

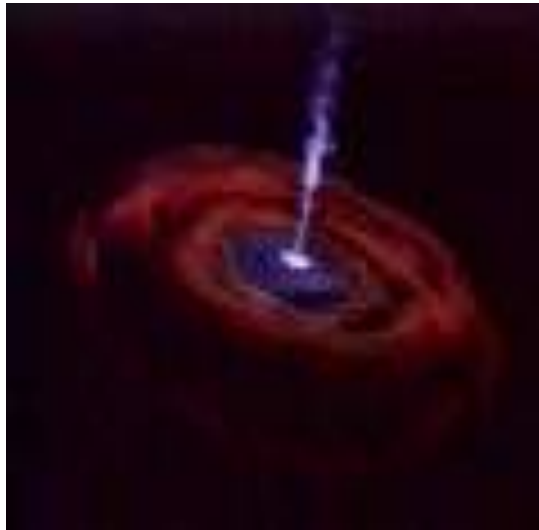
中国科学院紫金山天文台
(2019/10/17)

高红移类星体与超大质量黑洞
(High-redshift quasars and supermassive black holes)

吴学兵
(北京大学)

内容

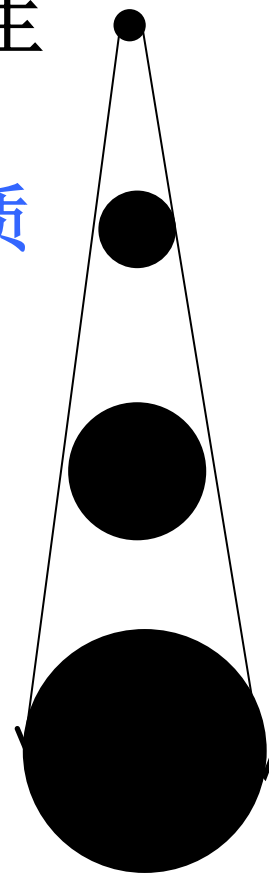
- 遥远的黑洞天体：类星体
- 发现红移5以上的类星体
- 发现宇宙早期的超级黑洞
- 总结与展望

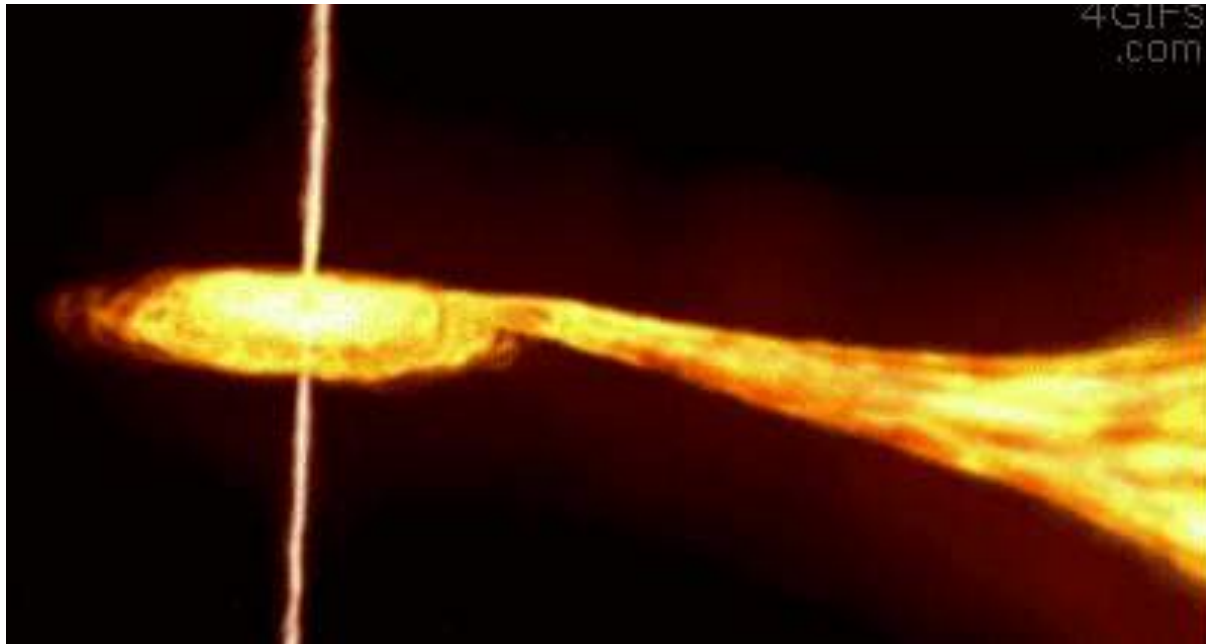


1、遥远的黑洞天体：类星体

宇宙中的四类黑洞

- 按**黑洞的质量**来划分
 - **原初(Primordial)**黑洞：宇宙大爆炸后产生 ($\sim 10^{12}$ 千克，寿命 $t=100$ 亿年)
 - **恒星级(Stellar Mass)**黑洞 ($\sim 10M_{\odot}$)：大质量恒星死亡的产物
 - **中等质量(Intermediate Mass)**黑洞 ($\sim 10^3-10^4M_{\odot}$)：星团内部大质量恒星死亡的产物 (极亮X射线源ULX) ?
 - **超大质量(Supermassive)**的黑洞 ($\sim 10^6 - 10^{10} M_{\odot}$)：存在于许多星系的中心
 - 第1种难以观测，后3种可以被观测！





