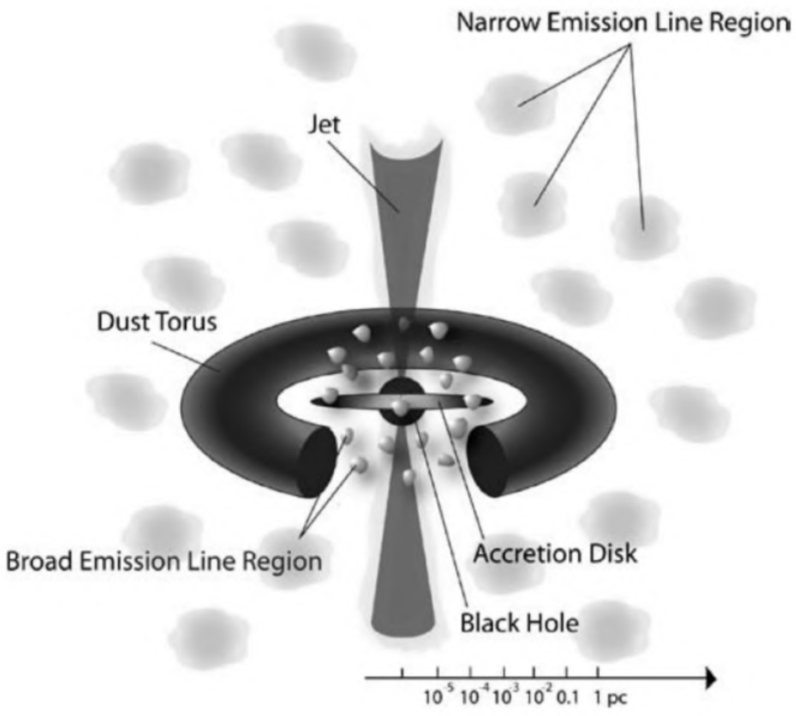
宽线区：黑洞周围气体动力学

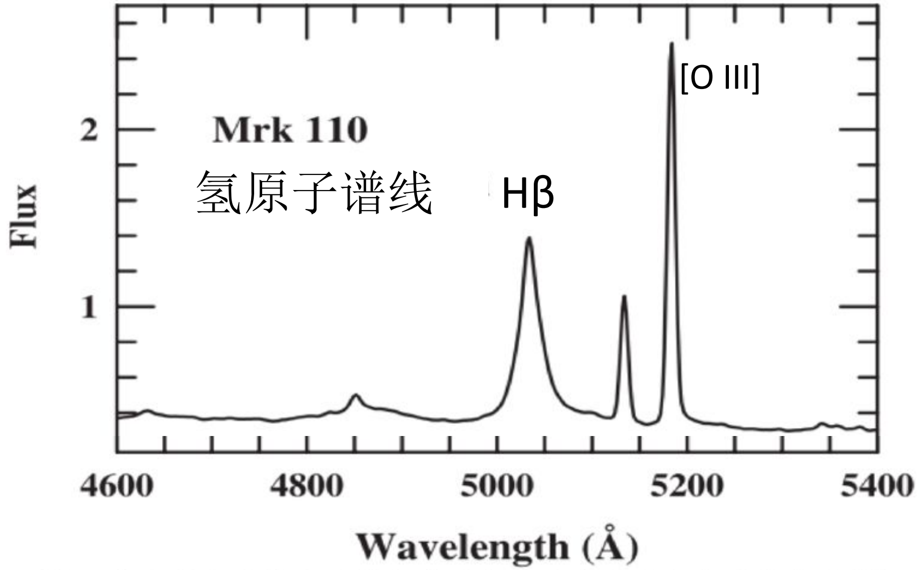


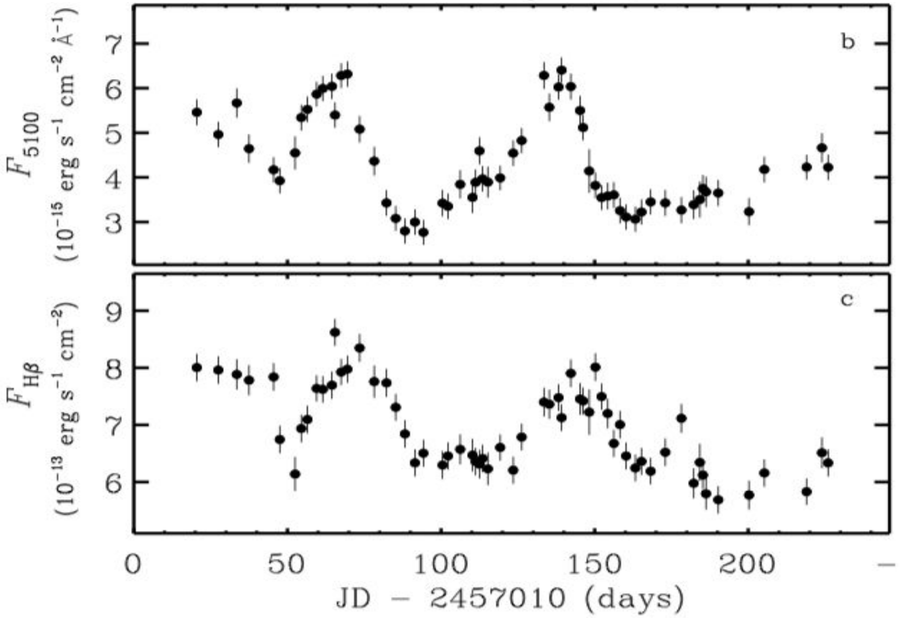
类星体/超大质量黑洞的研究阶段

- 红移: 宇宙学红移(1970-1980s)；
- 能源机制：黑洞吸积(1980s)；
- 黑洞质量测量：反响映射(1990-2000s)；
- 类星体结构的空间分辨：GRAVITY/VLT(2020s)
- 形成与演化问题：JWST时代(2021)？

反响映射: 宽线区尺度和黑洞质量







黑洞周围气体动力学

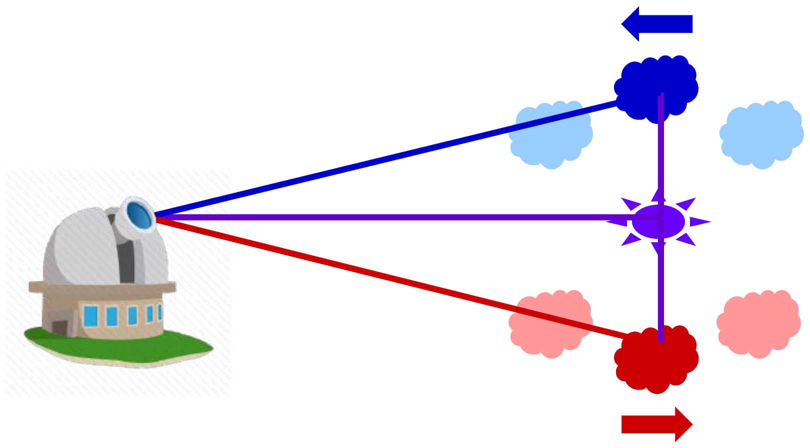
- $M_\bullet = f_{\rm BLR}\dfrac{R_{\rm H\beta}V^2}{G}$
- 复杂的MCMC测量过程

反响映射观测：测量光行差

$$c\tau_{\rm lag} = r - \boldsymbol{r} \cdot \boldsymbol{n}_{\rm obs}$$

BLR size

Parallel to LOS



测量光行差：平行方向

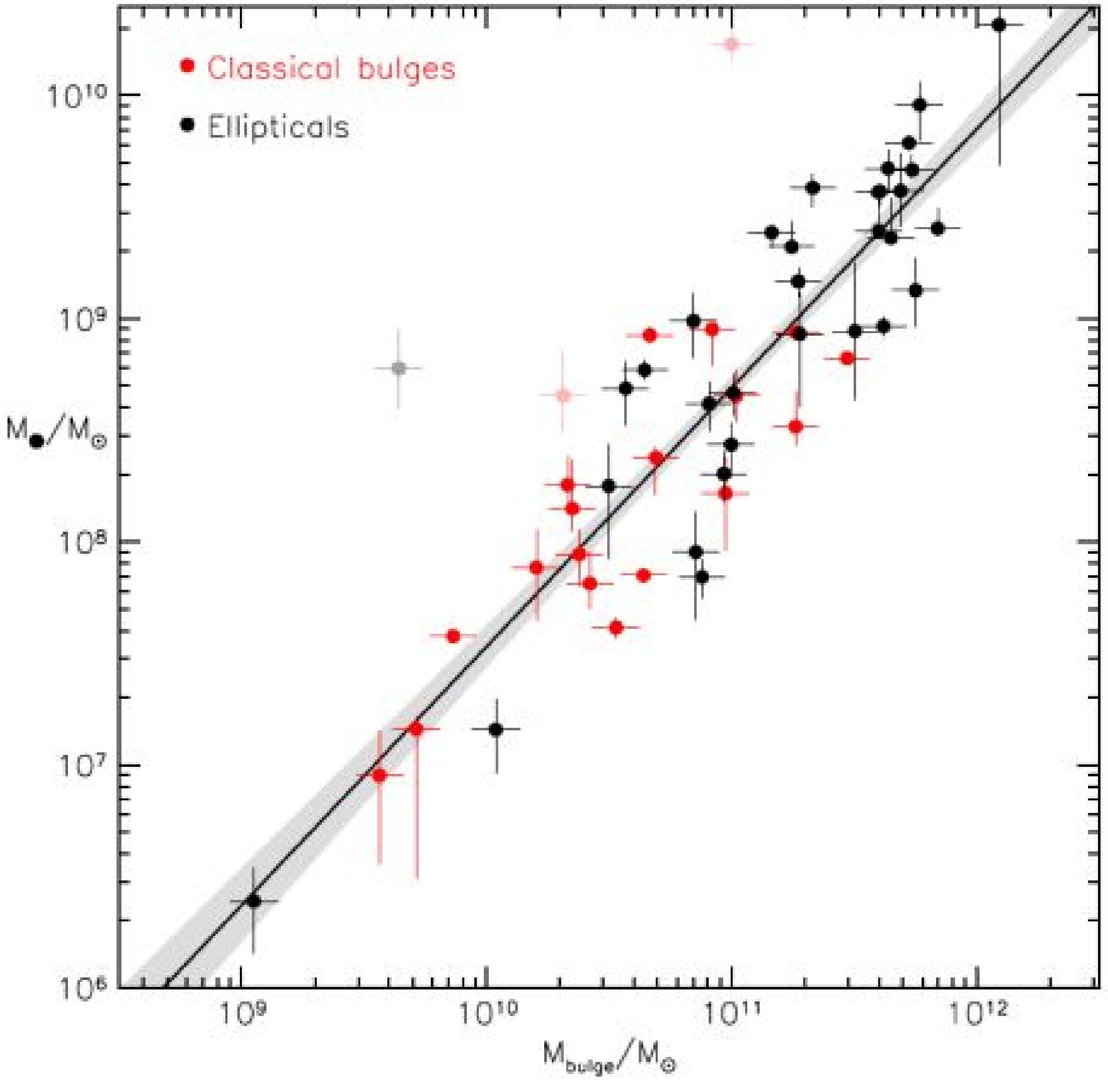
辐射区线尺度

LOS velocities versus lags

velocity delay maps

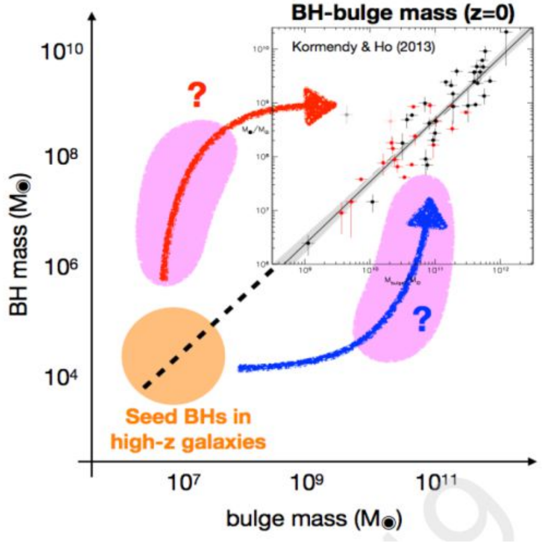
black hole mass

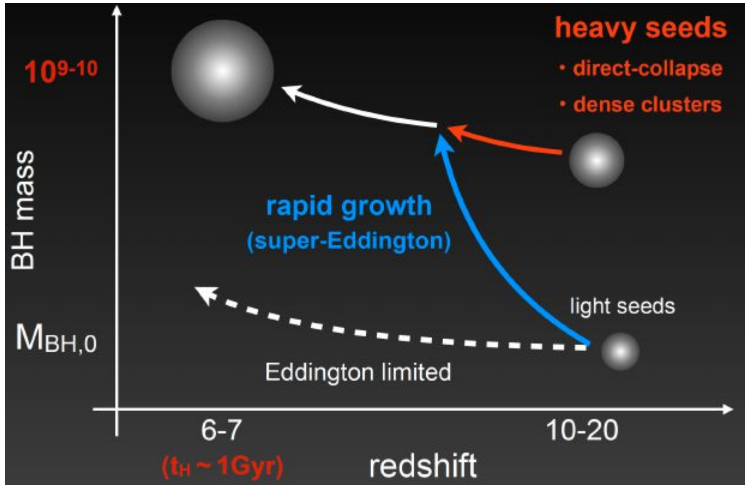
黑洞与星系：共同演化？



Richstone+(1998)
Kormendy & Ho (2013)

黑洞与星系：形成与共同演化？





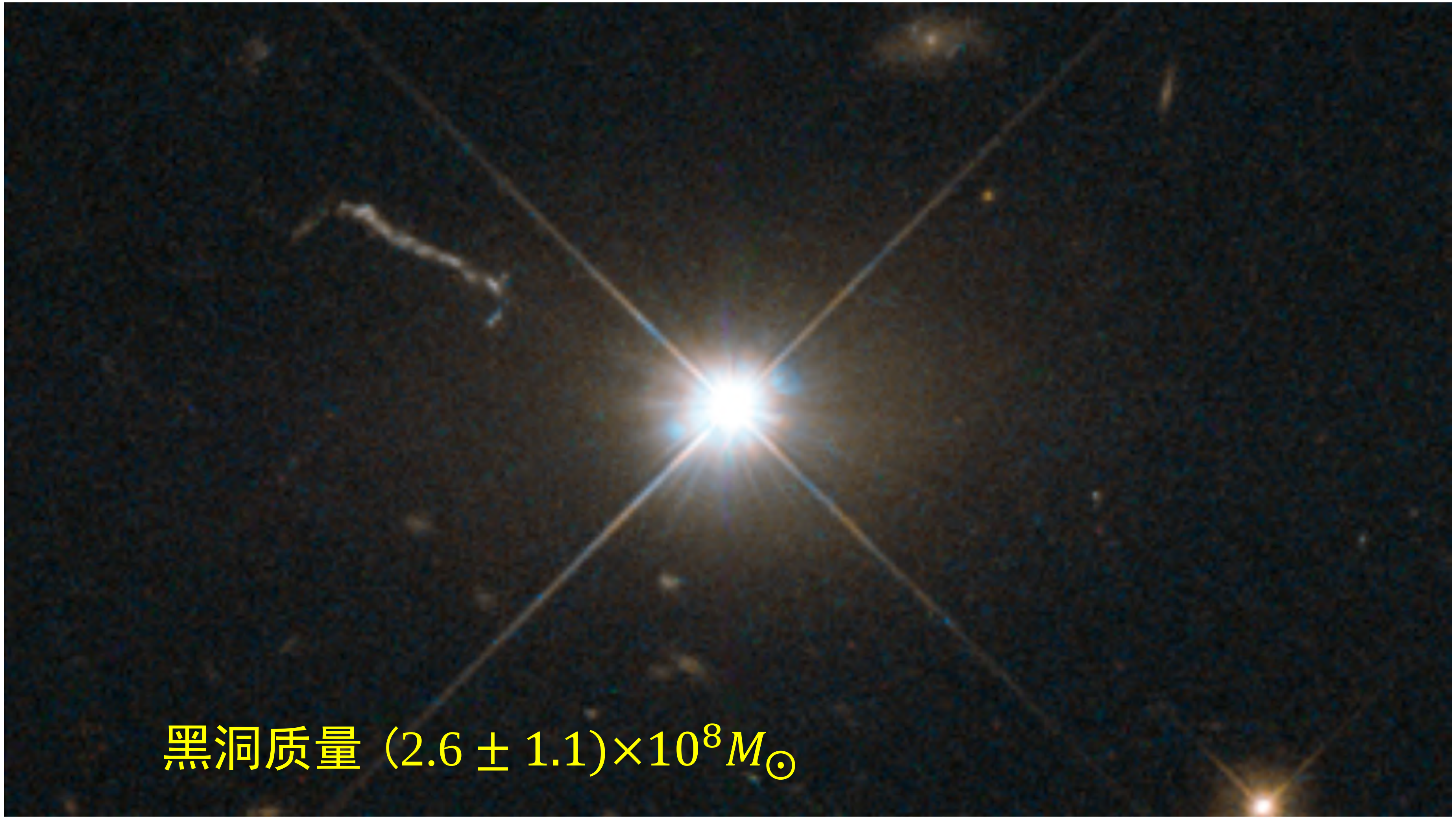
黑洞质量精度：100%～200%

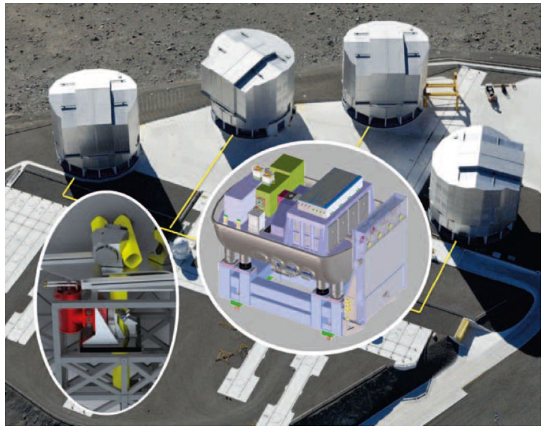
黑洞角动量：共同演化？

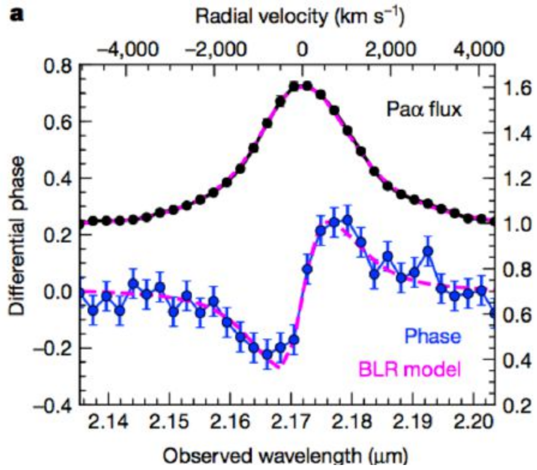
大质量黑洞形成：超爱快速增长阶段

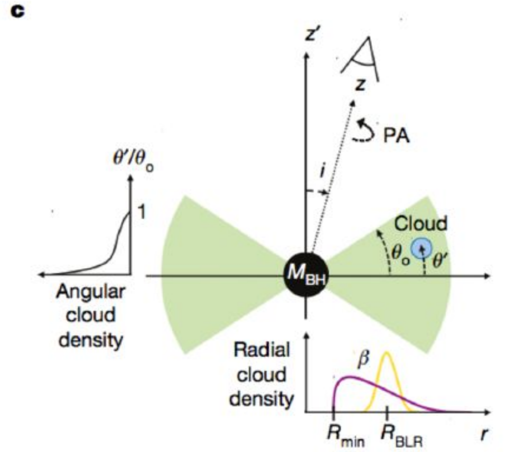
共同演化特征：10^7-10^8年延迟增长 (精度好于50%)

类星体：重大突破观测





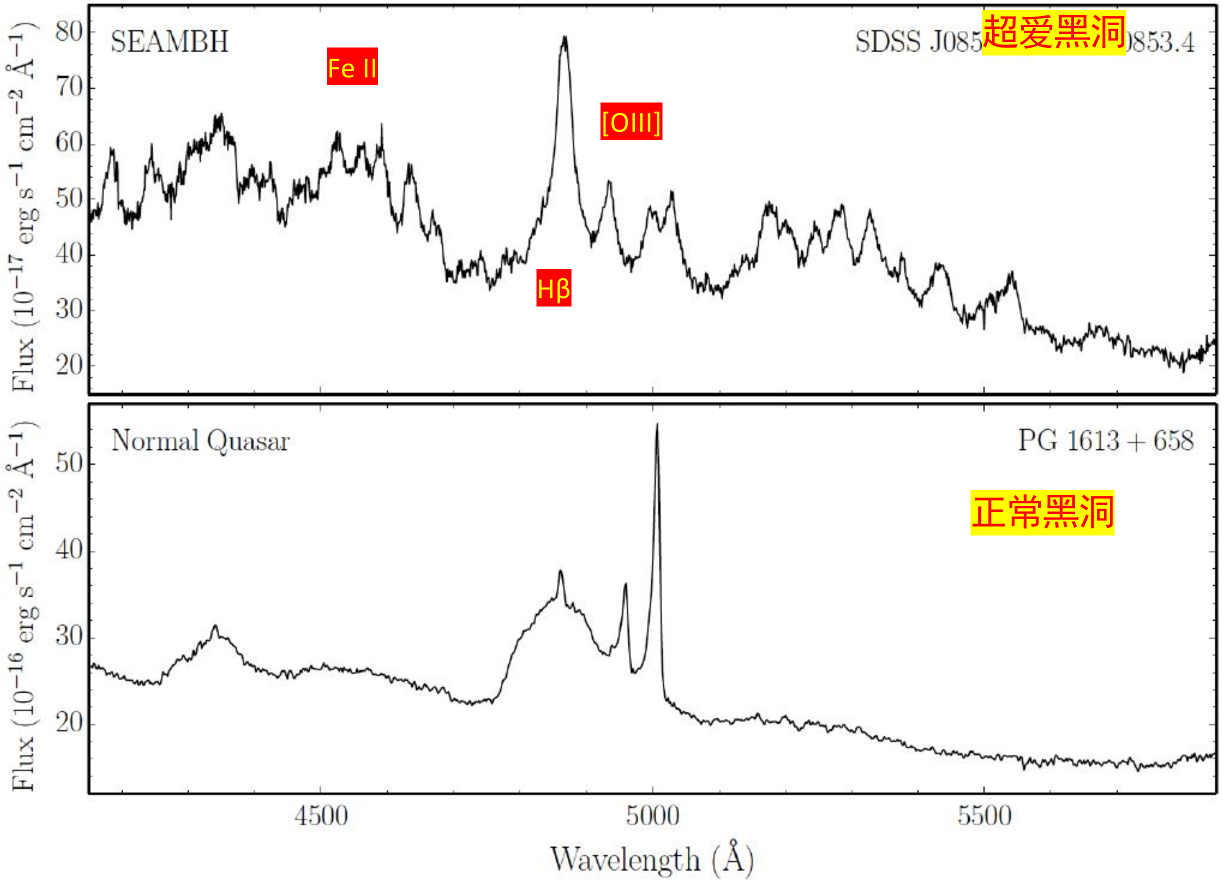




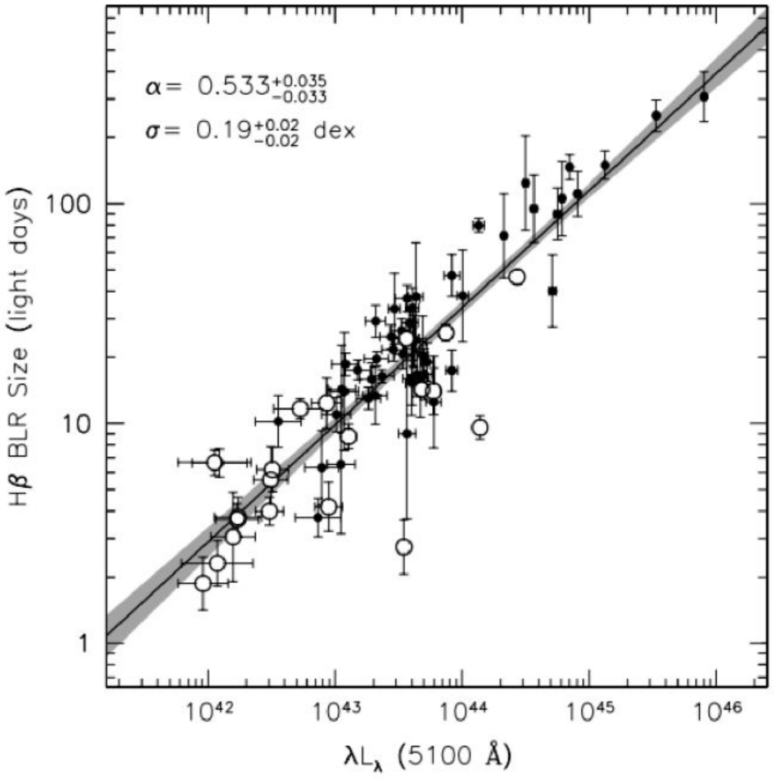
Gravity collaboration, 2018, Nature, 563, 567

