宇宙学距离的几何测量

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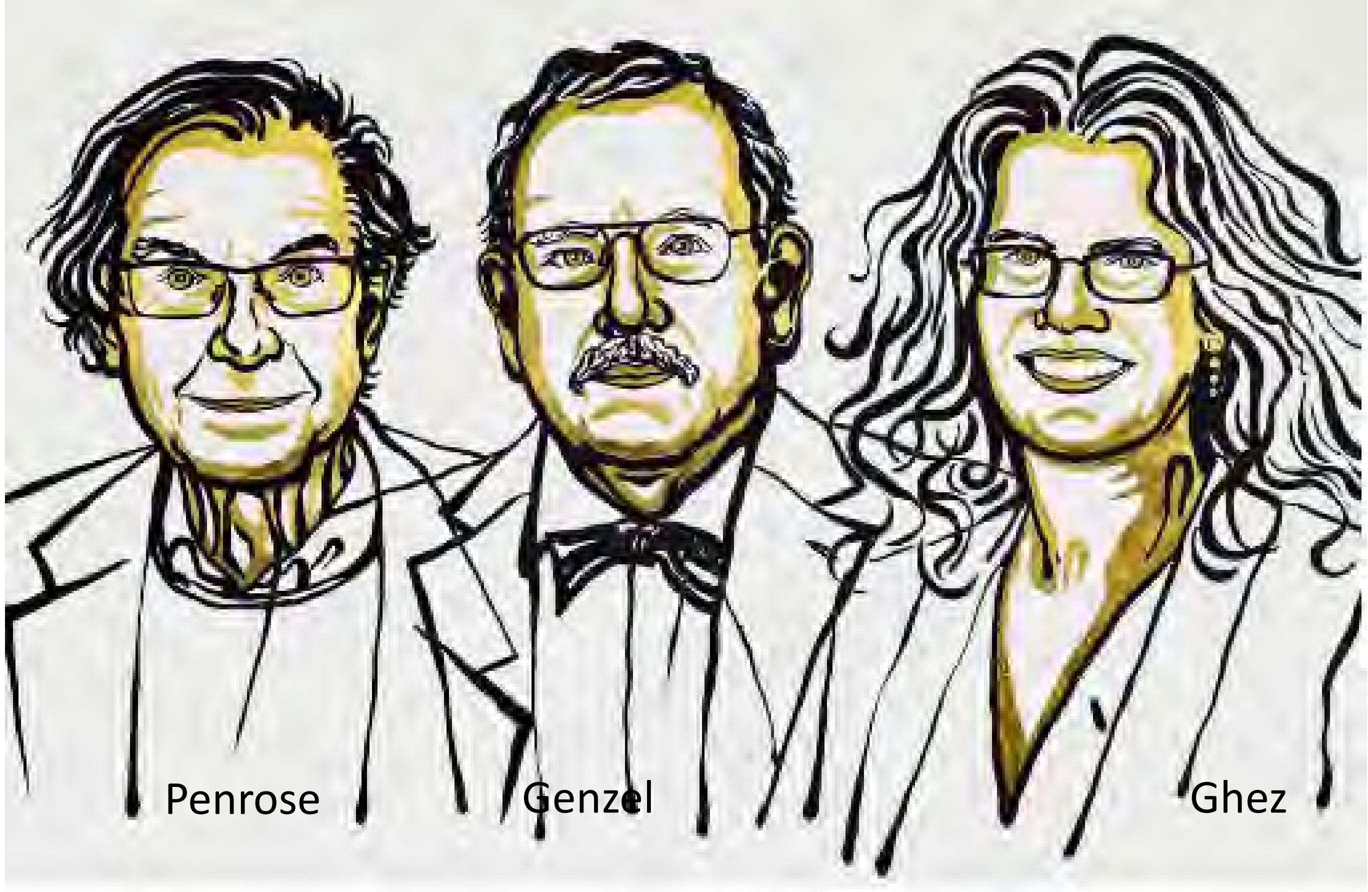
北京, 12月16日, 2020

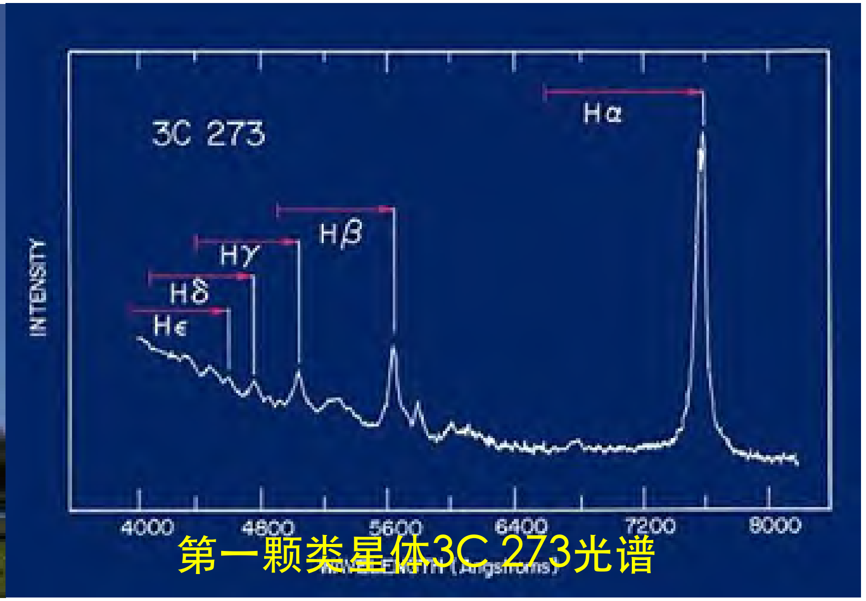
the discovery that black hole formation is a robust prediction of the general theory of relativity” and “for the discovery of a supermassive compact object at the centre of our galaxy”

Physics in 2020



- 黑洞是相对论的必然结果
- 银心大质量致密天体
- 河外大质量黑洞?

1963: 类星体的发现



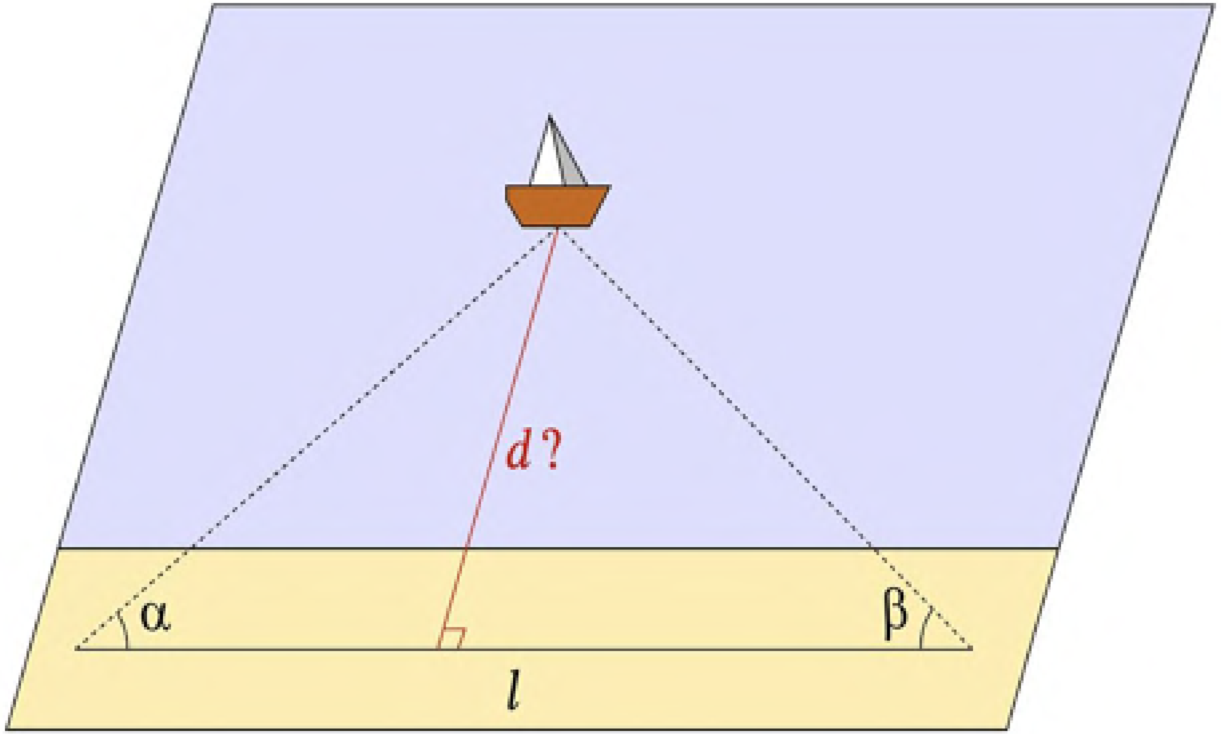
第一颗类星体3C 273光谱

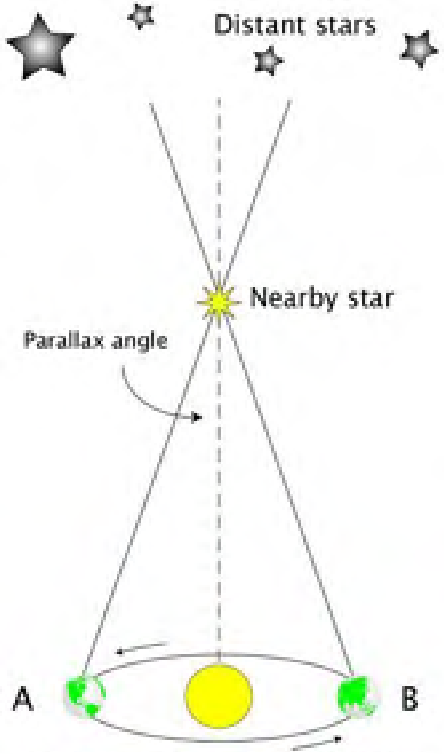
Penrose, R., 1965, PRL, 14, 57

第一句话：

类星体的发现重新燃起了引力塌缩的兴趣

几何方法

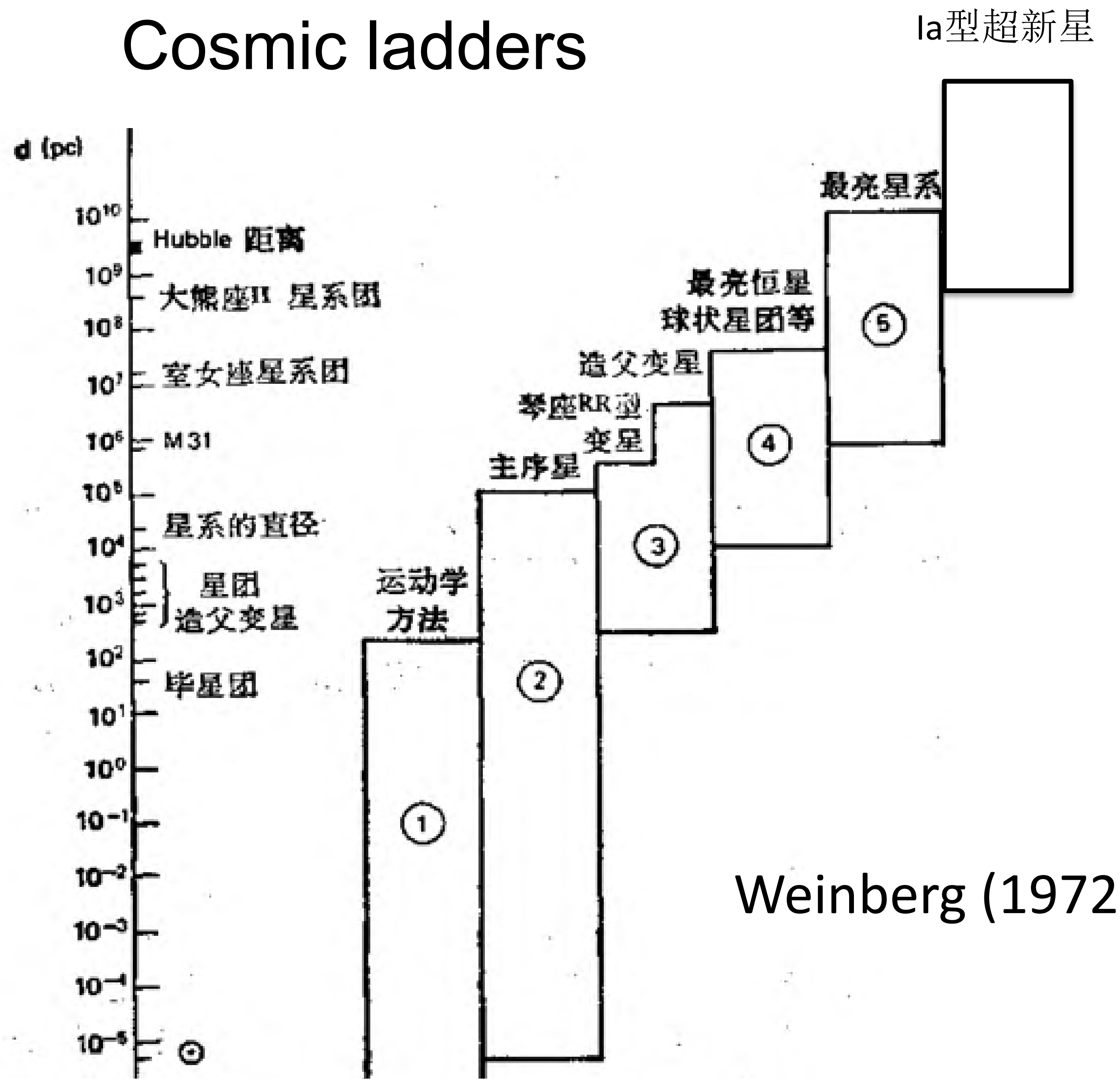




地球绕太阳转动

遥远的天体：如何测距?

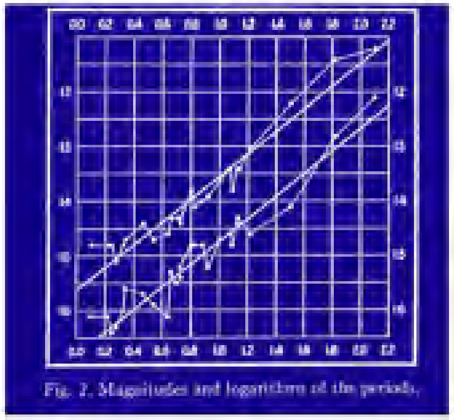
Cosmic ladders



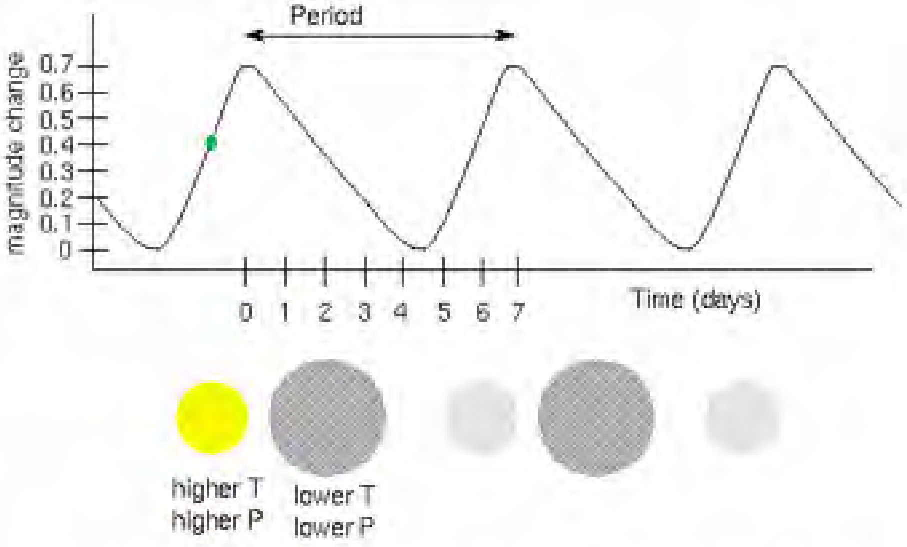
Weinberg (1972)

造父变星

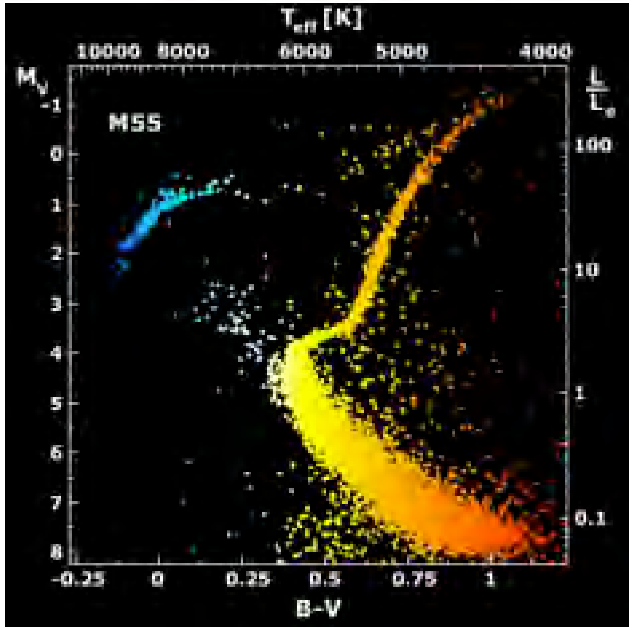
The Leavitt's Law



Leavitt (1908)
Leavitt & Pickering (1912)



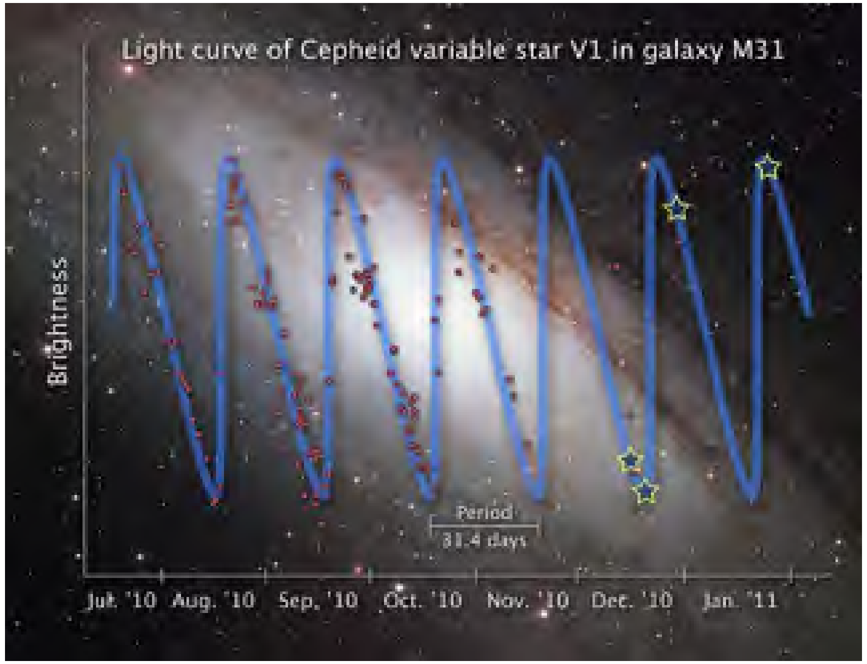
Cepheid variables: outward pressure (P) and inward gravity compression are out of sync, so star changes size and temperature: it **pulsates**. *RR-Lyrae* variables are smaller and have pulsation periods of less than 24 hours. Also, their light curve looks different from the Cepheid light curve.