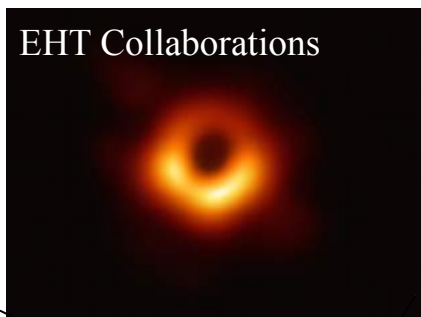
恒星级黑洞（约10个太阳质量）的X射线双星，从伴星吸积物质

中心为超大质量黑洞（百万到十亿个太阳质量）的类星体 / 星系，从寄主星系吸积物质

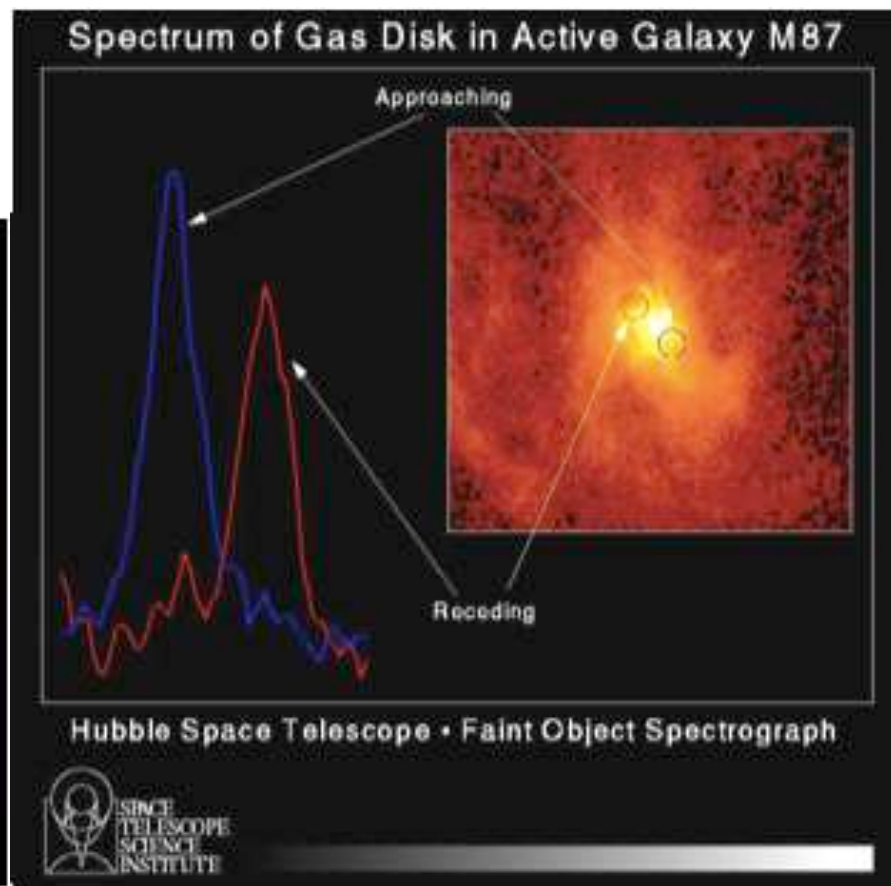
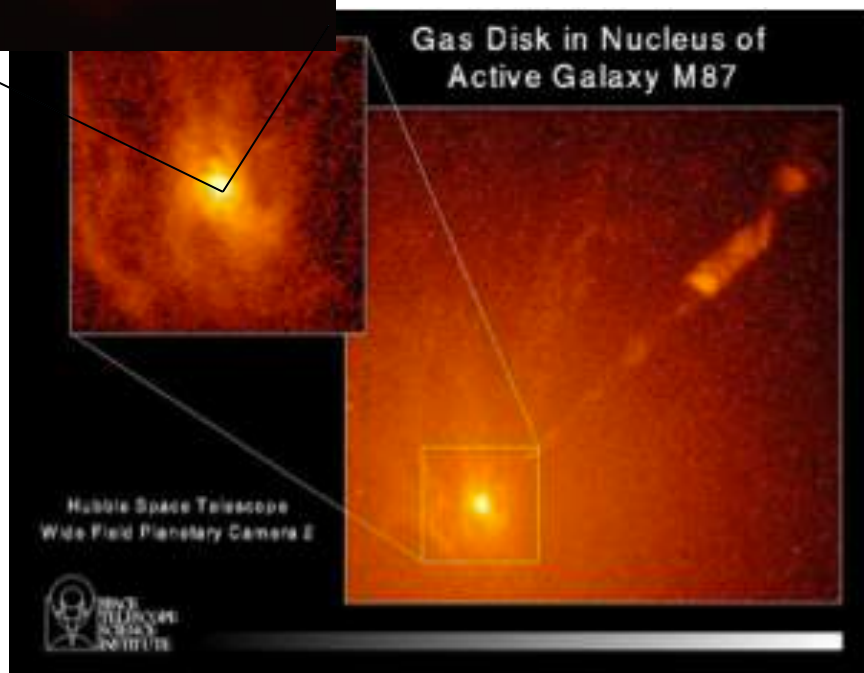