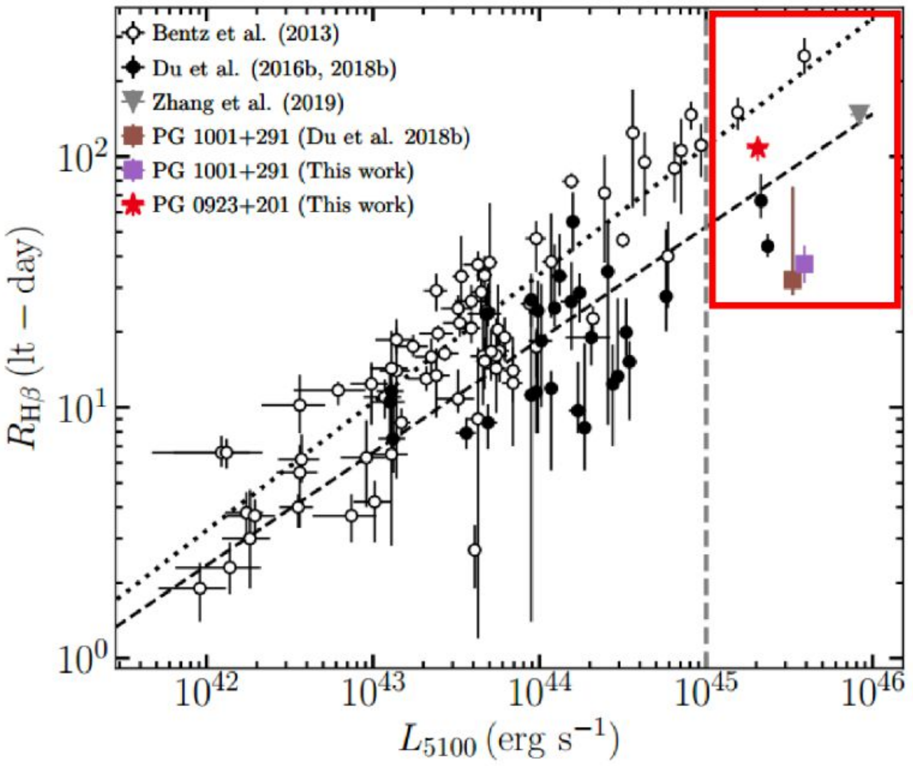
丽江反响映射观测：超爱黑洞（2012-）

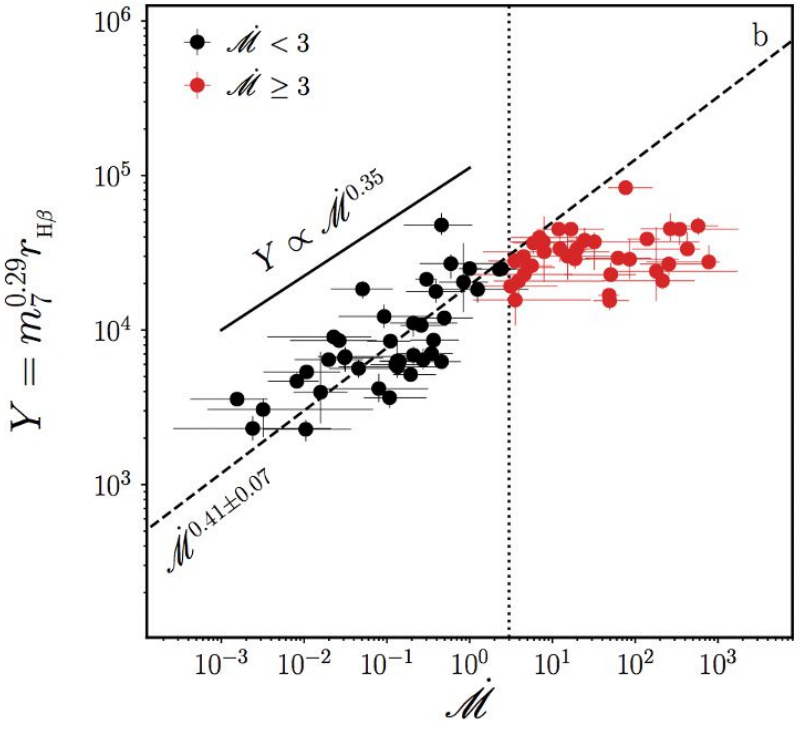
丽江2.4米望远镜



标准的*R*-*L*关系：礼崩乐坏







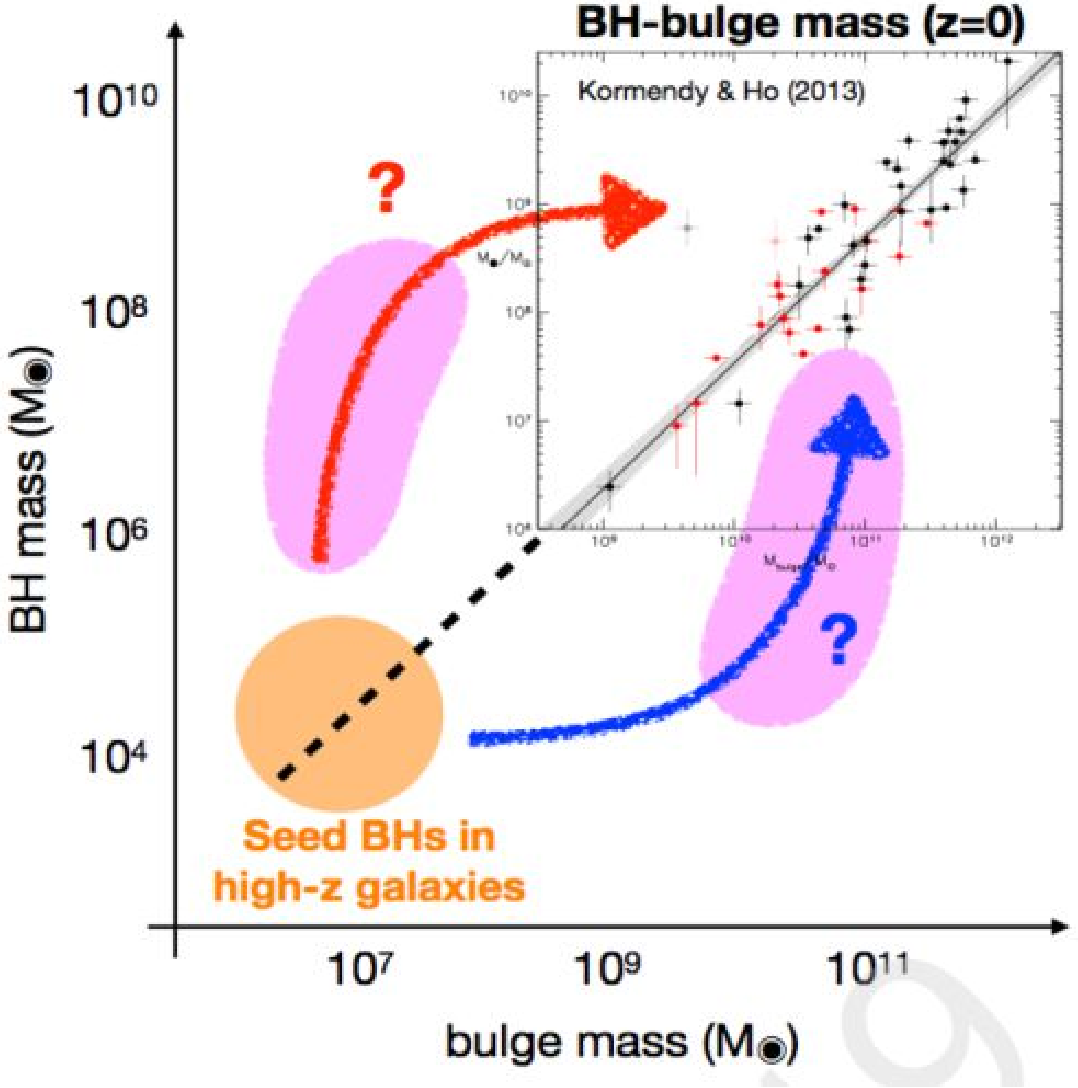
Kaspi+(2000); Bentz+(2013)
广泛用于大样本类星体：
黑洞质量

1）高吸积率；2）高光度；3）饱和光度

黑洞质量：光干涉+反响映射

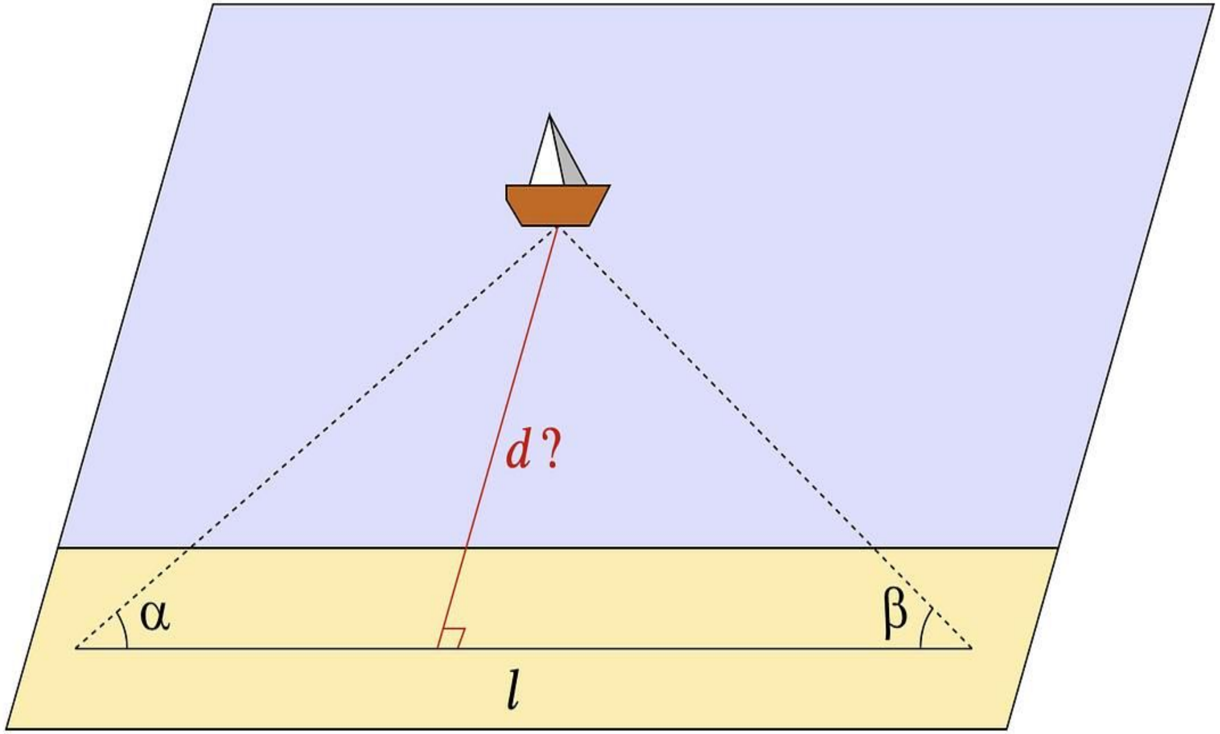
黑洞质量精度：50%

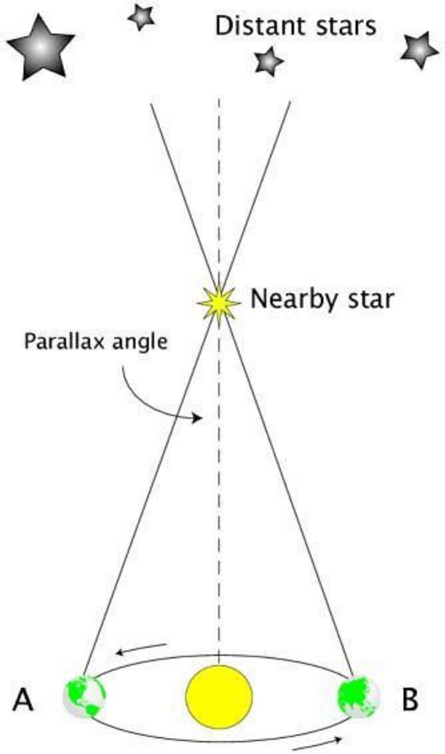
共同演化特征：10^7-10^8年延迟增长



精确宇宙学：几何测距

几何方法





地球绕太阳转动

遥远的天体：如何测距?

造父变星

The Leavitt's Law

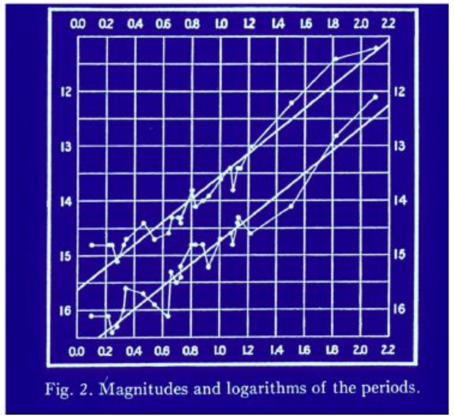
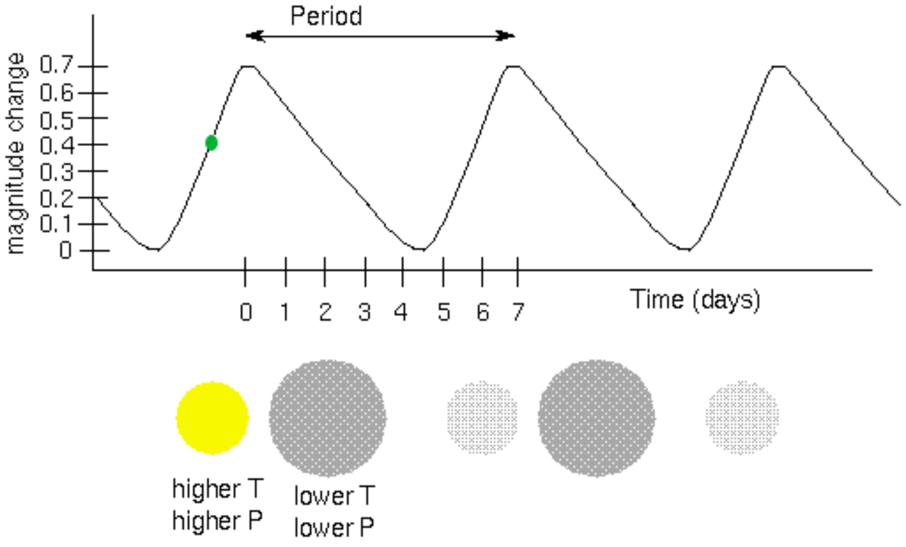
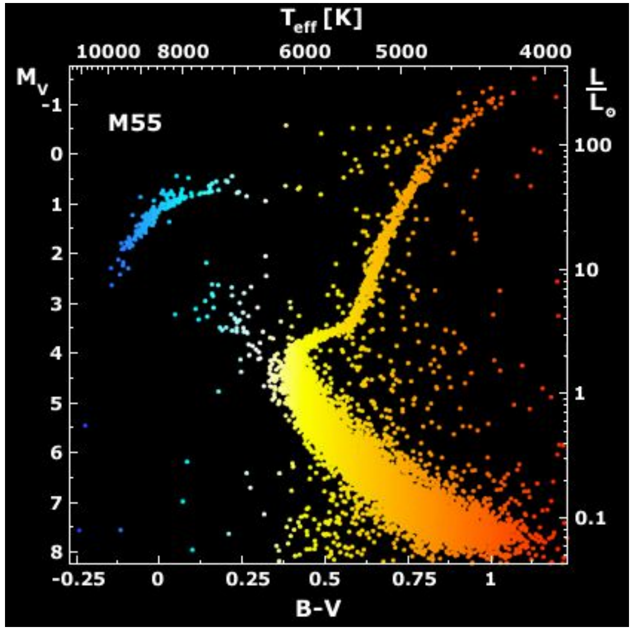


Fig. 2. Magnitudes and logarithms of the periods.

Leavitt (1908)
Leavitt & Pickering (1912)



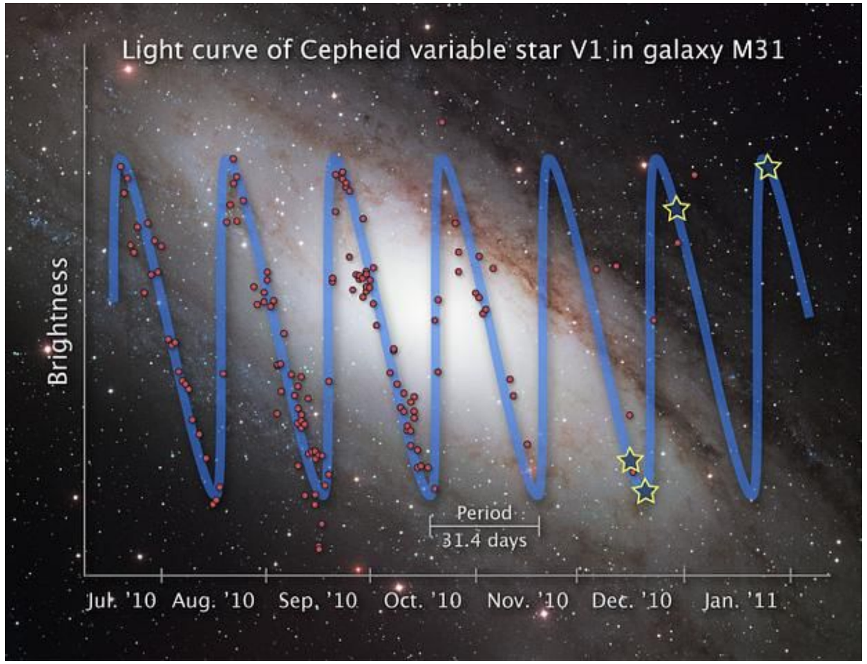
Cepheid variables: outward pressure (P) and inward gravity compression are out of sync, so star changes size and temperature: it **pulsates**. *RR-Lyrae* variables are smaller and have pulsation periods of less than 24 hours. Also, their light curve looks different from the Cepheid light curve.