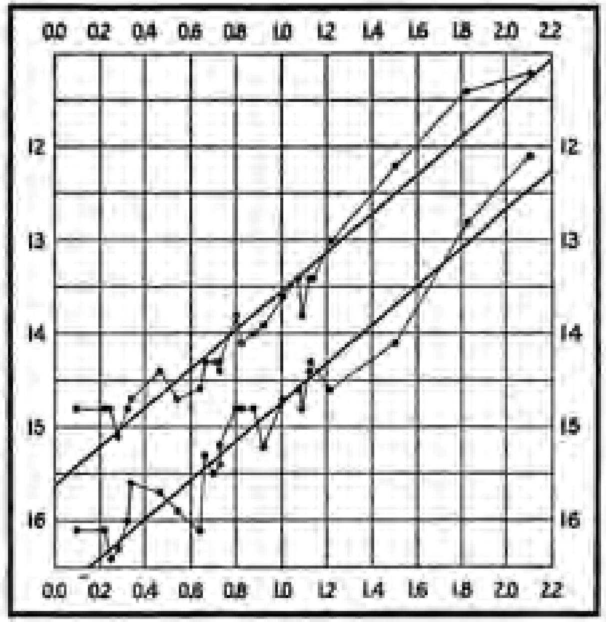


星族I：L ~10^3-$10^4 L_\odot$，M >3-4$M_\odot$，最大达20$M_\odot$

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

机制：氦元素电离导致不透明度变化不稳定性

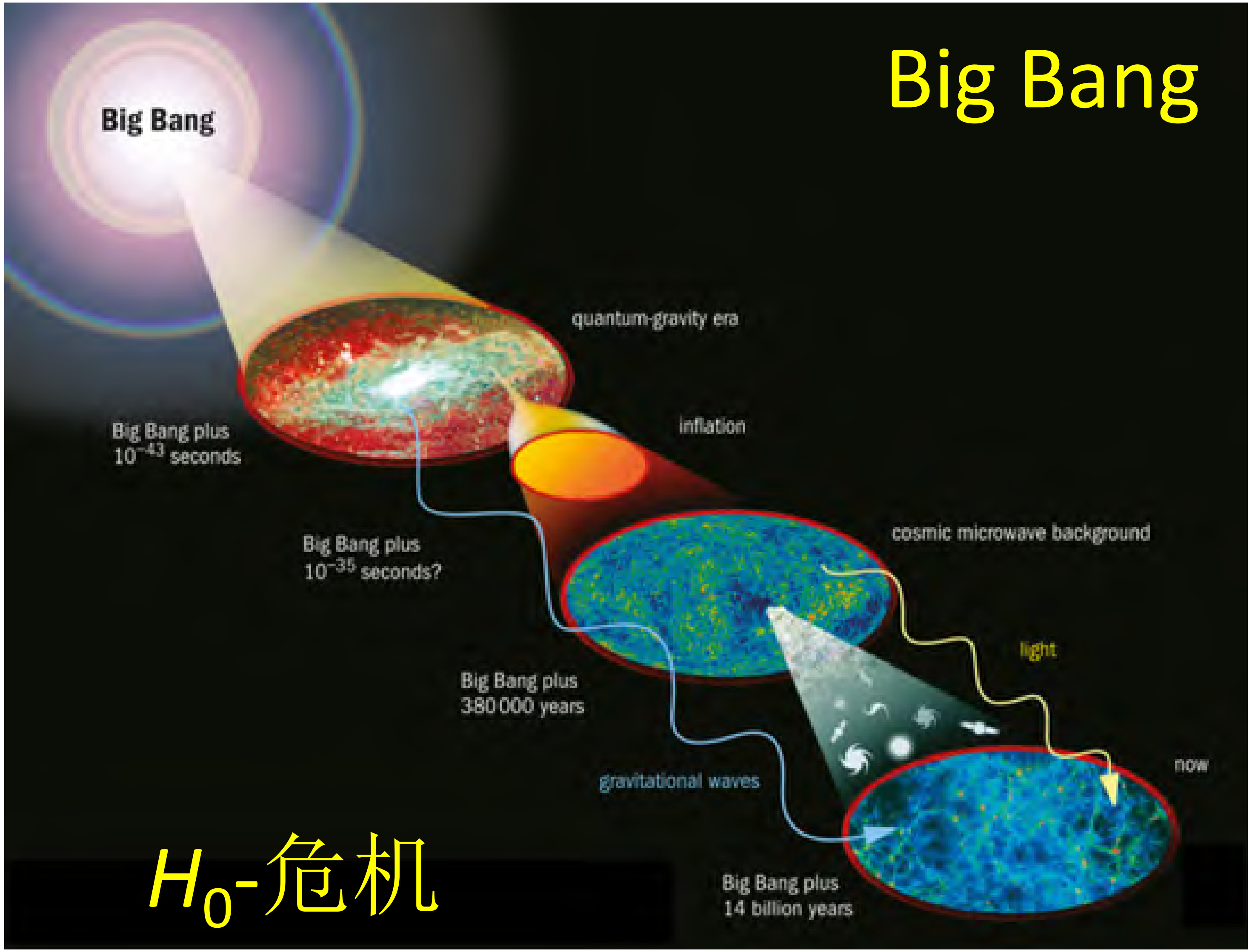




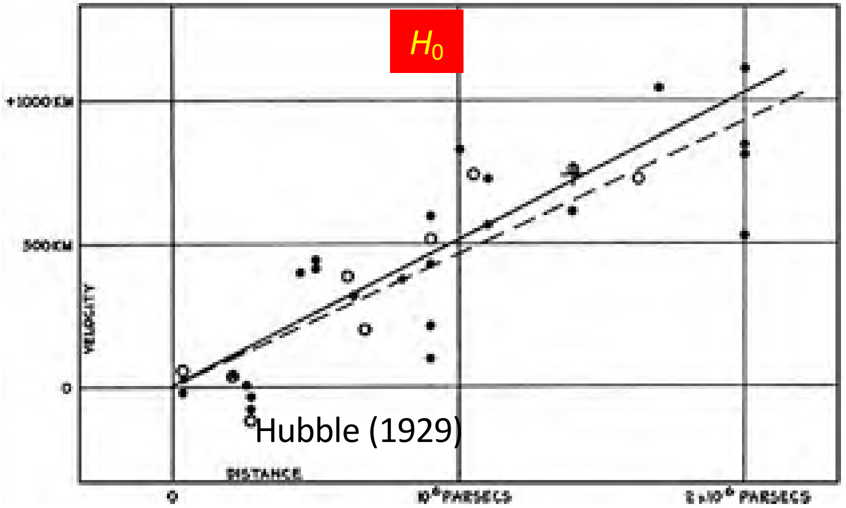
周期→光度→距离：消光改正

（内禀缺陷+统计弥散）

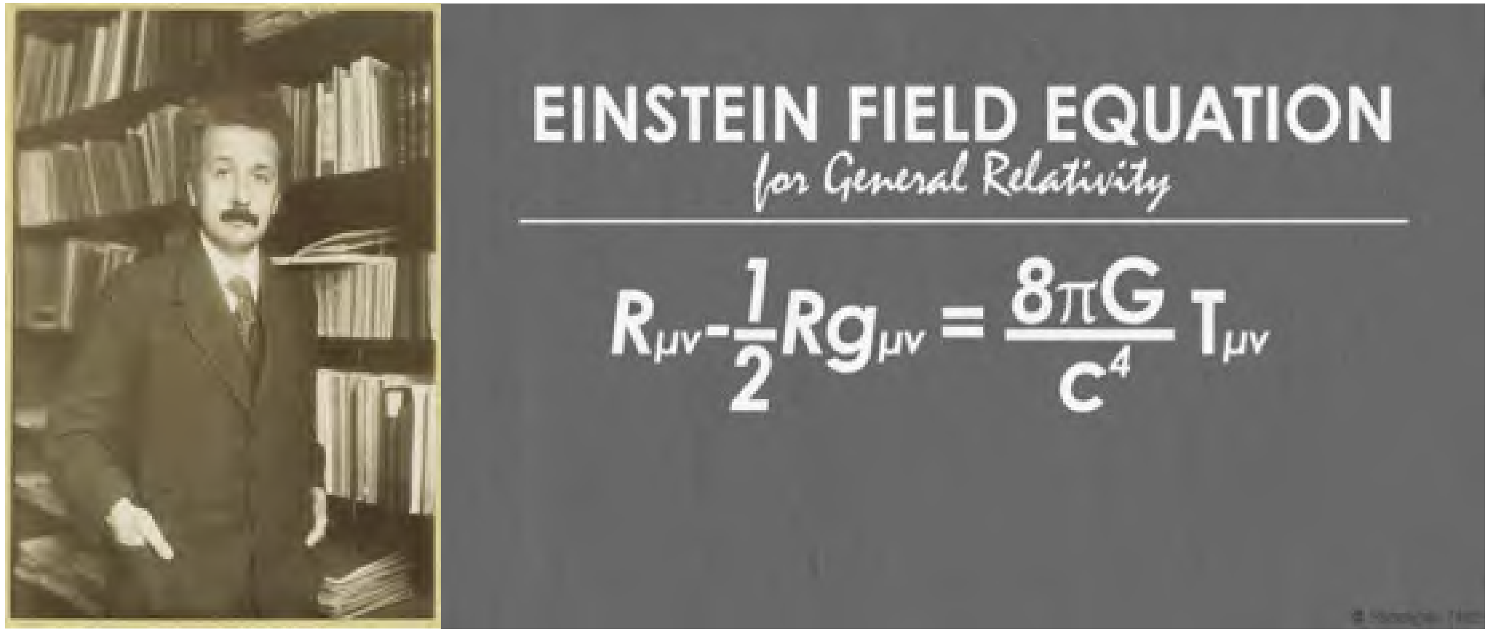
Hubble定律90周年



1）河外星系；2）宇宙膨胀



宇宙动力学方程

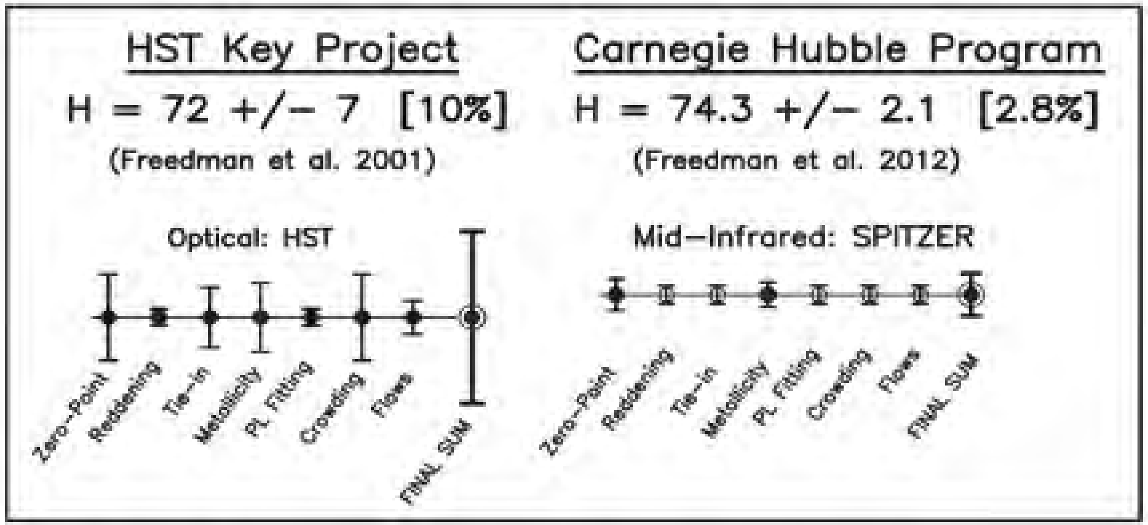


$$R_{\mu\nu}-\frac{1}{2}g_{\mu\nu}R-\Lambda g_{\mu\nu}=\frac{8\pi G}{c^4}T_{\mu\nu}$$

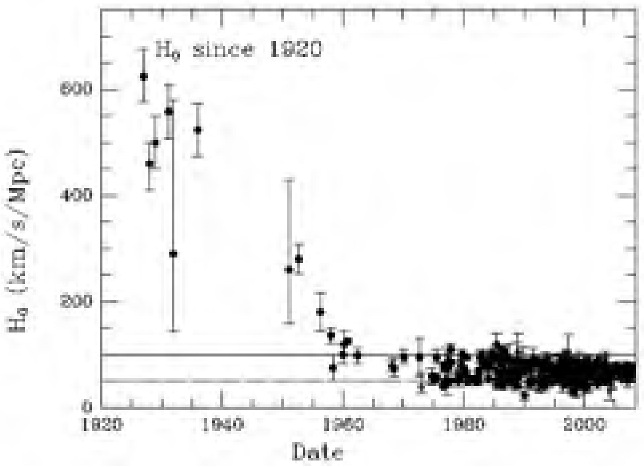
???

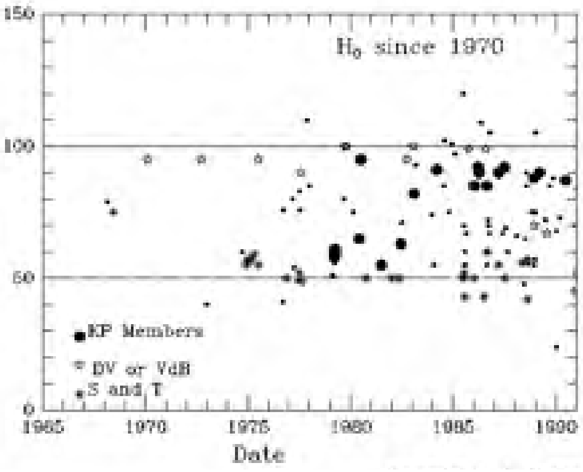
爱因斯坦一生中最大的错误

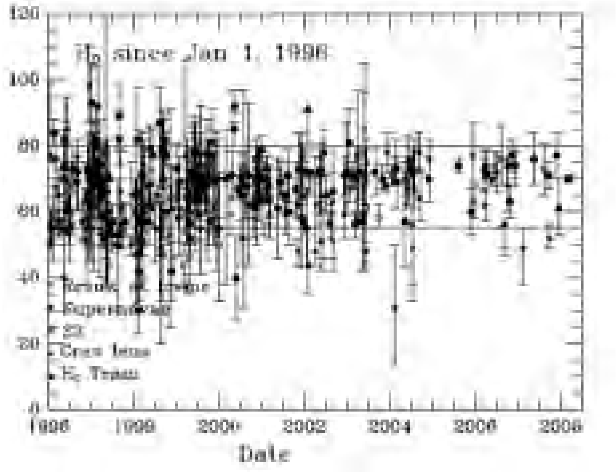
哈勃望远镜：造父变星测距



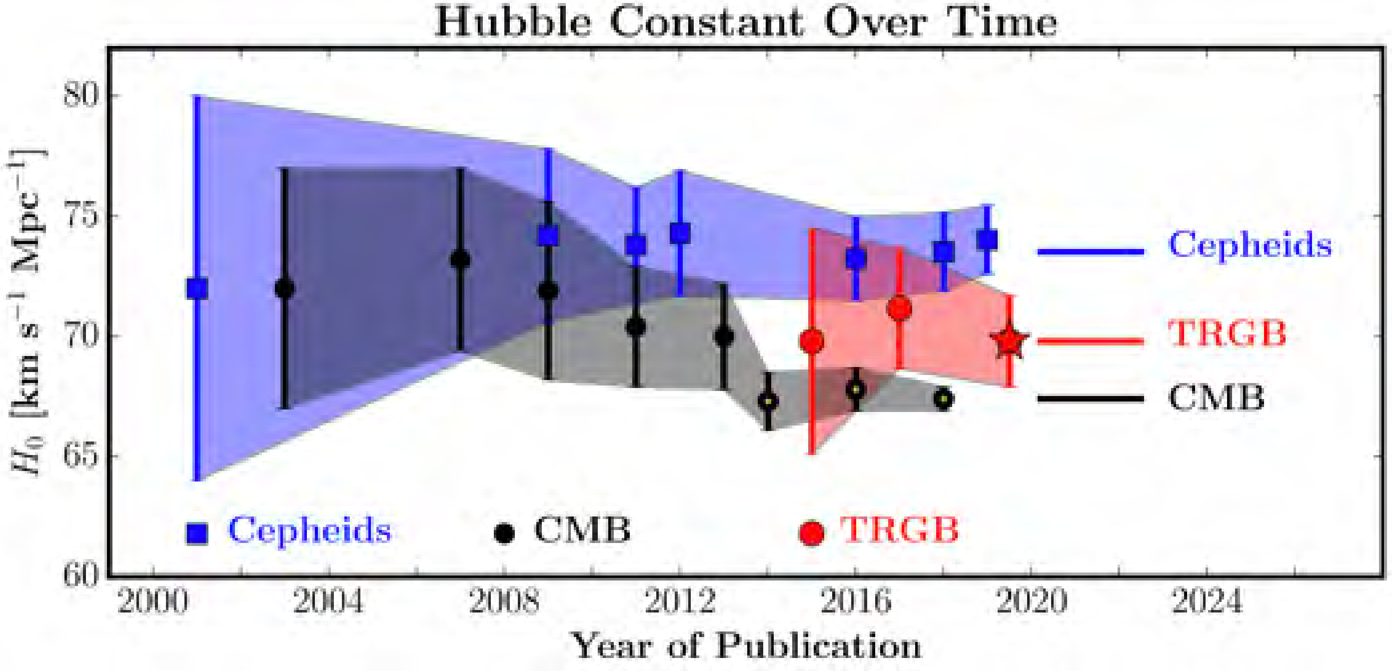
哈勃常数：最新测量

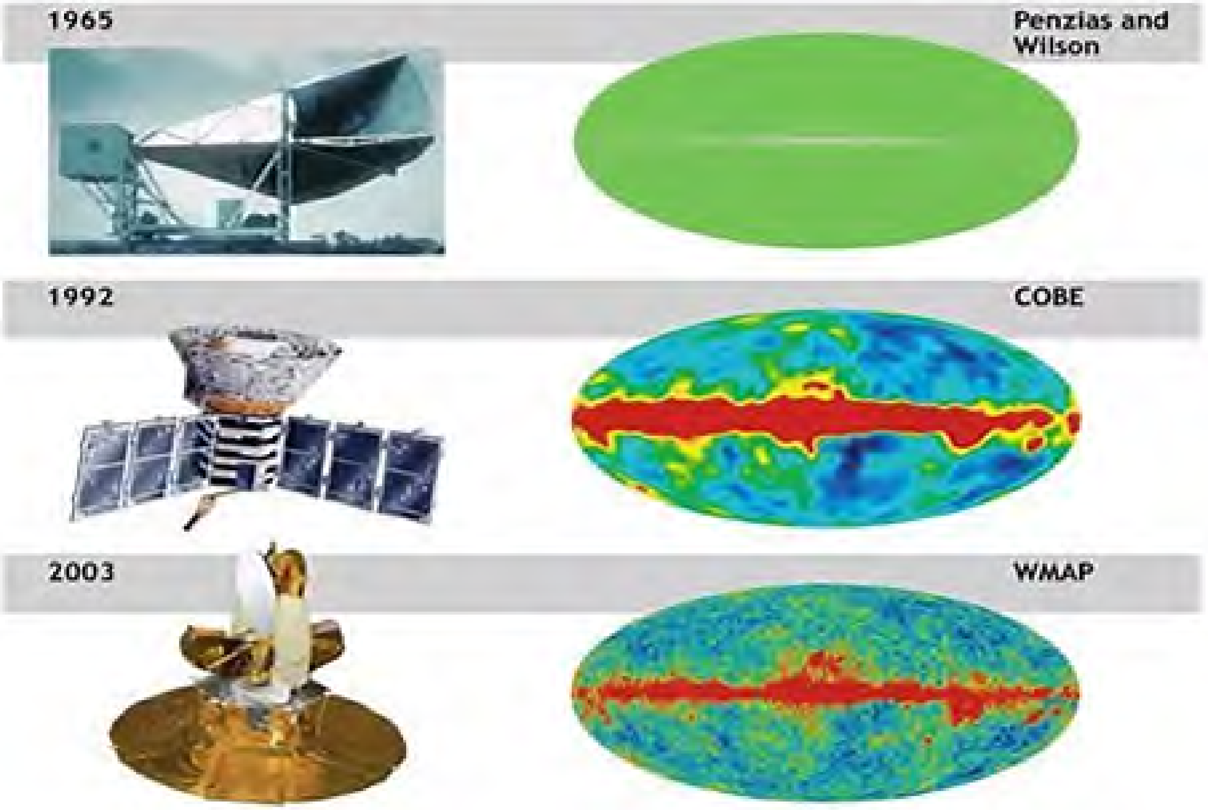




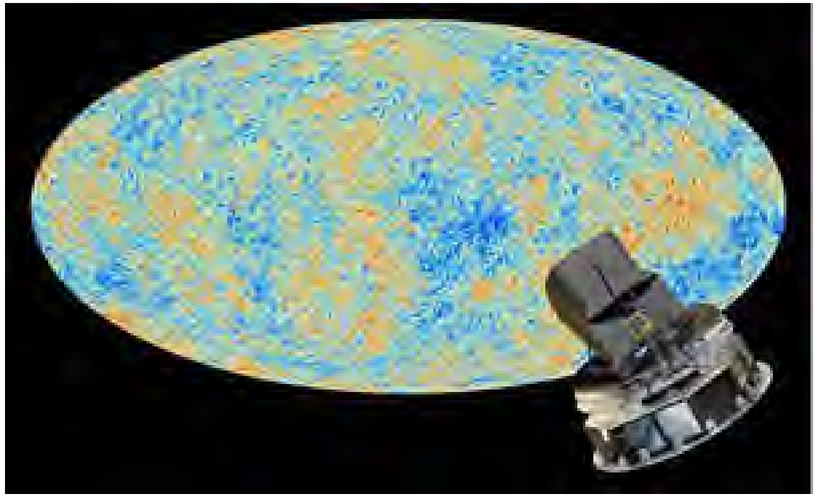


W. Freedman





Planck卫星



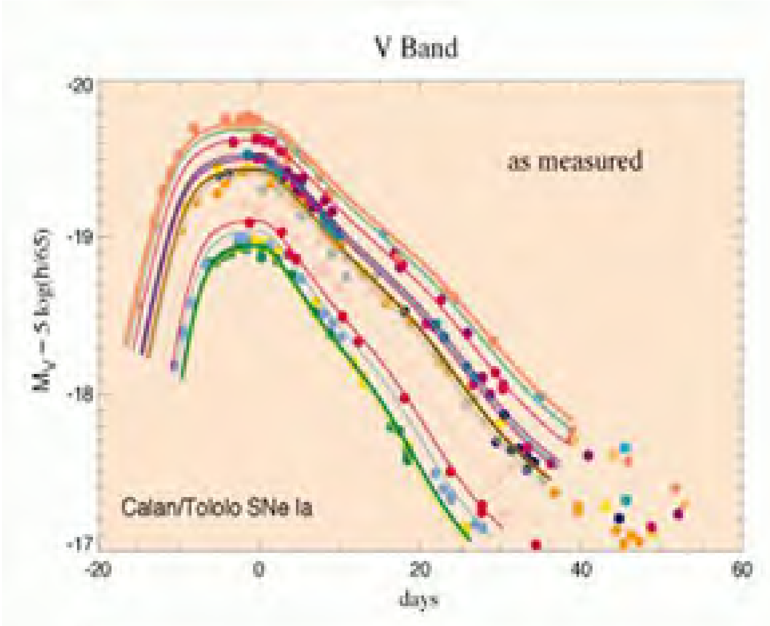
$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R - \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

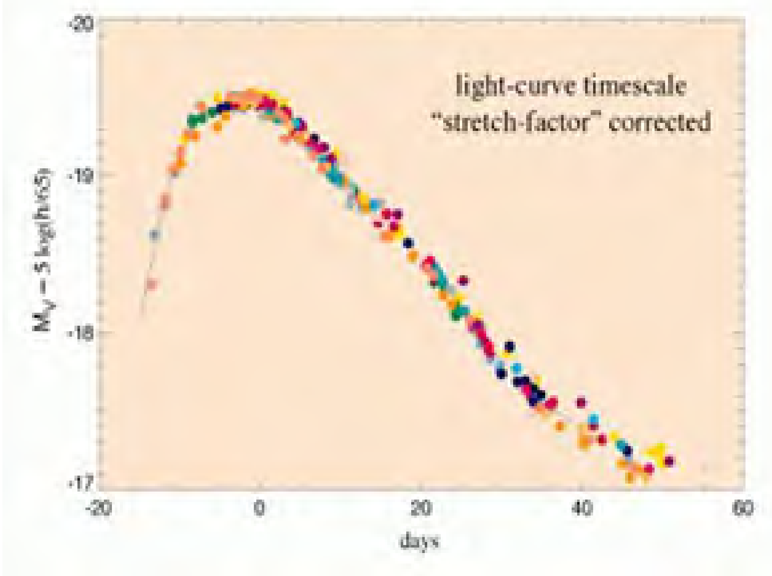
精度：~ 0.7%

丈量宇宙：Ia型超新星

白矮星塌缩、Chandra质量极限

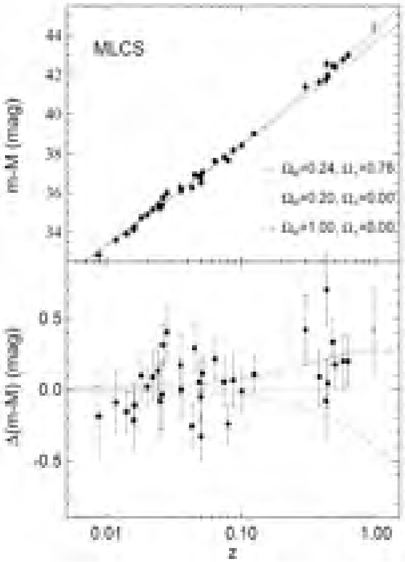
$$M_* = \frac{\omega_3^0\sqrt{3\pi}}{2}\left(\frac{\hbar c}{G}\right)^{3/2}\frac{1}{(\mu_e m_H)^2} \approx 1.43\left(\frac{2}{\mu_e}\right)^2 M_\Theta \qquad F = \frac{L}{4\pi d^2}$$

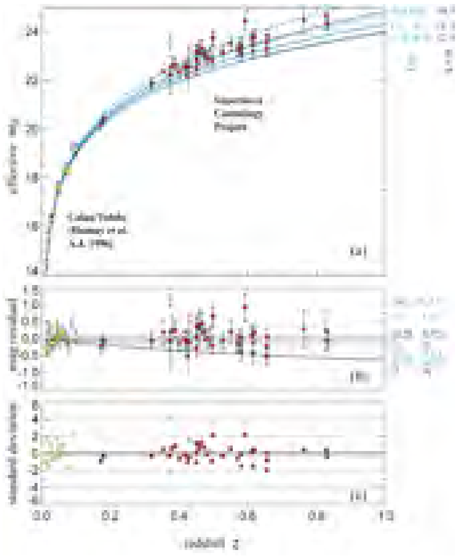


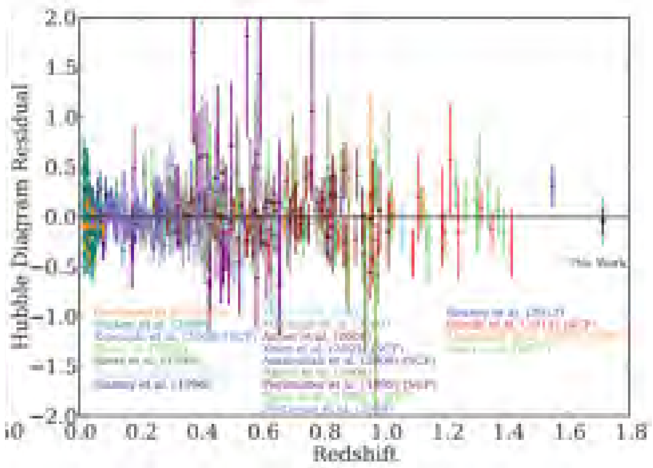


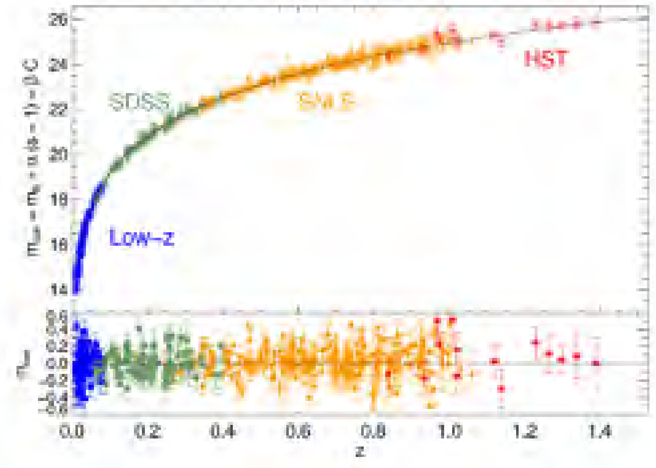
Ia型超新星：宇宙加速膨胀





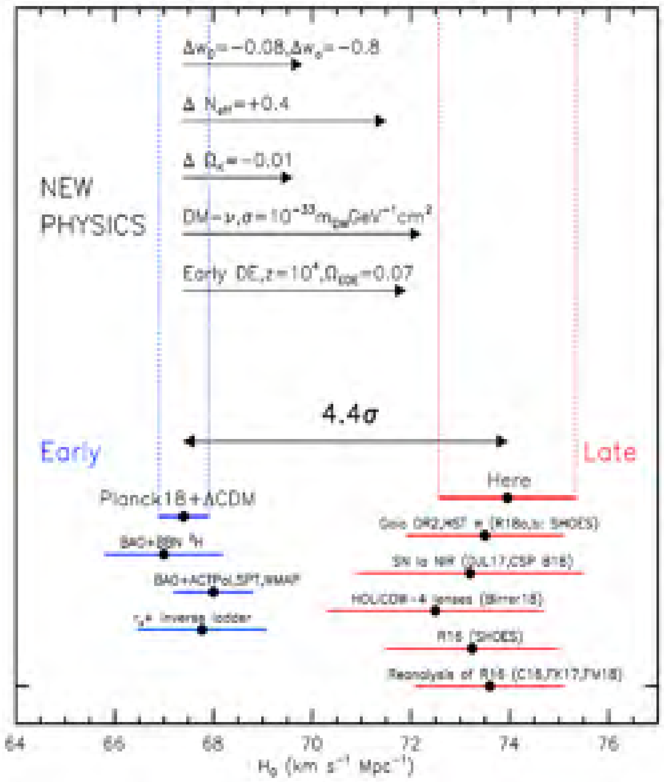


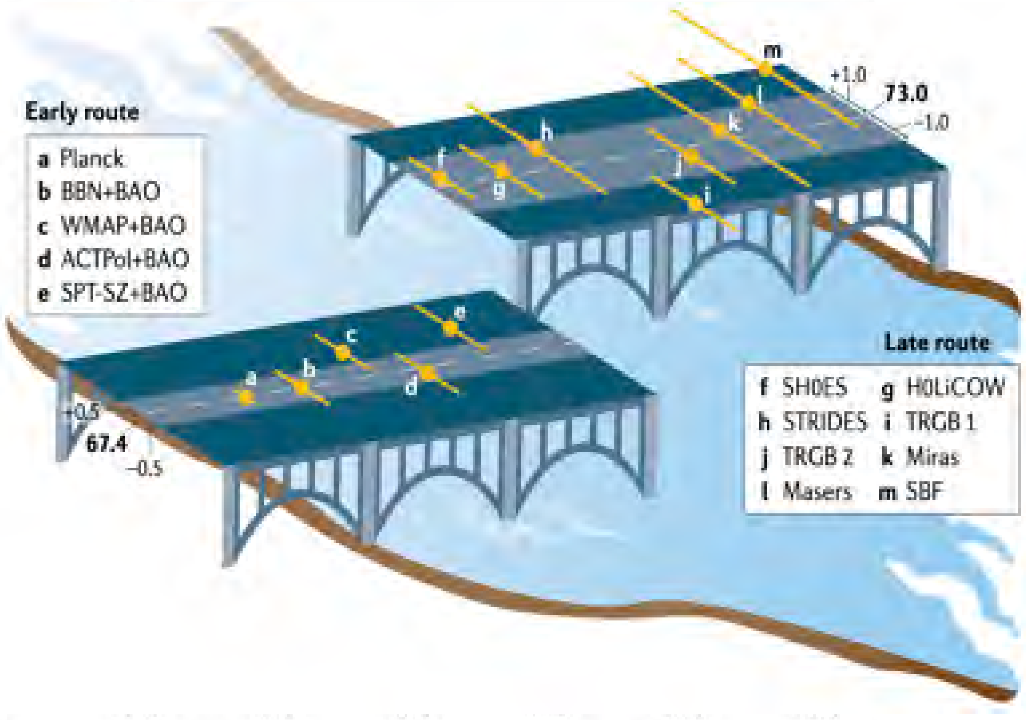




系统误差：消光、红化、标准化、距离阶梯

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！

类星体作为宇宙学探针

经历了十分艰难的历程

(1960s)