- 星系级黑洞（超大质量黑洞）

- $M \sim 10^6 - 10^9 M_{\odot}$, 通常位于星系核心, 可利用恒星动力学和气体动力学测量其质量



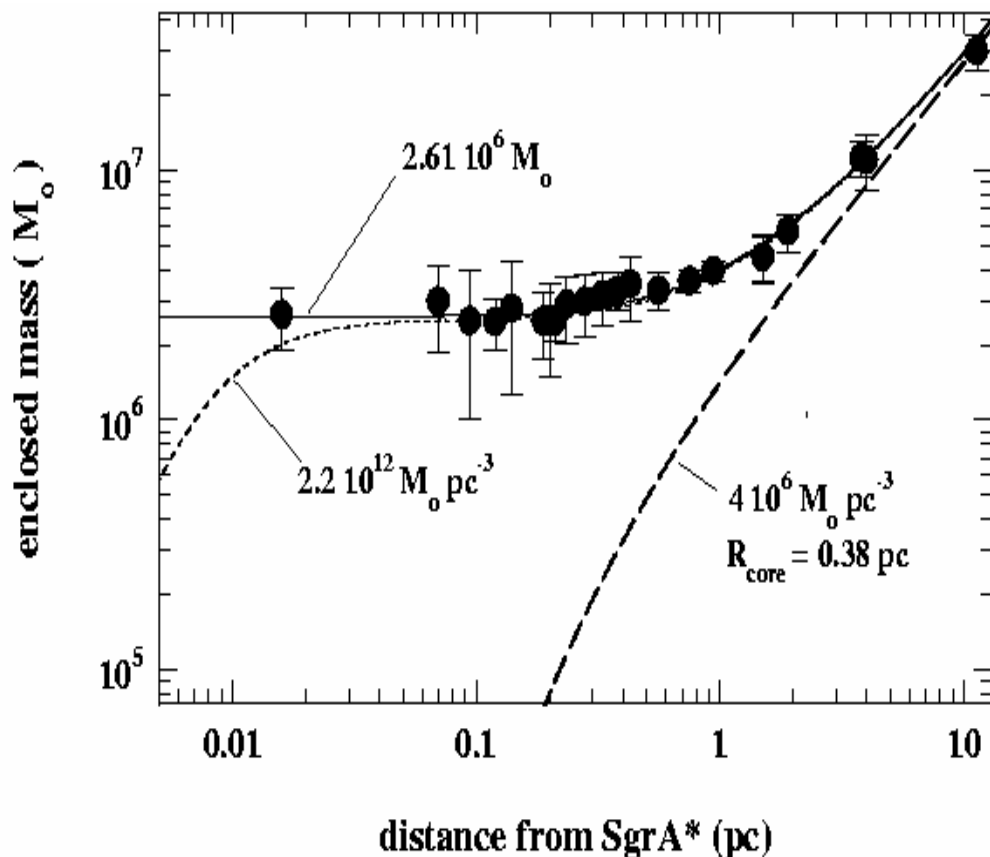
$$M_{\text{BH}} \propto V^2 R$$



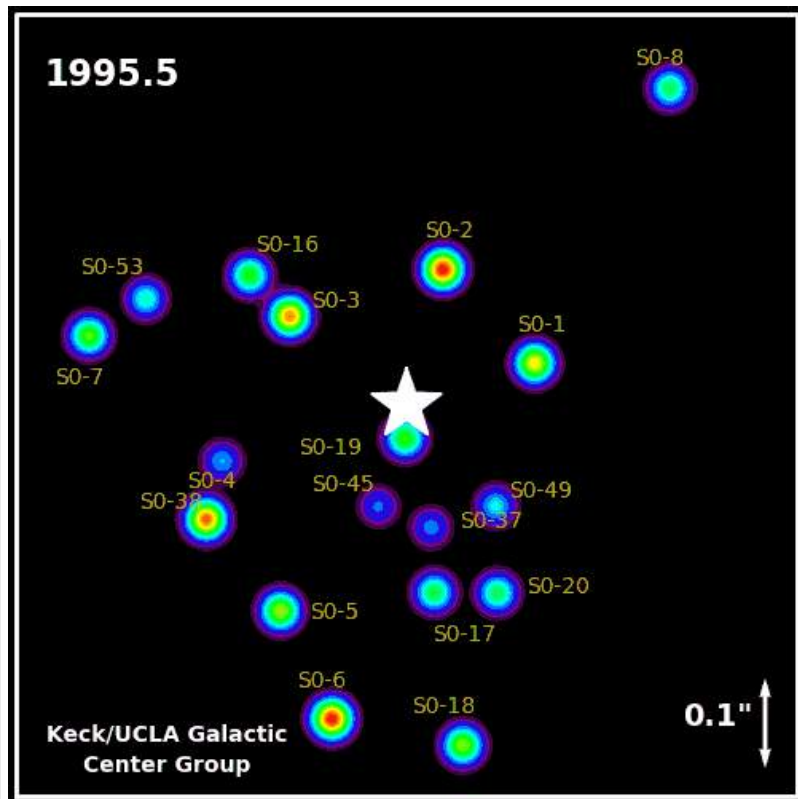
银河系中心的超大质量黑洞

- 由银心附近恒星的运动推测在银心集中了 $\sim 4 \times 10^6 M_{\odot}$ 的质量。

→ 超大质量的黑洞



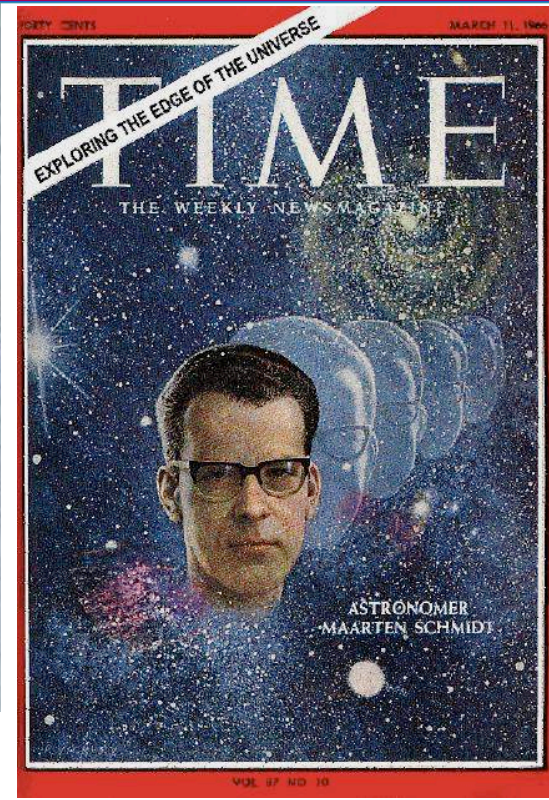
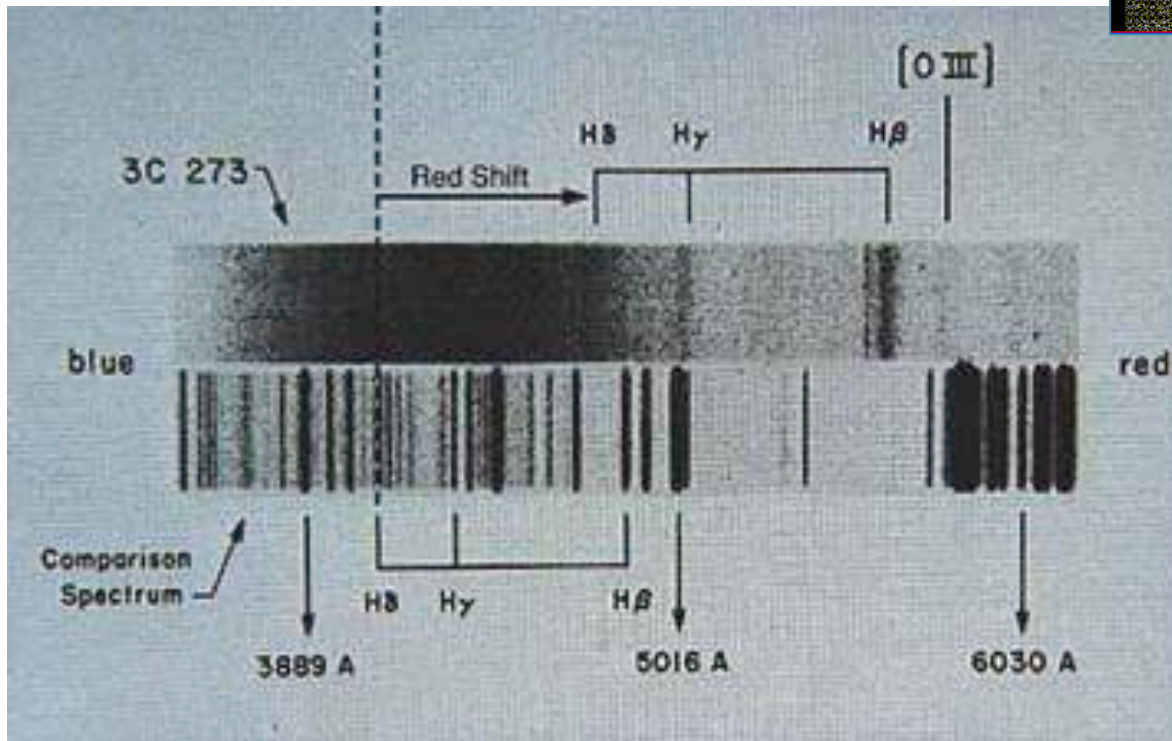
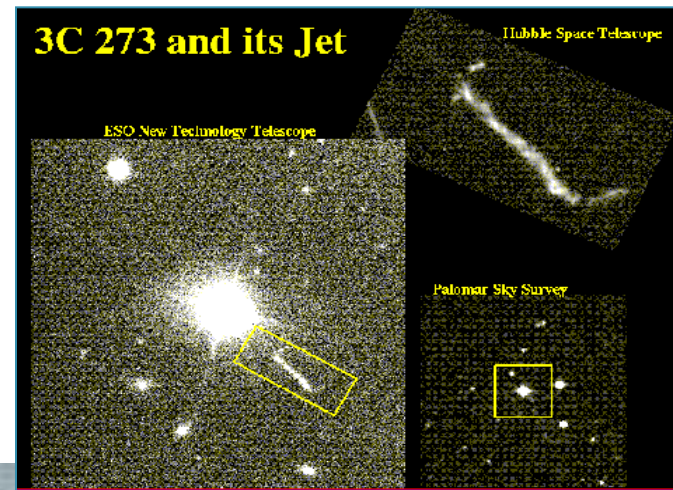