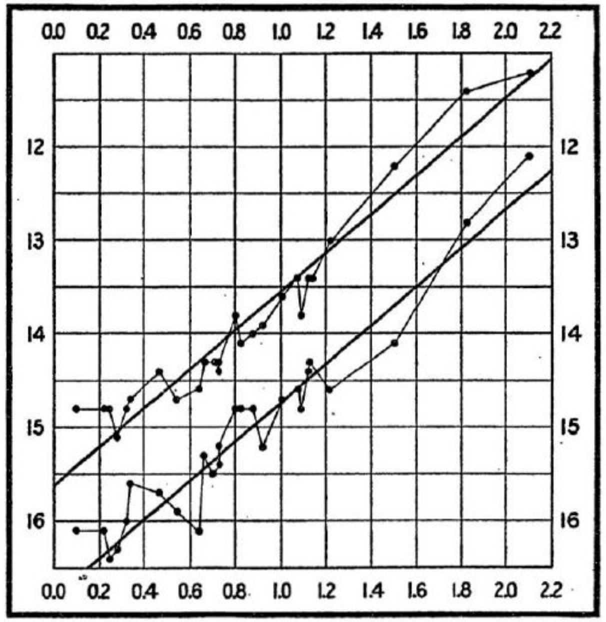


星族I：$L \sim 10^3\text{-}10^4 L_\odot$，$M > 3\text{-}4 M_\odot$，最大达$20 M_\odot$

星族II：$L \sim 10^3\text{-}10^4 L_\odot$，$M \sim M_\odot$，年老低质量

机制：氦元素电离导致不透明度变化不稳定性

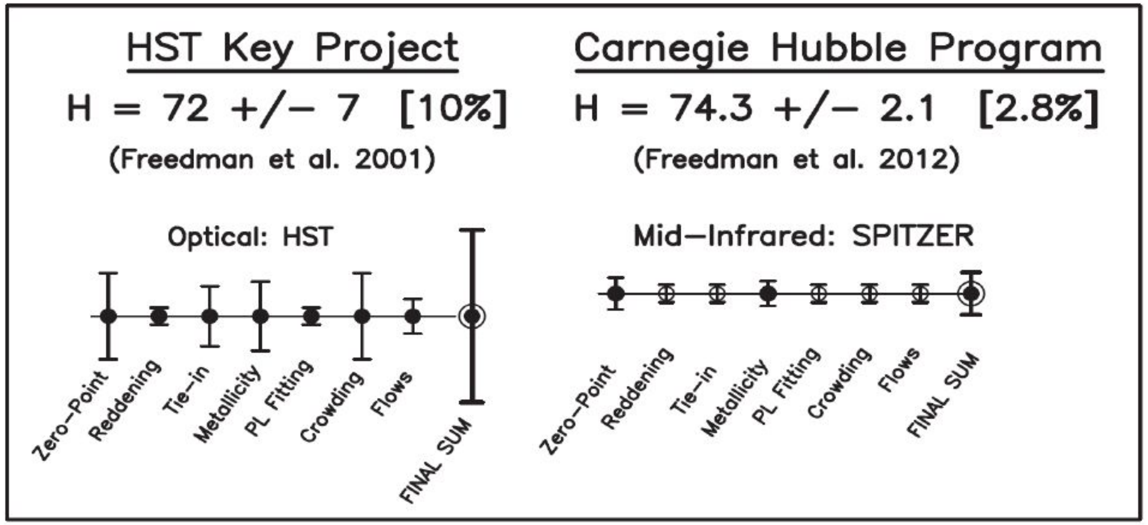




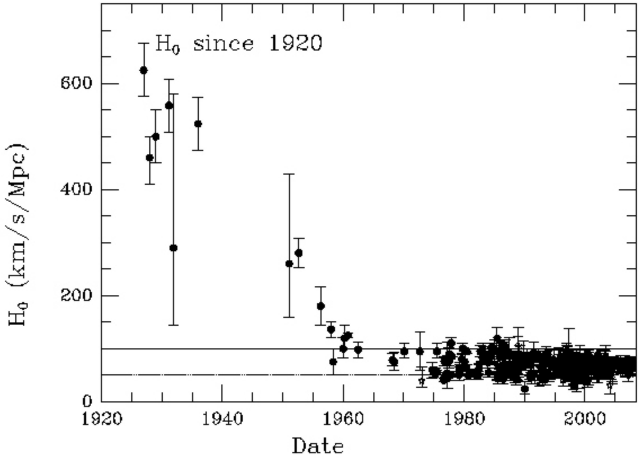
周期→光度→距离：消光改正

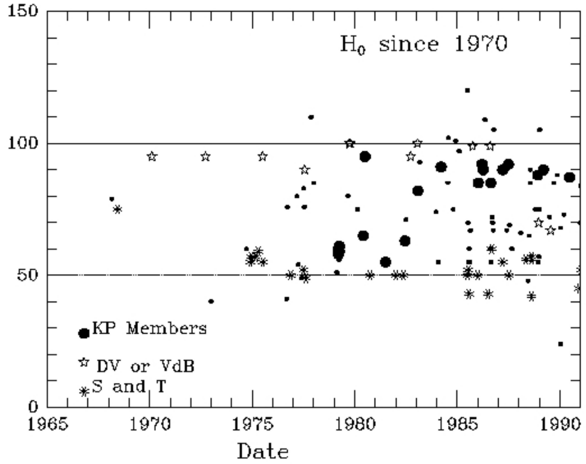
（内禀缺陷+统计弥散）

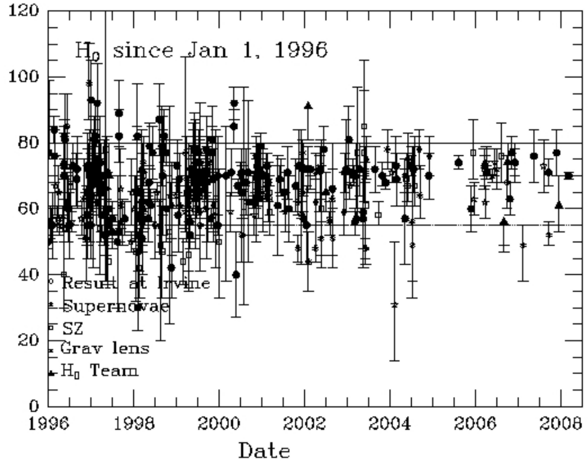
哈勃望远镜：造父变星测距



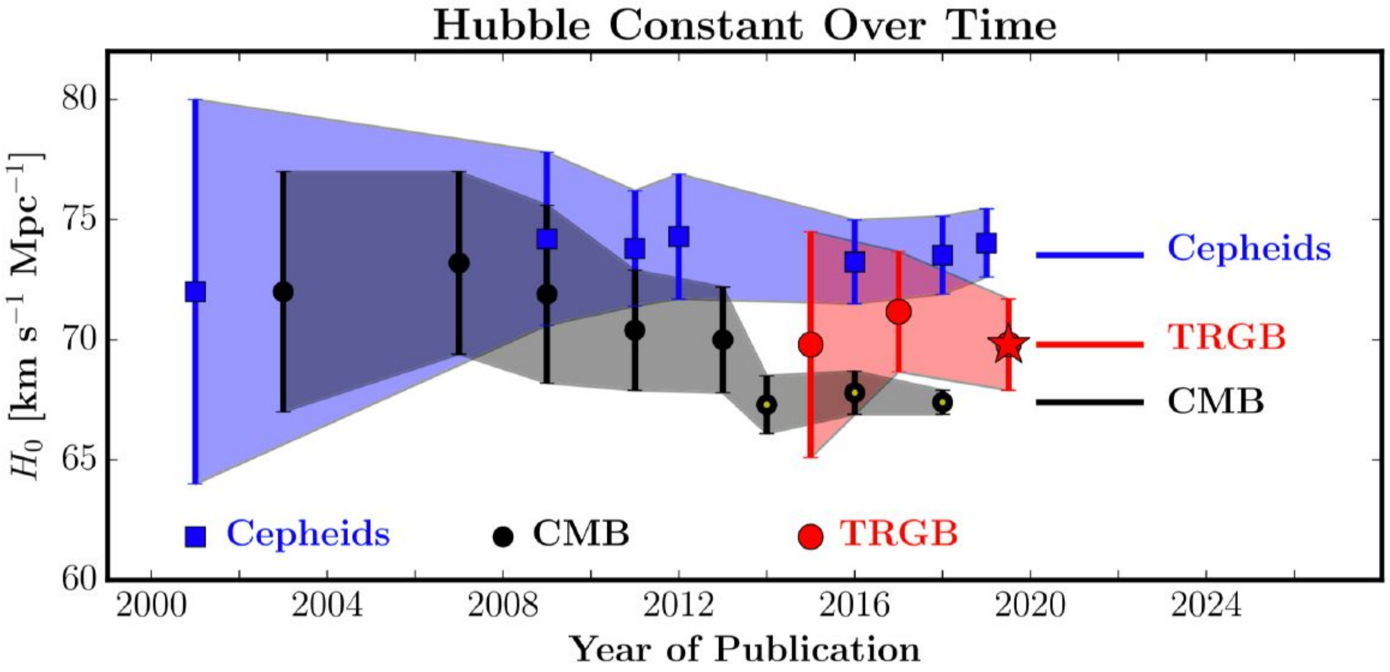
哈勃常数：最新测量





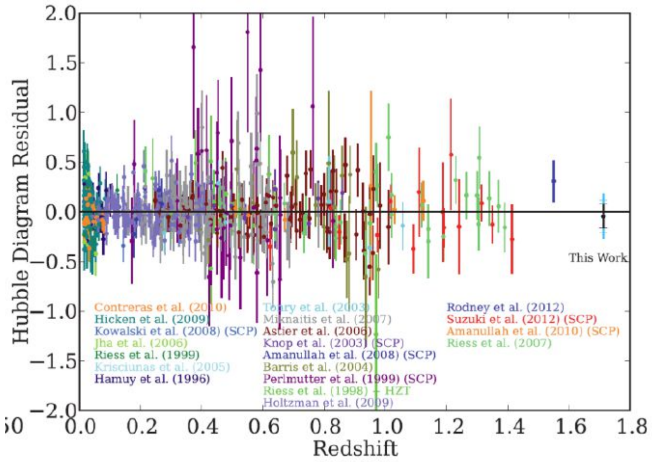


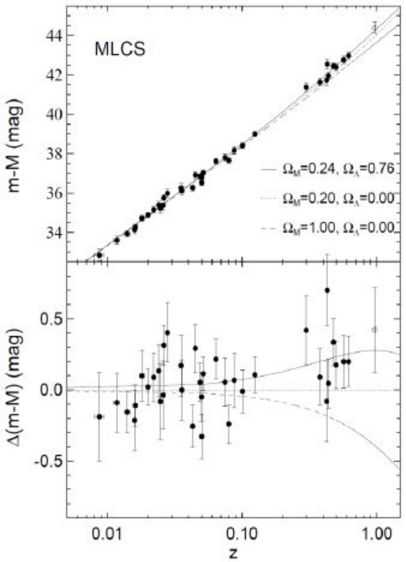
W. Freedman

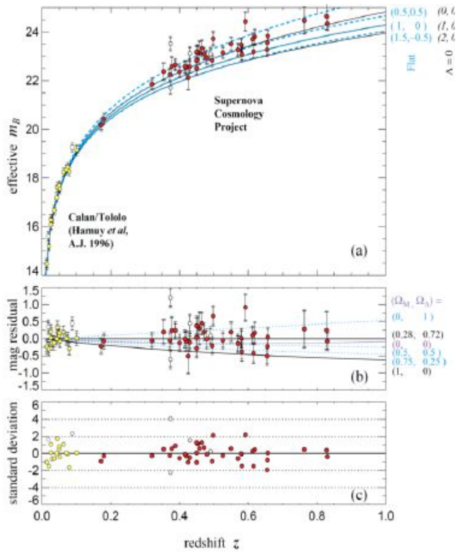


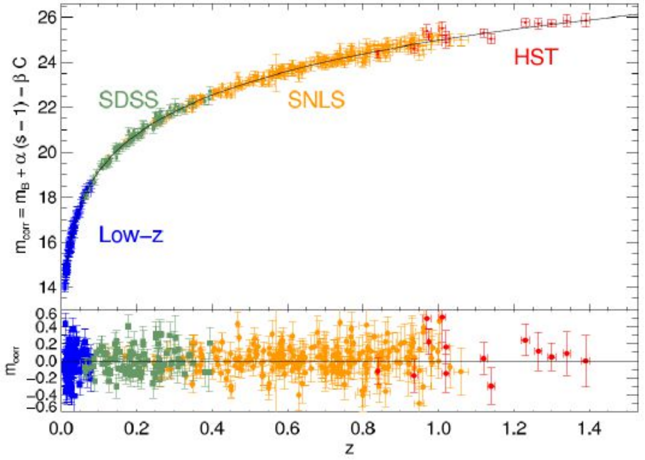
Ia型超新星：宇宙加速膨胀





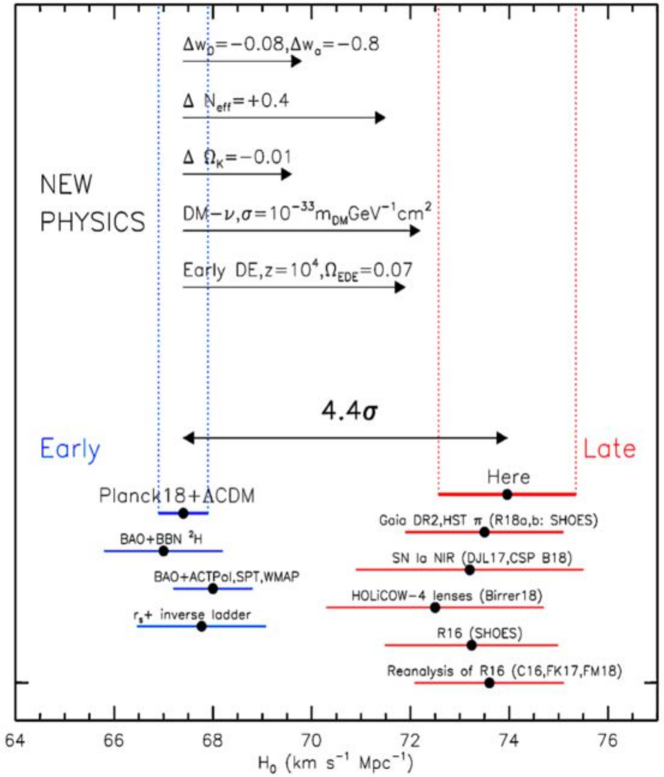


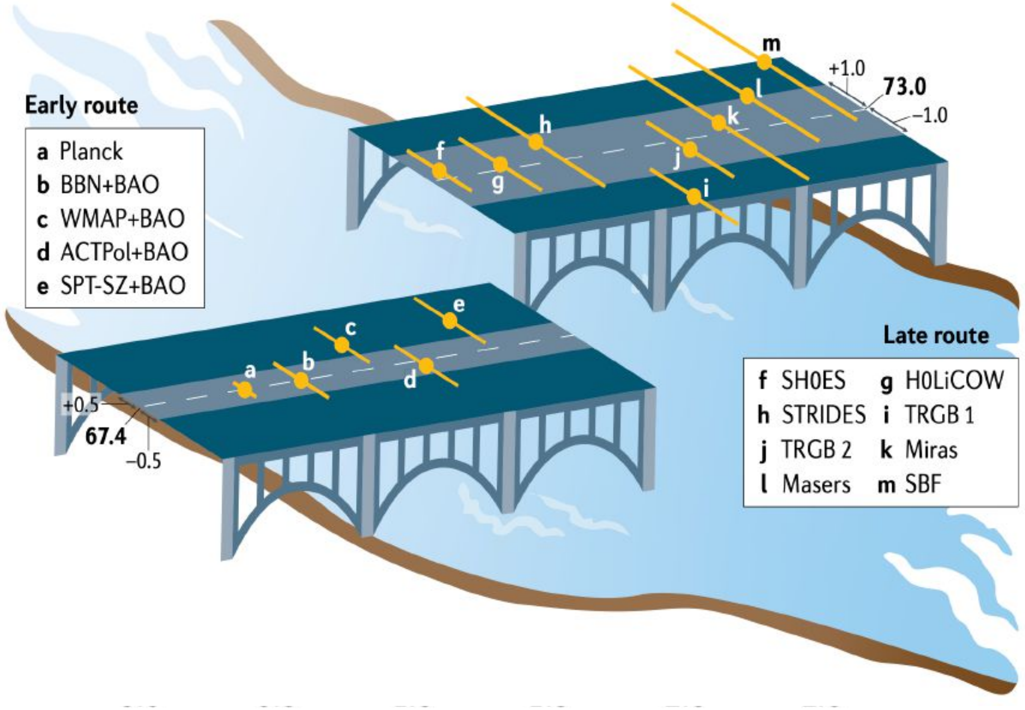




系统误差：消光、红化、标准化、距离阶梯

哈勃常数危机（Riess+2019/2020）



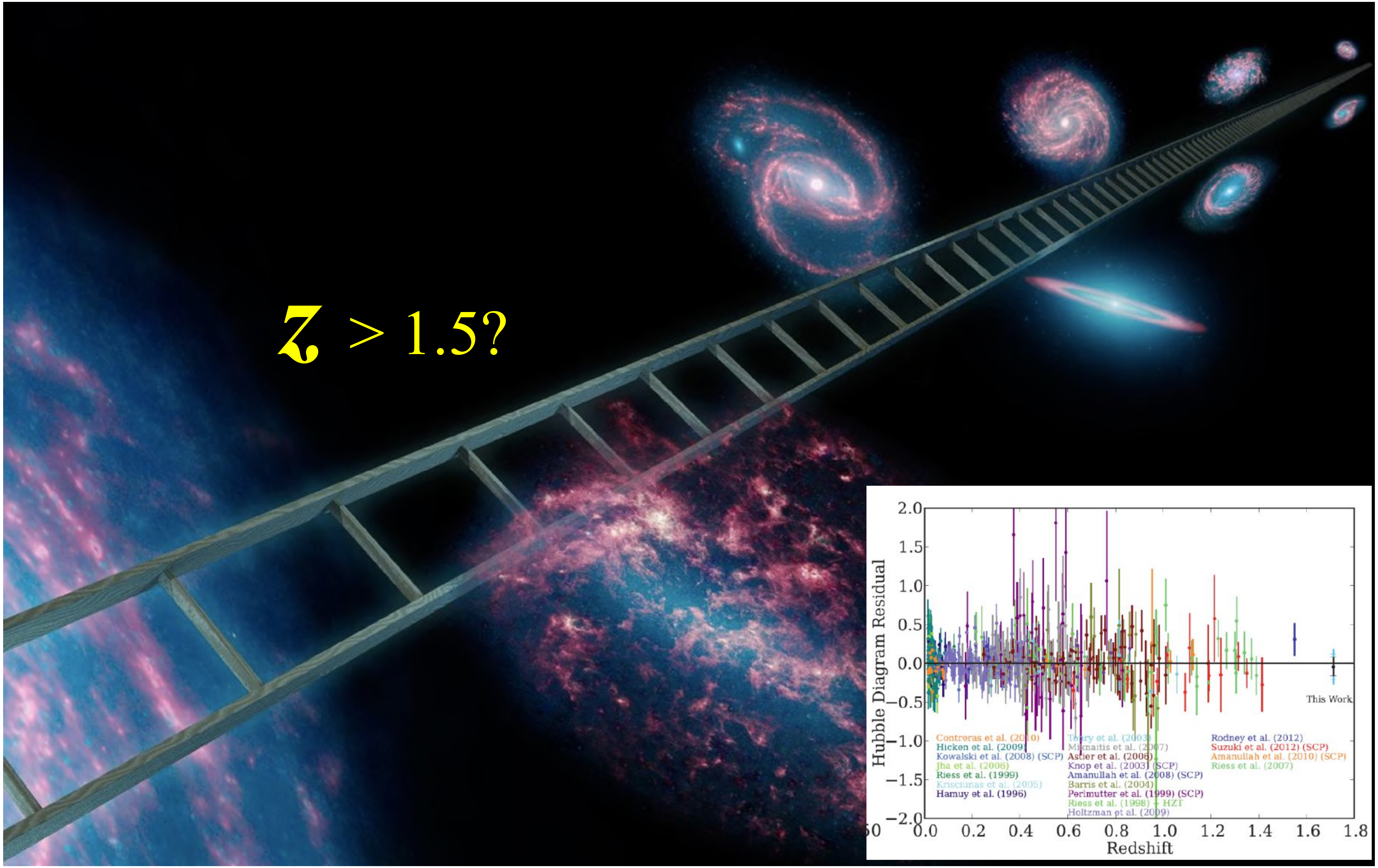


宇宙微波背景

造父变星等传统工具

- 标准宇宙学模型？
- 测量系统误差？
- 高红移测量？

宇宙学呼唤新工具！

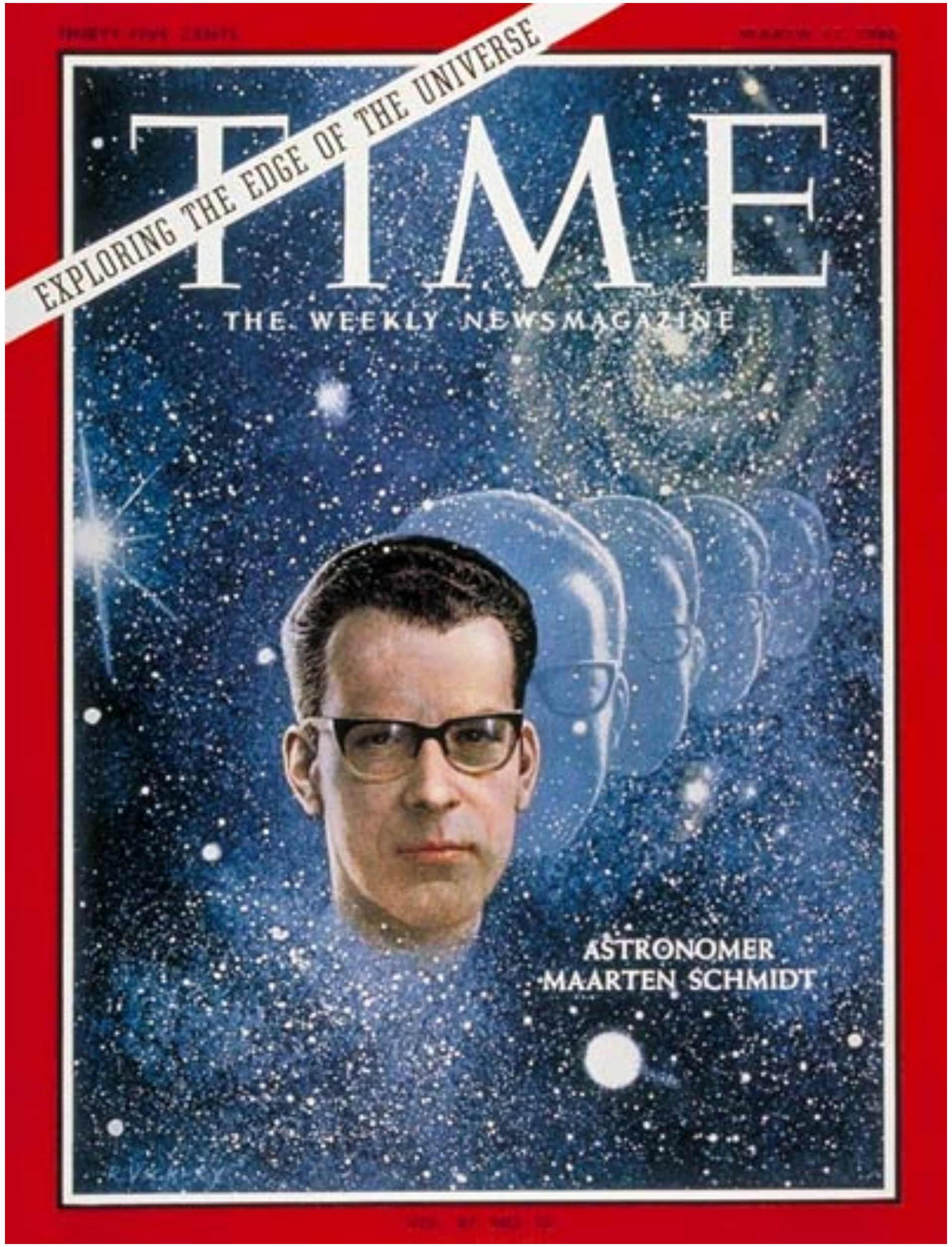


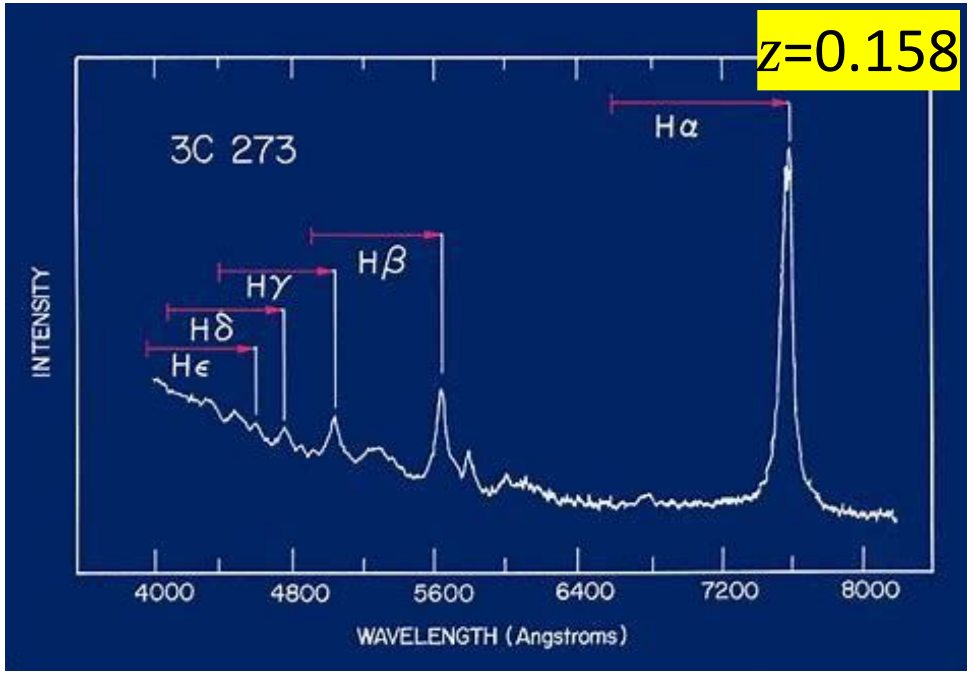
z > 1.5?
Hubble Diagram Residual
Redshift
This Work
Contreras et al. (2010)
Hicken et al. (2009)
Kowalski et al. (2008) (SCP)
Jha et al. (2006)
Riess et al. (1999)
Krisciunas et al. (2005)
Hamuy et al. (1996)
Tonry et al. (2003)
Miknaitis et al. (2007)
Astier et al. (2006)
Knop et al. (2003) (SCP)
Amanullah et al. (2008) (SCP)
Barris et al. (2004)
Perlmutter et al. (1999) (SCP)
Riess et al. (1998) + HZT
Holtzman et al. (2009)
Rodney et al. (2012)
Suzuki et al. (2012) (SCP)
Amanullah et al. (2010) (SCP)
Riess et al. (2007)