Quasars: standard candles

A. Sandage（1965）

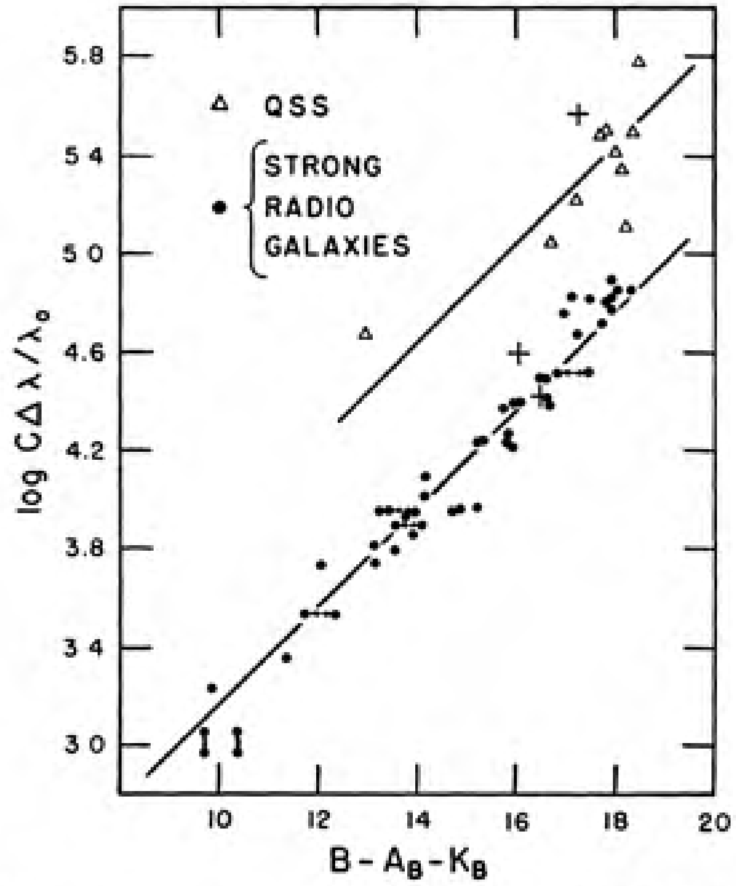


FIG 4.—The redshift-apparent-magnitude relation for strong radio galaxies (*circles*) and for quasi-stellar radio sources (*triangles*). Arrows connect dumbbell galaxies for which the magnitude of the bright component and of the two components combined is given. Correction for K-dimming has been applied to the galaxies. No K-correction has been applied for the quasi-stellar sources. The three crosses are discussed in § IV.

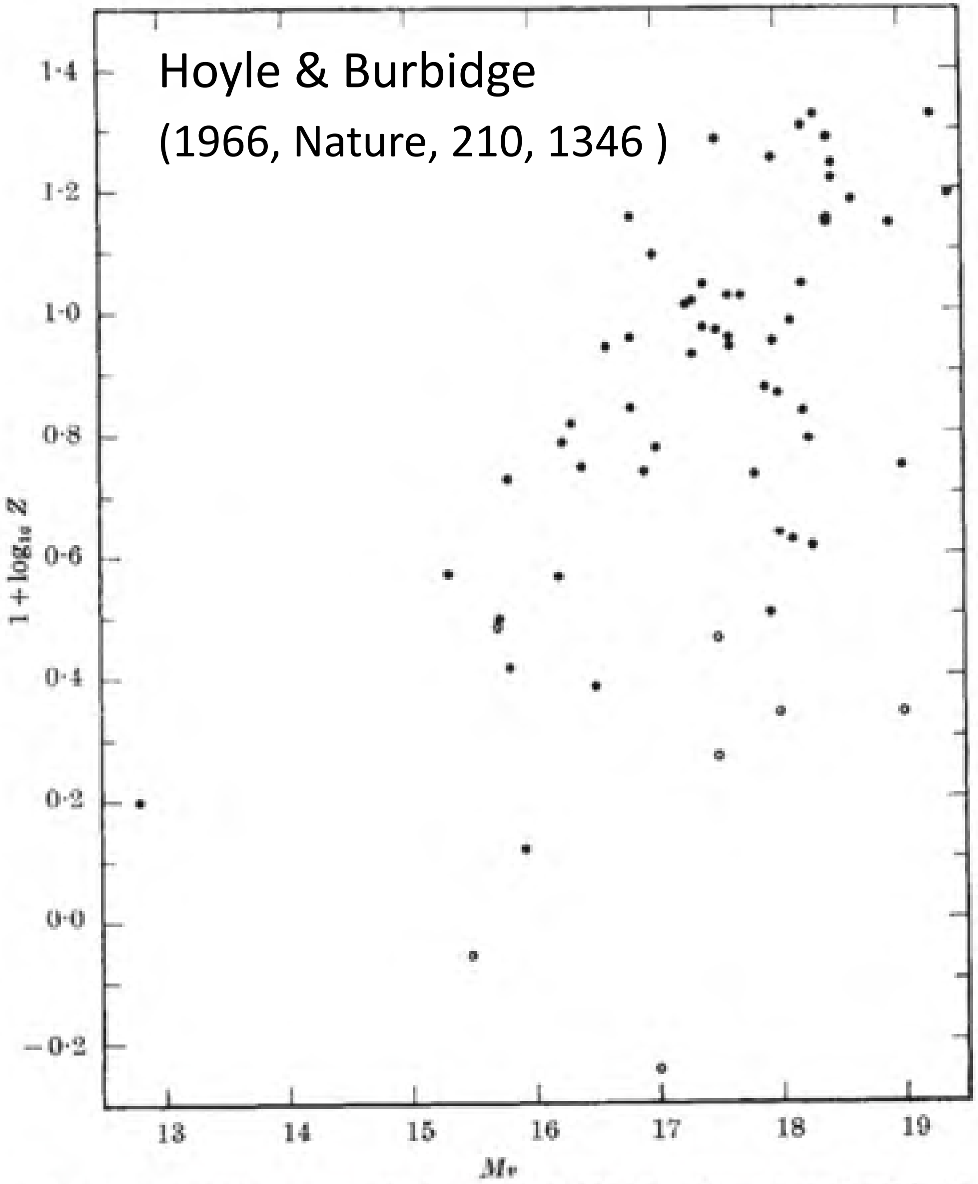


Fig. 3. Red-shift versus optical magnitude (M_v) for all quasi-stellar objects and N-type galaxies for which data are available. The list is compiled from published data from the observers working at Kitt Peak Observatory, Lick Observatory and Palomar Observatory. A large proportion of the objects are given in ref. 1. Others have been obtained from a list compiled by Burbidge, E. M., Lynds, C. R., and Schmidt, M., at the International Astronomical Union symposium in Erevan in May 1966

Red-shift Magnitude Relation for Quasi-stellar Objects

by

M. S. LONGAIR
P. A. G. SCHEUER

Cavendish Laboratory,
Free School Lane,
Cambridge

A red-shift magnitude correlation for quasi-stellar objects exists, but it does not imply a red-shift distance relation. If the red-shifts of quasi-stellar objects are cosmological their mean optical magnitude has changed with epoch.

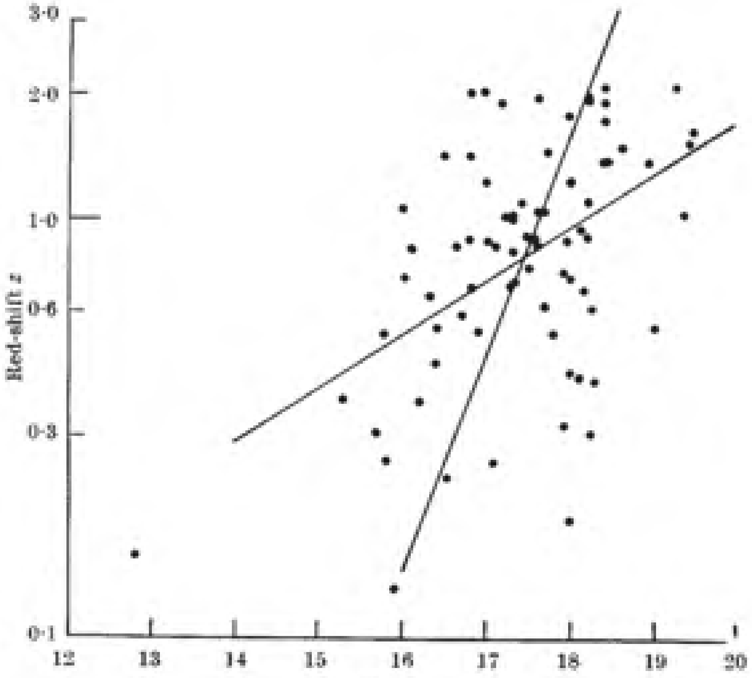


Fig. 2. Red-shift versus m_v. The regression lines are shown; the correlation coefficient is +0·489, and is significant at the 0·1 per cent level. The values of m_v are taken from ref. 2.

Schmidt (1968)

M. Schmidt

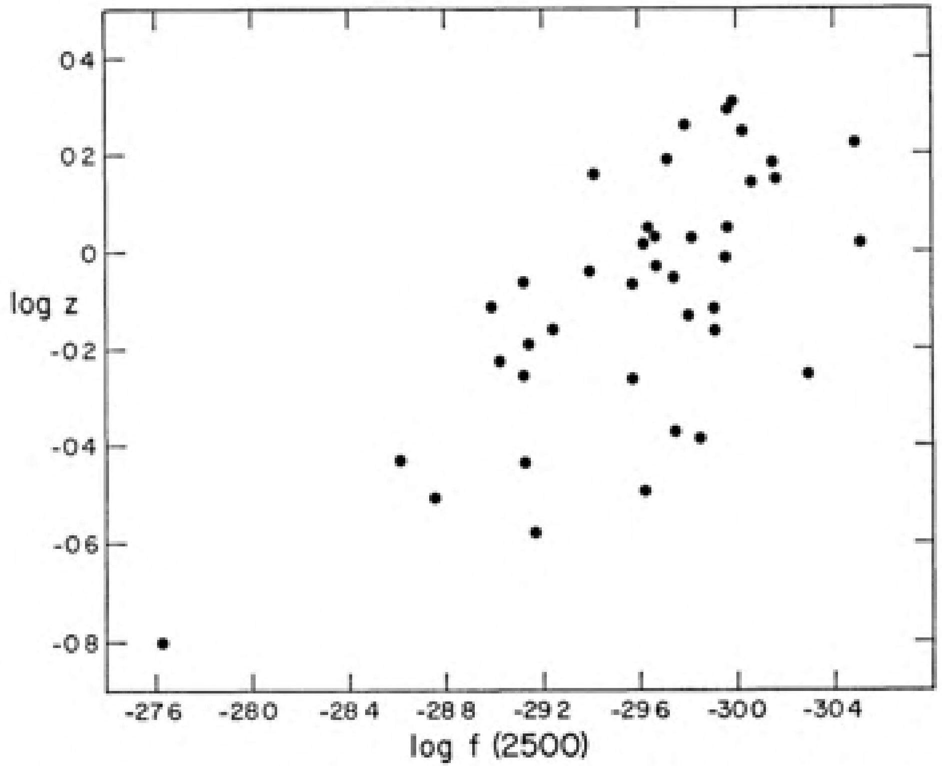


Fig. 2.—Redshift-magnitude diagram for 40 3CR QSS The flux density $f(2500)$ is measured at emitted wavelength 2500 Å over a band width of 1 c/s emitted, in units of W m^{-2} $(c/s)^{-1}$.

Bahcall & Hills (1973)

J.Bahcall

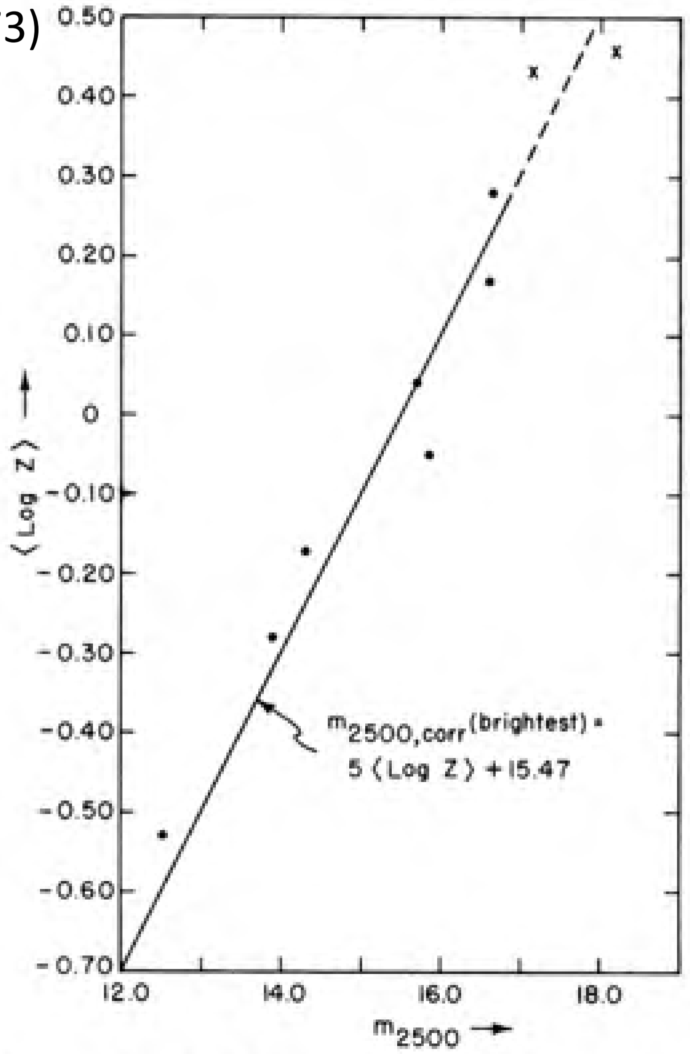


FIG. 1.—The Hubble diagram for the brightest of 105 quasars. The circles rep
sically brightest quasars (for $q_0 = +1$) in successive redshift bins containing 15
brightest objects are, respectively, 3C 273, 3C 232, PKS 1354+19, PKS 1252+1
3C 298, and TON 1530. The two crosses represent the large-redshift quasars PH
and PHL 938 ($z = 2.88$); they were not included in the analysis. The parameters
= 19.5 mag, bin size = 15, and log $F_{\min}$ = 22.4 clusters. The plotted points i
corrections. The straight line in figure 1 corresponds to objects ~5 mag brighter
cluster galaxies (i.e., log F = 24.2).

THE ASTROPHYSICAL JOURNAL, 183:759–766, 1973 August 1

THE REDSHIFT-MAGNITUDE RELATION FOR QUASI-STELLAR OBJECTS

G. R. BURBIDGE AND S. L. O'DELL
Department of Physics, University of California at San Diego
Received 1972 December 5; revised 1973 February 21

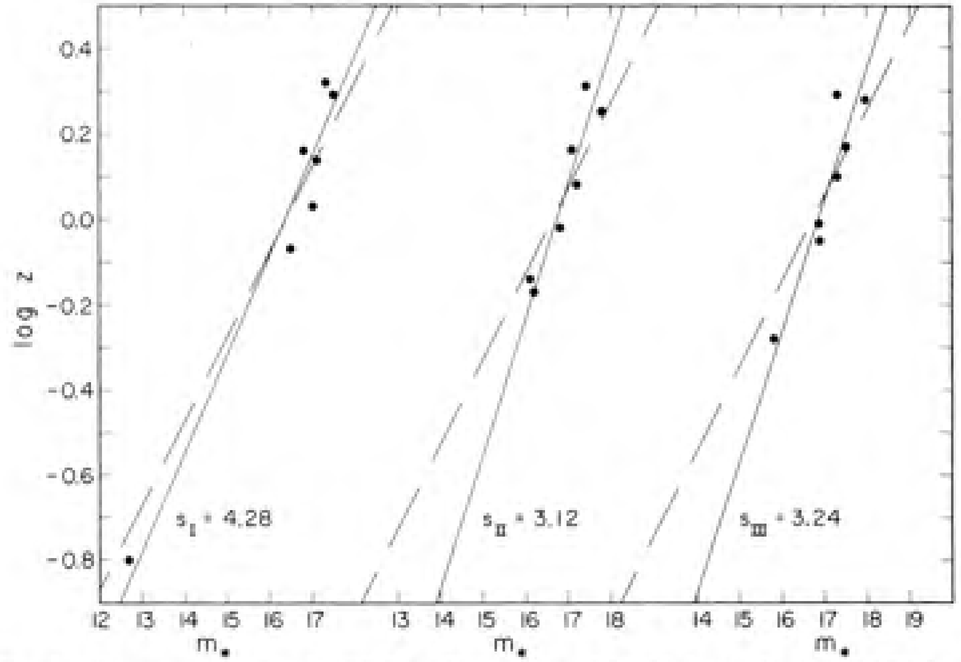
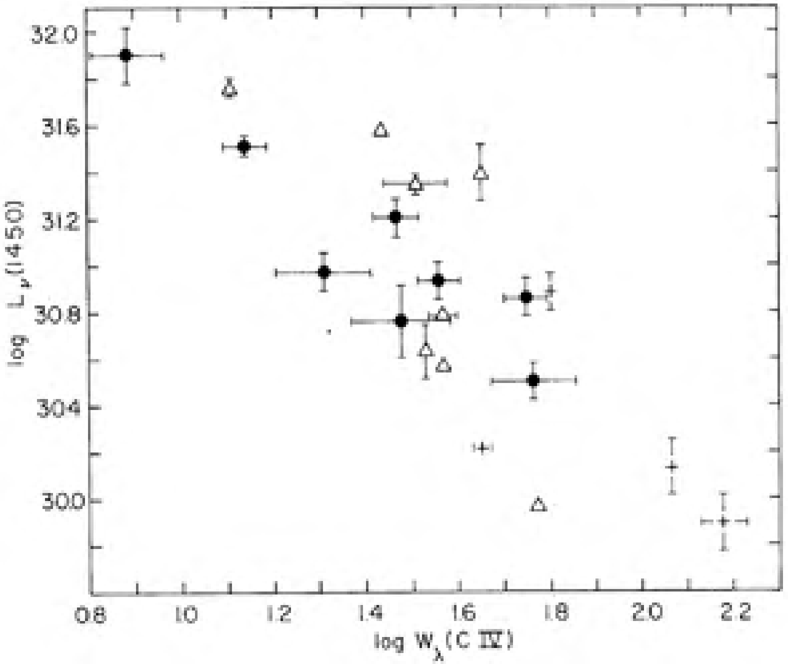


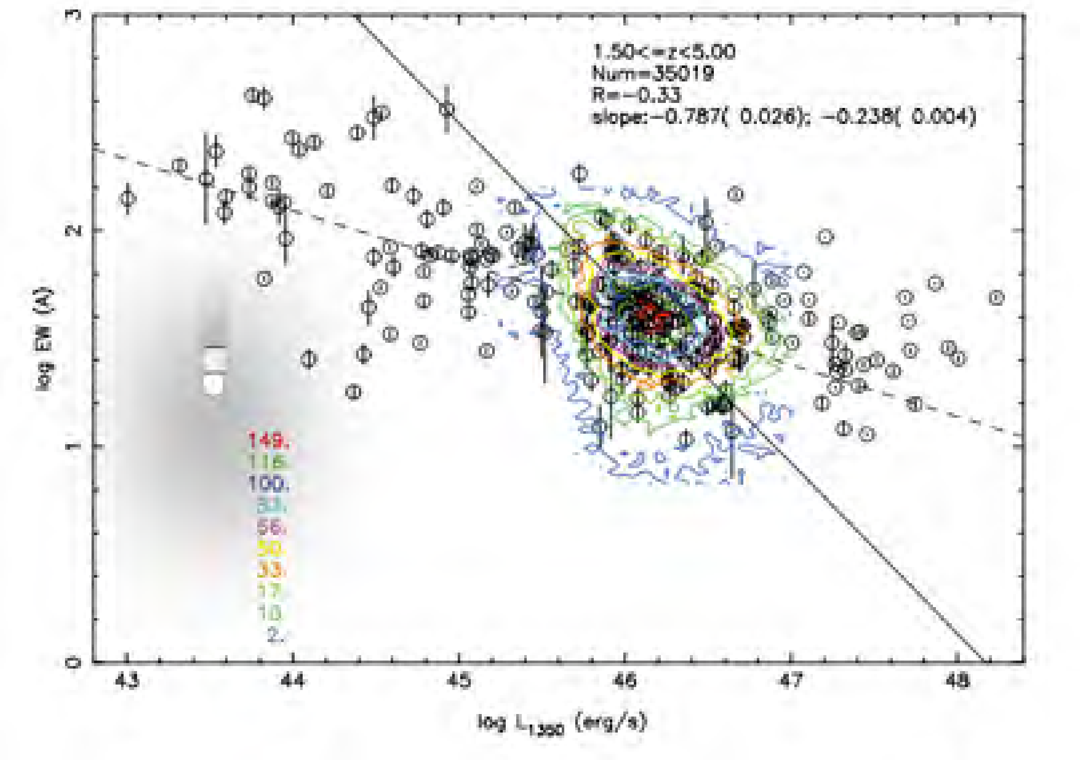
FIG. 2.—(log z, m_*)-diagram for (*a*) first, (*b*) second, and (*c*) third most luminous QSO in each group of 10 brighter than 18.0 + 5 log z. *Solid line*, the best-fitting slope for each luminosity class; *Dashed line*, predicted slope (5.0 mag per decade).