银心附近恒星的运动



遥远的黑洞天体—类星体

- 二次世界大战后，**雷达技术**用于天文观测，50年代起发现几百个强射电源（剑桥射电源表，1C, 2C, 3C…）
- Mathews & Sandage (1963) 证认3C48有**恒星状**的光学对应体，且光谱观测发现其有**宽发射线**但波长无法识别
- 1963年Maarten Schmidt证认出3C273光谱中强而宽的未知发射线实际上是**红移**了的氢、氧和其他元素的发射线。从而发现这些看起来类似恒星的天体实际上是非常遥远的天体—类星体(Quasar)
- 类星体是60年代天文学**四大发现**之一

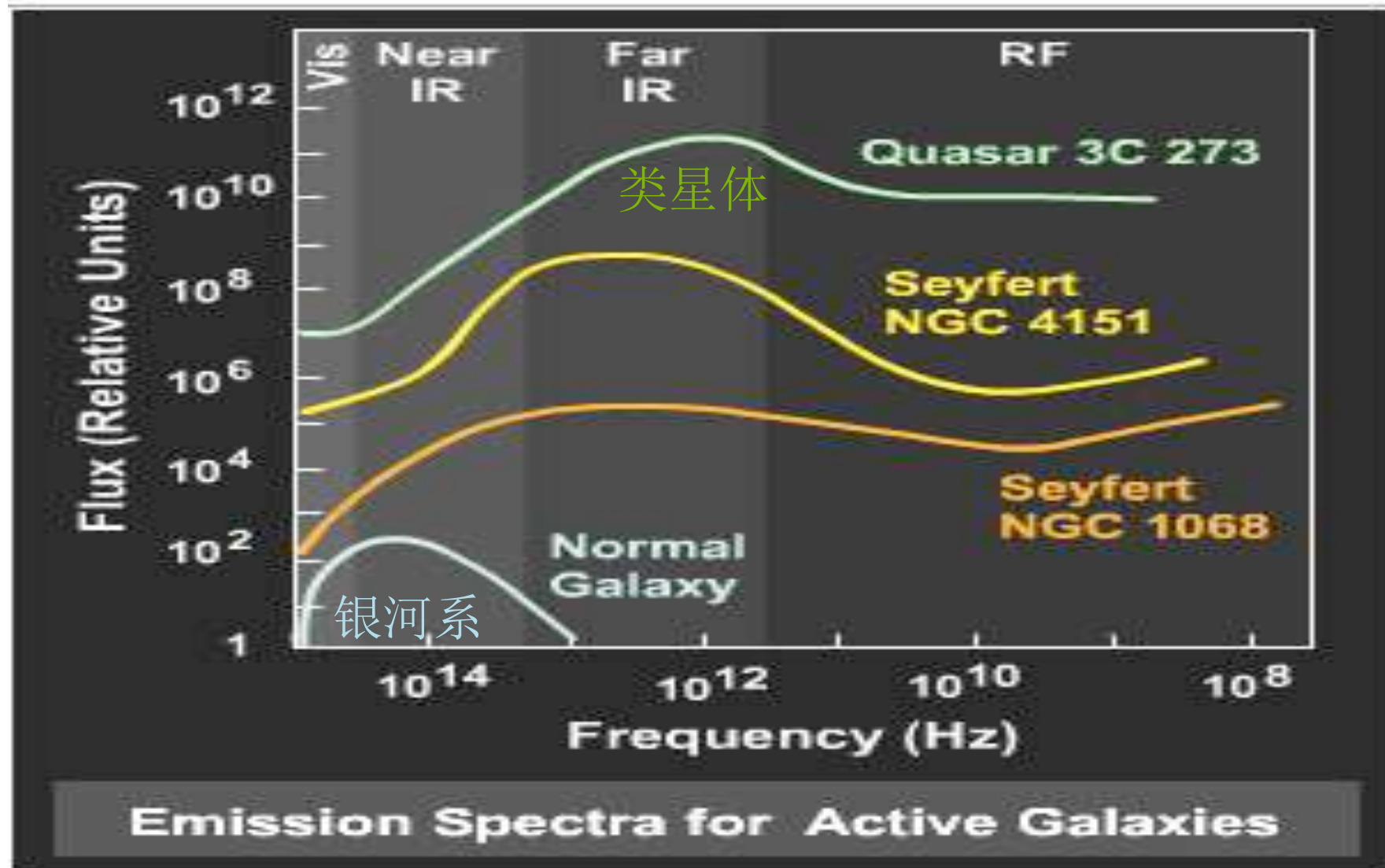
3C273光谱中有强而宽的未知发射线。
1963年Maarten Schmidt证认出它们实际上是红移了的H和其他元素的发射线。