类星体作为宇宙学探针

经历了十分艰难的历程

(1960s)



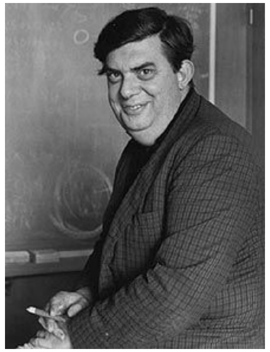


- 宇宙学红移
- 黑洞吸积：能源机制
- 反响映射：质量
- 共同演化
- 宽线区结构：VLT-GRAVITY

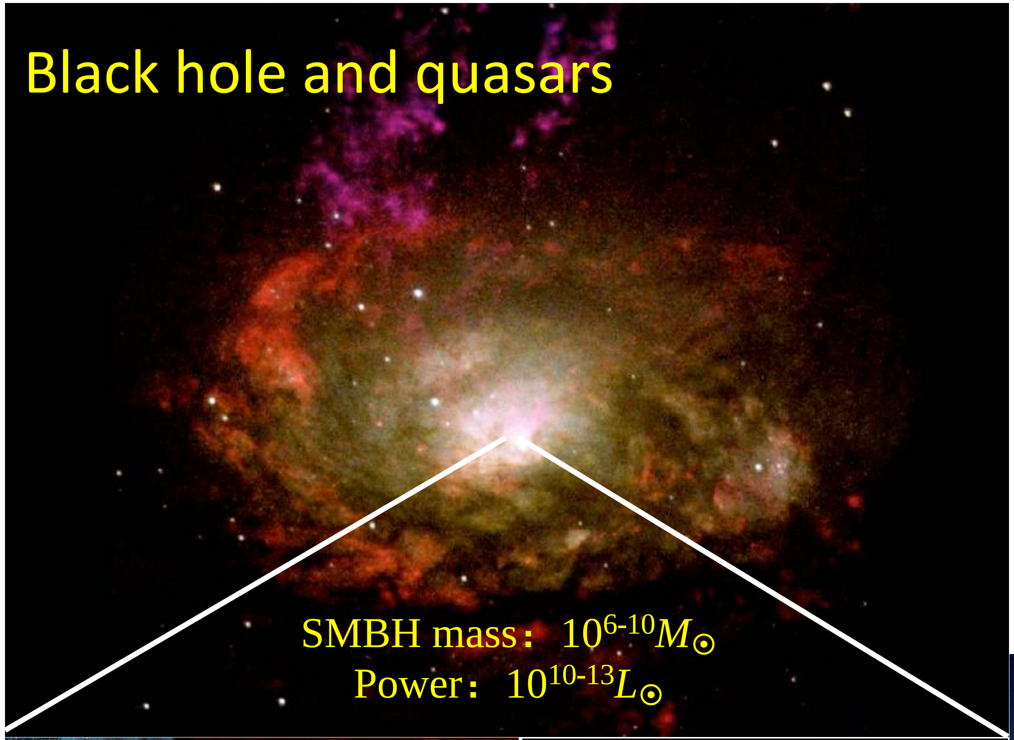
- Sandage (1965)
- Hoyle & Burbidge (1966)
- Longair (1967)
- Schmidt (1968)
- Bahcall & Hills (1973)
- Baldwin (1977)
- Weinberg (1972)
- Watson+(2012)
- Wang+(2013)
- Yoshii+(2014)
- La Francis+(2014)
- Honig+(2015)
- Risaliti & Lusso(2019)

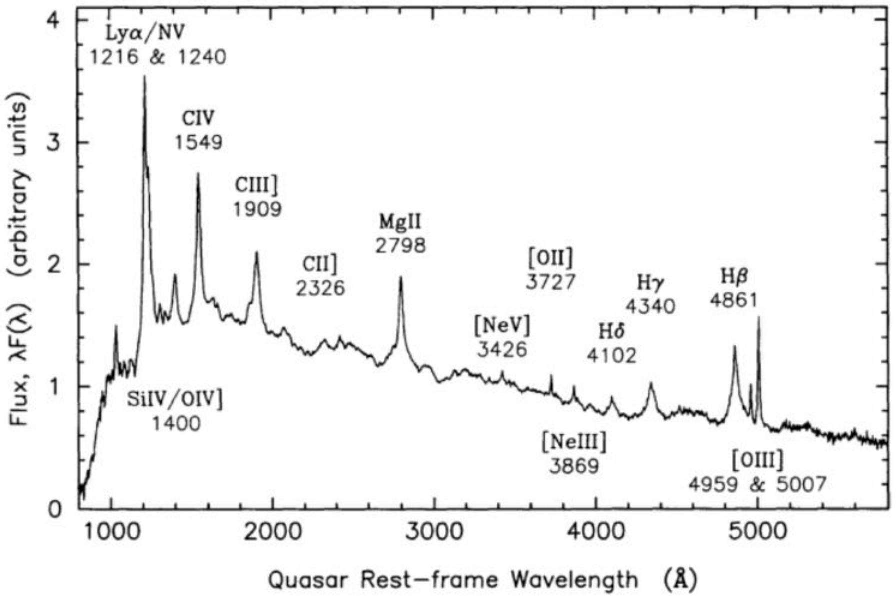
智慧迸发、群星闪烁

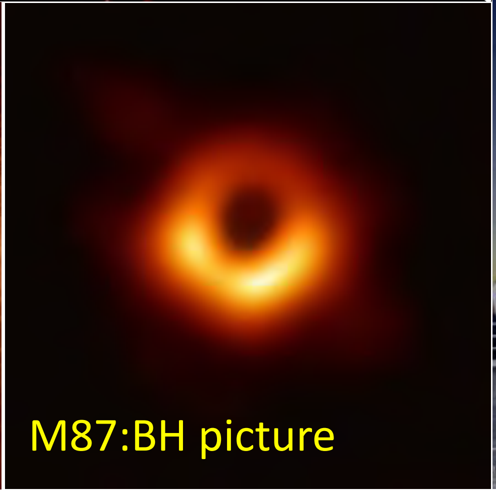






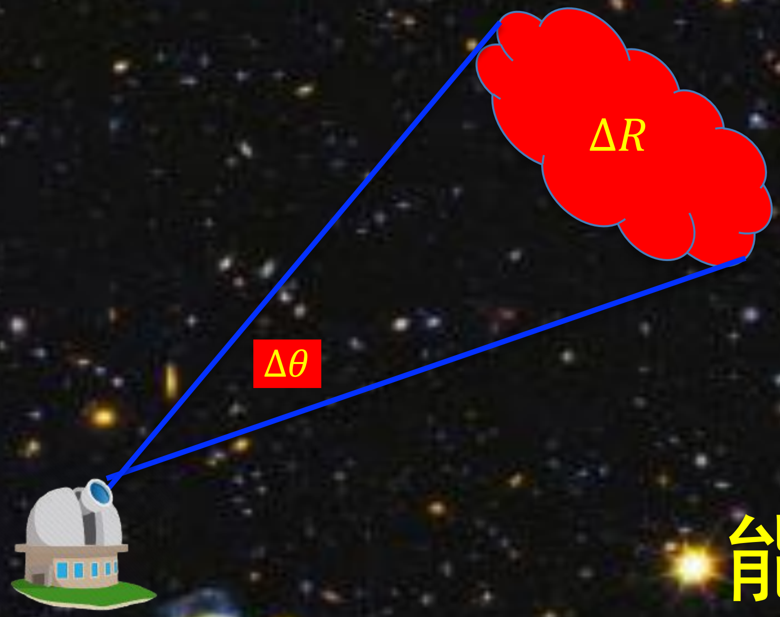




RM campaigns: ~150AGNs

几何测量的巨大困难：

- 要么角径好测，几何线尺度难；
- 要么线尺度好测，角径难。



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

能够达到的角分辨率：测量线尺度？

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

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

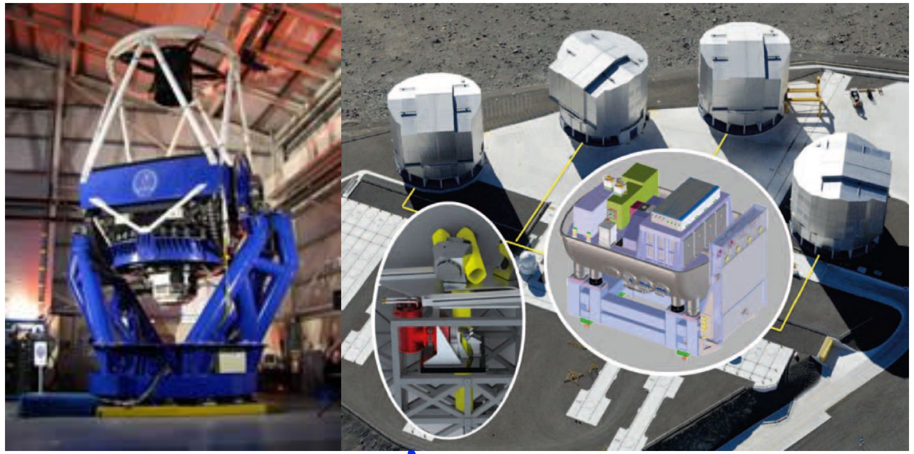
Jian-Min Wang[1,2,3*], Yu-Yang Songsheng[1,4], Yan-Rong Li[1], Pu Du[1] and Zhi-Xiang Zhang[5]

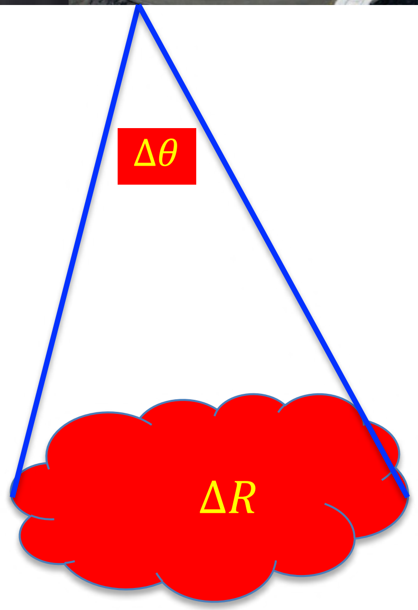
类星体视差：2m+VLT并肩作战

- 反响映射：辐射区域线尺度 (ΔR)
- GRAVITY：辐射区域的角直径 ($\Delta\theta$)

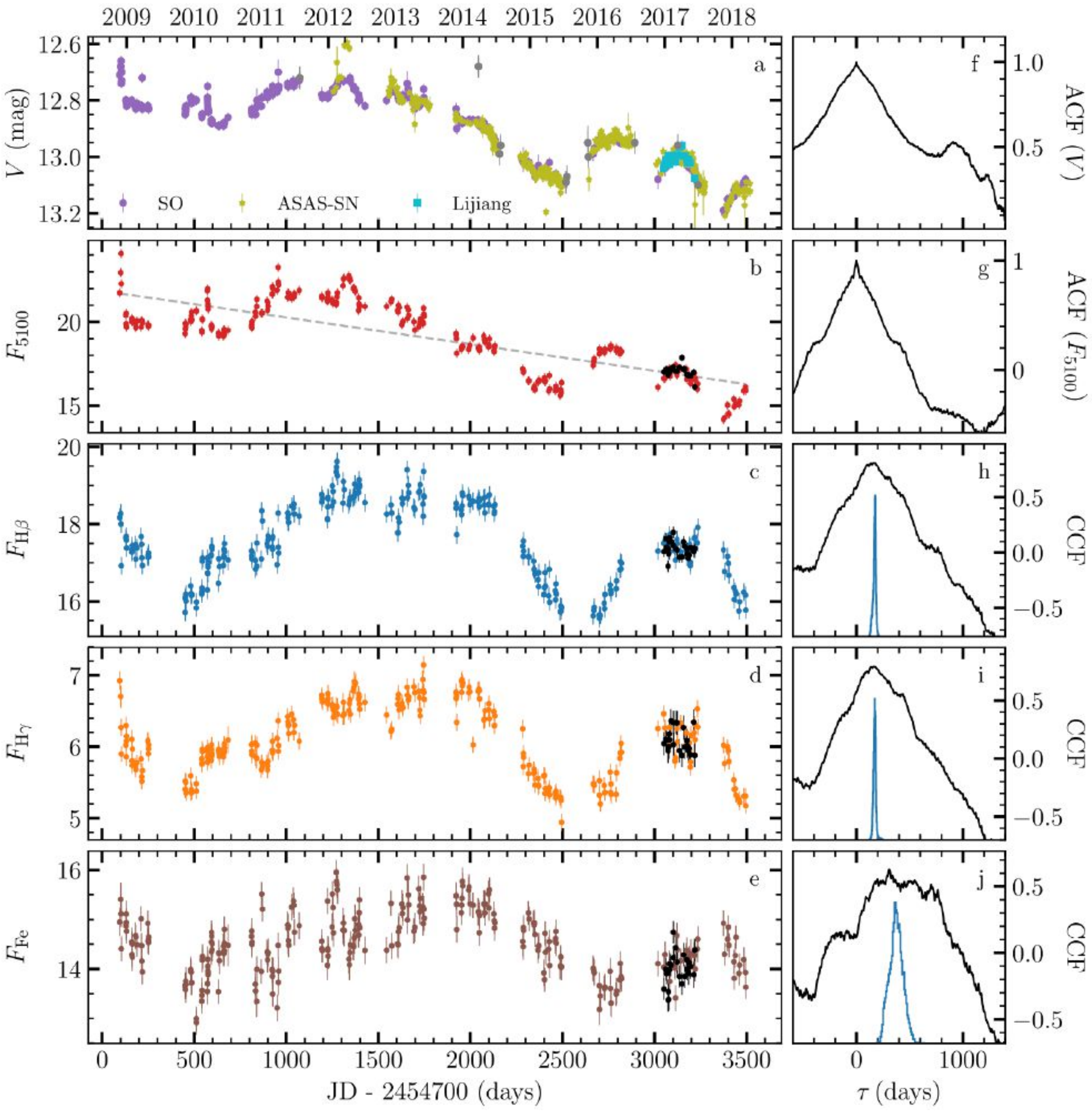
可以同时测量距离和黑洞质量

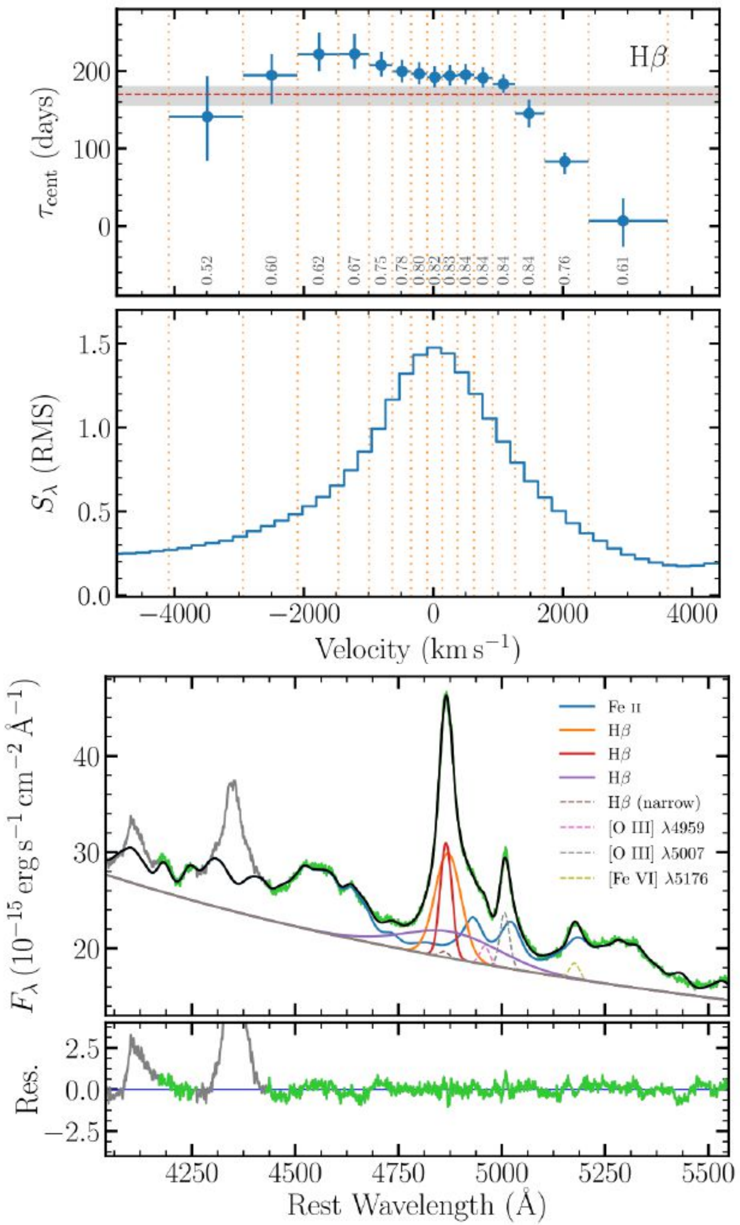
$$d = \frac{\Delta R}{\Delta\theta}; \qquad M_{\rm BH}$$



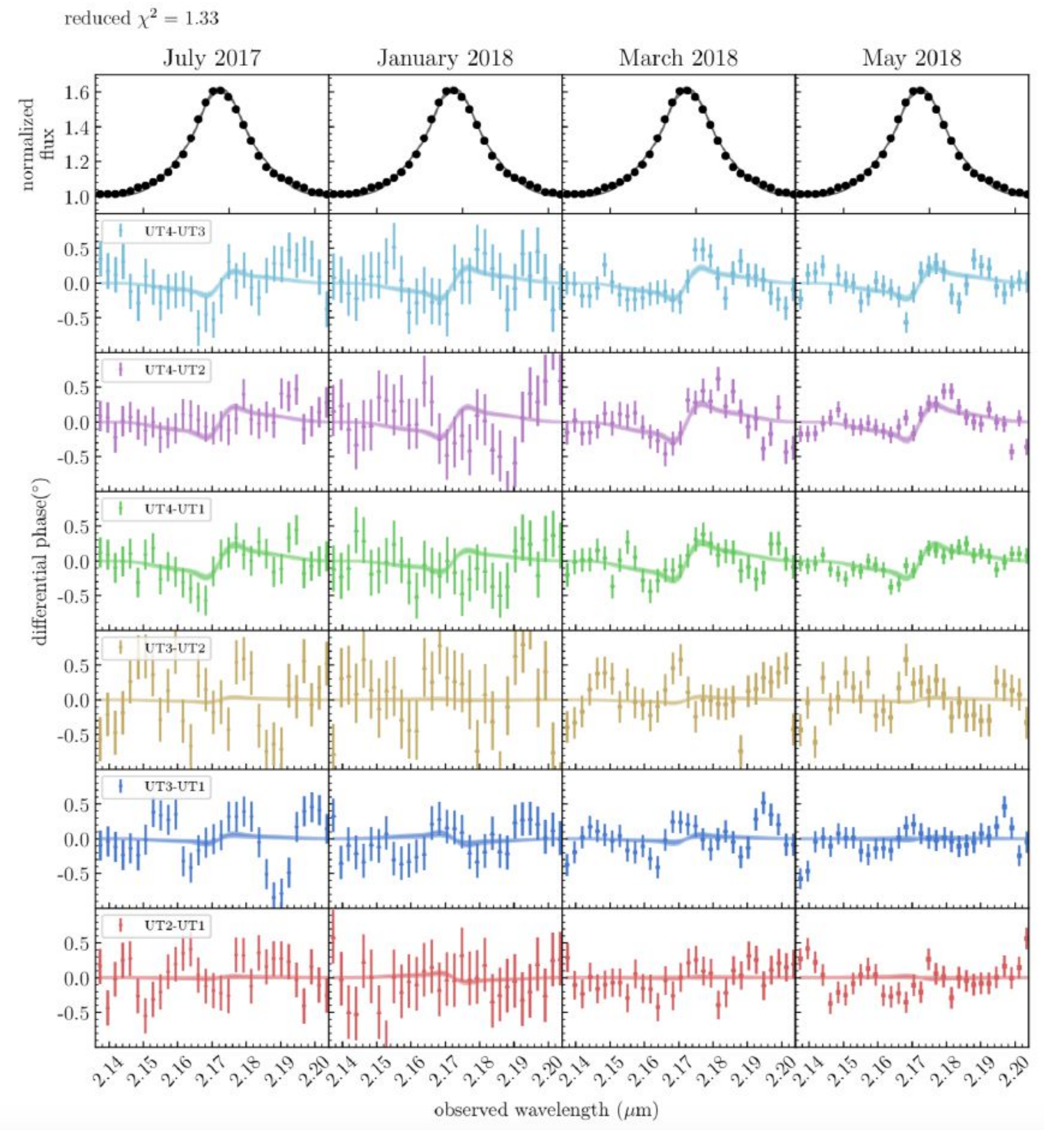


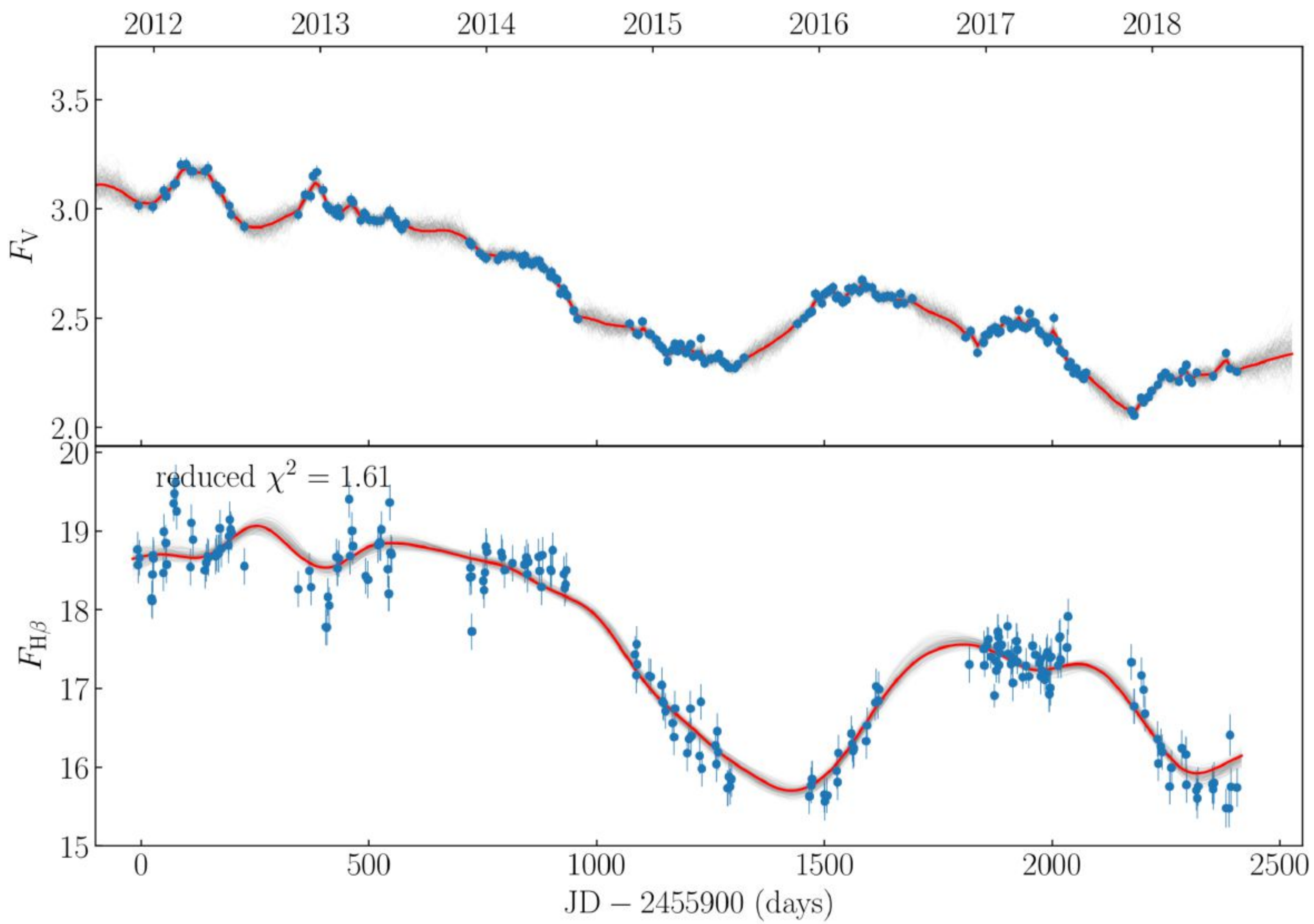
3C273: 反响映射(Zhang et al. 2019)