Baldwin 效应



Baldwin et al. (1977, 1978)

Baldwin effects in SDSS (Bian et al. 2012)



Baldwin+1981: BPT图 (>3300citations)

引力论和宇宙论

广义相对论的原理和应用

〔美〕S. 温伯格 著

来，许多射电源被证认为类星体。这种光源的角直径小到在 Palomar 都分辨不开。Schmidt 发现，其中有一个源 3C273 的红移 $z=0.158$，对应的光度距离(如果取 $H_0=75$km/sec/Mpc)是 630M……

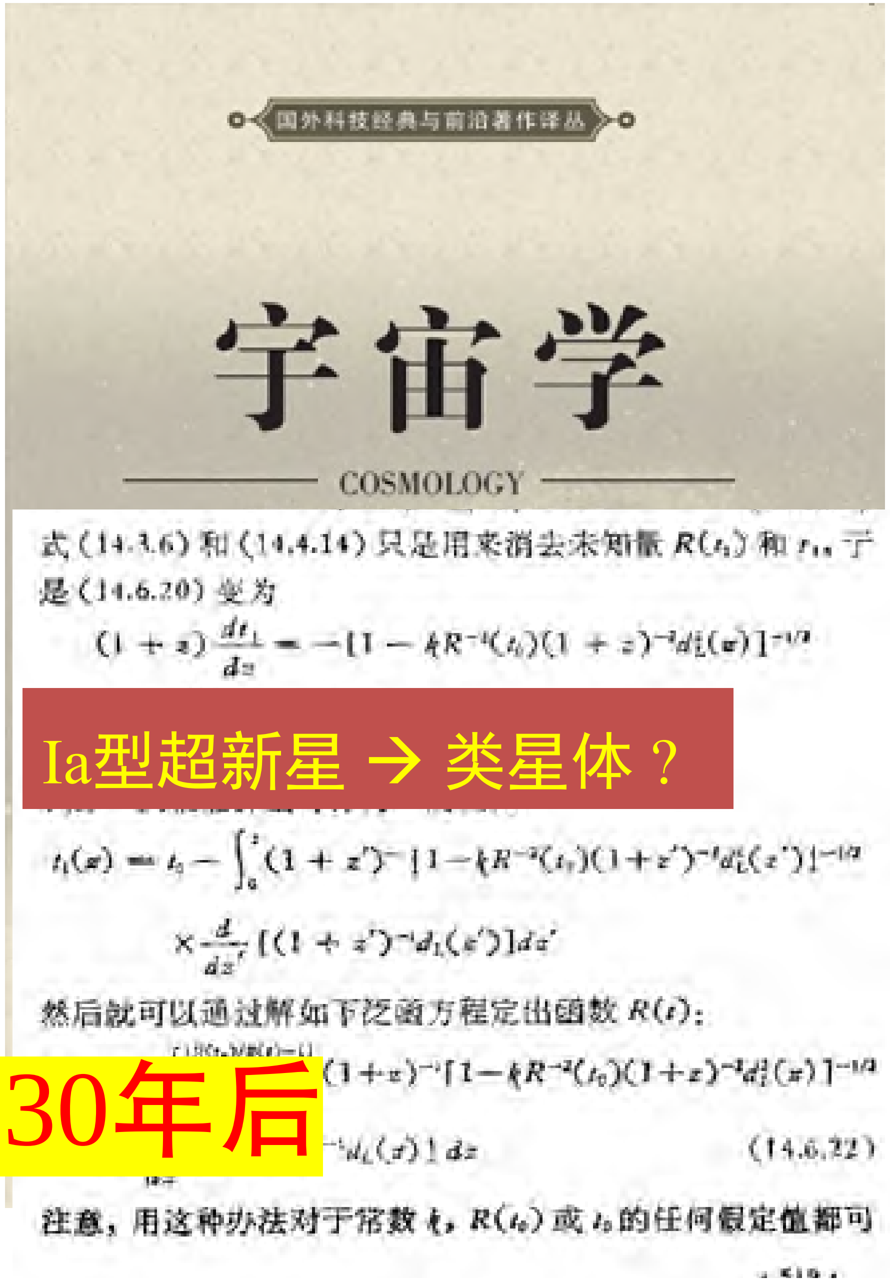
的都大……

150""pc……

中相当大一部分 $z>1$，少数 $z>2$。与此同时，月掩法和长基线射电干涉的应用，以及短周期时变的观测，弄清楚了这些天体的巨大能量输出主要来自直径远小于 1pc 的区域。因此，类星体的发现引起了人们对于在第十一章中已讨论过的引力坍缩理论的兴趣。它也开辟了把 d_L 和 z 之间的经验关系延伸到真正巨大的距离和红移去的可能性，……方法测定类星体的绝对光度。

可惜，《m_v-lg z》图没有显示出……关[32,34]。如果类星体确实处在宇宙学距离(关于这一点仍然

· 518 ·



国外科技经典与前沿著作译丛

宇宙学

COSMOLOGY

式(14.3.6)和(14.4.14)只是用来消去未知量 $R(t_1)$ 和 r_1，于是(14.6.20)变为

$$(1+z)\frac{dt_1}{dz}=-[1-kR^{-2}(t_0)(1+z)^{-2}d_L^2(z)]^{-1/2}$$

然后就可以通过解如下泛函方程定出函数 $R(t)$：

$$(14.6.22)$$

注意，用这种办法对于常数 k，$R(t_0)$ 或 t_0 的任何假定值都可

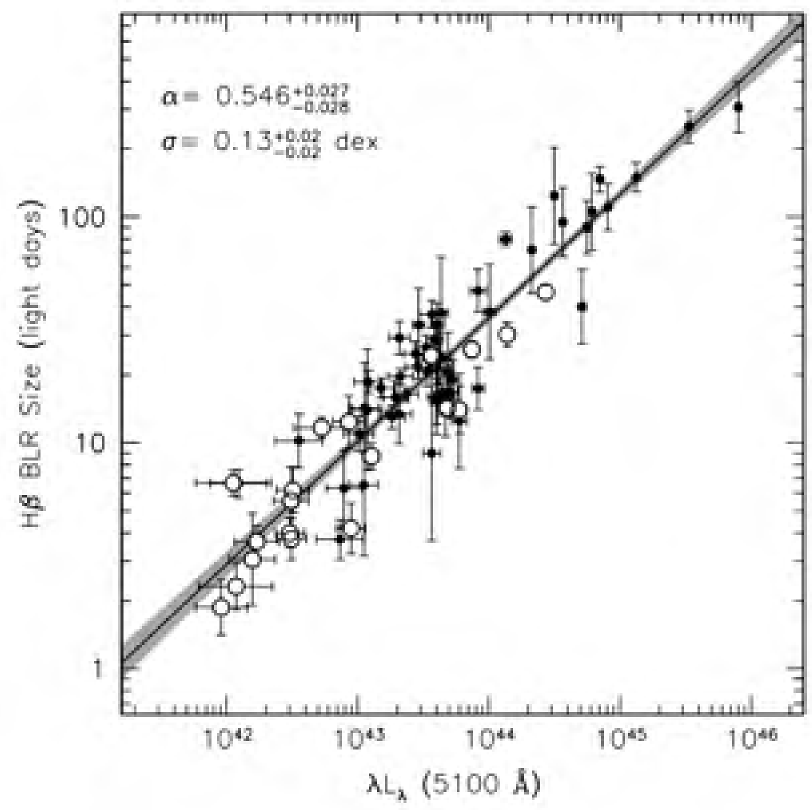
类星体 → Ia型超新星

Ia型超新星 → 类星体？

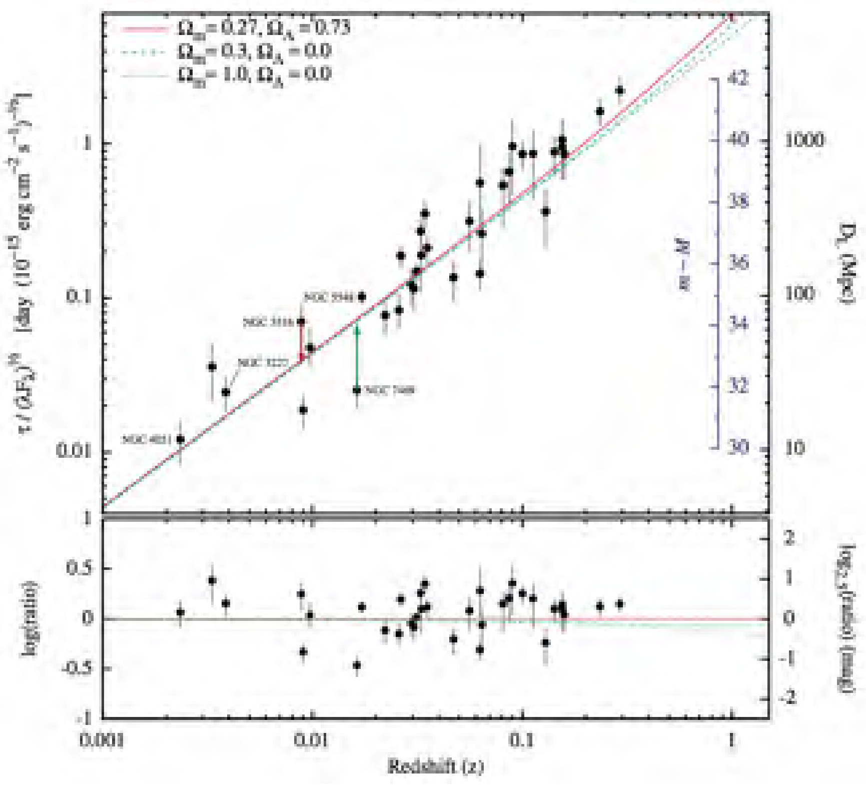
沉寂了30年后

R-L关系：测距

(Kaspi et al. 2000; Bentz et al. 2013)



Watson et al. (2012)



现实困难：1) (1+z) 因子时间很长; 2) 变幅小，很难测。

THE ASTROPHYSICAL JOURNAL LETTERS, 784:L11 (5pp), 2014 March 20
doi:10.1088/2041-8205/784/1/L11

A NEW METHOD FOR MEASURING EXTRAGALACTIC DISTANCES

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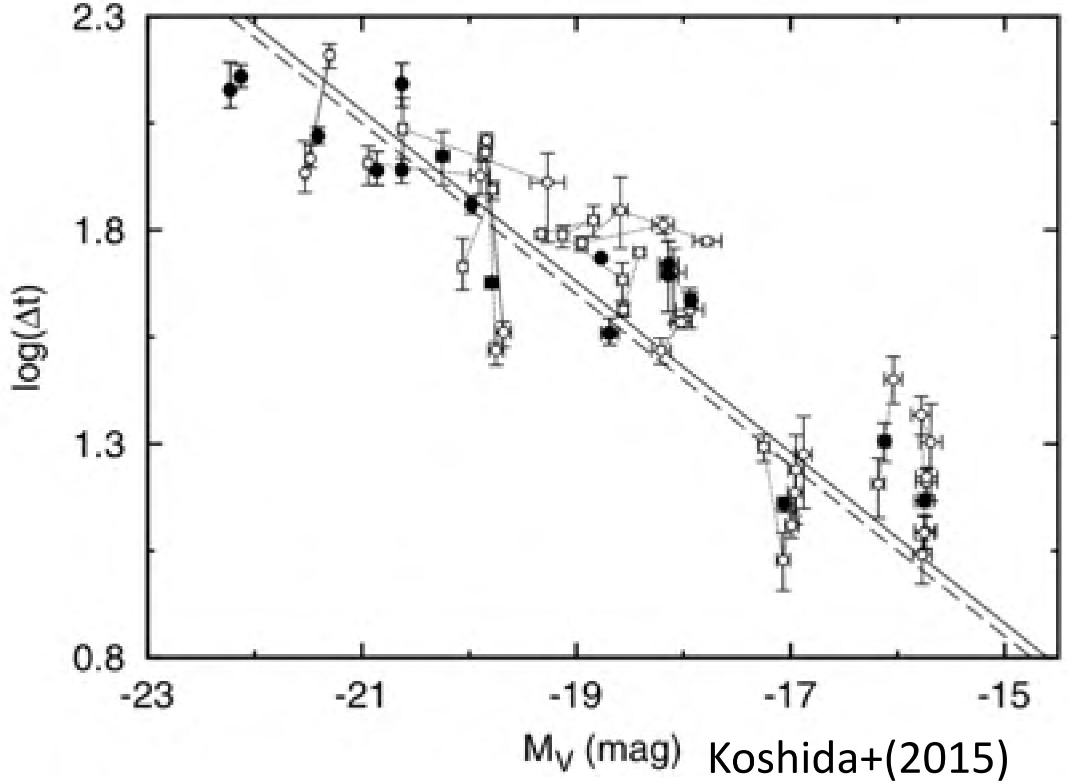
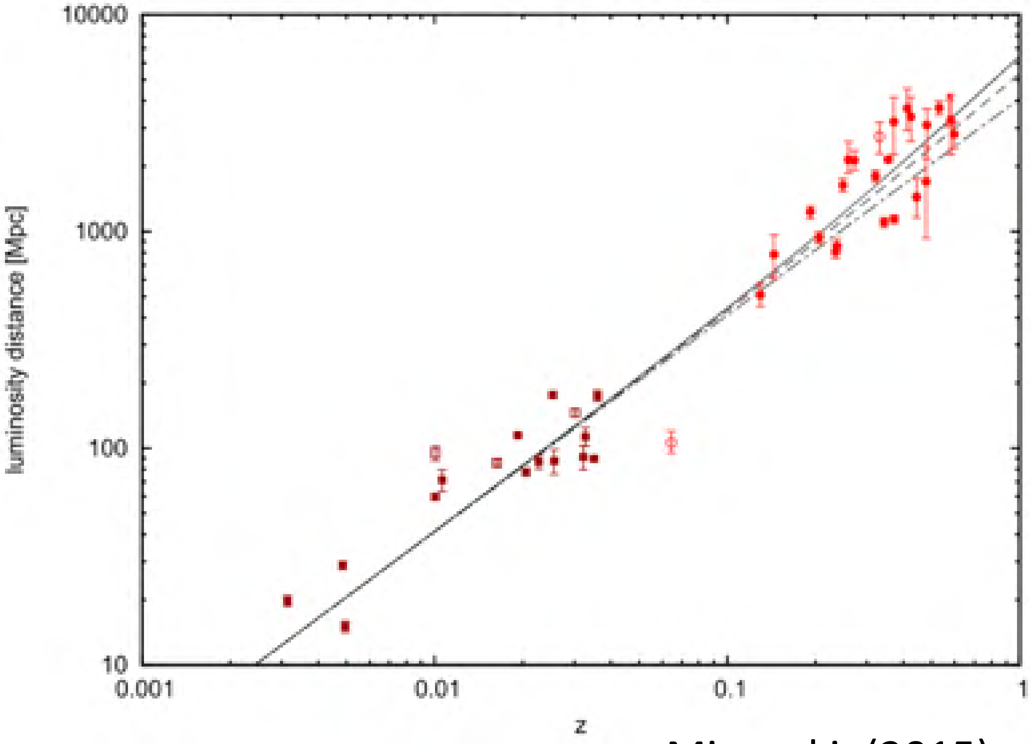
Received 2013 October 15; accepted 2014 February 23; published 2014 March 7



Koshida+(2015)



Minezaki+(2015)

The Astrophysical Journal Letters, 787:L12 (6pp), 2014 May 20 doi:10.1088/2041-8205/787

A NEW COSMOLOGICAL DISTANCE MEASURE USING ACTIVE GALACTIC NUCLEUS X-RAY VARIABILITY

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[1] Dipartimento di Matematica e Fisica, Università Roma Tre, Via della Vasca Navale 84, I-00146, Roma, Italy; lafranca@fis.uniroma3.it
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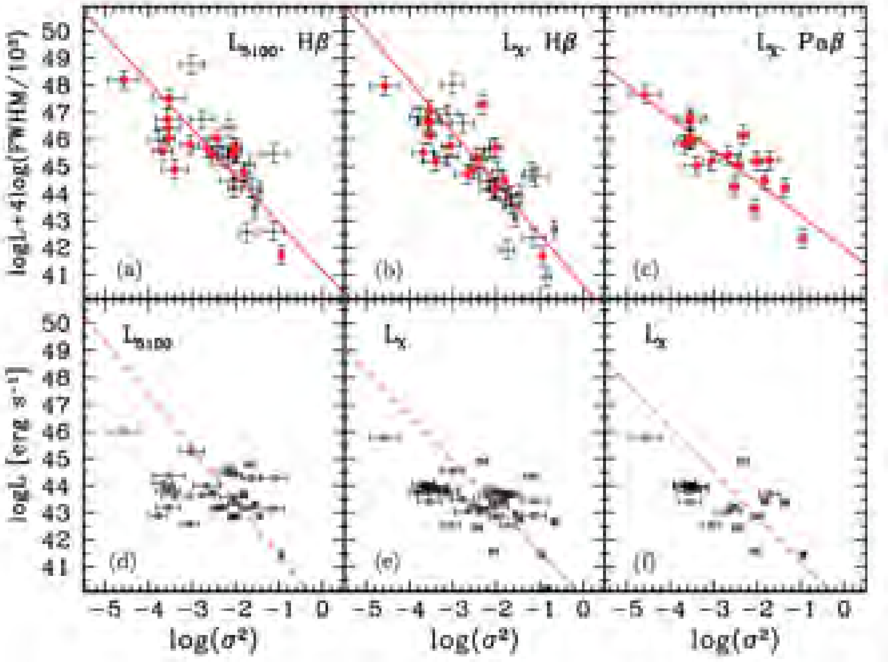
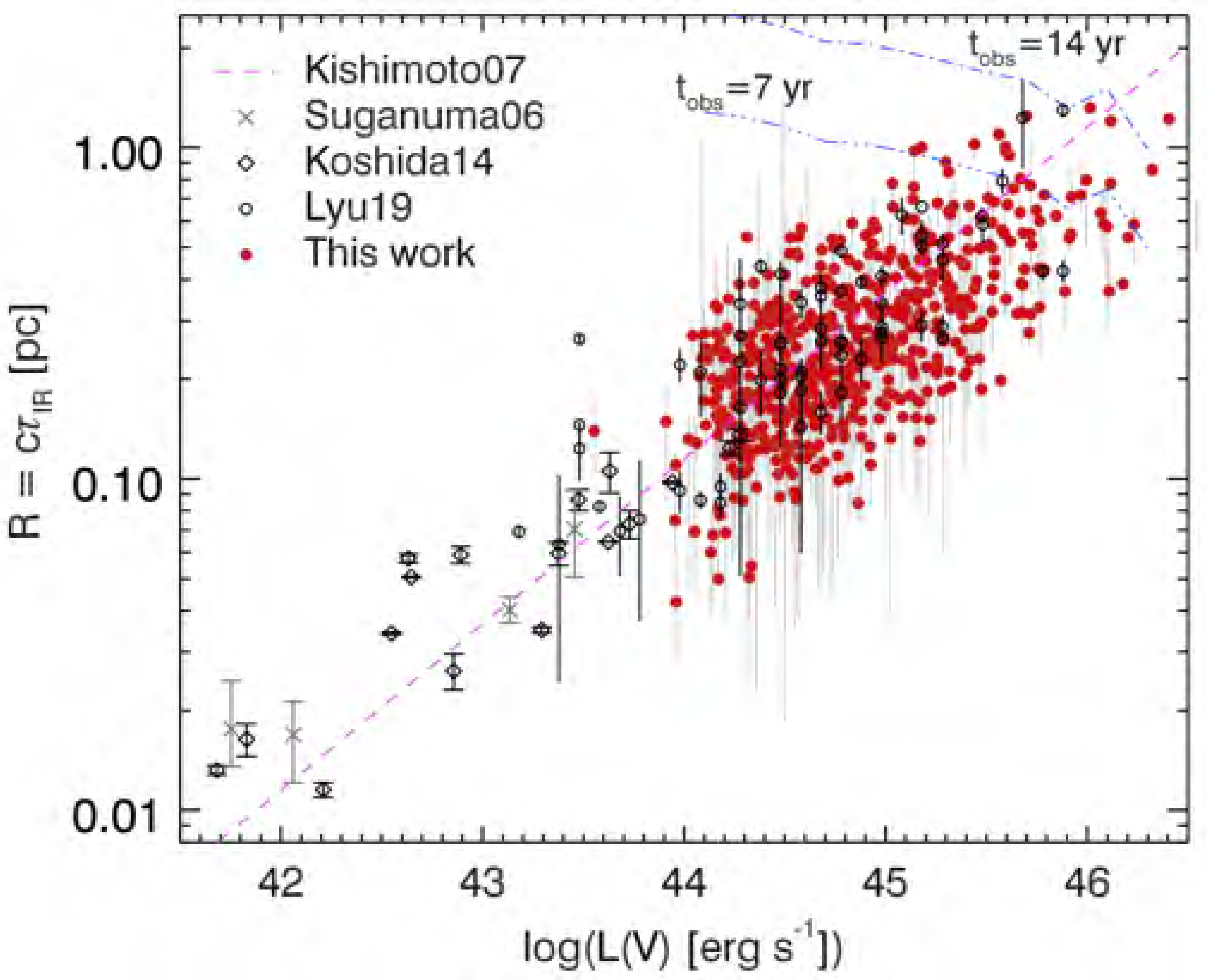
Received 2014 March 18; accepted 2014 April 8; published 2014 May 7



$$\sigma^2_{\rm rms} = \frac{1}{N\mu^2}\Sigma_{i=1}^{N}\left[(X_i-\mu)^2-\sigma_i^2\right], \quad \log\frac{L}{\rm erg\,s^{-1}} + 4\log\frac{\rm FWHM}{10^3\,\rm km\,s^{-1}} = \alpha\log\sigma^2_{\rm rms}+\beta,$$

SDSS(Strip82) + WISE (Yang+2020)



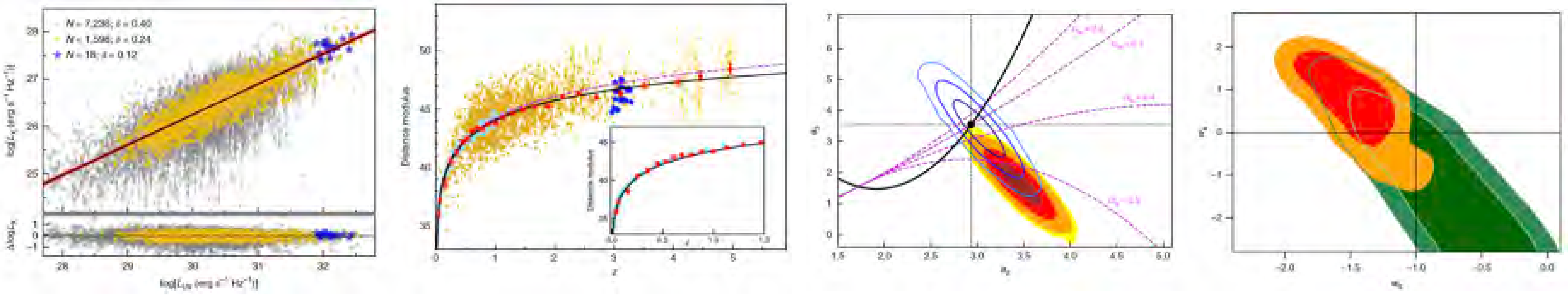
用于测量距离：

如何提高精度?