类星体3C 273的谱线红移量达到0.16

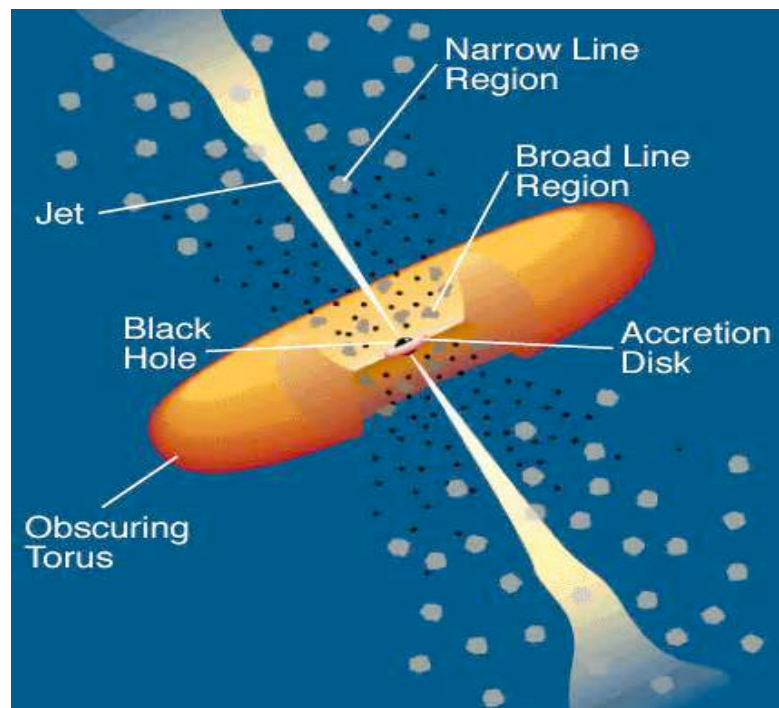
红移 $z = (\lambda - \lambda_0) / \lambda_0$ ，红移越大，天体离我们越远！