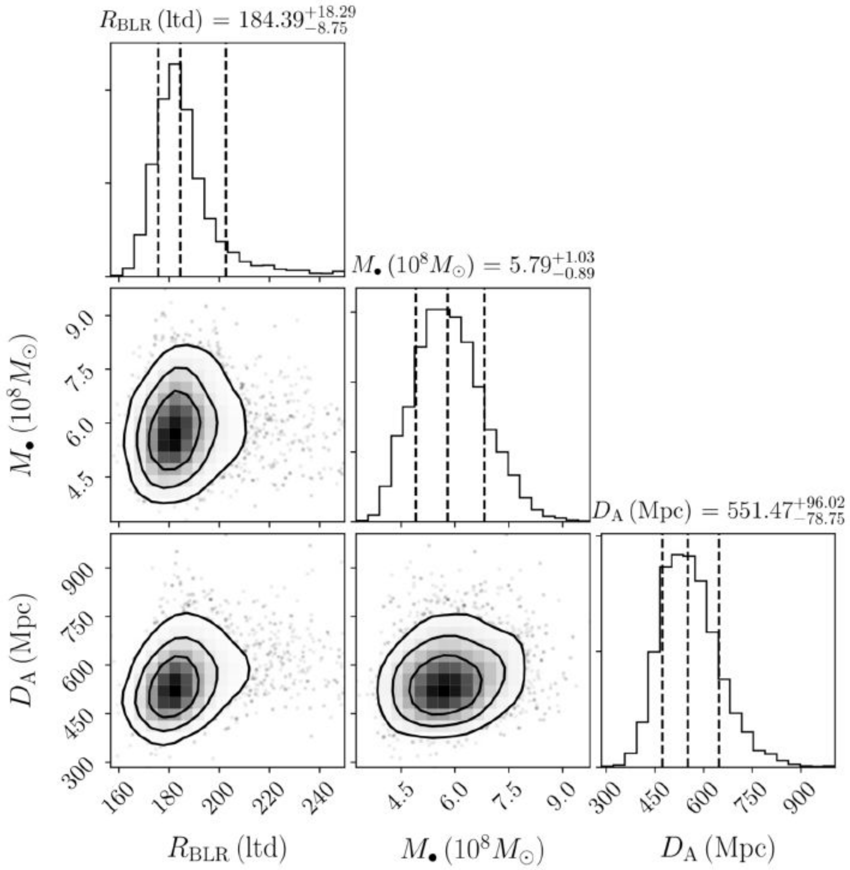


SARM分析：质量与距离





类星体几何距离：首次SARM分析



$M_\bullet (10^8 M_\odot)$ $5.78^{+1.11}_{-0.88}$

$D_{\rm A}$(Mpc) $551.50^{+97.31}_{-78.71}$

$$H_0 = 71.5^{+11.9}_{-10.6}\ {\rm km\,s^{-1}\,Mpc^{-1}}$$

纯几何测量：

- 👍不依赖于消光
- 👍不依赖于标准化
- 👍不依赖于阶梯校 (造父变星、超新星)
- 👍系统误差检验

SARM分析亟待扩大样本，实现高精度H_0测量！

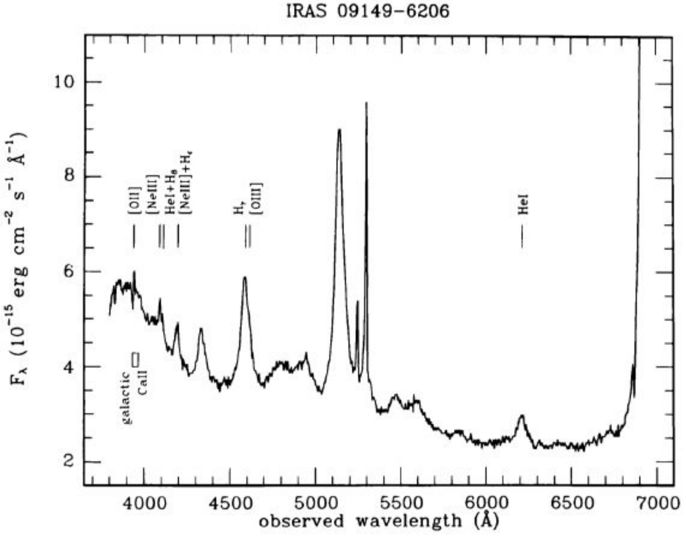
Astronomy & Astrophysics manuscript no. gravity_blr
September 21, 2020

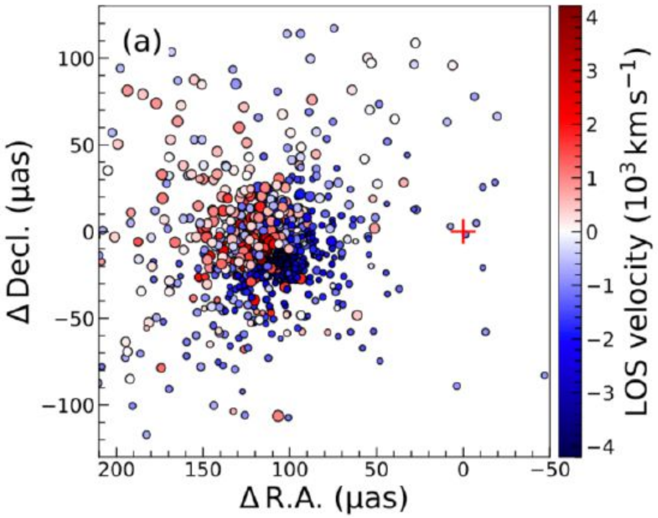
arXiv:2009.08463

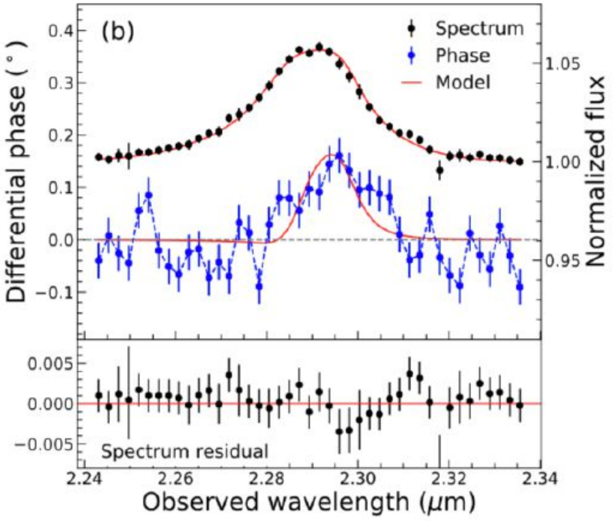
GRAVITY: 第二个类星体

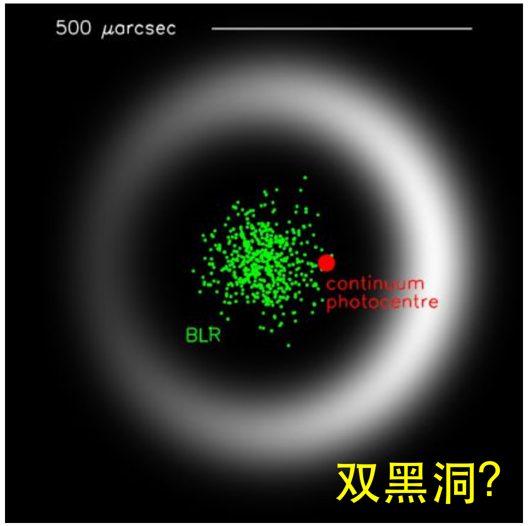
The spatially resolved broad line region of IRAS 09149−6206

GRAVITY Collaboration: A. Amorim[19,21], W. Brandner[22], Y. Clénet[2], R. Davies[1], P. T. de Zeeuw[1,17], J. Dexter[24,1], A. Eckart[3,18], F. Eisenhauer[1], N.M. Förster Schreiber[1], F. Gao[1], P. J. V. Garcia[15,20,21], R. Genzel[1,4], S. Gillessen[1], D. Gratadour[2,25], S. Hönig[5], M. Kishimoto[6], S. Lacour[2,16], D. Lutz[1], F. Millour[7], H. Netzer[8], T. Ott[1], T. Paumard[2], K. Perraut[12], G. Perrin[2], B. M. Peterson[9,10,11], P. O. Petrucci[12], O. Pfuhl[16], M. A. Prieto[23], D. Rouan[2], J. Shangguan[1⋆], T. Shimizu[1], M. Schartmann[1], A. Sternberg[8,14], O. Straub[1], C. Straubmeier[3], E. Sturm[1], L. J. Tacconi[1], K. R. W. Tristram[15], P. Vermot[2], S. von Fellenberg[1], I. Waisberg[13], F. Widmann[1], and J. Woillez[16]









my & Astrophysics manuscript no. gravi-agn_ngc3783_astro-ph ©ESO 2021
/ 2, 2021

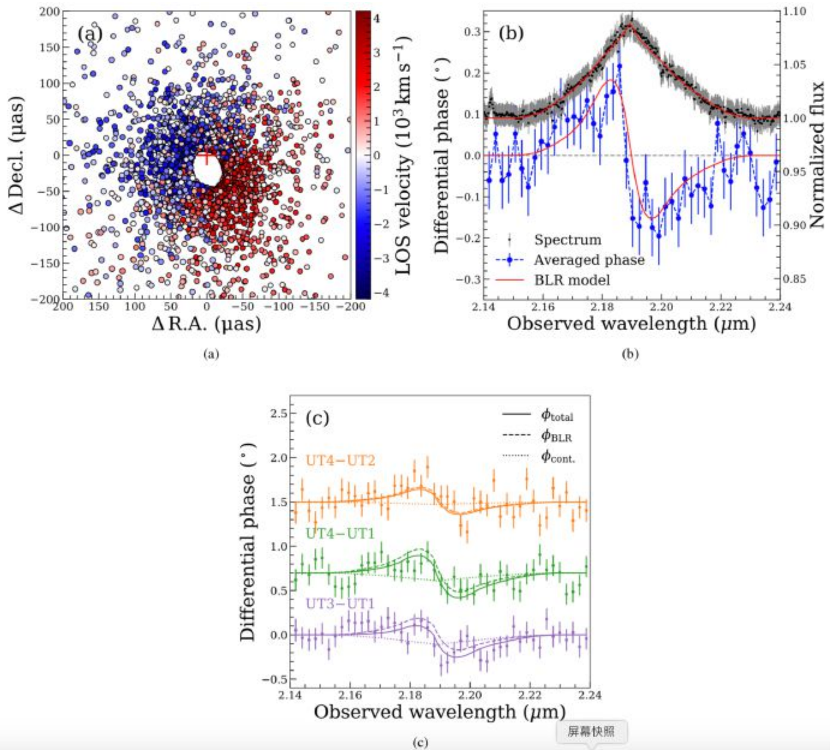
GRAVITY: 第三个源

The central parsec of NGC 3783: a rotating broad emission line region, asymmetric hot dust structure, and compact coronal line region

GRAVITY Collaboration★: A. Amorim[19, 21], M. Bauböck[1], W. Brandner[22], M
P. T. de Zeeuw[1, 17], J. Dexter[24, 1], A. Drescher[1, 27], A. Eckart[3, 18], F. Eisenhauer
P. J. V. Garcia[15, 20, 21], R. Genzel[1, 4], S. Gillessen[1], D. Gratadour[2, 25], S. Hönig[5],
S. Lacour[2, 16], D. Lutz[1], F. Millour[7], H. Netzer[8], T. Ott[1], T. Paumard[2], K. Perrau
P. O. Petrucci[12], O. Pfuhl[16], M. A. Prieto[23], D. Rouan[2], J. Sanchez-Bermudez
M. Schartmann[1], J. Stadler[1], A. Sternberg[8, 14], O. Straub[1], C. Straubmei
K. R. W. Tristram[15], P. Vermot[2], S. von Fellenberg[1], I. Waisberg[13], F.

(Affiliations can be found after the references)

Received xxx, 2020; accepted January 29, 2021



超爱黑洞：高红移宇宙膨胀历史

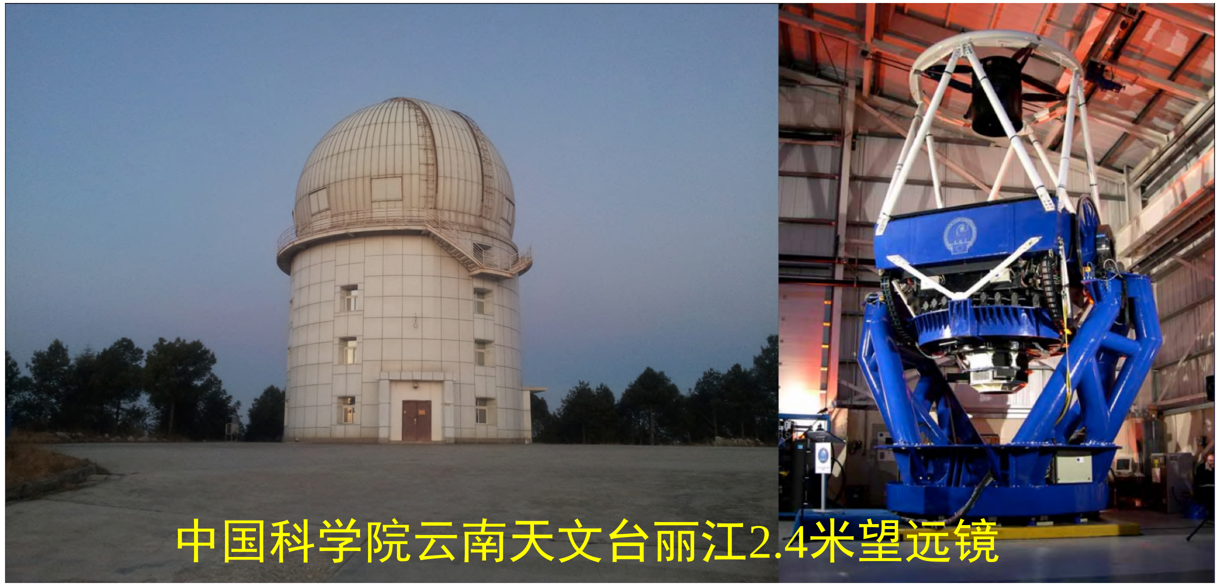
PRL **110,** 081301 (2013) PHYSICAL REVIEW LETTERS week ending 22 FEBRUARY 2013

Super-Eddington Accreting Massive Black Holes as Long-Lived Cosmological Standards

Jian-Min Wang,[1,2,*] Pu Du,[1] David Valls-Gabaud,[3,1,2] Chen Hu,[1] and Hagai Netzer[4]

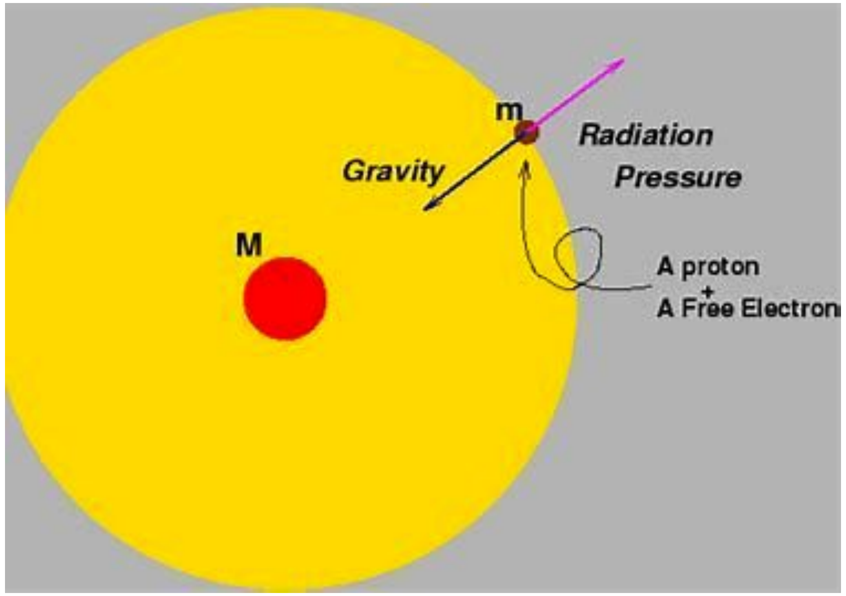
[1]*Key Laboratory for Particle Astrophysics, Institute of High Energy Physics, CAS, 19B Yuquan Road, Beijing 100049, China*
[2]*National Astronomical Observatories of China, CAS, 20A Datun Road, Beijing 100020, China*
[3]*LERMA, CNRS UMR 8112, Observatoire de Paris, 61 Avenue de l'Observatoire, 75014 Paris, France*
[4]*School of Physics and Astronomy and The Wise Observatory, The Raymond and Beverley Sackler Faculty of Exact Sciences, Tel-Aviv University, Tel-Aviv 69978, Israel*

(Received 27 August 2012; published 19 February 2013)