TERS
https://doi.org/10.1038/s41550-018-0657-z
nature astronomy

Cosmological constraints from the Hubble diagram of quasars at high redshifts

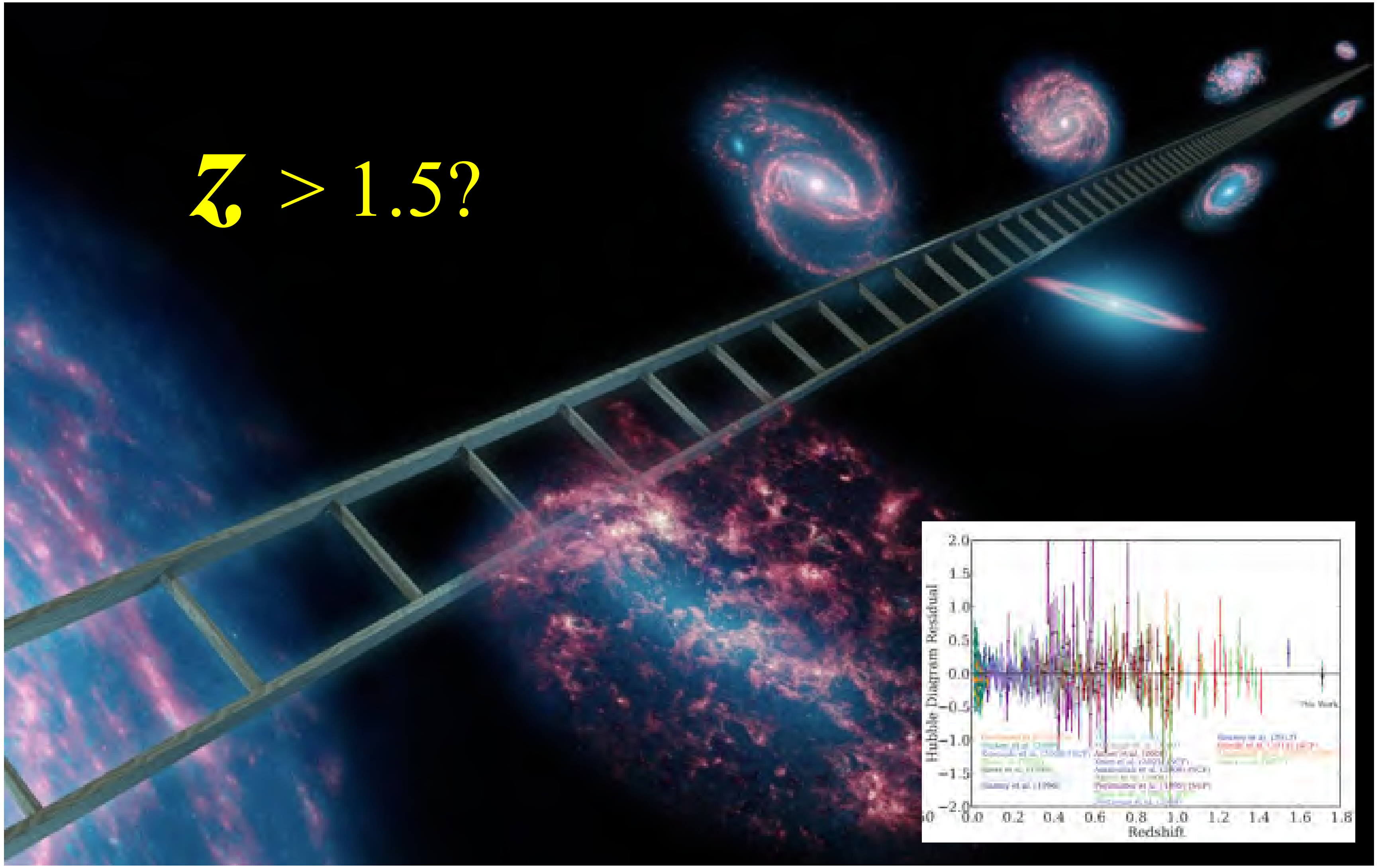
G. Risaliti [1,2]* and E. Lusso [3]

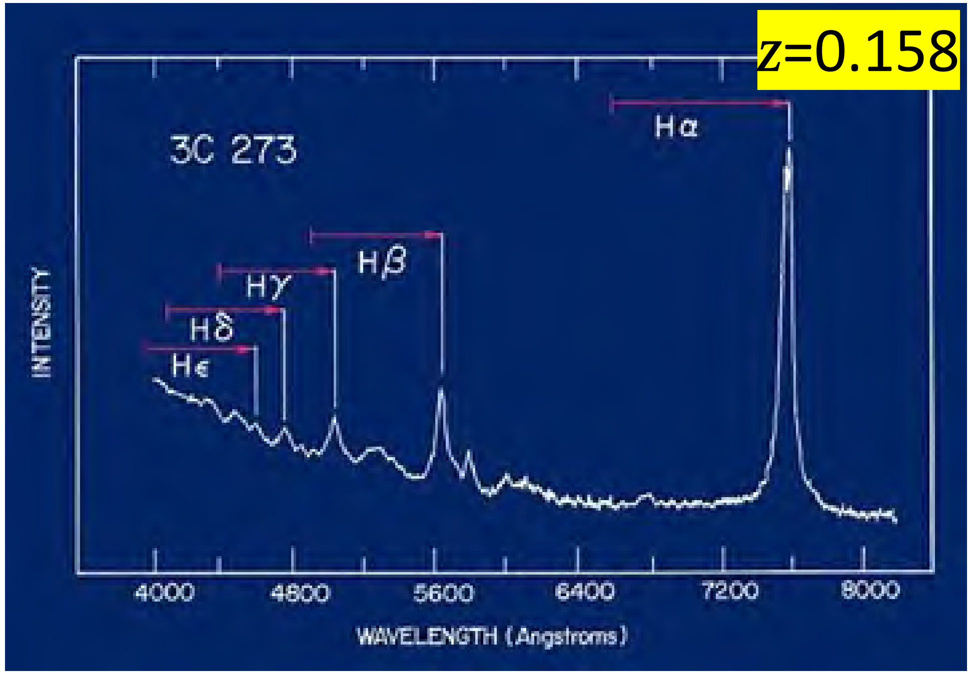


重温S. Weinberg（1972）

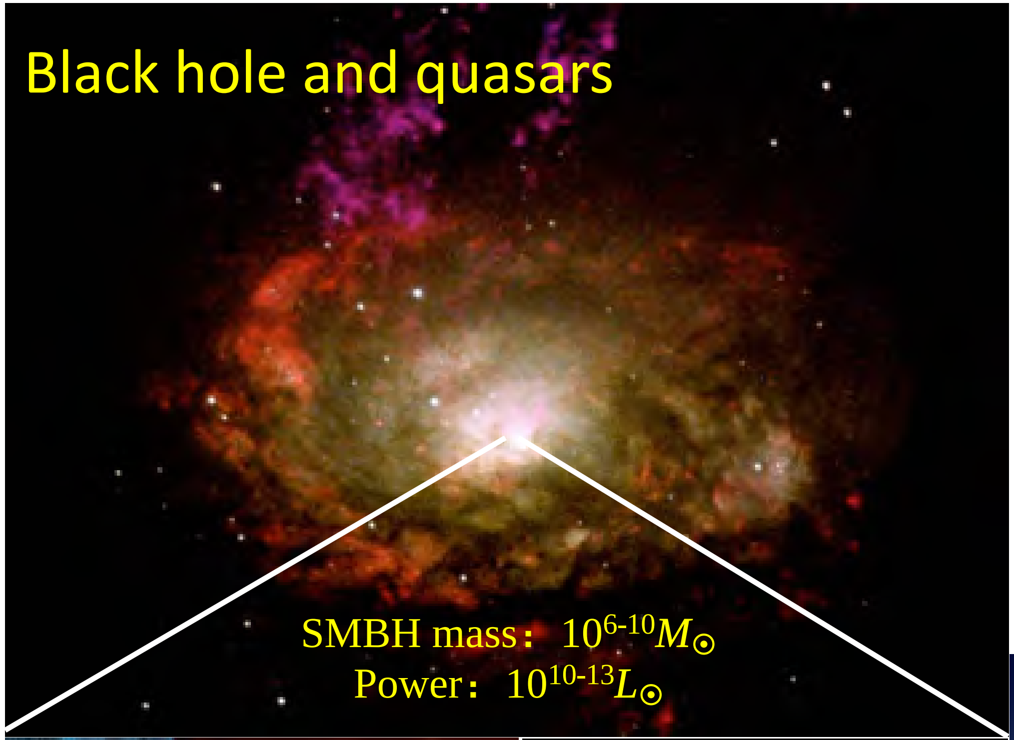
存在某些疑问[49,43]），那么它们的绝对星等就一定有很大弥散，只有当我们学会了如何区分不同绝对光度的类星体时，把类星体的红移同视星等作比较才会具有宇宙学上的意义。

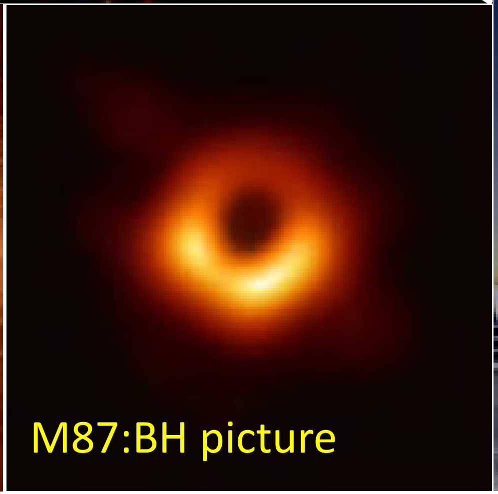
距离阶梯中断：类星体时代？

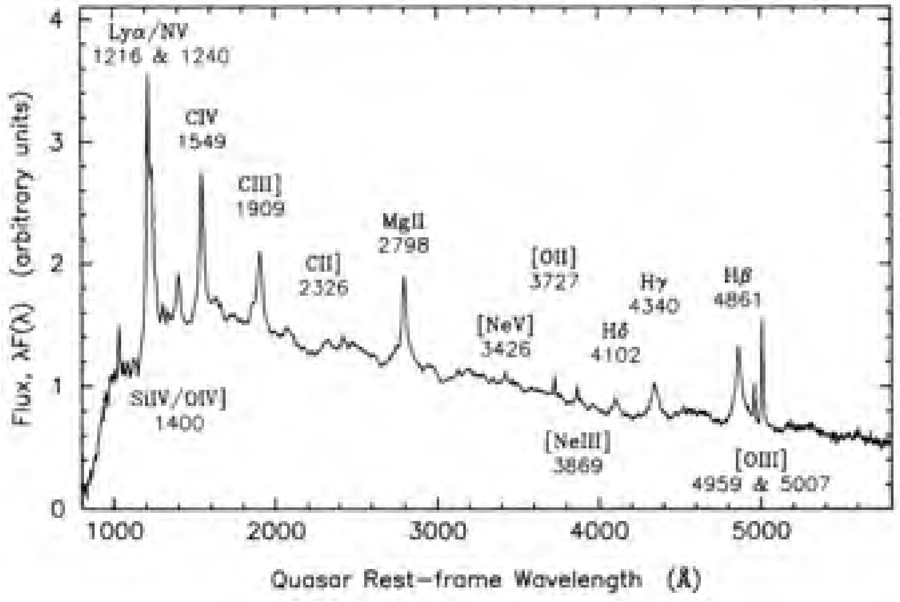




- 宇宙学红移
- 黑洞吸积：能源机制
- 反响映射：质量
- 共同演化
- 宽线区结构：VLT-GRAVITY







~ 1million QSOs

RM campaigns: ~100AGNs

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。

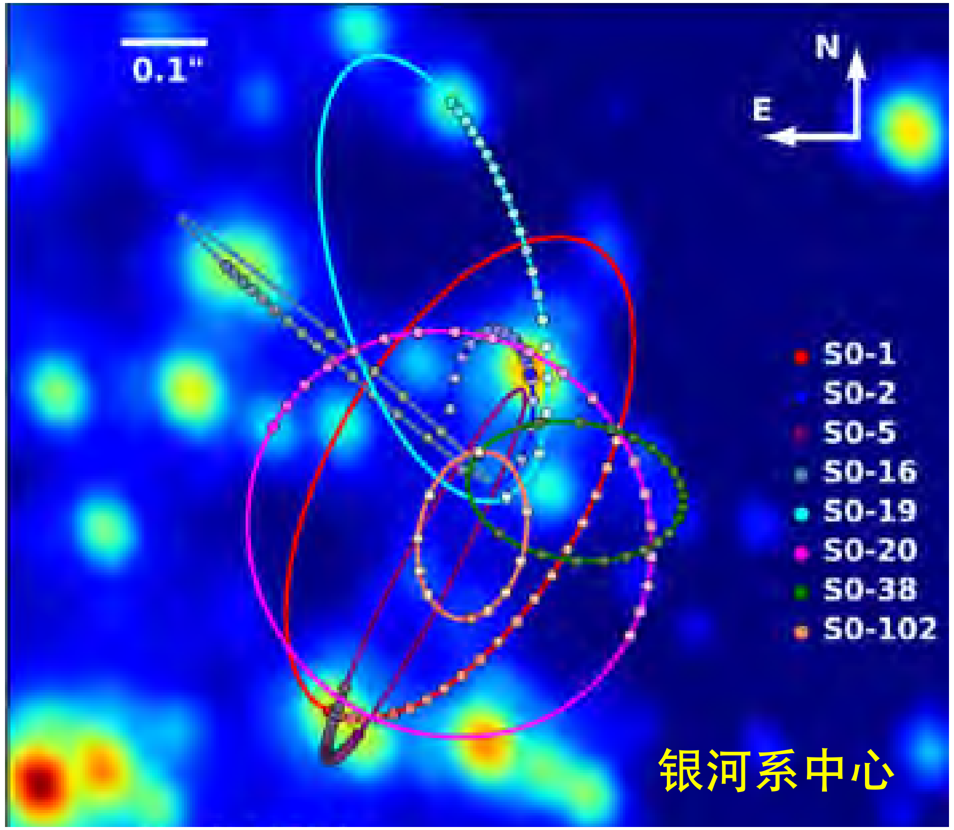
$$D = \frac{\Delta R}{\Delta\theta} \rightarrow z\text{-}D\text{关系}$$

能够达到的角分辨率：测量线尺度？

VLT干涉：4 $\otimes$ 8 米 (2017)

高空间分辨率：解析宽线区

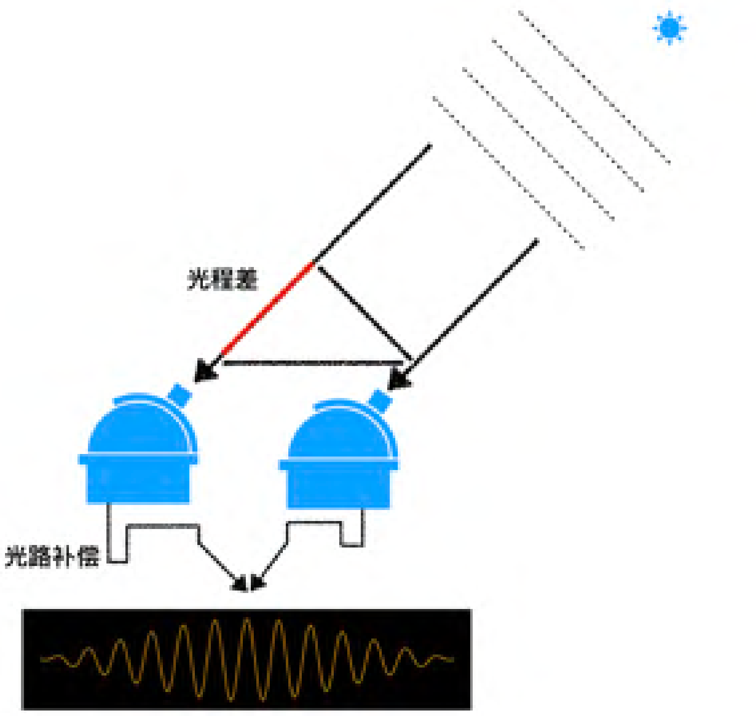
(分辨率:10μas)

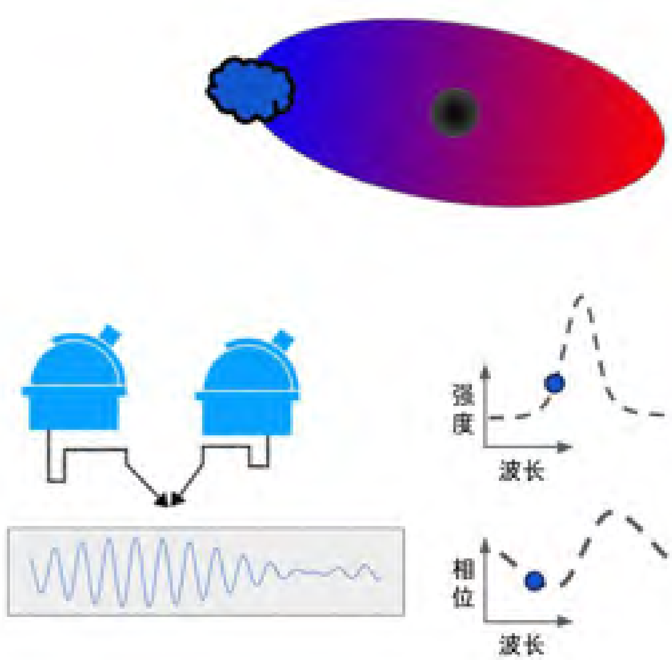


河外天体

类星体

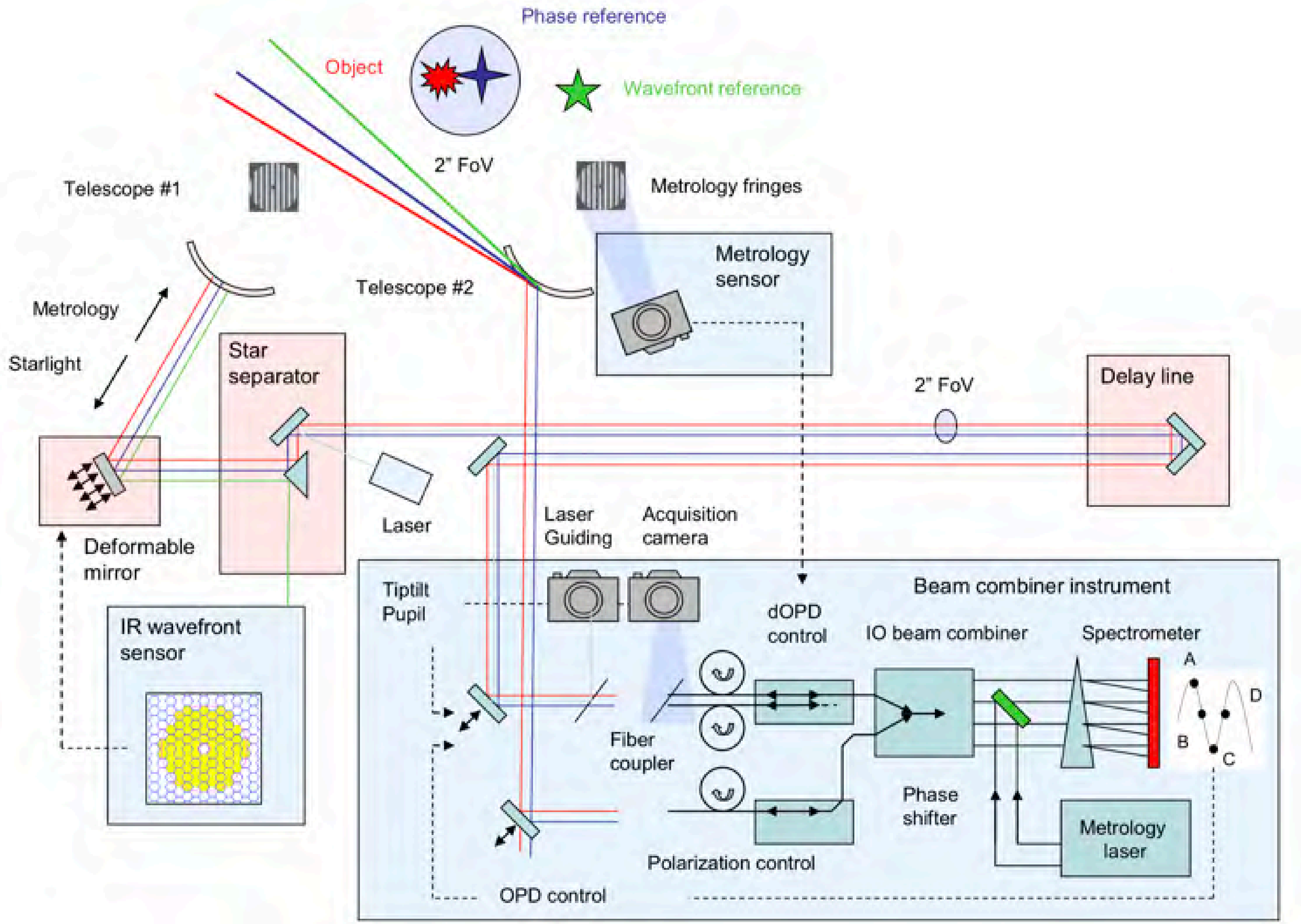
AO+干涉+光谱定位：分辨率10μas





可见光波段：相干时标一般短于10毫秒，

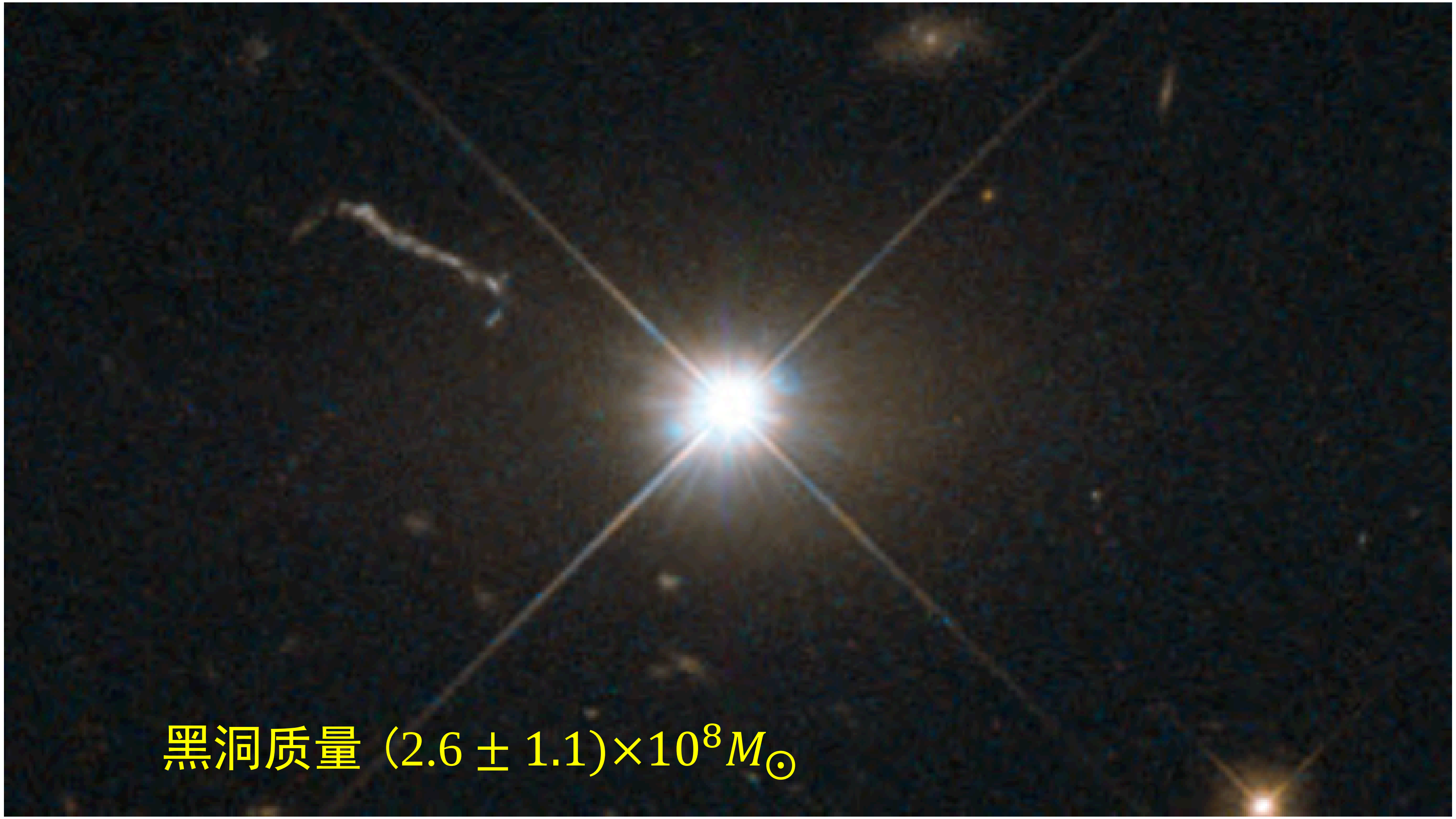
近红外波段：一般短于百毫秒。

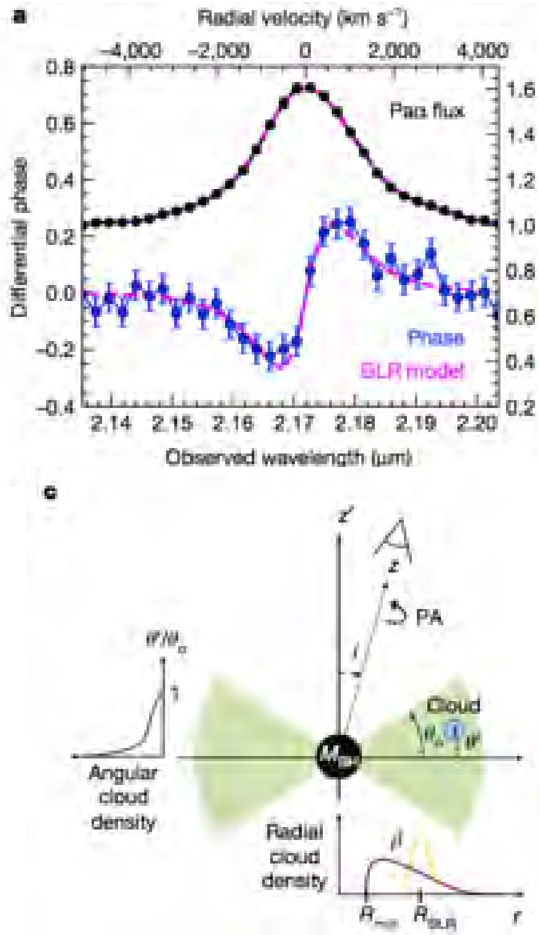


Phase reference
Object
Wavefront reference
2" FoV
Telescope #1
Metrology fringes
Metrology
Telescope #2
Metrology sensor
Starlight
Star separator
2" FoV
Delay line
Laser
Laser Guiding
Acquisition camera
Deformable mirror
Beam combiner instrument
Tiptilt Pupil
dOPD control
IO beam combiner
Spectrometer
IR wavefront sensor
A
D
B
C
Fiber coupler
Phase shifter
Metrology laser
Polarization control
OPD control