类星体发光比银河系大非常多，几乎全波段都有辐射！

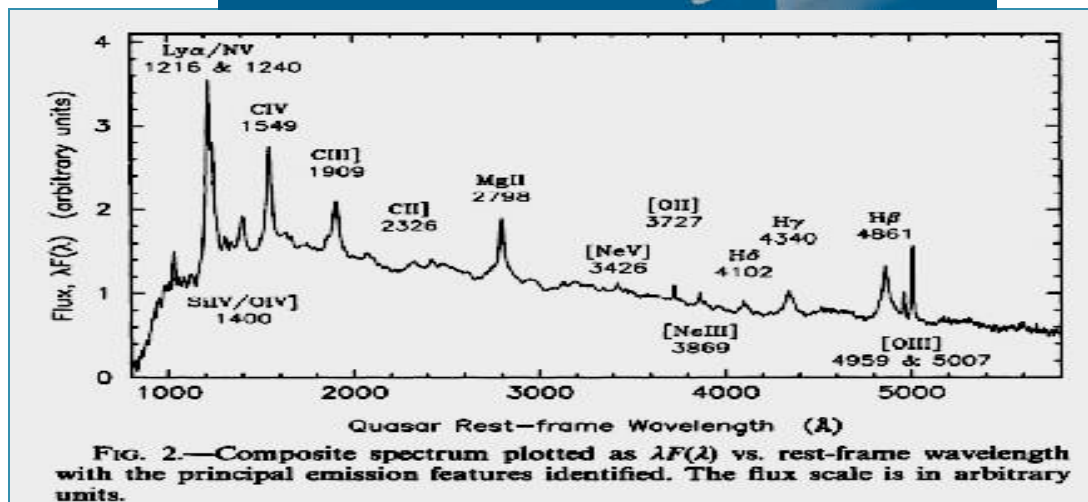


类星体的理论图像

- 中心能源为**超大质量黑洞**(10^7 - 10^{10} 太阳质量)+**吸积盘**+**喷流**
- 外面有宽发射线区、尘埃环、窄发射线区、寄主星系



类星体光谱中有强而宽的发射线

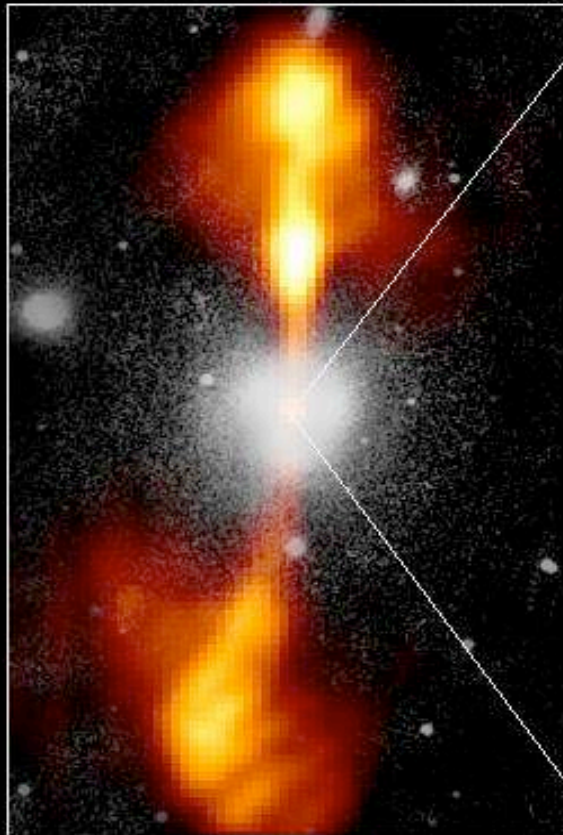


Core of Galaxy NGC 4261

Hubble Space Telescope

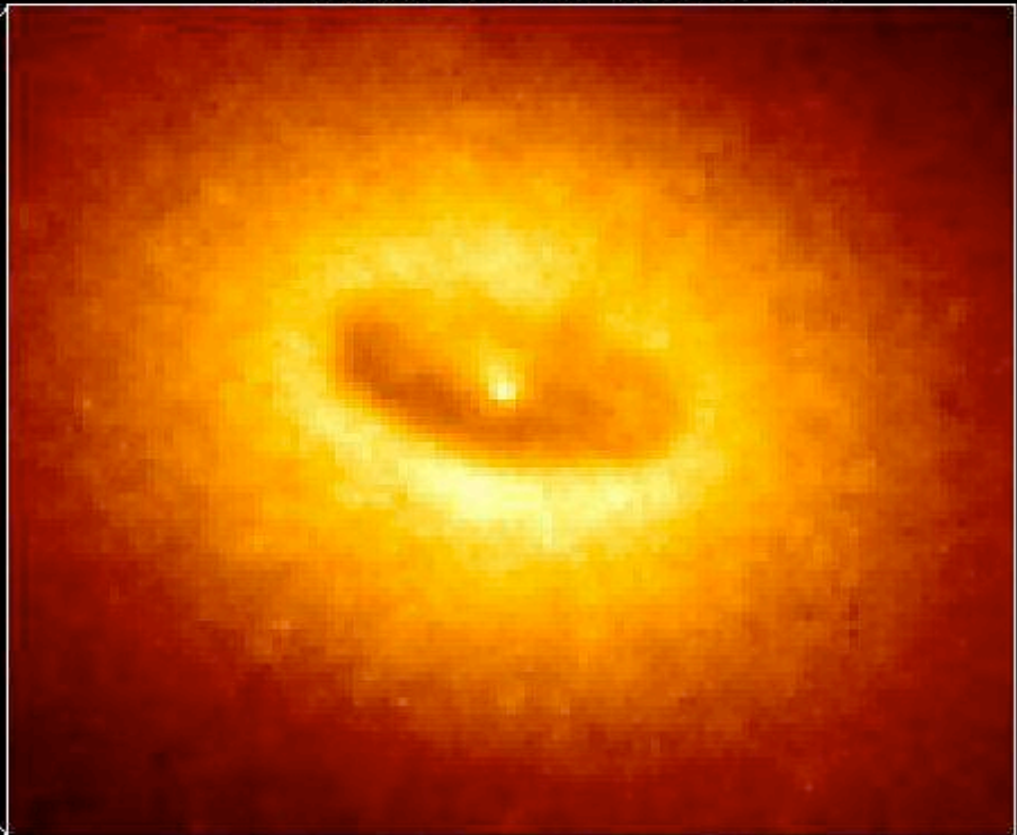
Wide Field / Planetary Camera

Ground-Based Optical/Radio Image



380 Arc Seconds
88,000 LIGHTYEARS

HST Image of a Gas and Dust Disk



17 Arc Seconds
400 LIGHTYEARS

如何发现类星体

- 类星体只有**10%**是有强射电辐射的，因此早期采用的对**射电源**的光学对应体进行光谱证认的观测方法只能发现少数类星体
- 由于**X射线**探测技术的局限，目前**X射线**巡天的深度和广度还很有限，依靠**X射线源**的光谱证认只能发现少数低红移的类星体
- 目前发现类星体主要是从**光学 / 红外测光巡天**选取类星体候选体，然后通过**光学 / 红外光谱**观测来确认是否是类星体(宽发射线)并确定红移