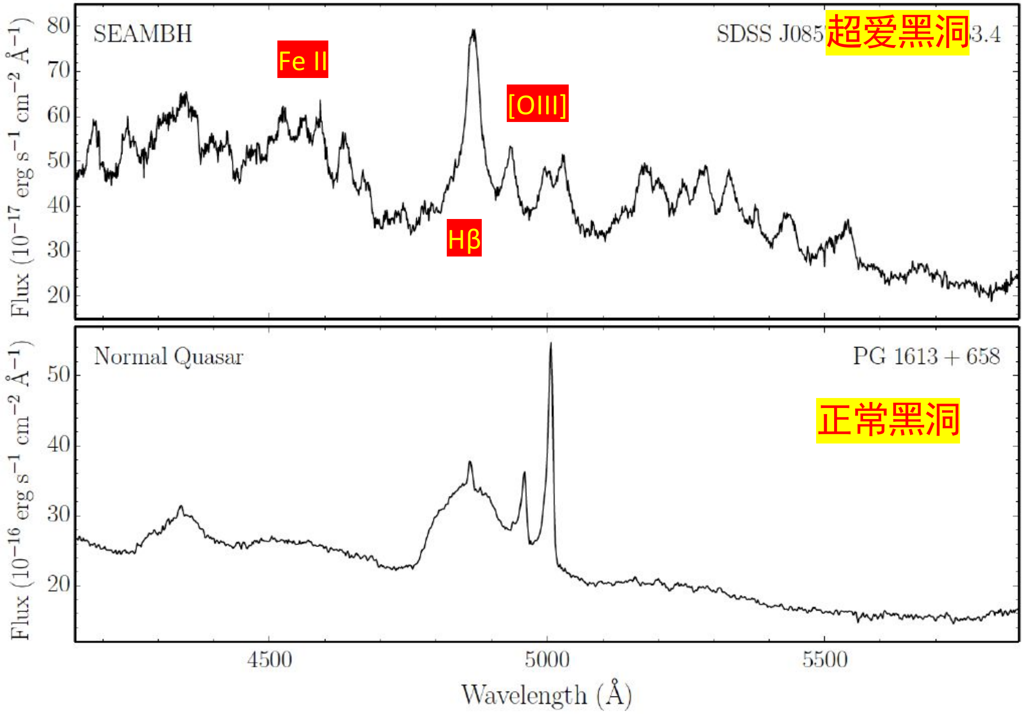
中国科学院云南天文台丽江2.4米望远镜

超爱黑洞：丽江观测计划



- 辐射压=引力 →爱丁顿极限

  吸积率： $\sim 1.0 M_8 M_{\odot}\mathrm{yr}^{-1}$

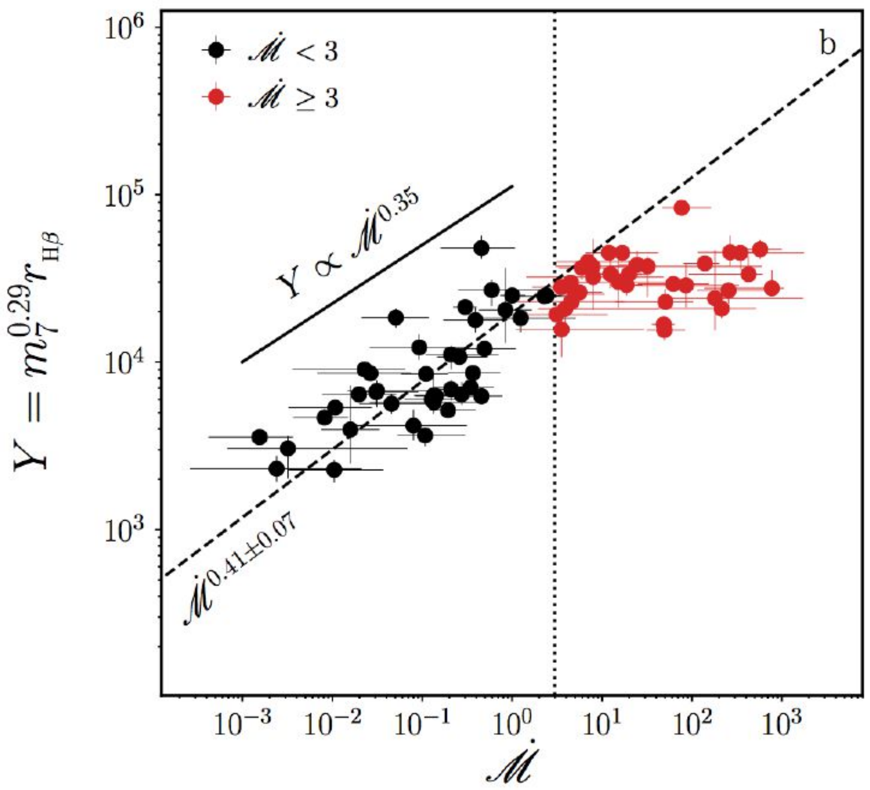


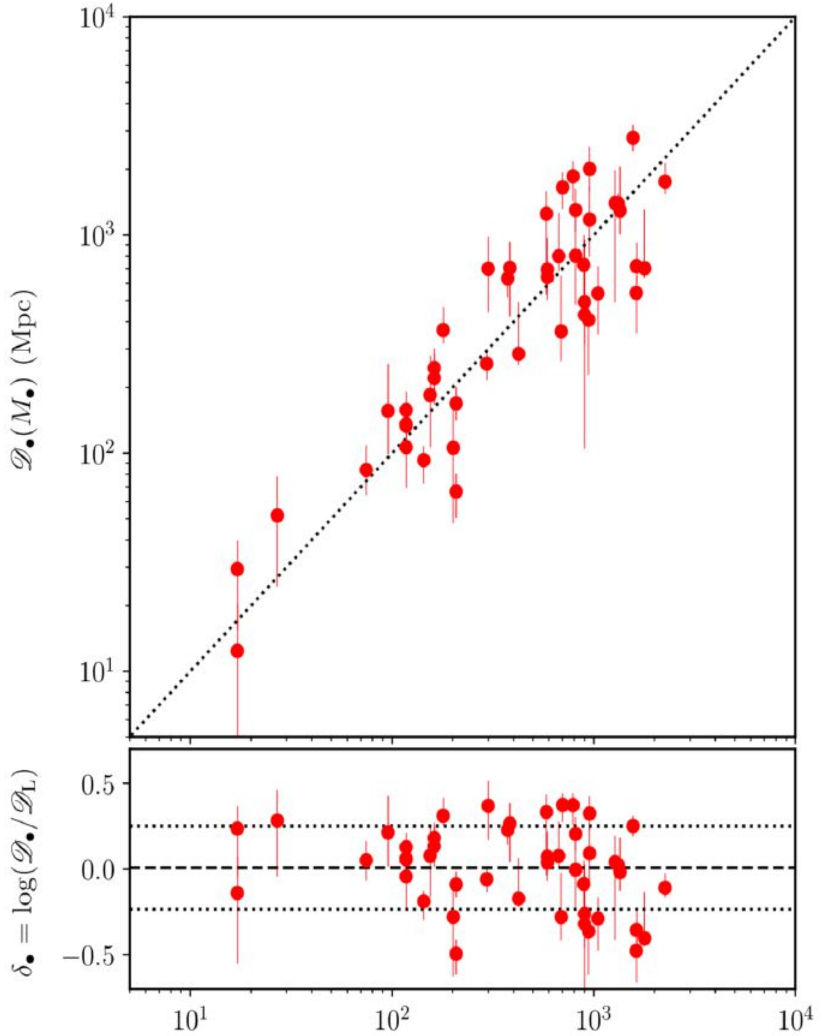
观测计划目标

1）黑洞快速增长

2）黑洞烛光

超爱黑洞：饱和光度与距离测量





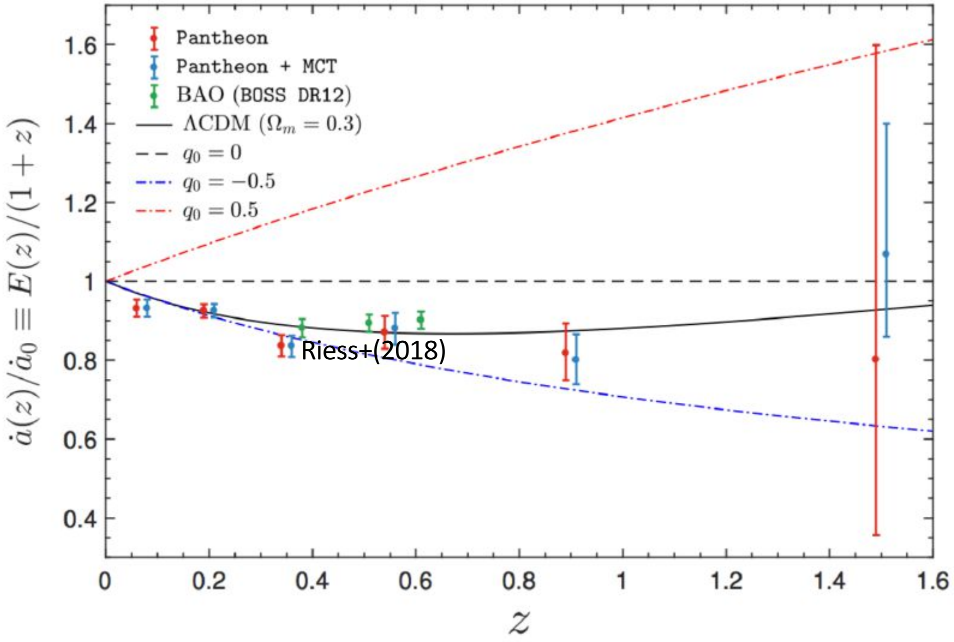
- 超爱黑洞: 吸积率10^3
- 饱和光度-*L*：0.2dex

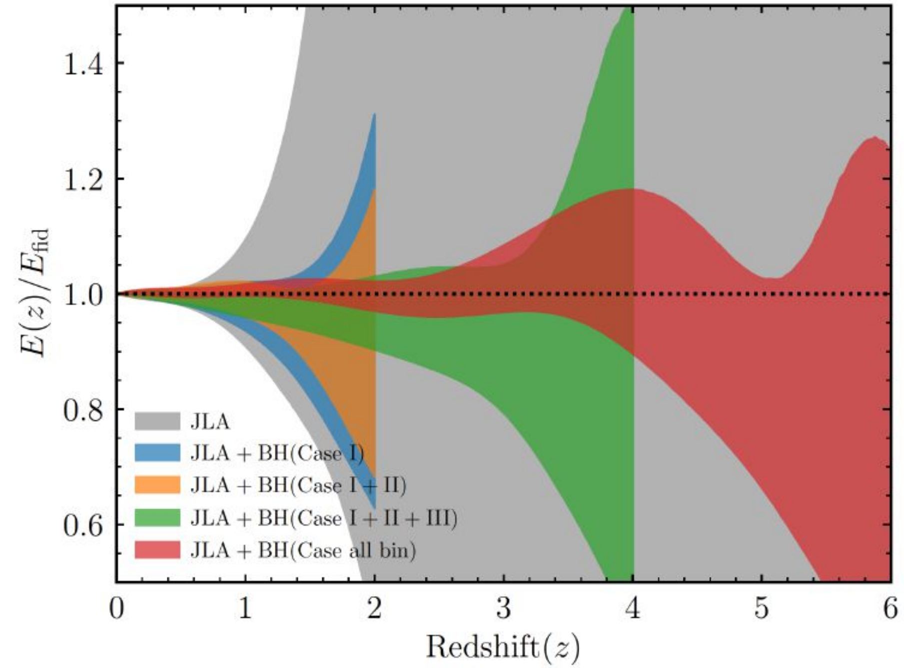
黑洞照亮：高红移宇宙膨胀历史

PHYSICAL REVIEW D **97**, 123502 (2018)

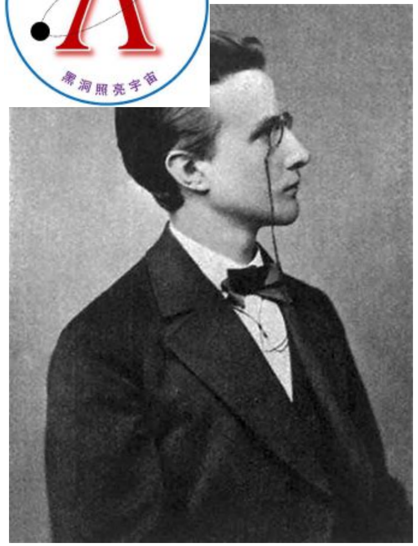
Super-Eddington accreting massive black holes explore high-z cosmology: Monte-Carlo simulations

Rong-Gen Cai,* Zong-Kuan Guo,† and Qing-Guo Huang‡





重大问题：宇宙结构和动力学

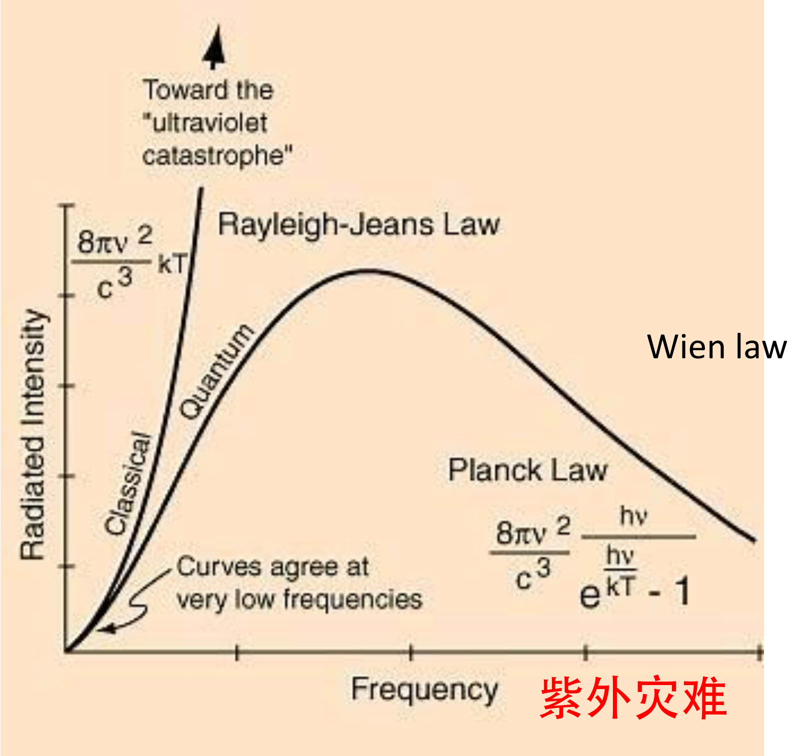


"量子"诞生

Max Planck

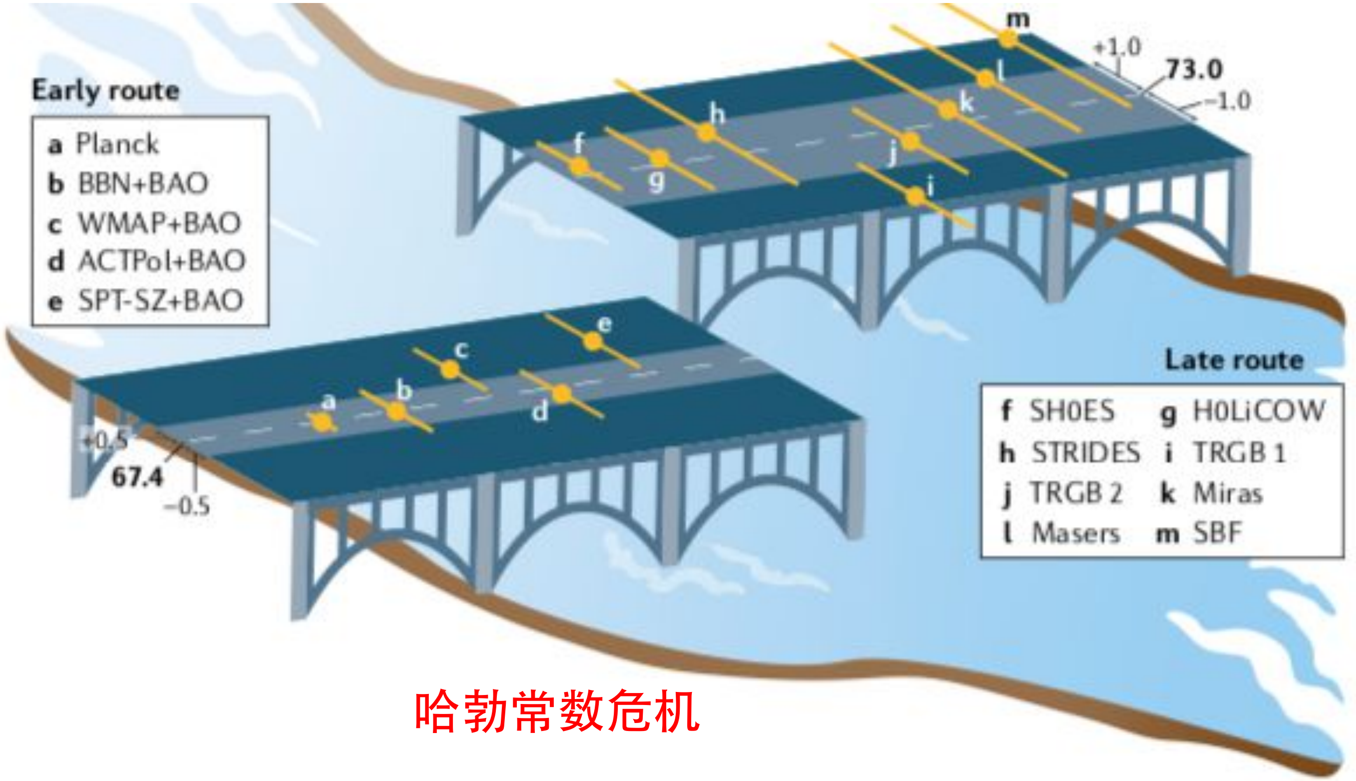
"新物理"诞生?