一束光线通过GRAVITY的动画

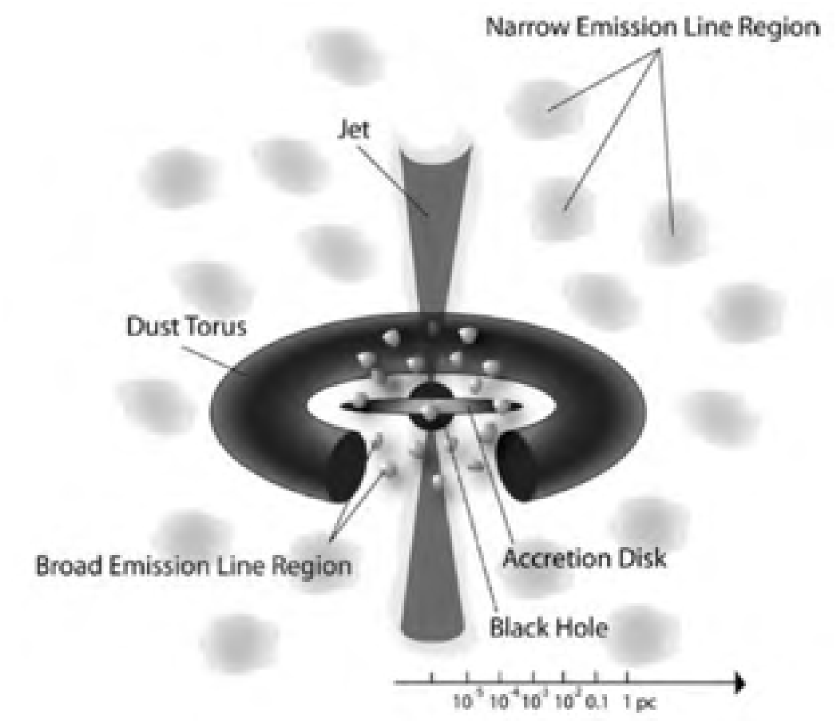
Credit:MPE (https://www.eso.org/public/videos/eso1622b)

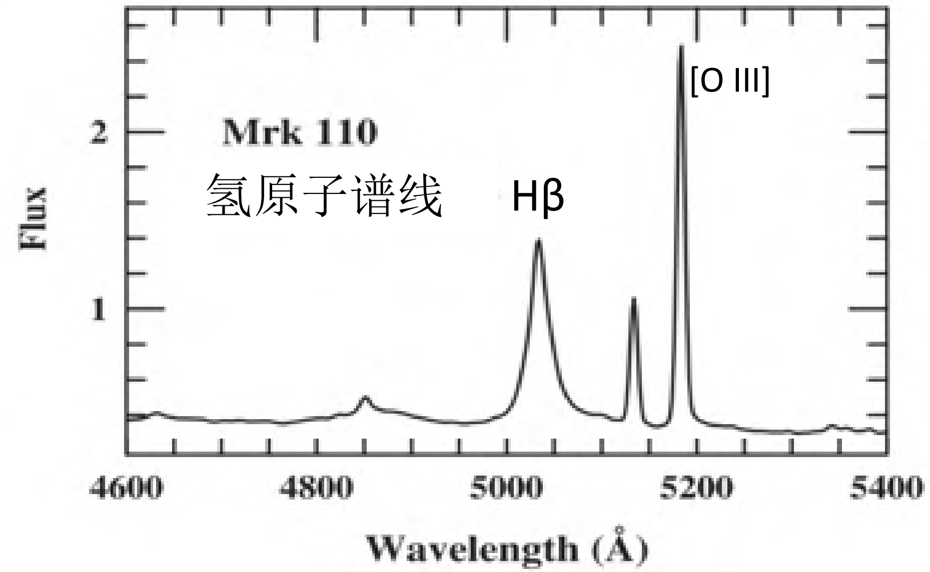


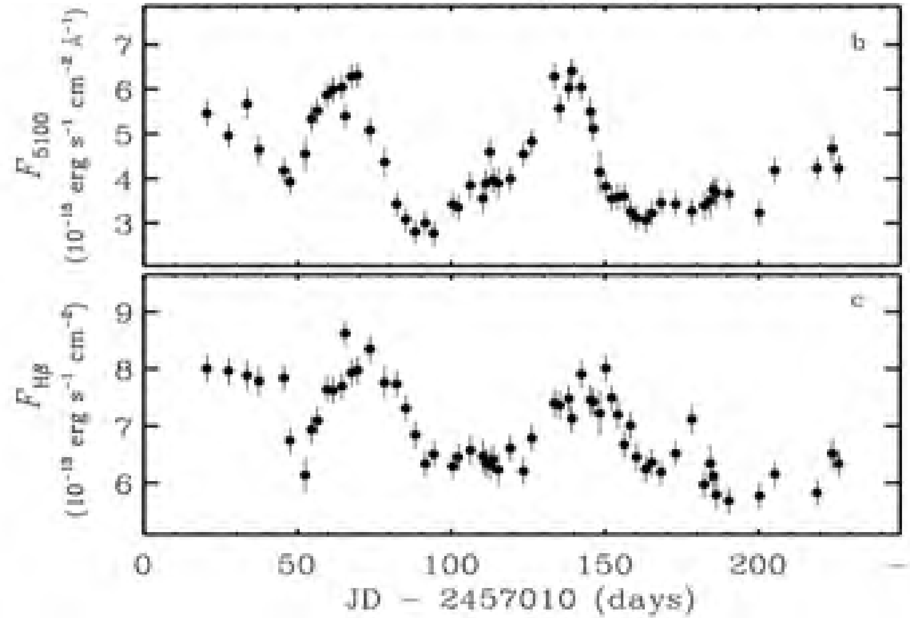


Gravity collaboration, 2018, Nature, 563, 567

反响映射: 宽线区尺度和黑洞质量







黑洞周围气体动力学

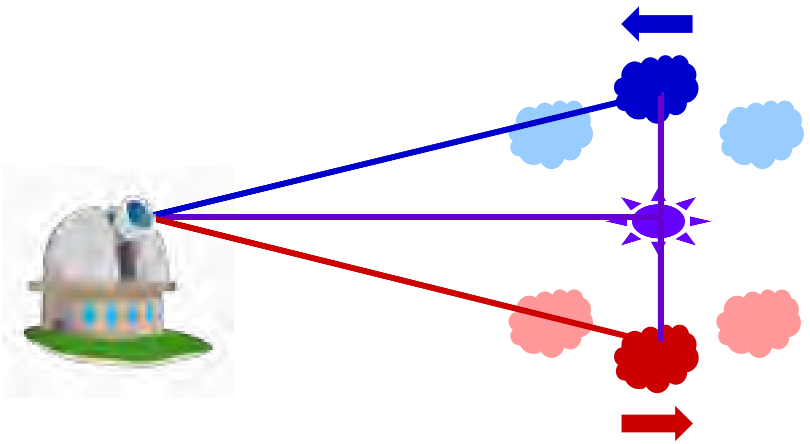
- $M_{\bullet} = f_{\rm BLR}\frac{R_{\rm H\beta}V^2}{G}$
- 复杂的MCMC测量过程

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

干涉测量：高空间分辨率

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

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

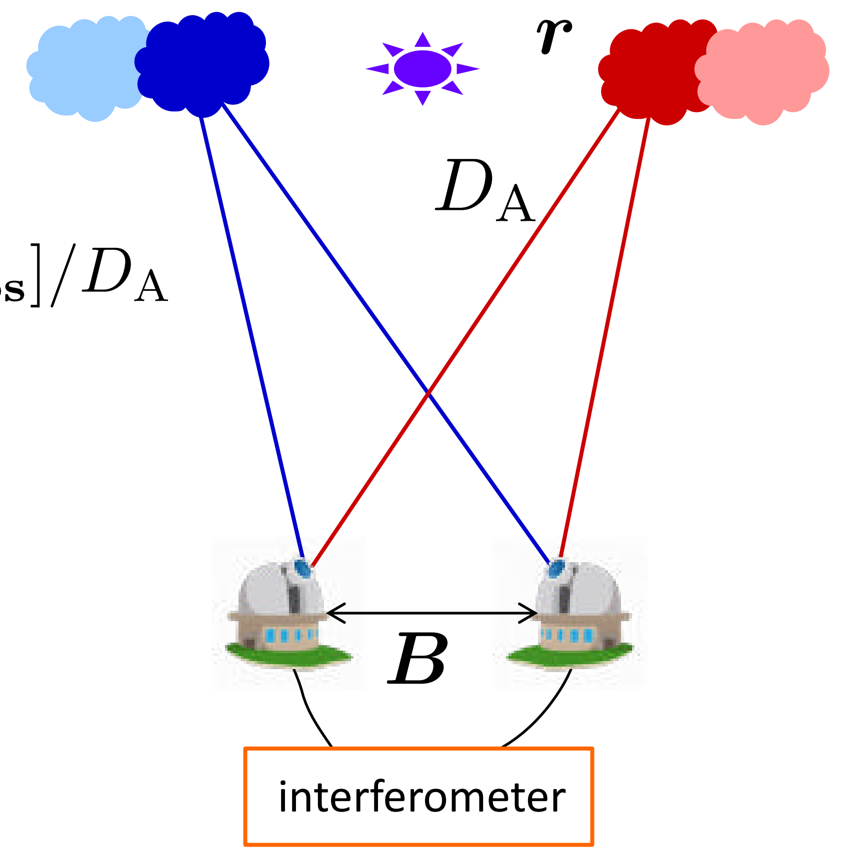
Angular size

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



nature astronomy

LETTERS

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

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

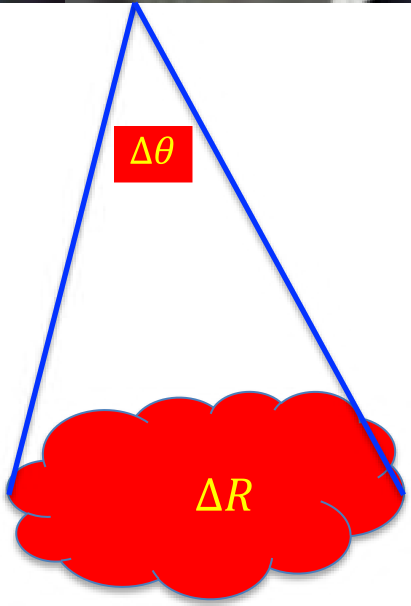
Jian-Min Wang[1,2,3*], Yu-Yang Songsheng[1,4], Yan-Rong Li[1], Pu Du[1] and Zhi-Xiang Zhang[5]

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

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



SARM：宇宙学距离的几何测量

测量角径尺度

测量区域线尺度

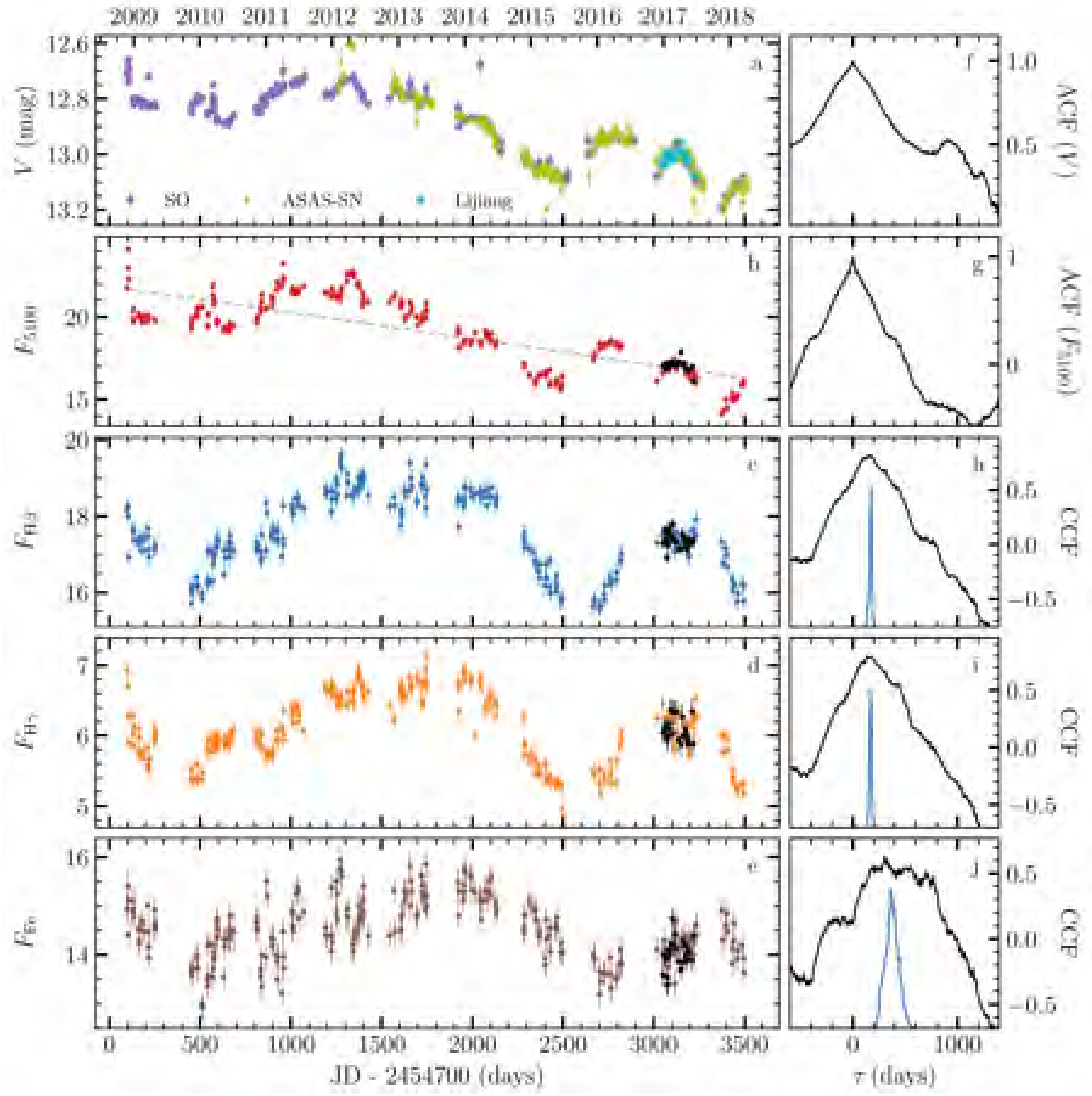
SpectroAstrometry+RM=SARM

SARM：珠联璧合

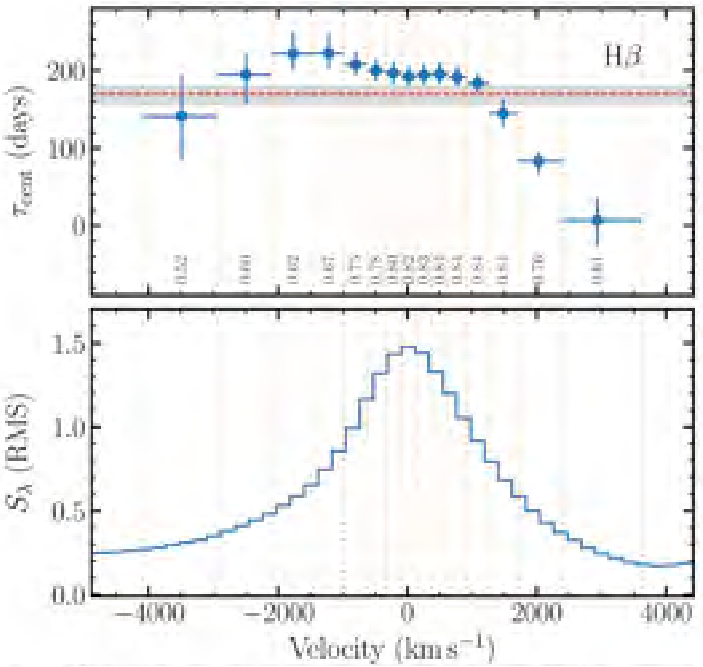
黑洞质量和距离

（Wang+2019）

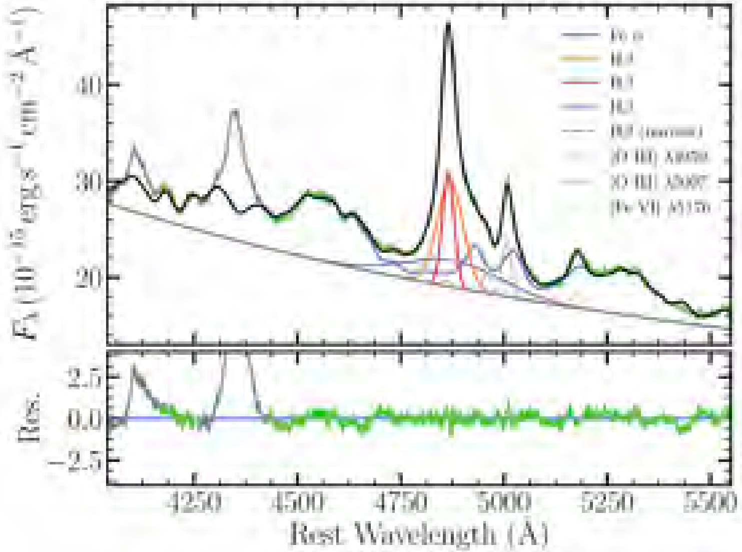
3C273: 10年监测



2009 2010 2011 2012 2013 2014 2015 2016 2017 2018
V (mag)
SO
ASAS-SN
Lijiang
ACF (V)
ACF (F_{5100})
F_{5100}
$F_{H\beta}$
$F_{H\gamma}$
F_{He}
CCF
JD - 2454700 (days)
τ (days)

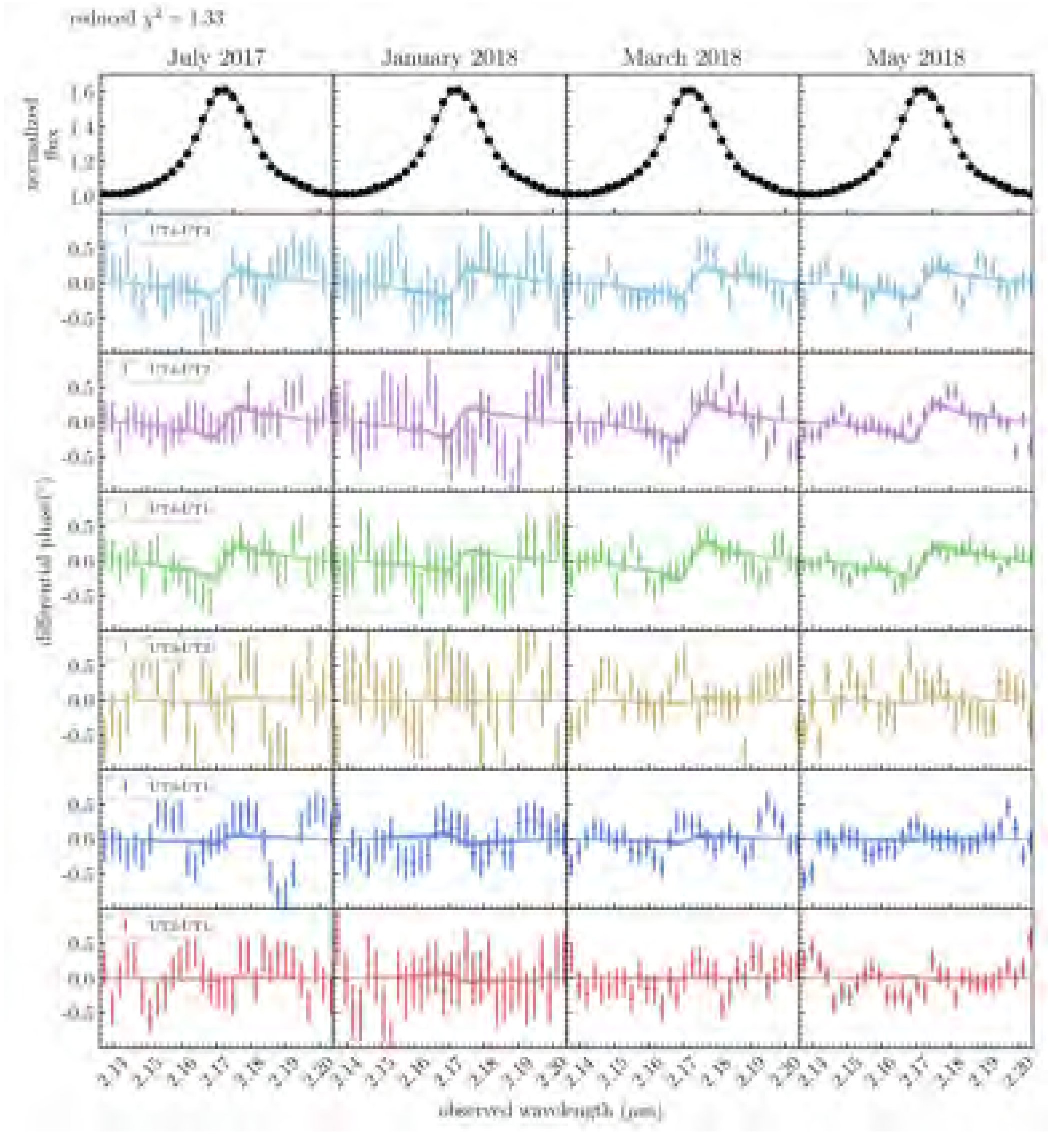


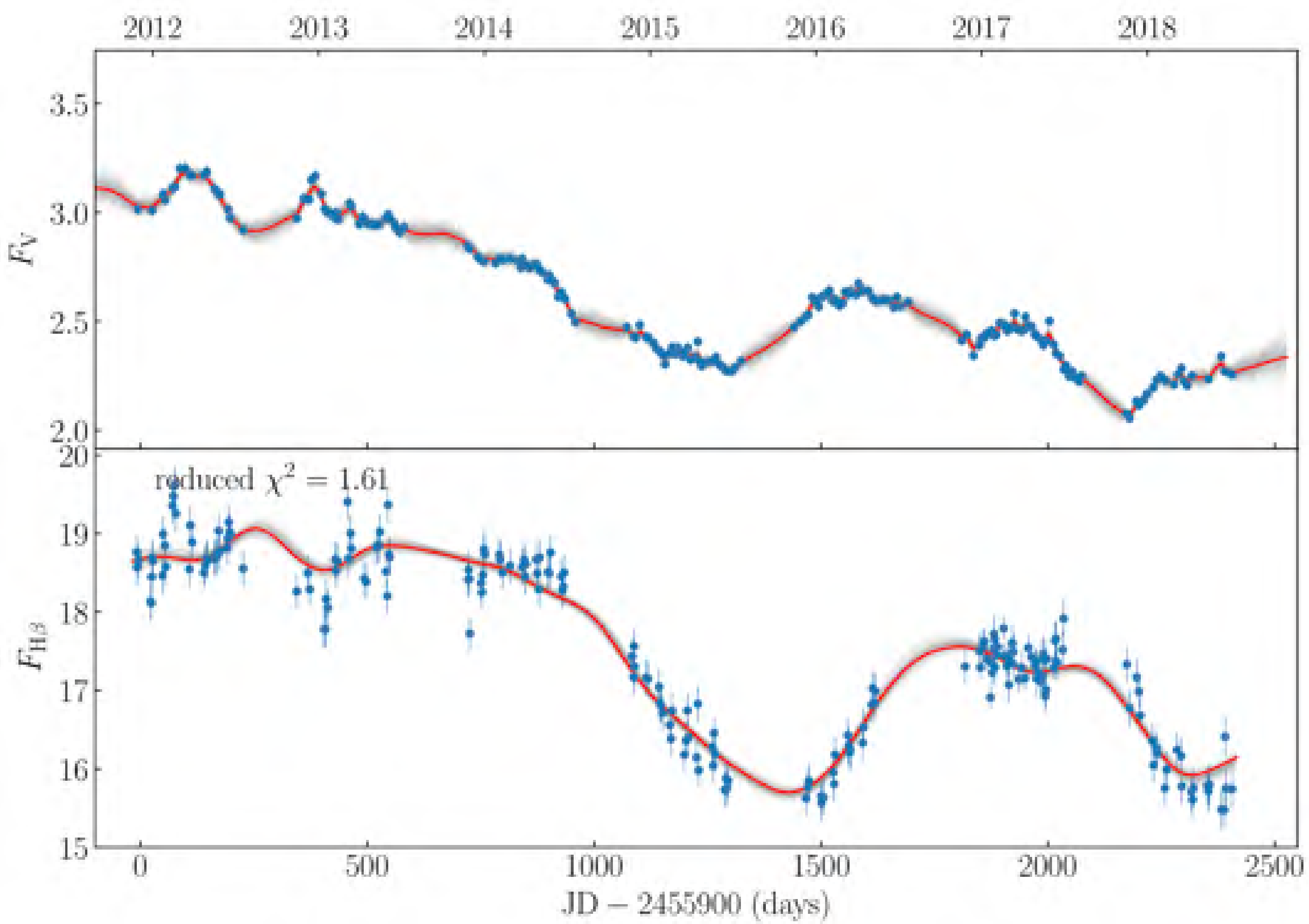
Hβ
τ_{cent} (days)
S_λ (RMS)
Velocity (km s^{-1})