目前光学波段最成功的类星体巡天是美国**SDSS** (I-IV期), 10多年已发现**50万个**类星体

美国SDSS光学测光与光谱巡天

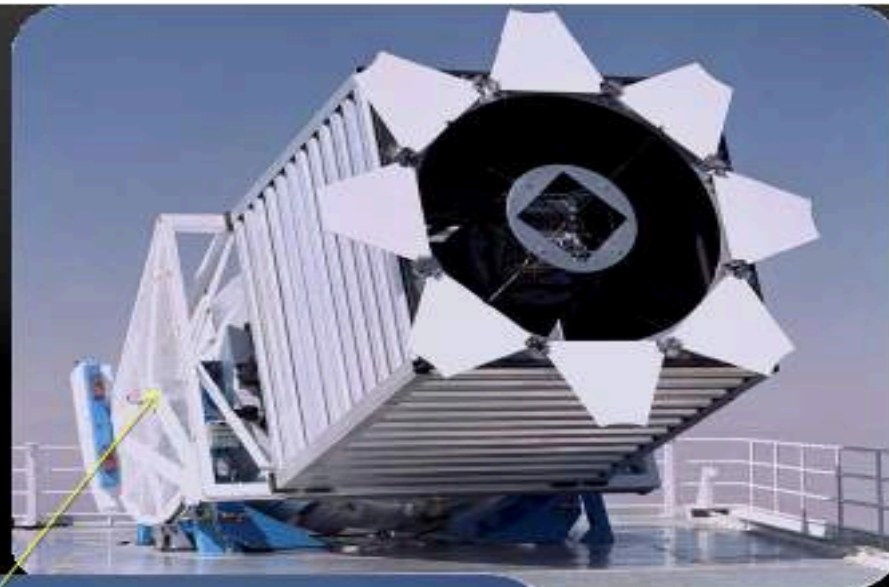
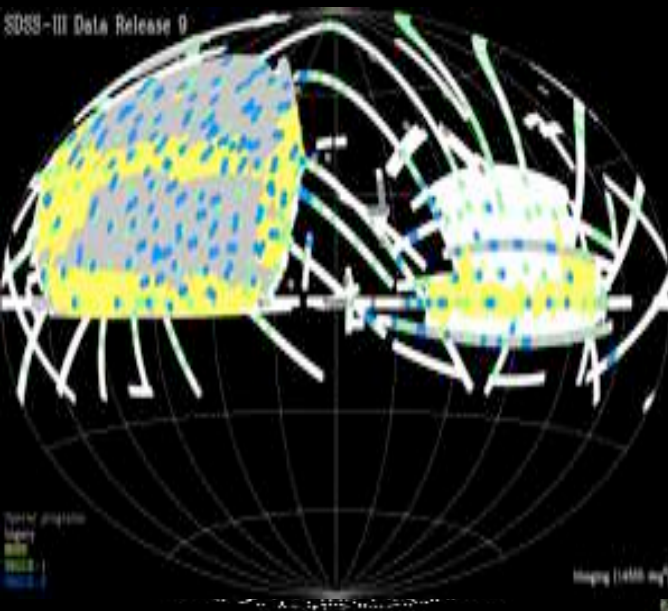
SDSS SURVEY

蓝 *u* *g* *r* *i* *z* 红

3551 Å 4686 Å 6165 Å 7481 Å 8931 Å

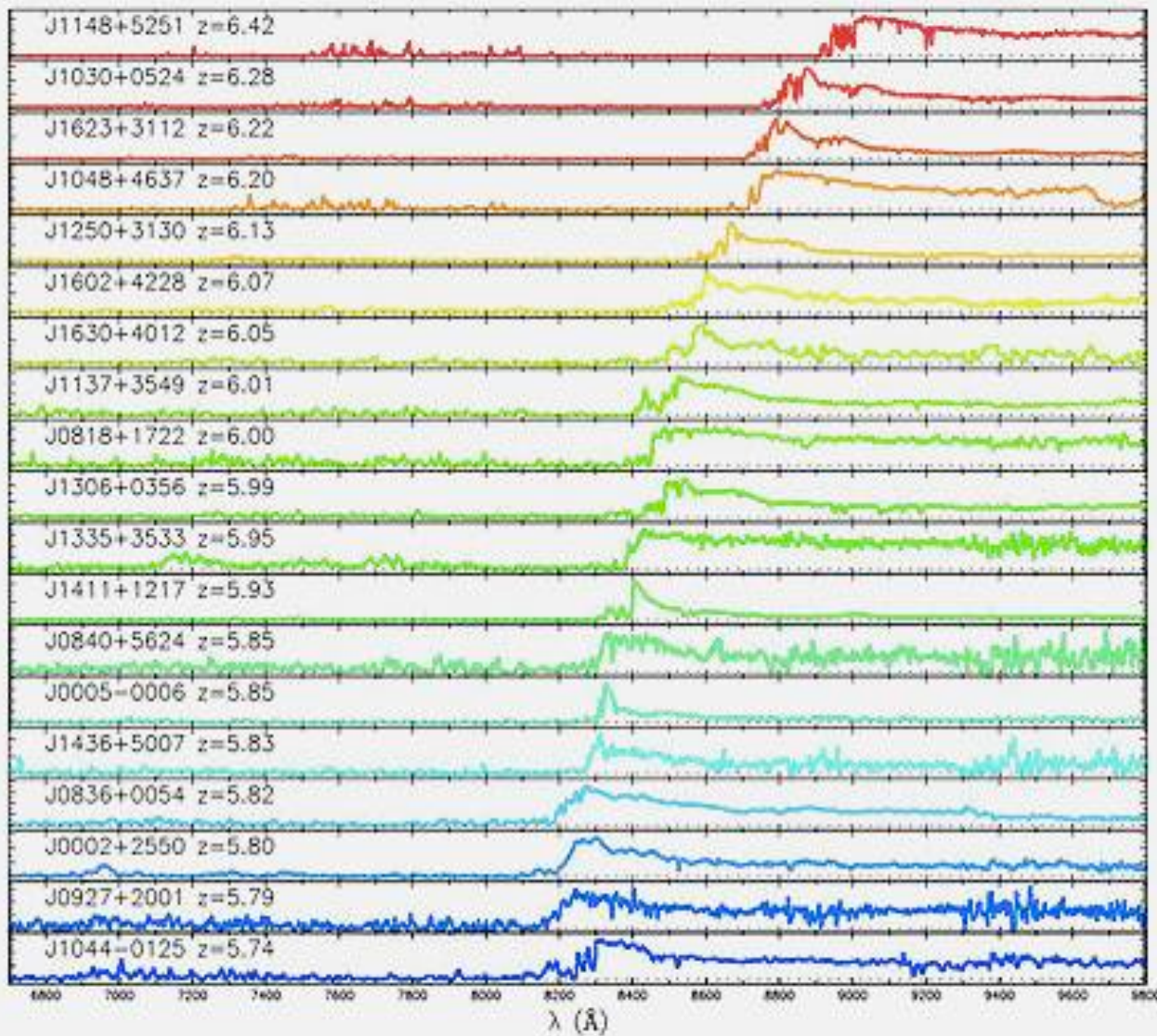
22.0 22.2 22.2 21.3 20.5

SDSS-III Data Release 9



2.5-meter
telescope at
Apache Point
Observatory,
New Mexico.