Adams Riess



Wien law

紫外灾难

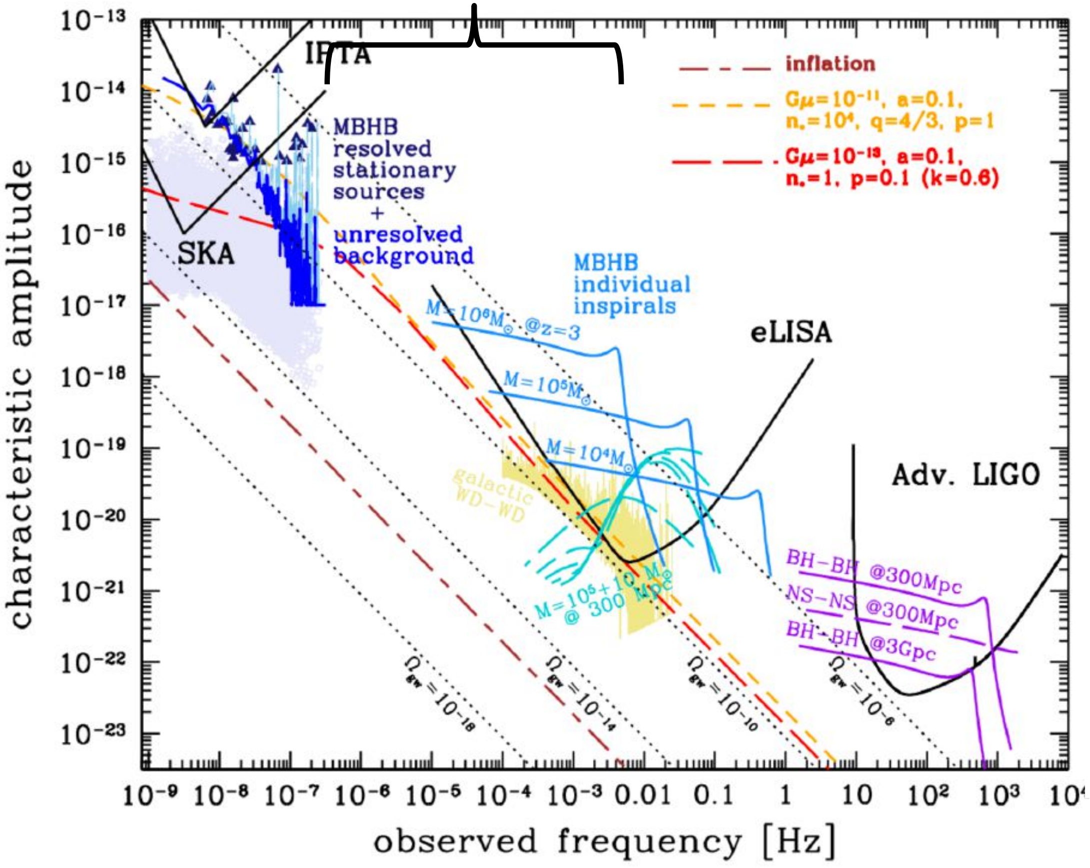


哈勃常数危机

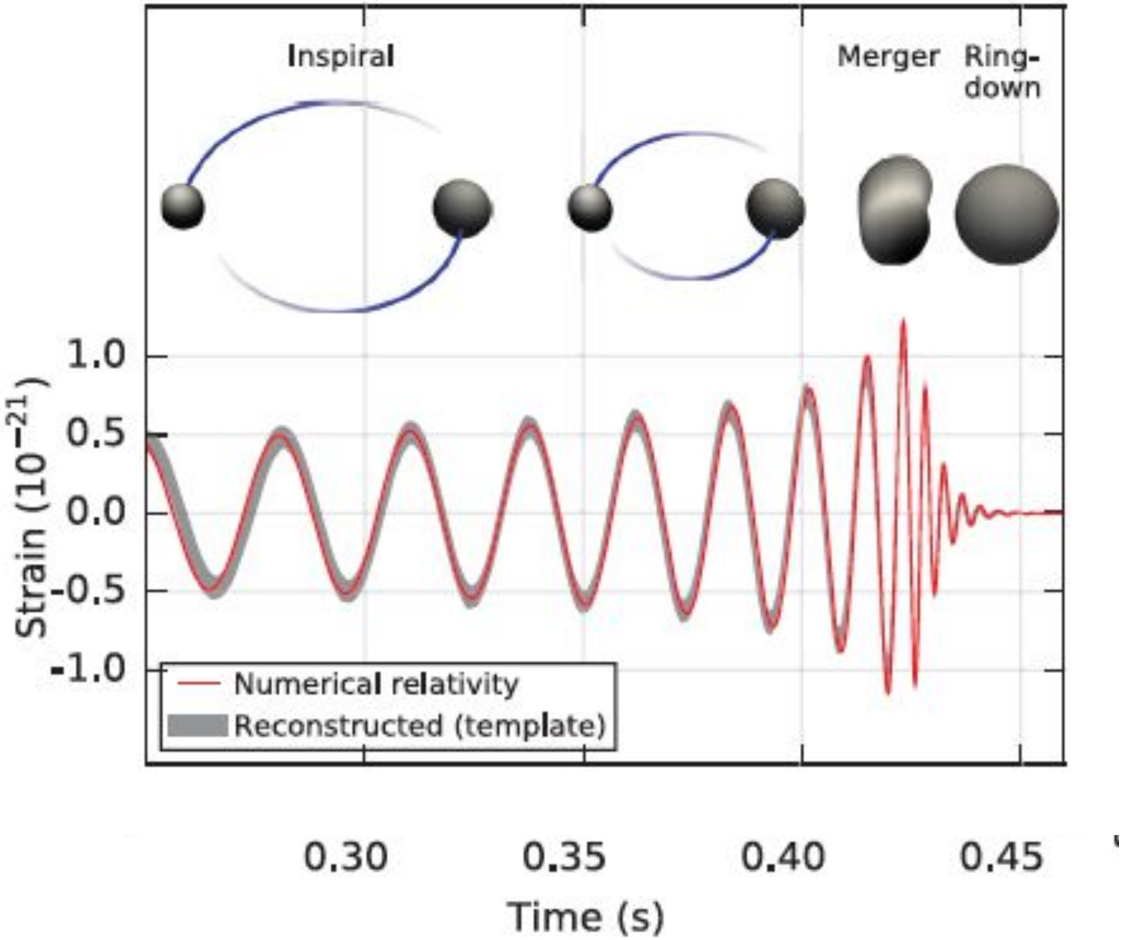
大质量双黑洞：低频引力波

密近双黑洞：轨道参数

CB-SMBHs

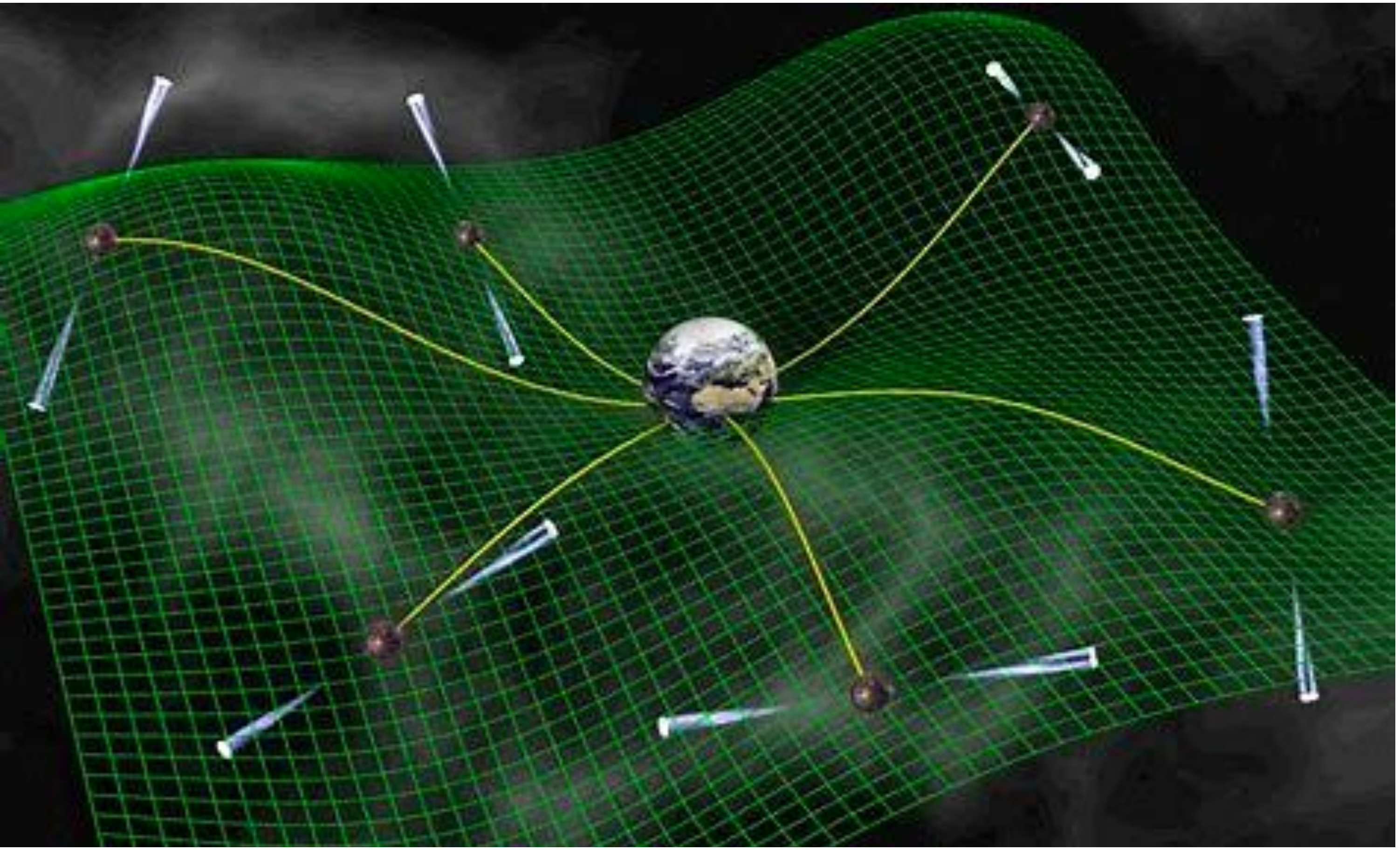


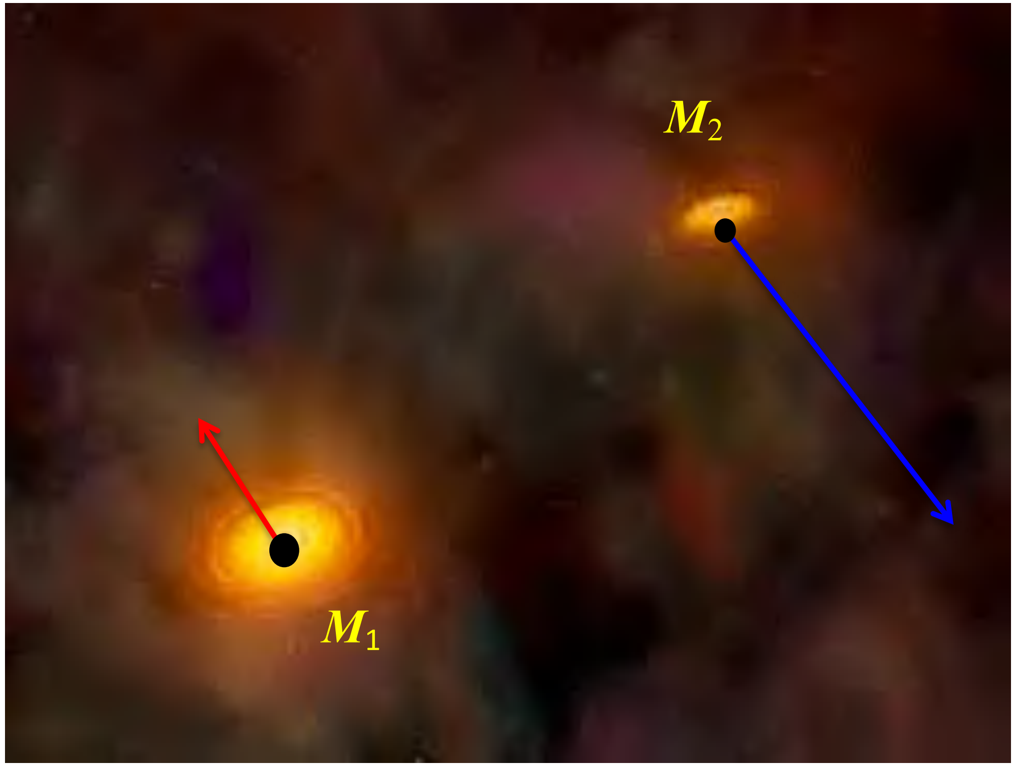
LIGO: 100Hz-GWs

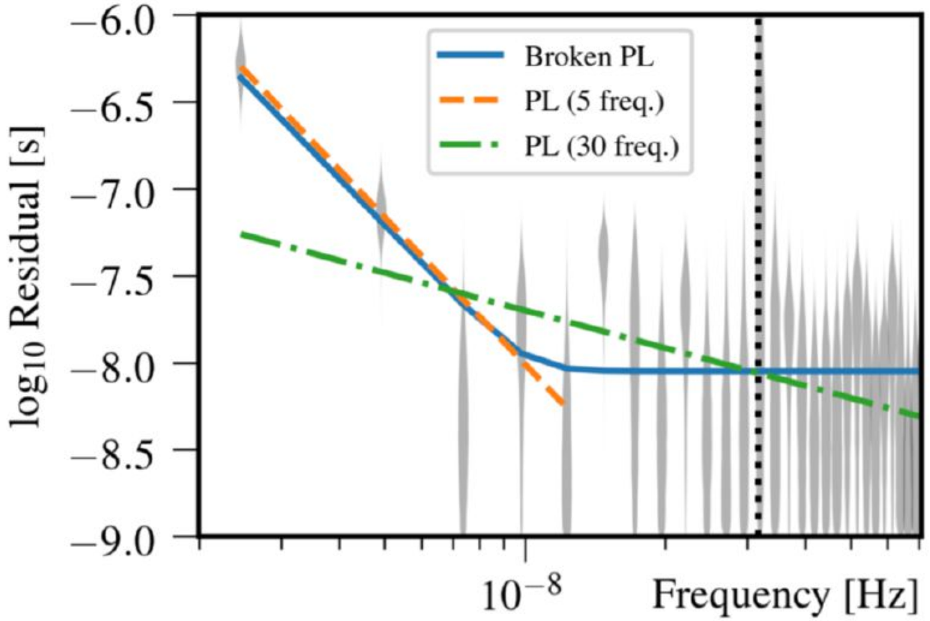


周期 ～ 10-100yrs： PTA难于探测整体波形，不能探测波形变化

PTA：低频引力波
大质量双黑洞：观测？







Arzoumanian+2009.04496

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

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

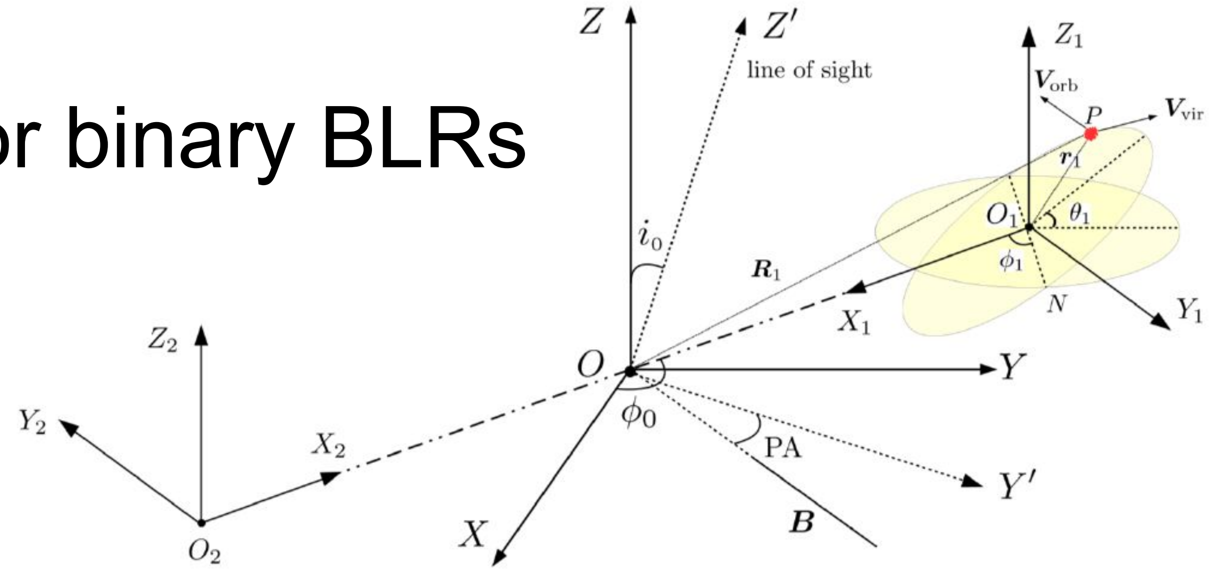
Jian-Min Wang[1,2,3], Yu-Yang Songsheng[1,2], Yan-Rong Li[1], and Zhe Yu[1,2]

Blandford & McKee(1982):
2D-transfer functions of
a single BLR

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

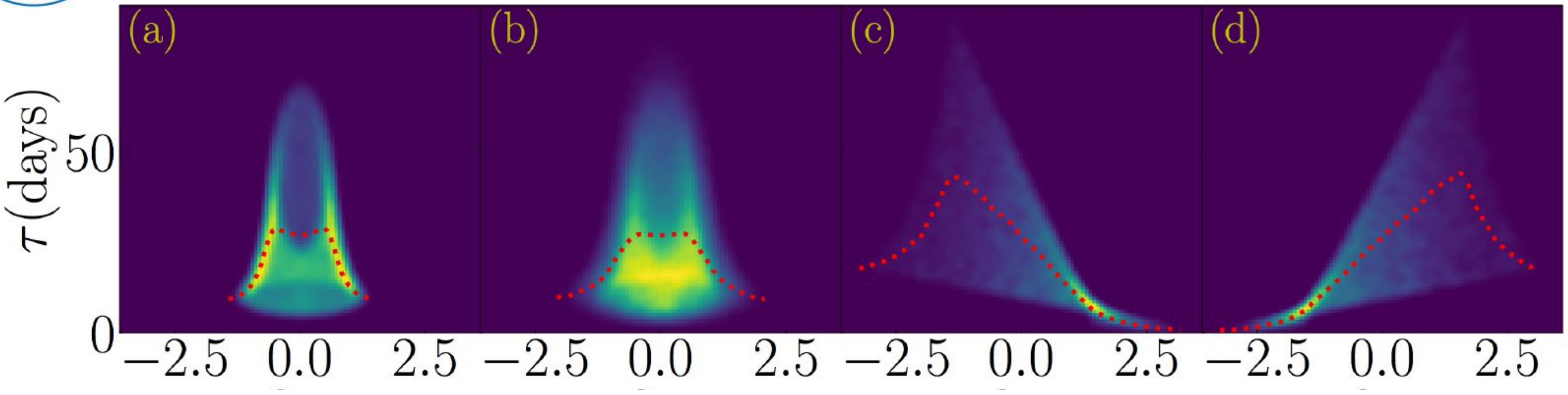
$$\tilde{L}_{\ell,c} = \mathscr{F}[L_{\ell,c}(v,\,t)],$$

For binary BLRs

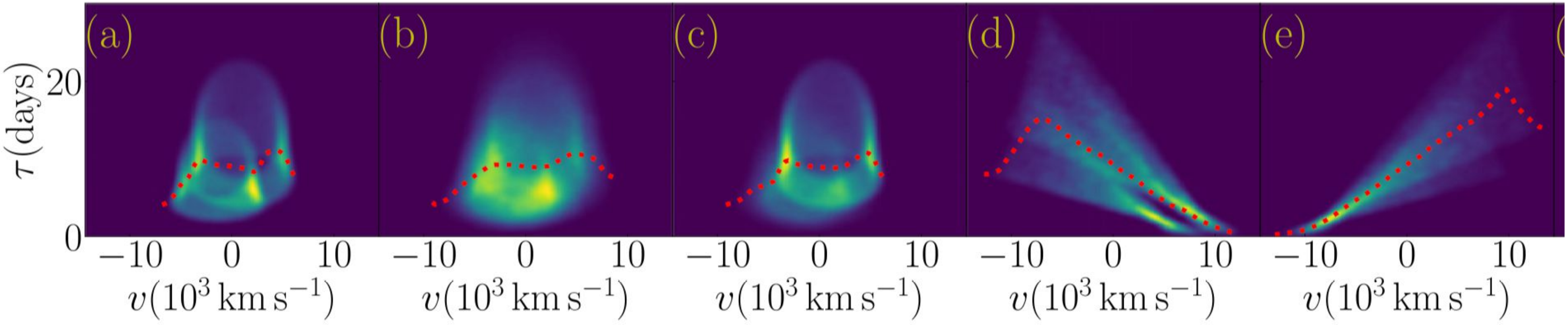


$$\Psi_{tot}(v,\,t) = \frac{\Psi_1(v,\,t)}{1+\Gamma_0} + \frac{\Psi_2(v,\,t)}{1+\Gamma_0^{-1}},$$

Songsheng+(2020); Kovacevic+(2020)



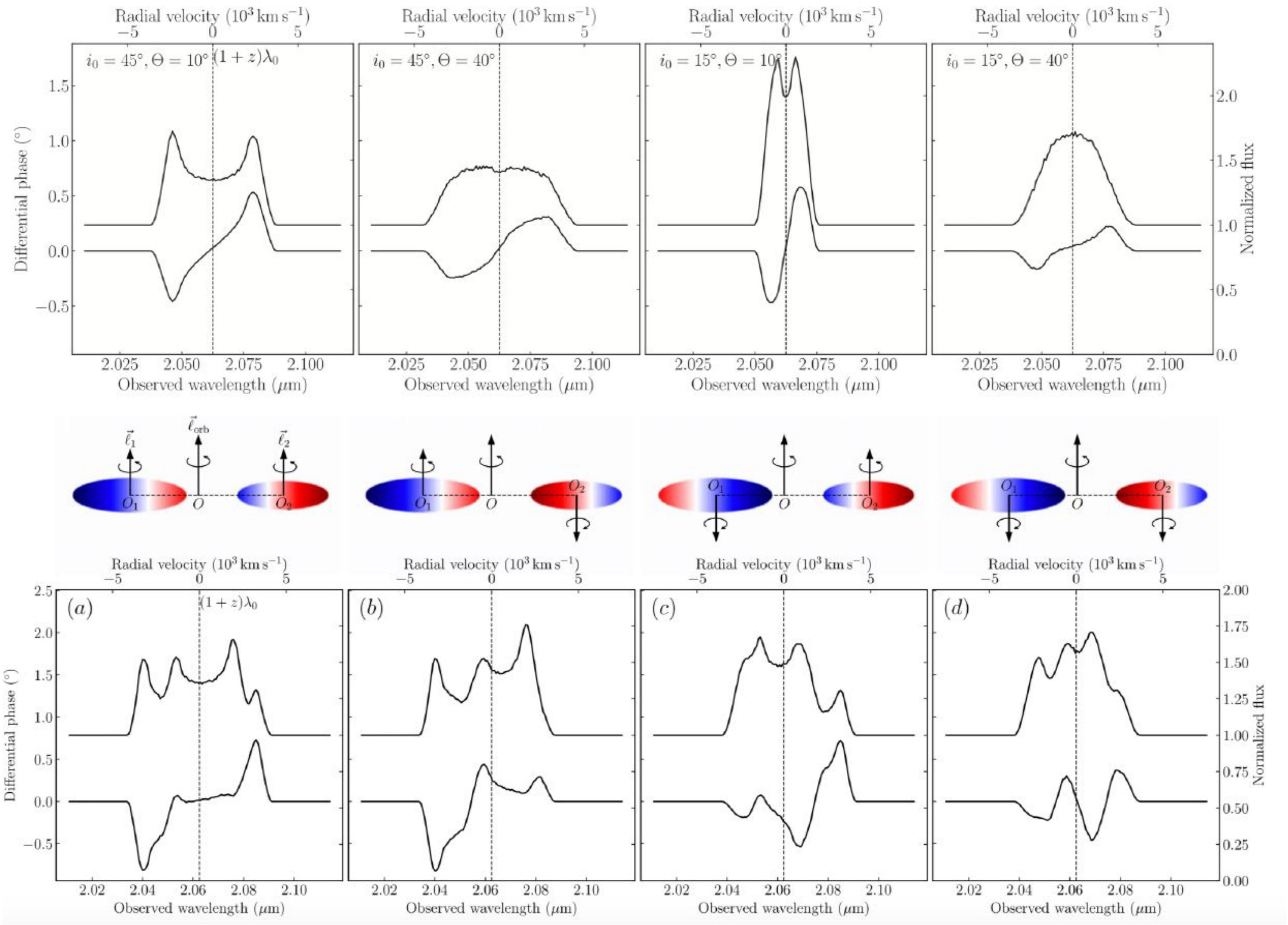
A single BLR

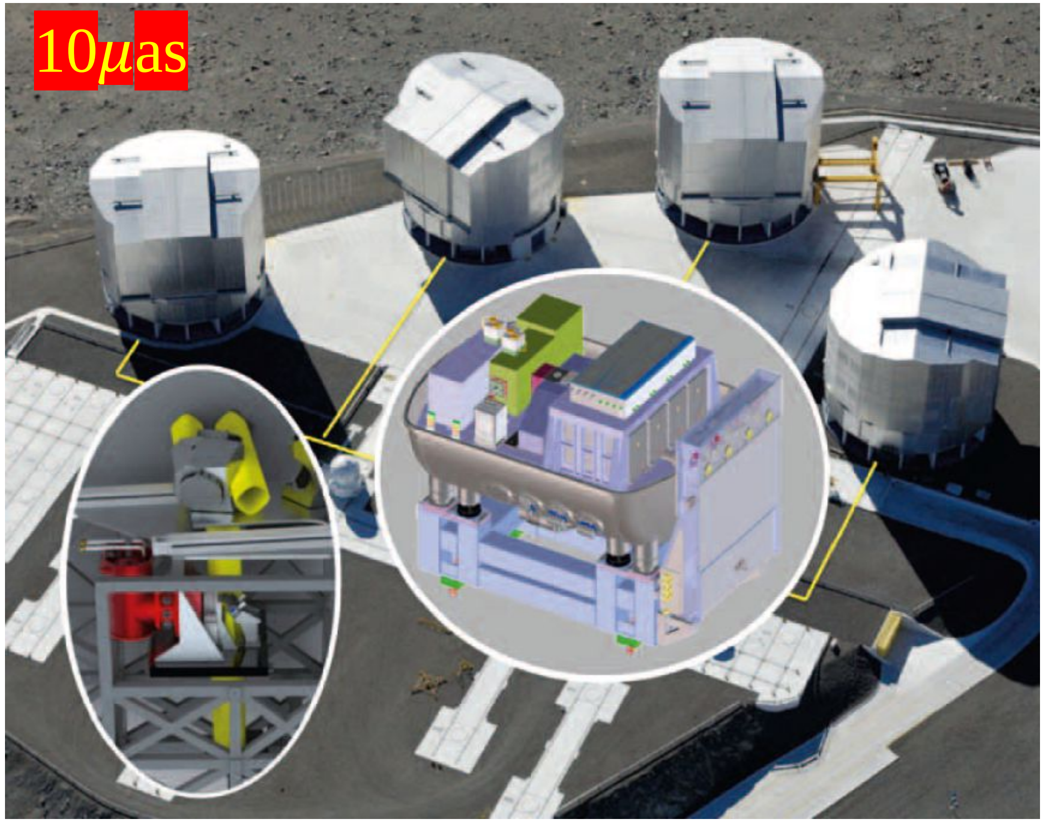


RM: 2D transfer functions
（Wang+2018；Songsheng+2019; Kovacevic+2019）

Offsets are due to orbital motion

Signals: GRAVITY/VLTI (Songsheng+2019, Kovacevic+2020)

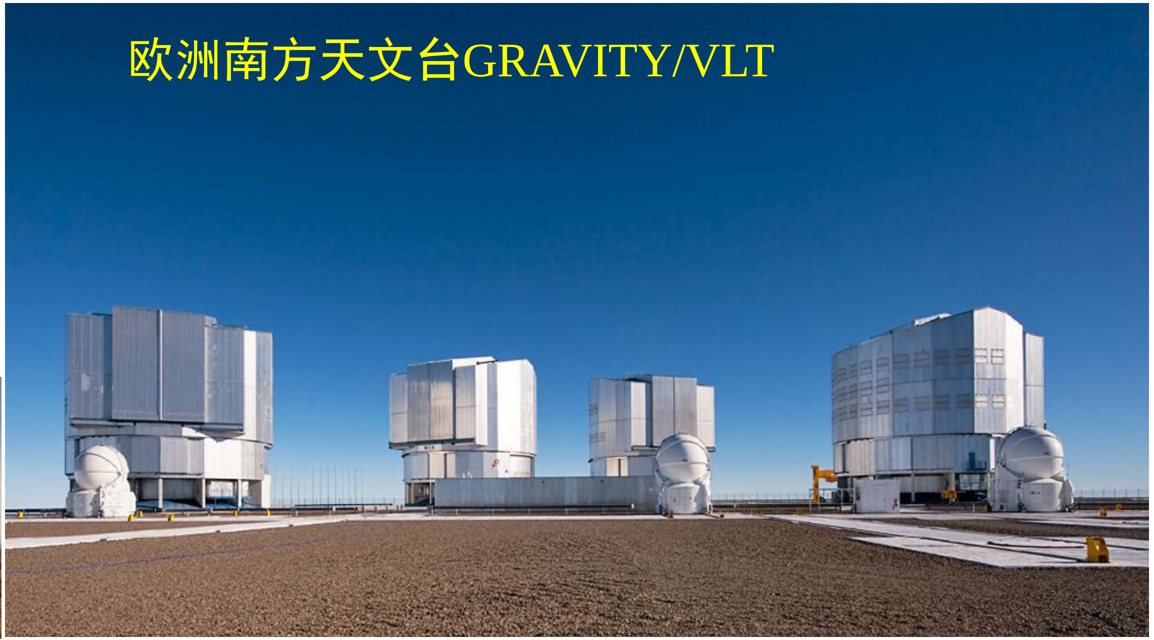




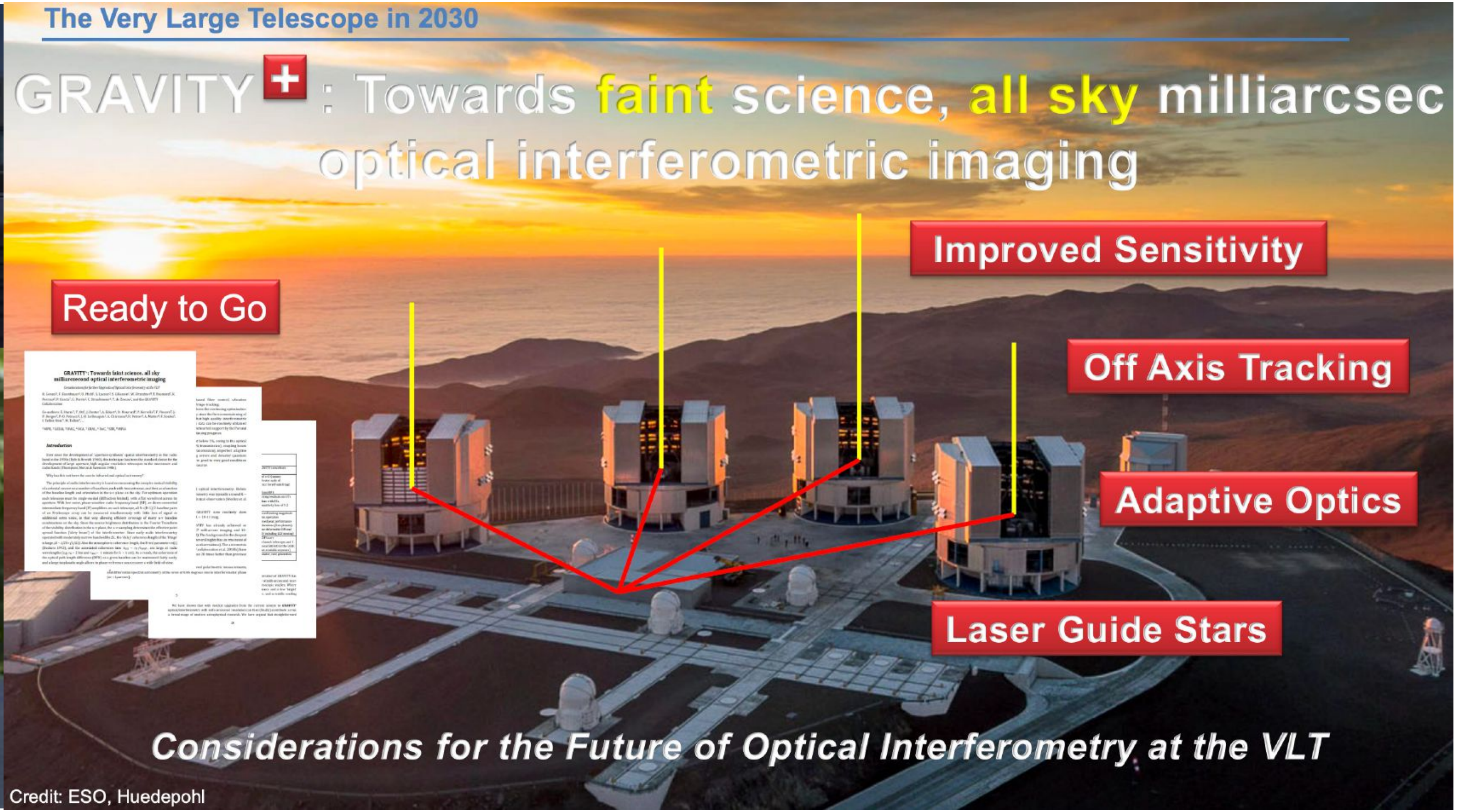
More complicated signals see Kovacevic+2020