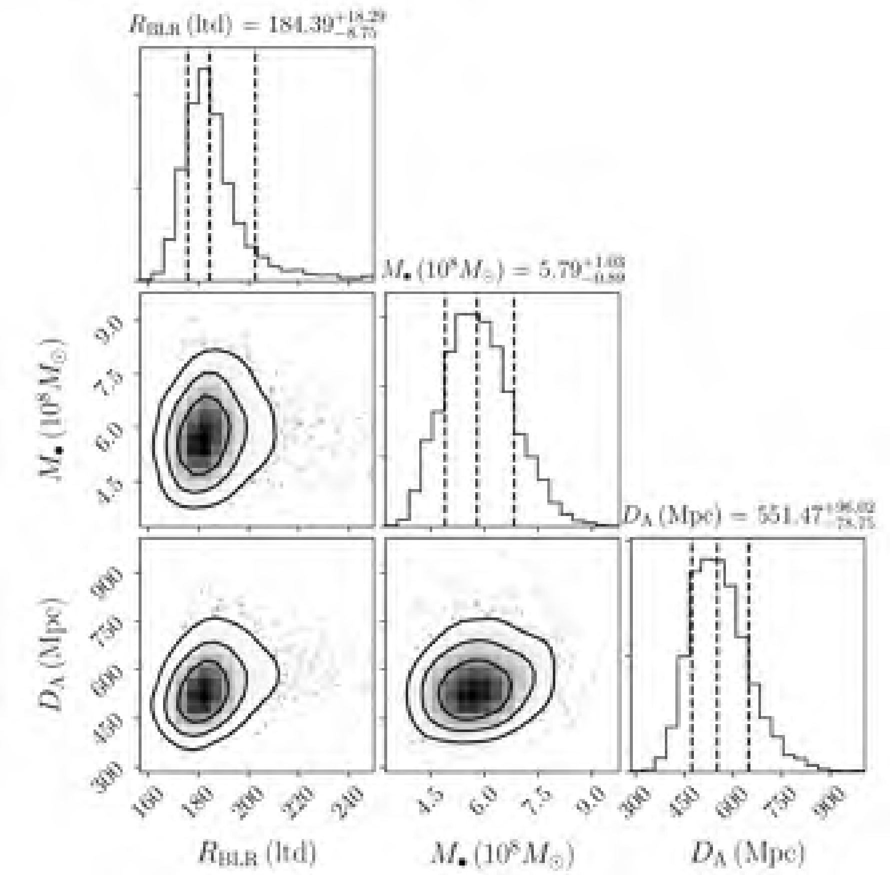
F_λ (10^{-15} erg s^{-1} cm^{-2} Å^{-1})
Res.
Rest Wavelength (Å)

SARM分析：质量与距离





类星体几何距离：首次SARM分析



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

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

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

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)

SARM分析亟待扩大样本，实现高精度H_0测量！

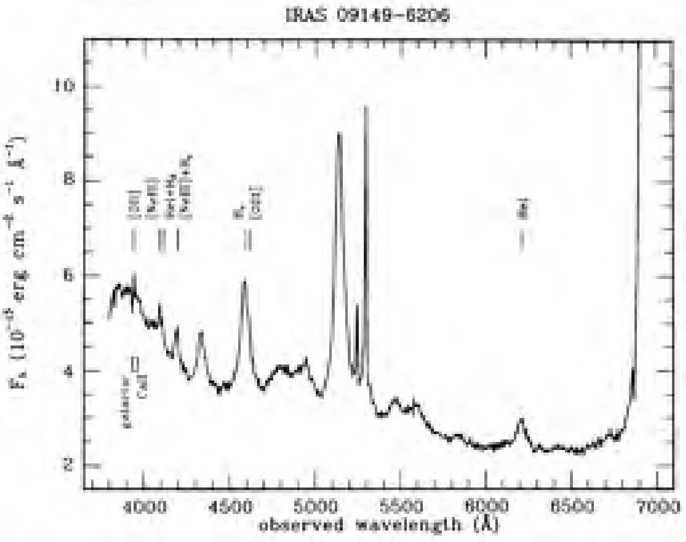
ronomy & Astrophysics manuscript no. gravity_blr
tember 21, 2020

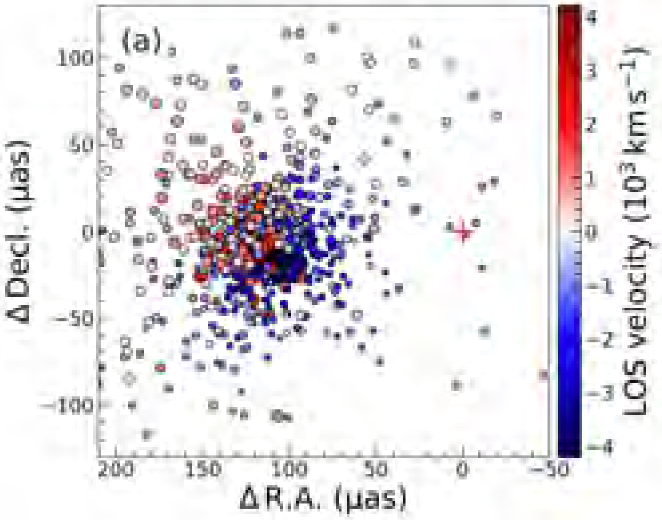
arXiv:2009.08463

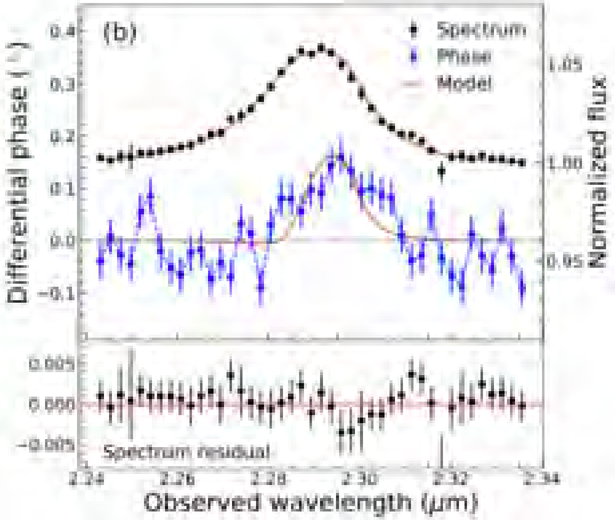
GRAVITY: 第二个类星体

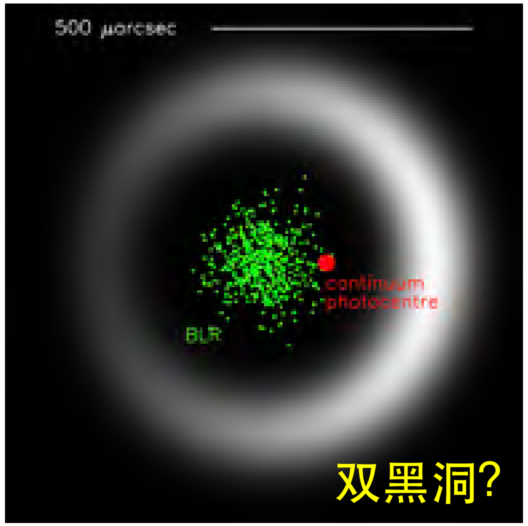
The spatially resolved broad line region of IRAS 09149−6206

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]









双黑洞?

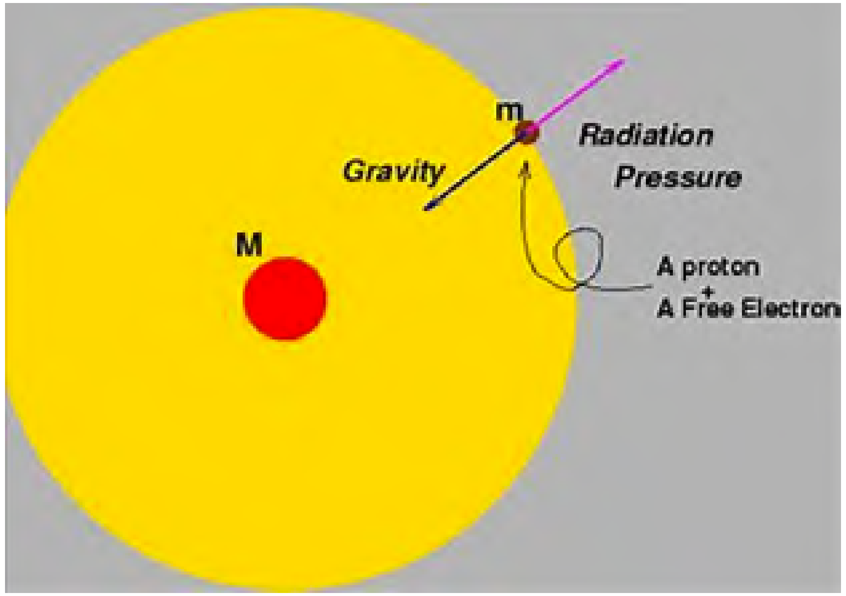
超爱黑洞：高红移宇宙膨胀历史

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

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

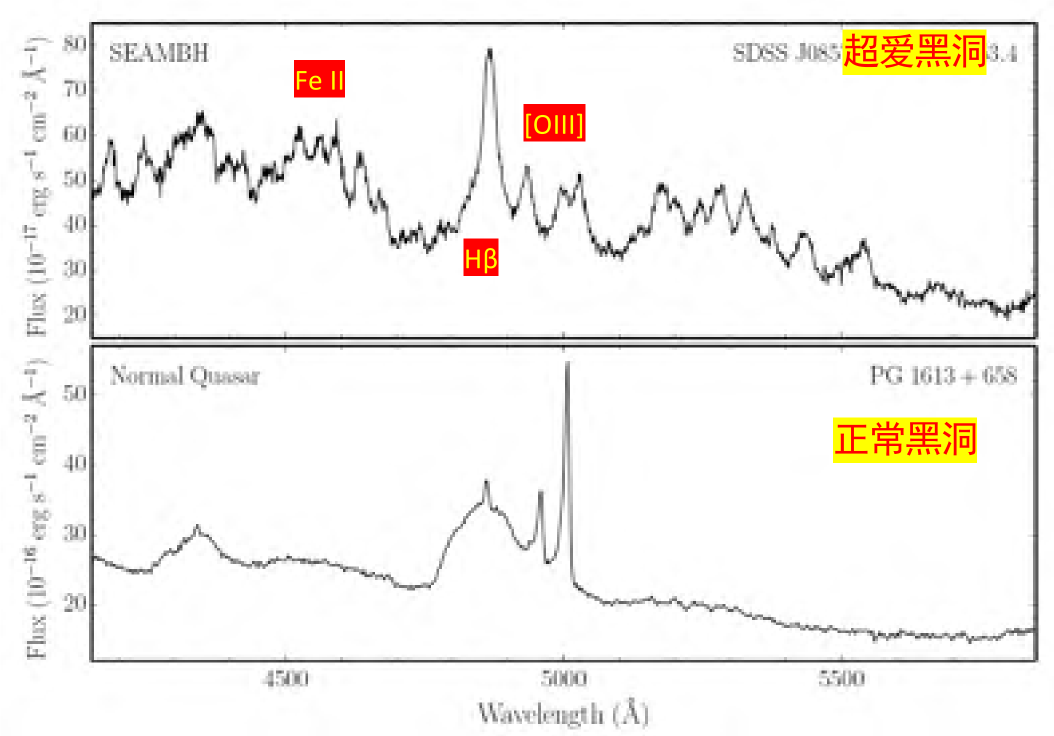
Jian-Min Wang,[1,2,*] Pu Du,[1] David Valls-Gabaud,[3,1,2] Chen Hu,[1] and Hagai Netzer[4]
[1]*Key Laboratory for Particle Astrophysics, Institute of High Energy Physics, CAS, 19B Yuquan Road, Beijing 100049, China*
[2]*National Astronomical Observatories of China, CAS, 20A Datun Road, Beijing 100020, 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)

超爱黑洞：丽江观测计划



- 辐射压=引力 →爱丁顿极限

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

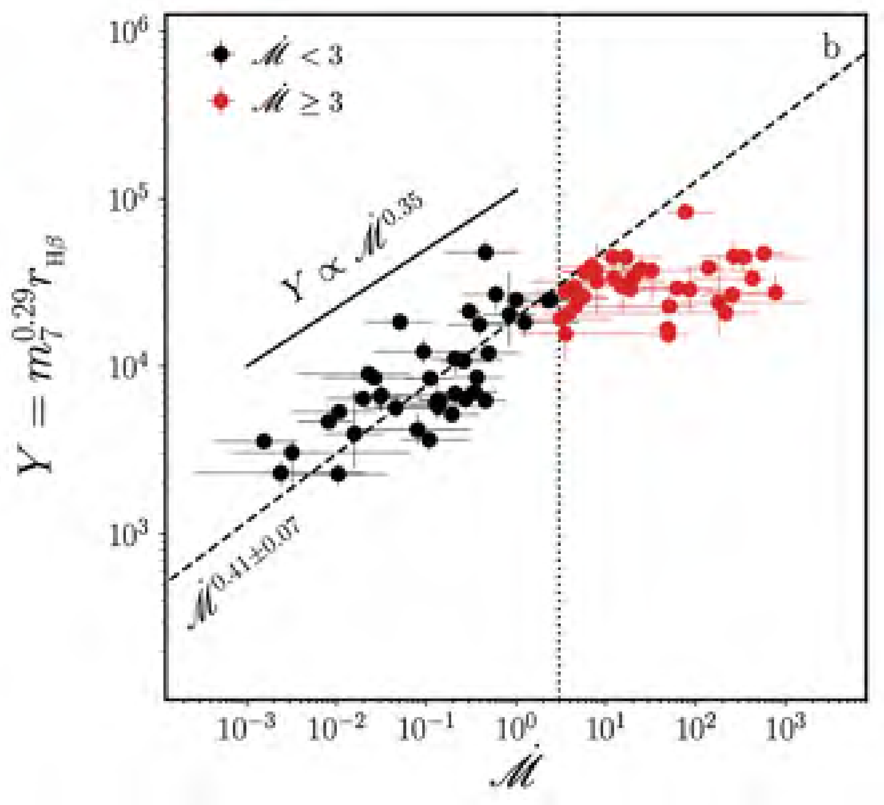


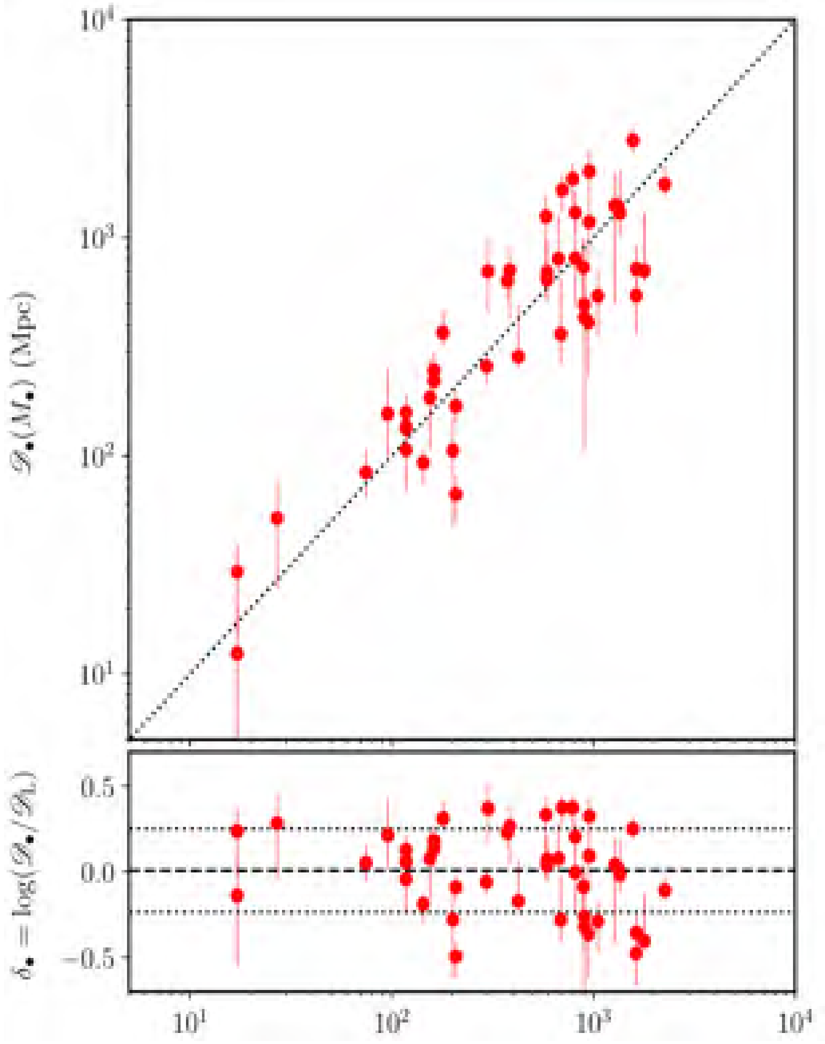
观测计划目标

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





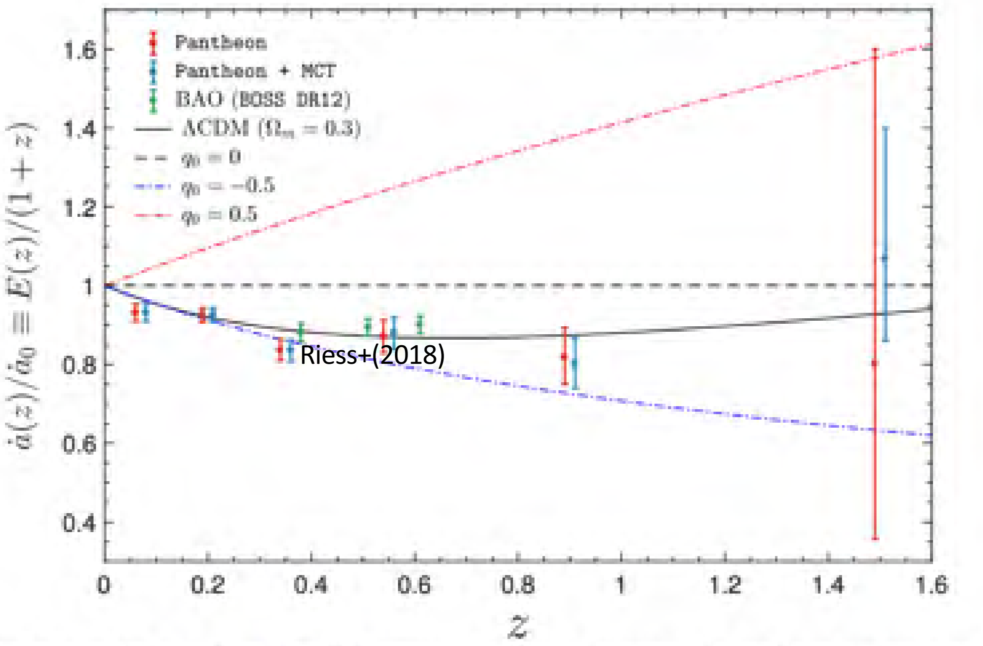
- 超爱黑洞: 吸积率10^3
- 饱和光度-*L*：0.2dex

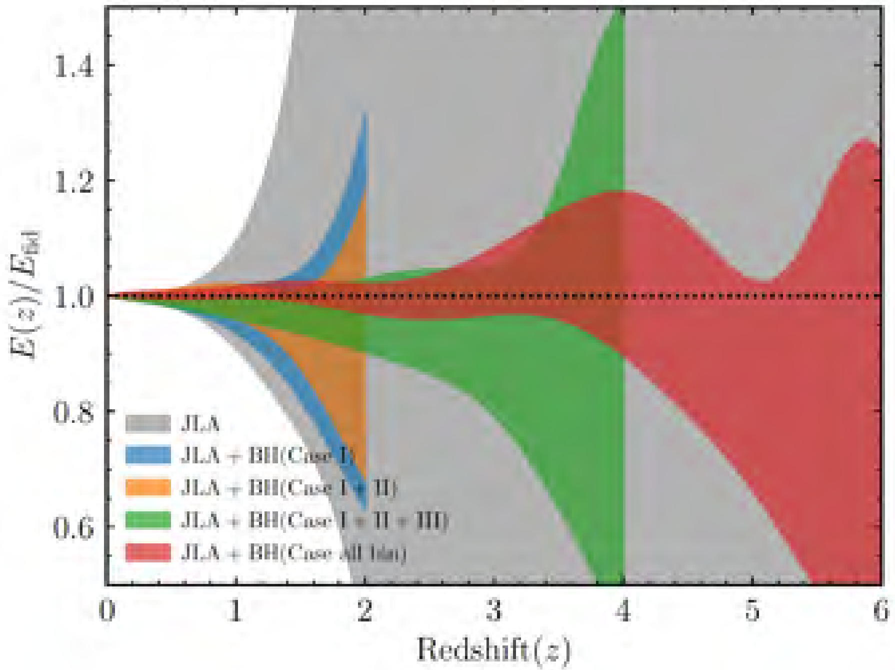
黑洞照亮：高红移宇宙膨胀历史

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‡





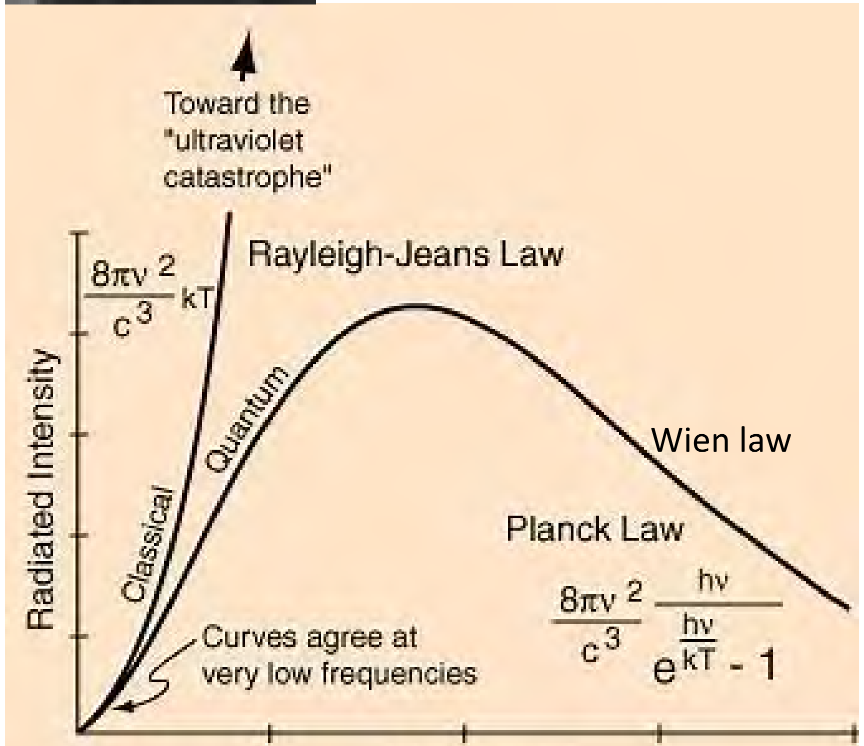
重大问题：宇宙结构和动力学

“量子”诞生

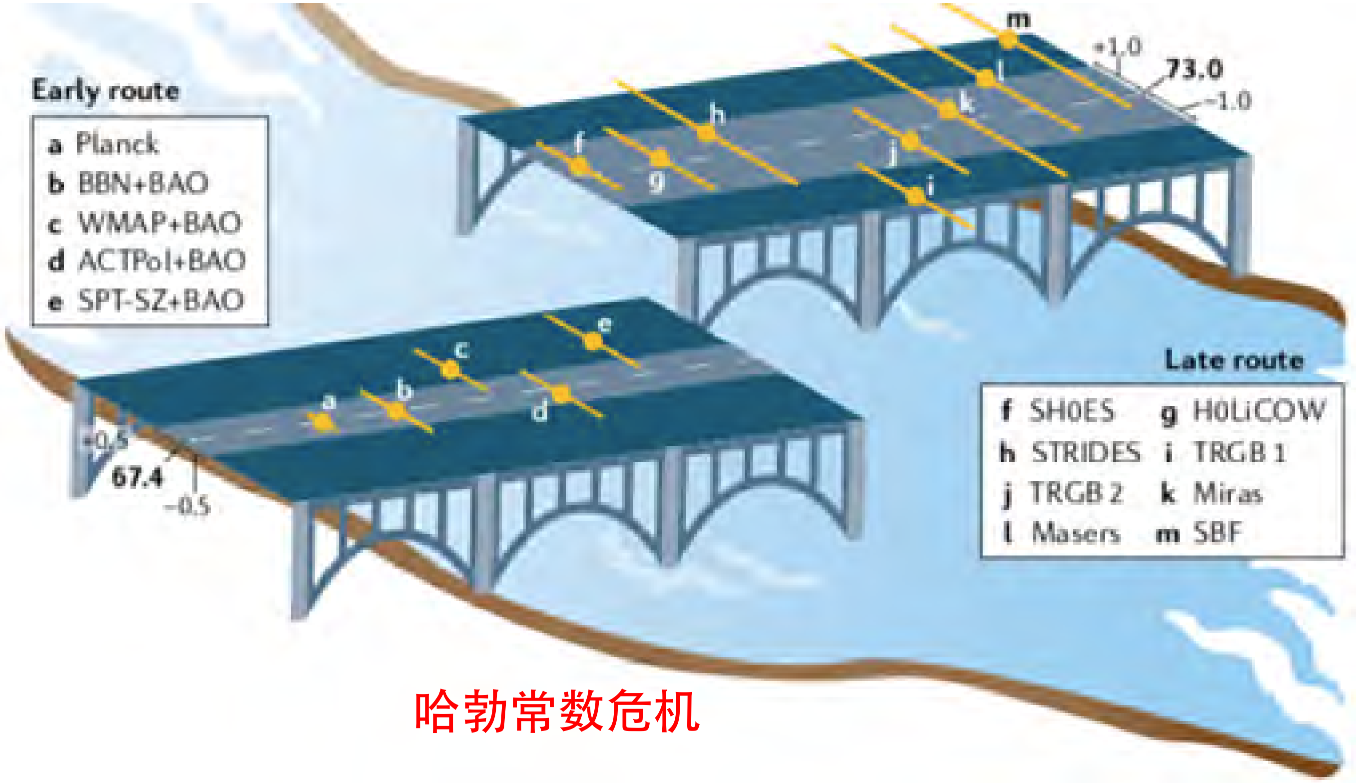
Max Planck

“新物理”诞生?