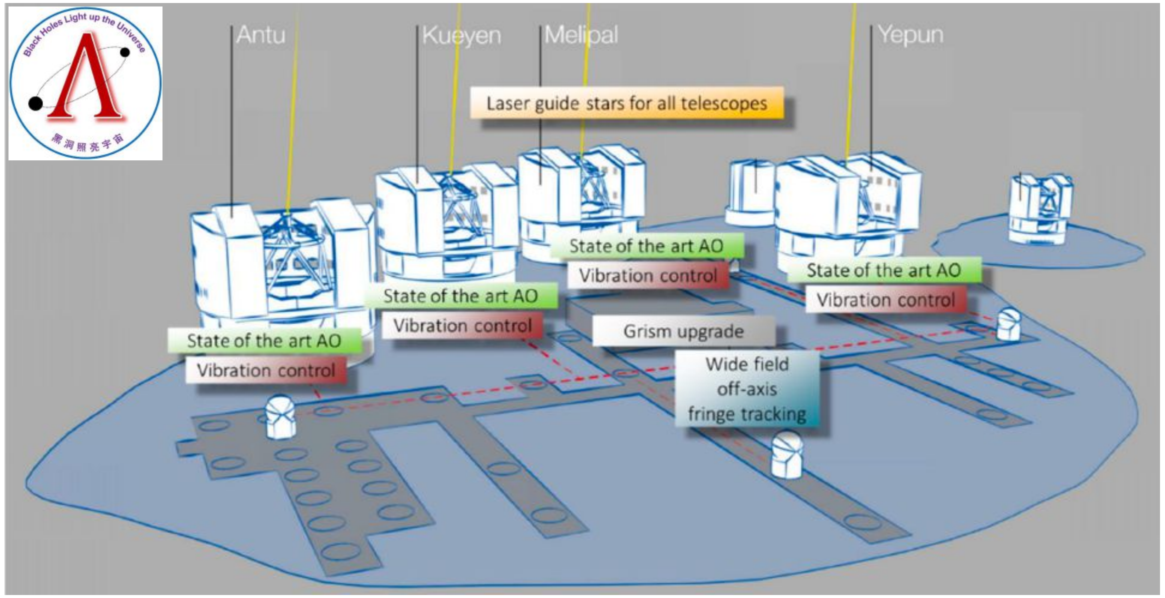
最大射电和

最大光学望远镜联合



未来3-5年内：GRAVITY+





- 银心黑洞
- 河外天文

超爱黑洞、双黑洞

GRAVITY+: Towards Faint Science, All Sky, High Contrast, Milli-Arcsecond Optical Interferometric Imaging

White Paper and Proposal

2020/07/23

For the GRAVITY+ Consortium (MPE, LESIA, IPAG, UoC, CENTRA, MPIA, UoS):

F. Eisenhauer[1] (PI), P. Garcia[2,3,4] (CoI), R. Genzel[1,5], S. Hönig[6] (CoI*), L. Kreidberg[7,8] (CoI), J.-B. Le Bouquin[9] (CoI), P. Léna[10], T. Paumard[10] (CoI), C. Straubmeier[11] (CoI)

Senior Team Members and Associated Partners:

A. Amorim[2,12], W. Brandner[8], M. Carbillet[13], V. Cardoso[2,14], Y. Clénet[10], R. Davies[1], D. Defrère[15], T. de Zeeuw[1,16], G. Duvert[9], A. Eckart[11,17], S. Esposito[18], M. Fabricius[1,19], N.M. Förster Schreiber[1], P. Gandhi[6], E. Gendron[10], S. Gillessen[1], D. Gratadour[10], K.-H. Hofmann[17], M. Horrobin[11], M. Ireland[20], P. Kervella[10], S. Kraus[21], S. Lacour[10], O. Lai[22], B. Lopez[22], D. Lutz[1], F. Martinache[22], A. Meilland[22], F. Millour[22], T. Ott[1], R. Oudmaijer[23], F. Patru[10], K. Perraut[9], G. Perrin[10], R. Petrov[22], S. Quanz[24], S. Rabien[1], A. Riccardi[18], R. Saglia[1,19], J. Sánchez Bermúdez[8,25], D. Schertl[17], J. Schubert[1], F. Soulez[26], E. Sturm[1], L.J. Tacconi[1], M. Tallon[26], I. Tallon-Bosc[26], E. Thiébaut[26], F. Vidal[10], G. Weigelt[17], A. Ziad[13]

Supporters:

O. Absil[15], A. Alonso-Herrero[27], R. Bender[1,19], M. Benisty[9,28], J.-P. Berger[9], E. Banados[8], C. Boisson[29], J. Bouvier[9], P. Caselli[1], A. Cassan[30], B. Chazelas[31], A. Chiavassa[32], F. Combes[33], V. Coudé du Foresto[10], J. Dexter[1,34], C. Dougados[9], Th. Henning[8], T. Herbst[8], J. Kammerer[20], M. Kishimoto[35], L. Labadie[11], A.-M. Lagrange[9], A. Marconi[36], A. Matter[13], Z. Meliani[29], F. Ménard[9], J. Monnier[37], D. Mourard[13], H. Netzer[38], N. Neumayer[8], B. Peterson[39,40,41], P.-O. Petrucci[9], J.-U. Pott[8], H.W. Rix[8], D. Rouan[10], H. Sana[42], D. Segransan[31], H. Sol[29], E. van Dishoeck[1,16], F. Vincent[10], M. Volonteri[30], A. Zech[29]

(Affiliations can be found after the references)

超爱黑洞

3.2.2 Super-Eddington Accretion

Today more than 100 QSOs at z>6 are known (Banados et al. 2016). These SMBHs must have been growing at the most efficient rate in order to appear so early in the history of the Universe. Super-Eddington accretion on to massive black hole seeds may play an important role and be commonplace in the early Universe (e.g., Regan et al. 2009). Indeed, cases with ratio of bolometric and Eddington luminosity $L_{bol}/L_{edd} > 9$ have been suggested at high redshift (e.g., Tang et al. 2019). However, such claims are based on black hole mass estimates derived from the local $R_{BLR} - L_{AGN}$ scaling relation, assuming the calibration in the local Universe is independent of redshift.

Super-Eddington accreting massive black holes in the local Universe usually have smaller BLRs than AGN with the same luminosities (Du et al. 2018). Spectro-astrometry with GRAVITY+ will extend size measurements and, combined with reverberation mapping, study physics of the super-Eddington accretion processes (e.g., self-shadowing effects in slim disks, Wang et al. 2014).

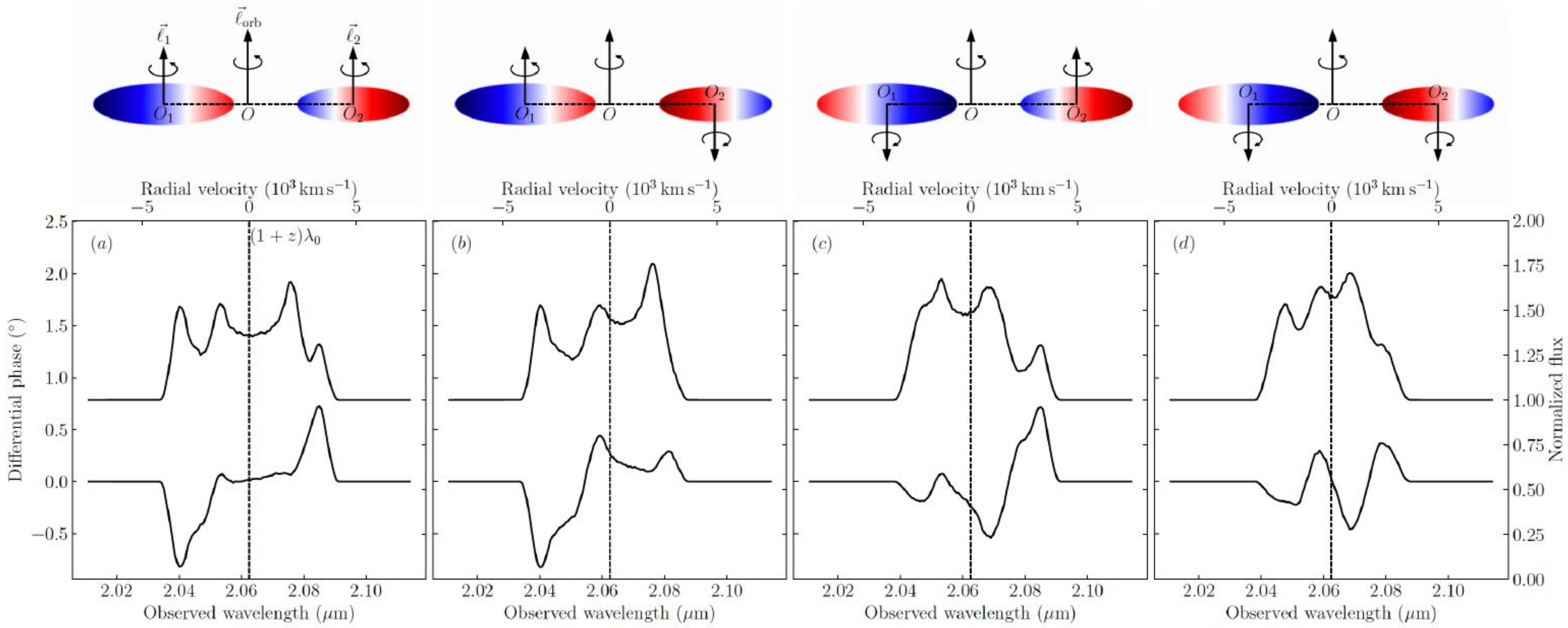
快速超爱吸积 → 超大质量黑洞

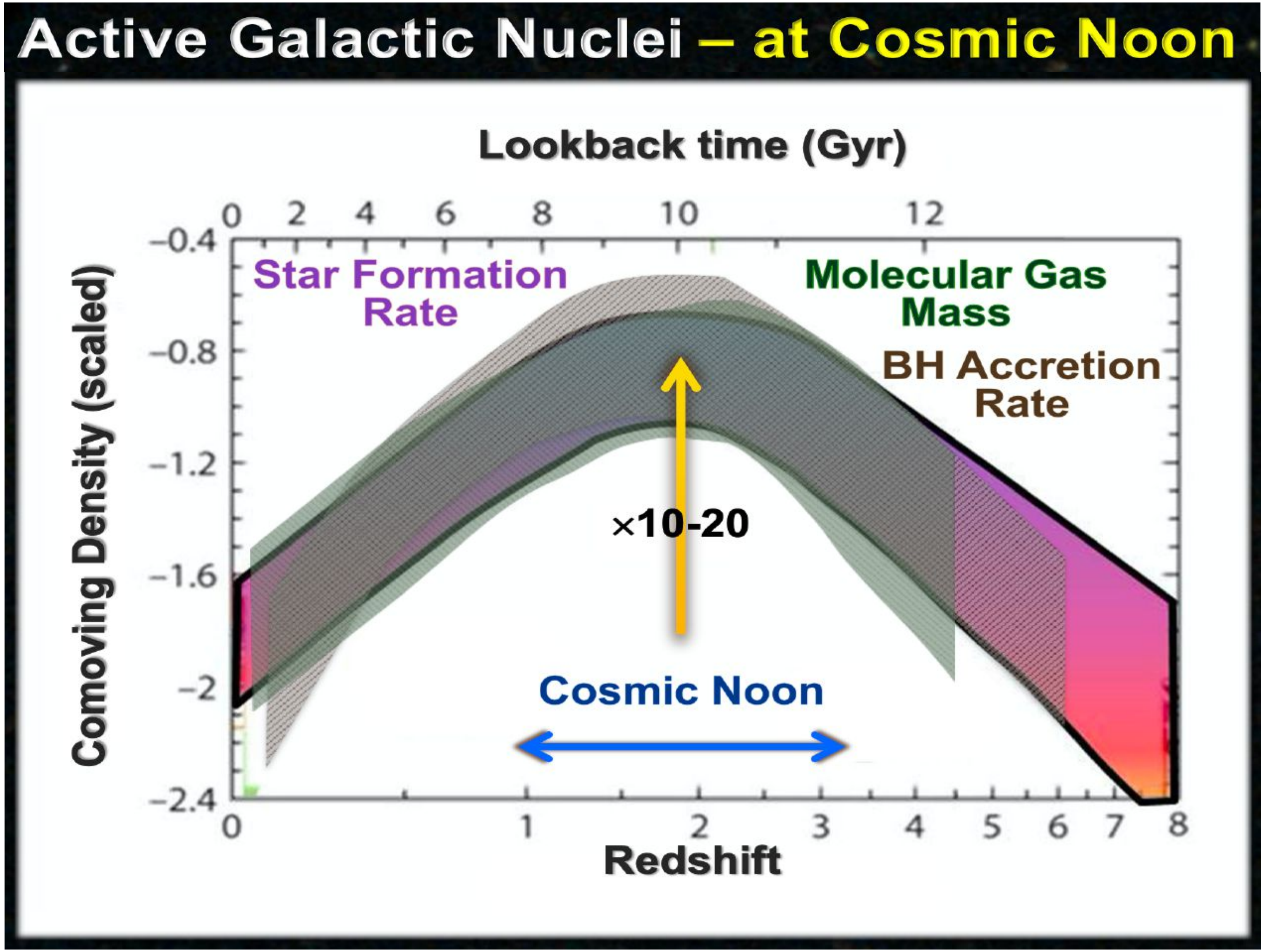
大质量双黑洞

3.2.4 The Last Parsec Problem – Binary Supermassive Black Holes

binary SMBH identification via double-peaked emission line profiles and dual jets/outflows remains ambiguous.

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,





核心科学目标：

- z=2-3的黑洞测量

  黑洞演化、与星系关系

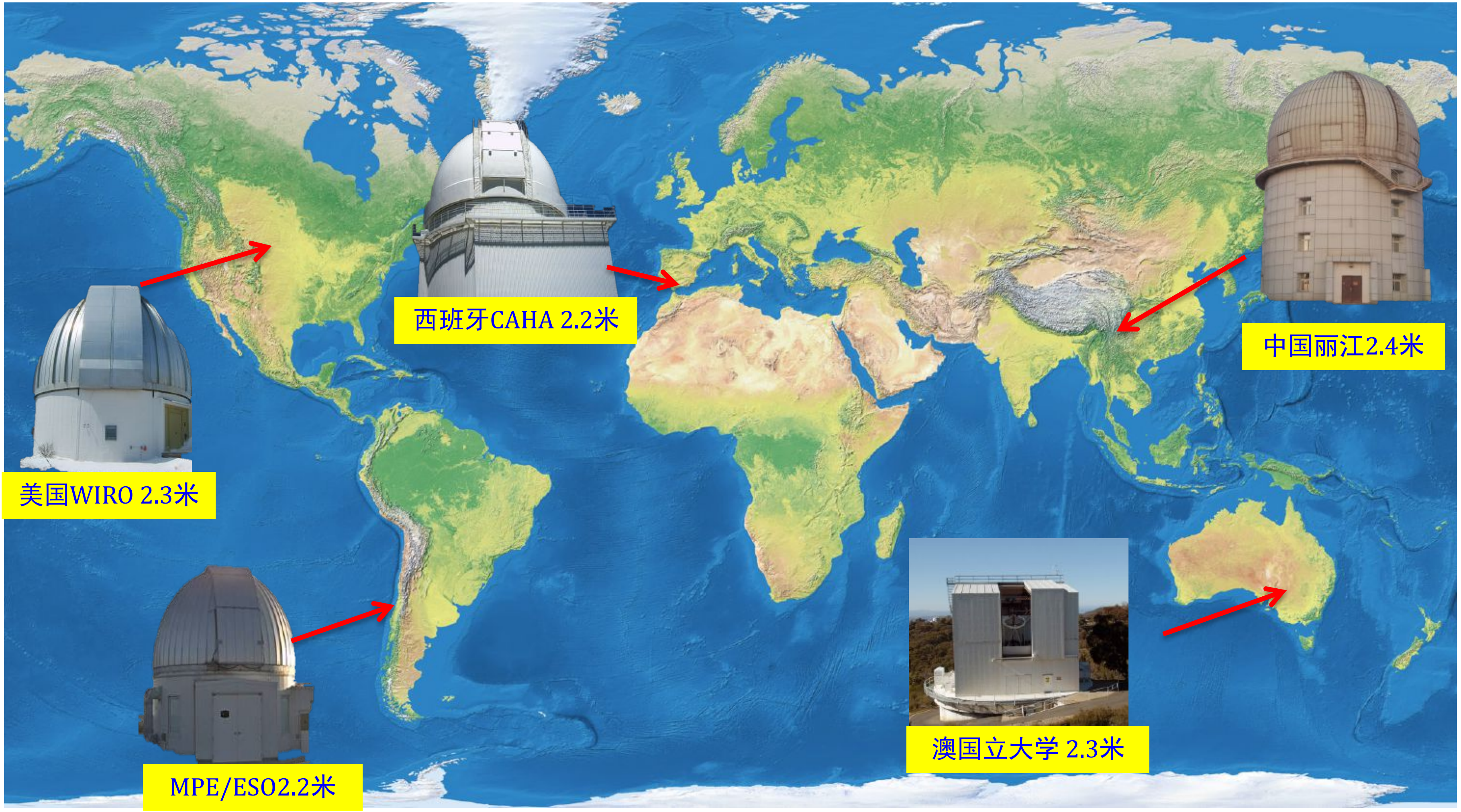
- 精确测量距离：

  宇宙膨胀历史/暗能量

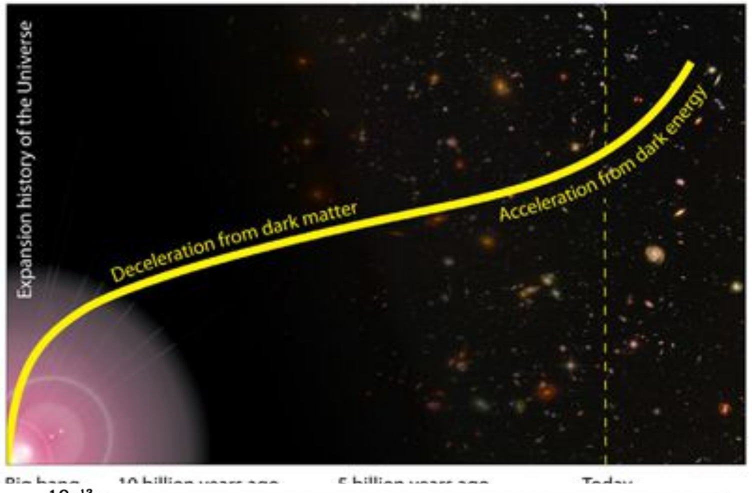
- 大质量双黑洞：

  低频引力波物理

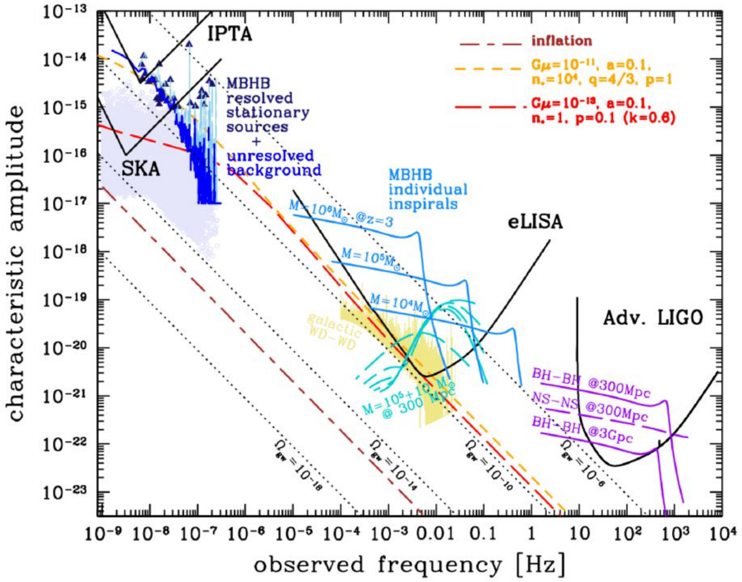
光干涉+反响映射：SARM计划”



结　论



- 光干涉和反响映射：
  - ➢技术获得：难度大
  - ➢科学价值：平等
- 宇宙学距离：光干涉+反响映射
  - –高精度测量哈勃常数
  - –哈勃参量：测量延伸到z=2-3
  - –期待：暗能量演化？
- 低频引力波：大质量双黑洞PTA+GRAVITY+RM



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