Adams Riess

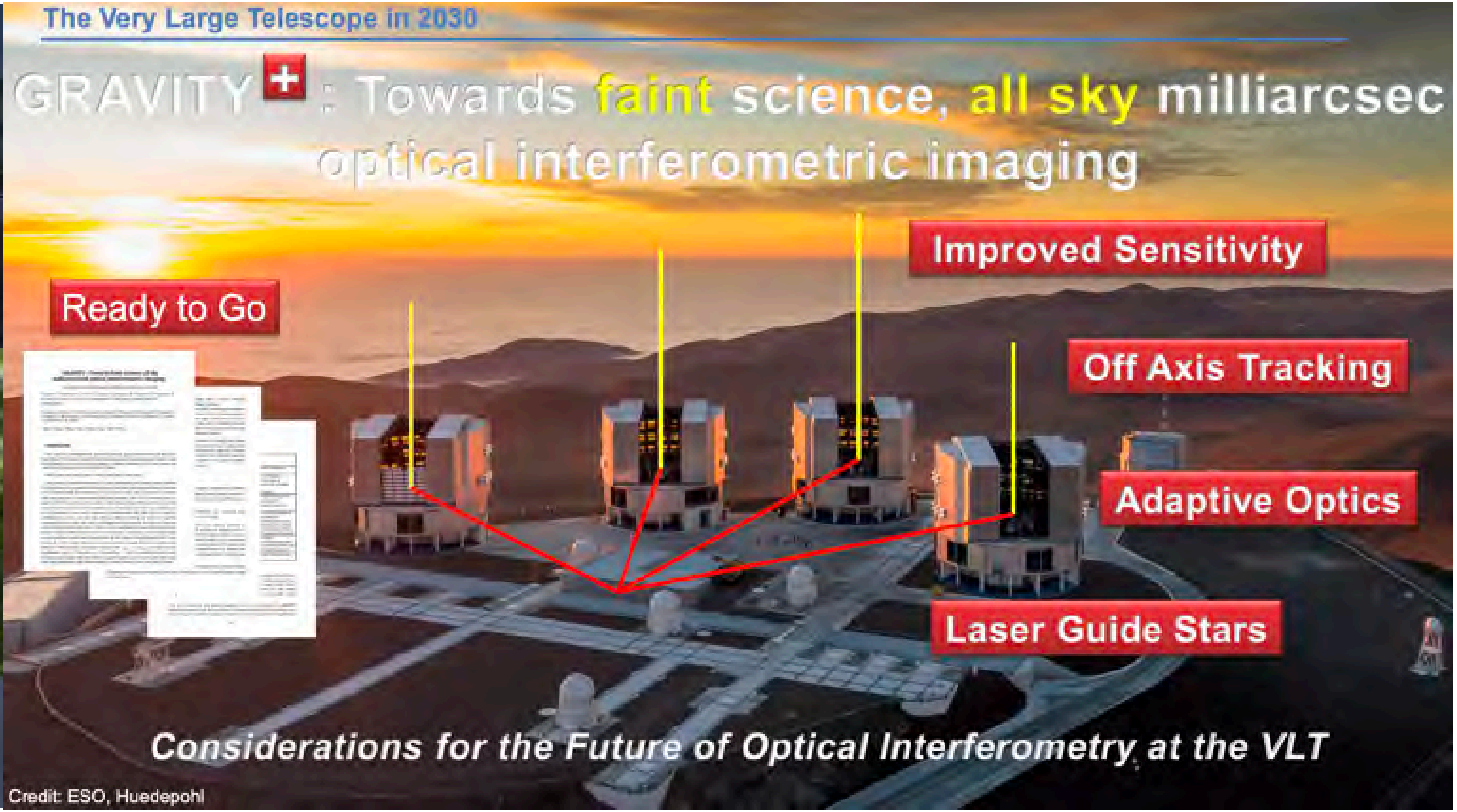


紫外灾难

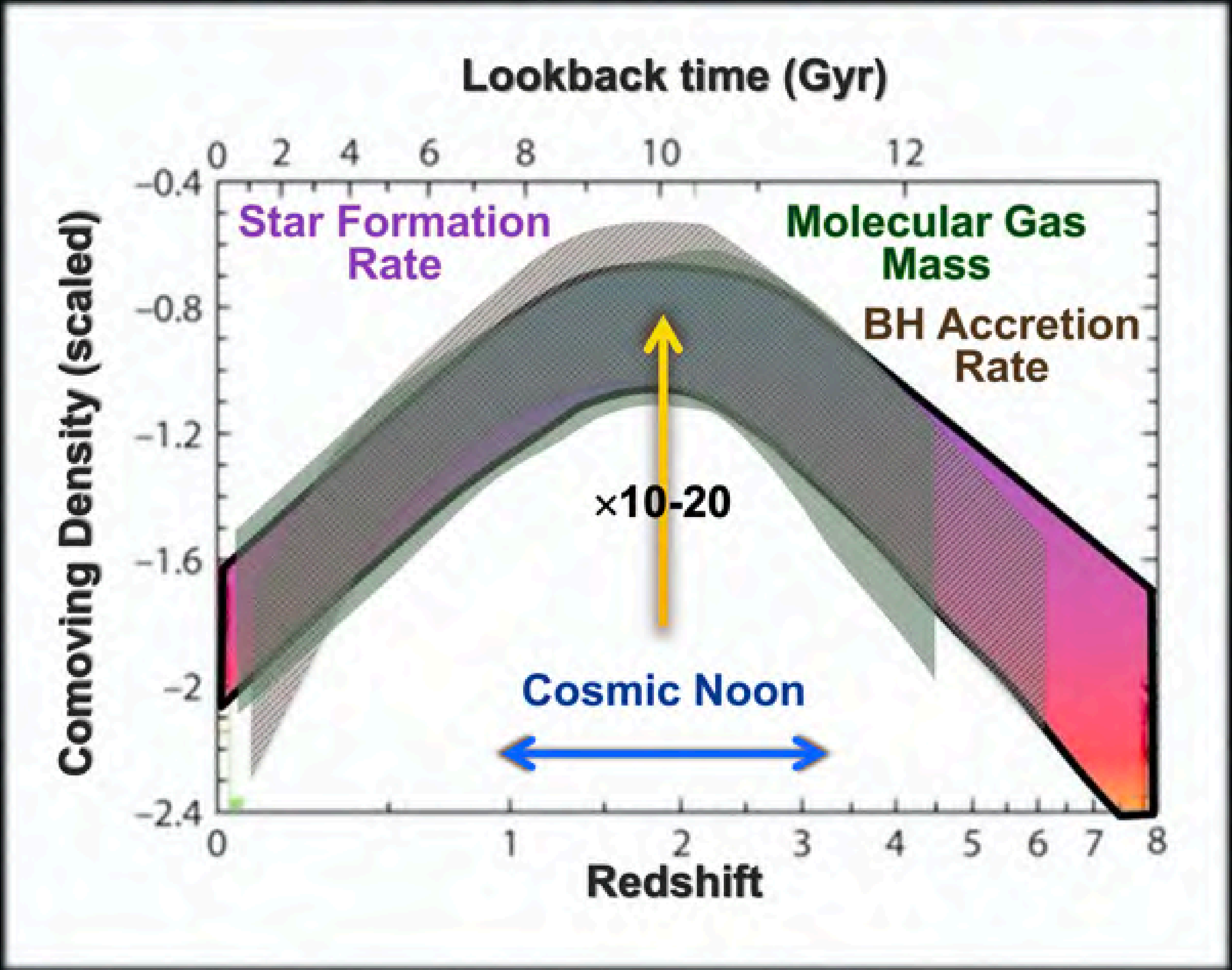


哈勃常数危机

未来3-5年内：GRAVITY+



Active Galactic Nuclei – at Cosmic Noon



吸积盘外区/宽线区：自引力主导

强烈的恒星形成与演化

LIGO: Laser Interferometry Observatory

ZTF: Zwicky Transient Facility

类星体：金属丰度、恒星形成、致密双星与引力波

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 AND JAIN-MIN WANG

吸积盘上的恒星形成与演化：

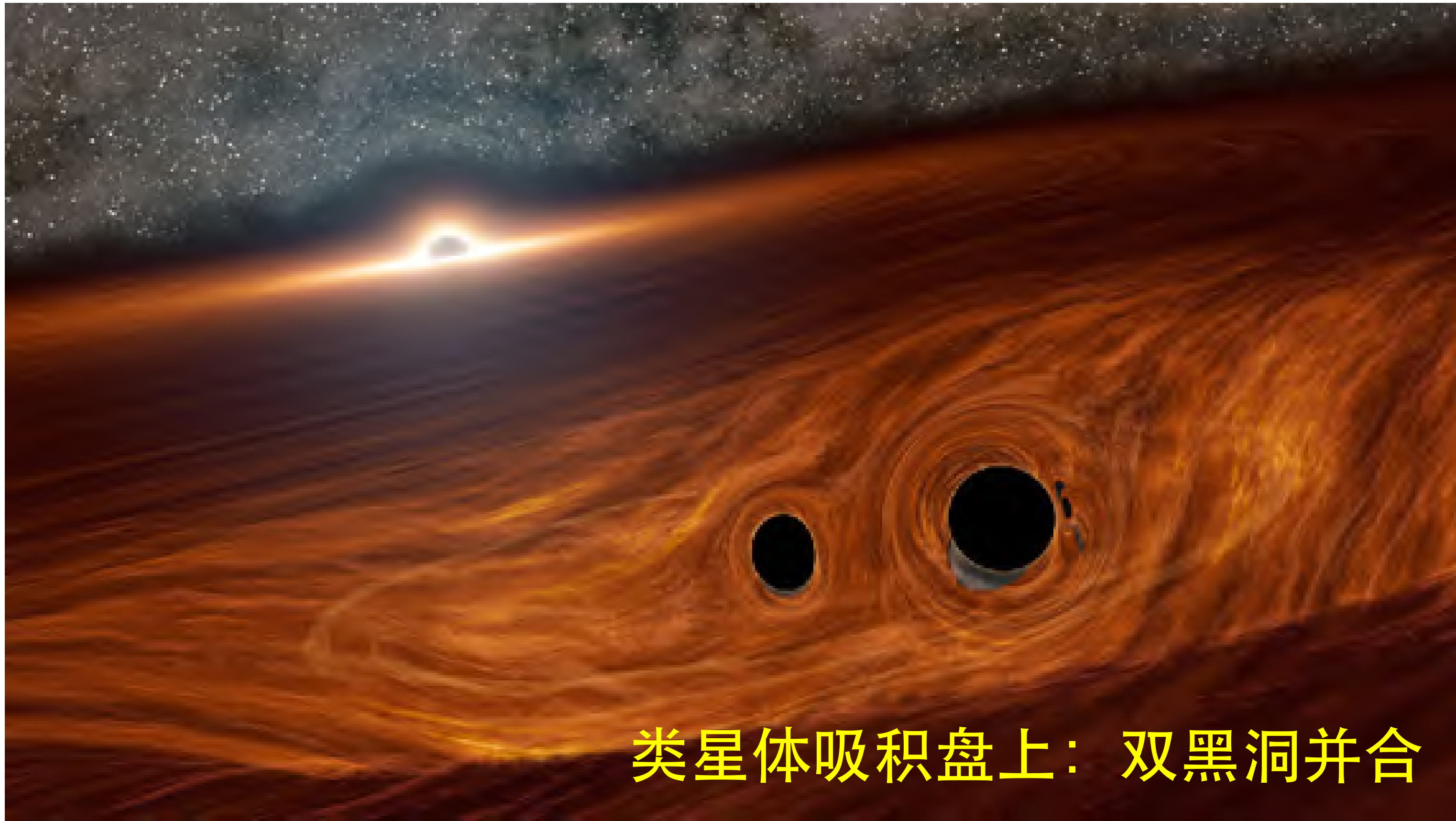
星暴与黑洞触发

Wang, J.-M. +2012, ApJ, 746, 137

Wang, J.-M.+2011, ApJ, 739, 3

Wang, J.-M.+2010, ApJ, 719, L148

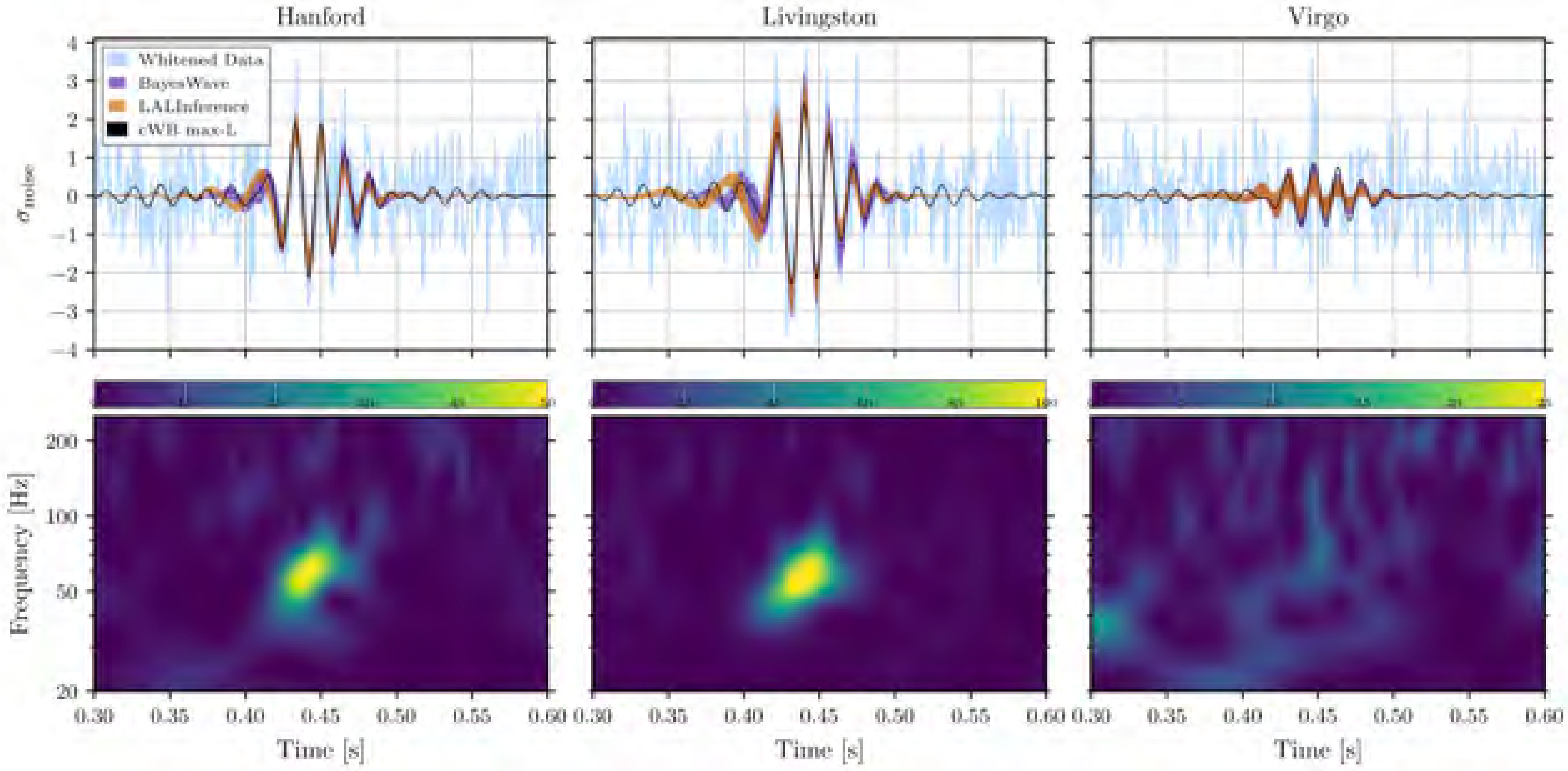
Wang, J.-M.+2017, Nature Astronomy, 1, 775



LIGO Collaboration 2020, PRL, 125, 101102

$$\text{GW190521: } 85^{+21}_{-14}M_\odot + 66^{+17}_{-18}M_\odot$$

$$150M_\odot$$



$$142^{+28}_{-16}M_\odot$$

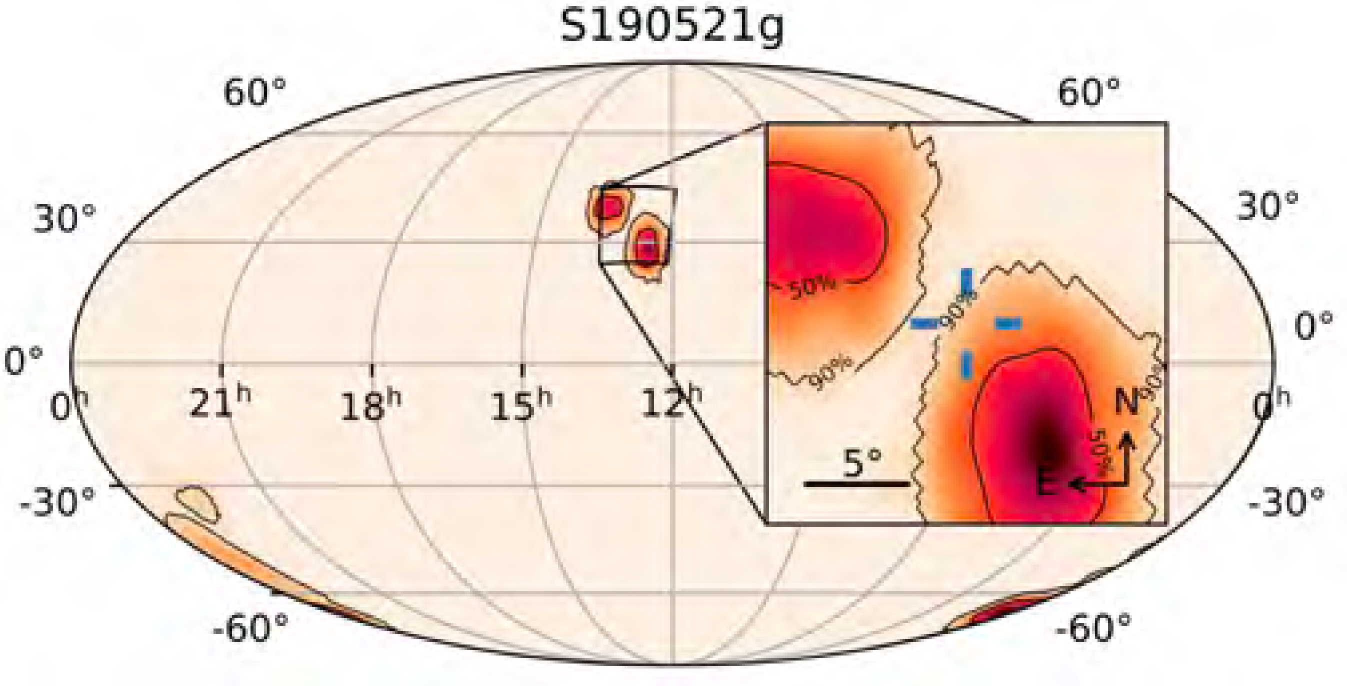
遗迹黑洞质量

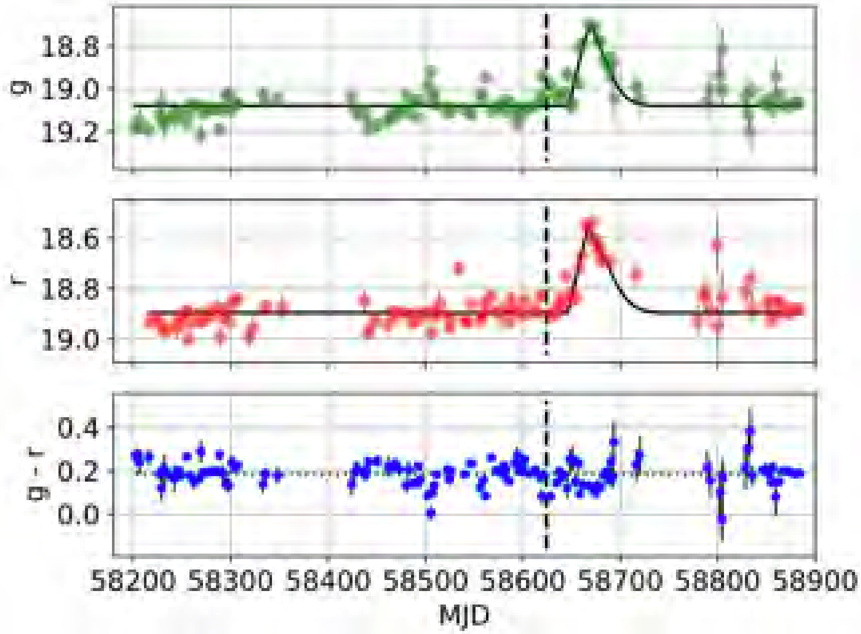
引力波损失：$9M_\odot$

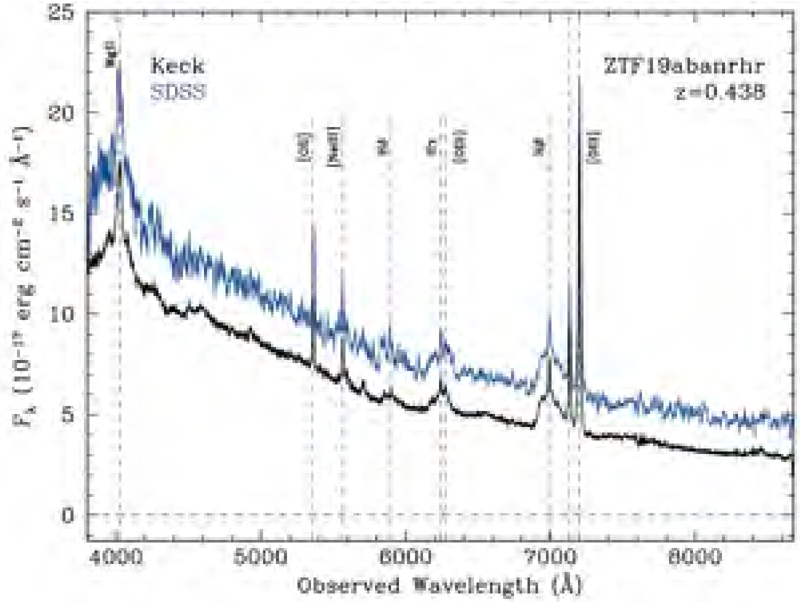
Graham, S.+2020, PRL, 124, 251102

但见文章arXiv:2009.12346

GW190521的电磁对应体







寄主星系：SDSS J1249+3449

*Graham, M. J. +2020, PRL, 124, 251102

*Yang, Y., Gayathri, V. Marka, S.+2020, PRL, 2009.13739

*Chen, H.-Y., Haster, C.-J. Vitale, S.+2020, PRL, arXiv:2009.14057

*Mukherjee, S. Ghosh, A., Graham, M. J.+2020, PRL. arXiv:2009.14199

*McKernan, B.; Ford, K. E. S.; Shaughnessy, R. O’ 2020, MNRAS, in press

*McKernan, B.; Ford, K. E. S.; O'Shaugnessy, R. 2019, MNRAS, 494, 1203

*McKernan, B.; Ford, K. E. S.; Bartos, I.+2019, ApJ, 884, L50

*Cantiello, M. , Jermyn, A. & Lin, D. N. C. 2020, 2020arXiv200903936

论文井喷式涌现

- 类星体：LIGO引力波、测量距离
- 高能所的GECAM?

“超大质量黑洞反响映射观测”计划

1）黑洞超快增长过程、协同演化机制

2）测量哈勃常数、宇宙膨胀历史

3）双黑洞证认、轨道参数测量、低频引力波

结 论

- 宇宙学距离(SARM)：光干涉+反响映射
  - –哈勃常数？
  - –哈勃参量：几何测量延伸到z=2-3
- 期待：暗能量演化？