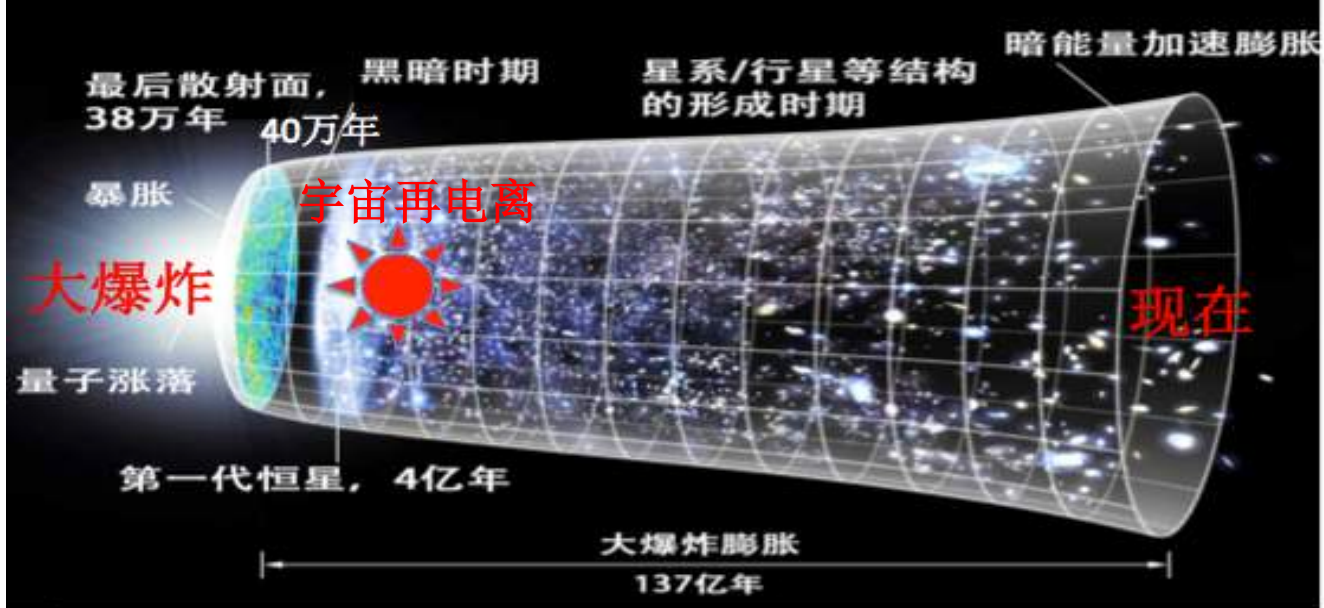
发现最遥远的类星体



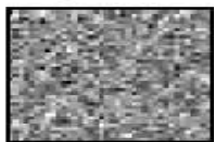
樊晓晖
美国Arizona大学
校董教授

2002年发现红移为
6.42的类星体，保
持世界记录近10年

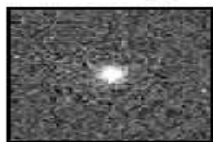
遥远的类星体 可以作为探索 早期宇宙结构 与演化的探针



$z_{DE,3\sigma} > 23.32$



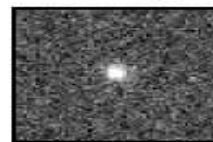
$J1 = 20.73 \pm 0.03$



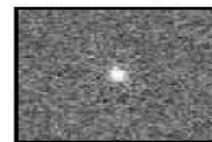
$J = 20.30 \pm 0.02$



$H = 20.16 \pm 0.03$

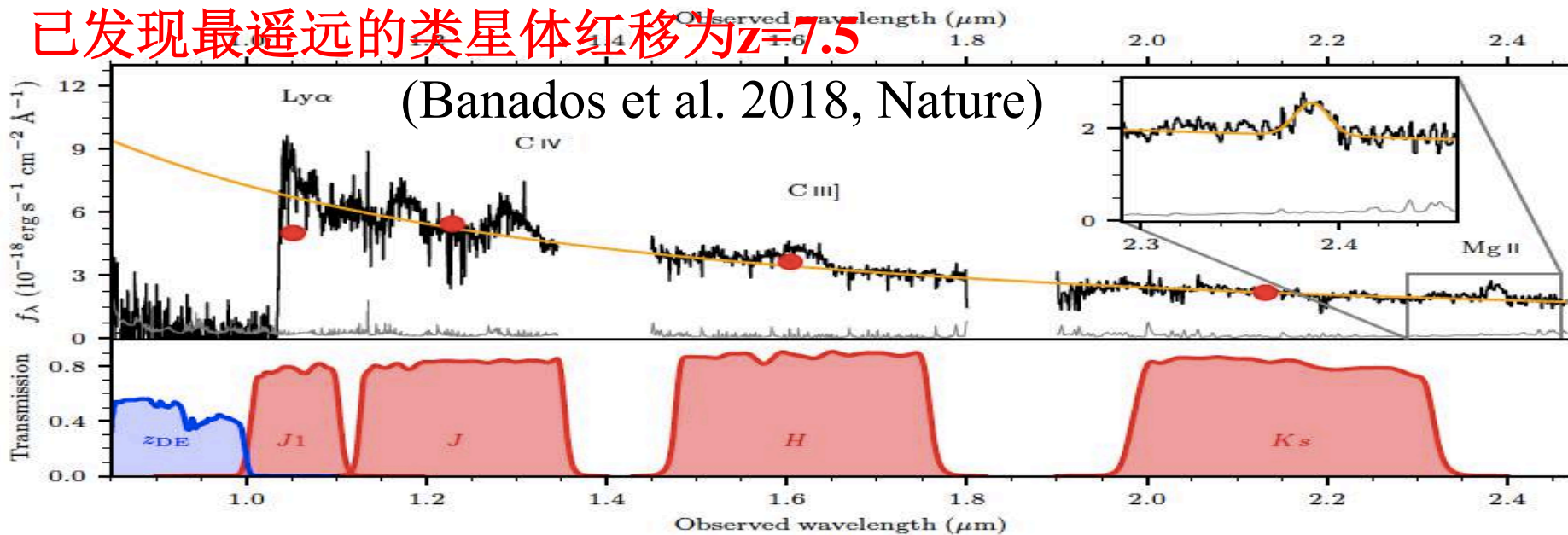


$Ks = 20.10 \pm 0.04$



已发现最遥远的类星体红移为 $z=7.5$

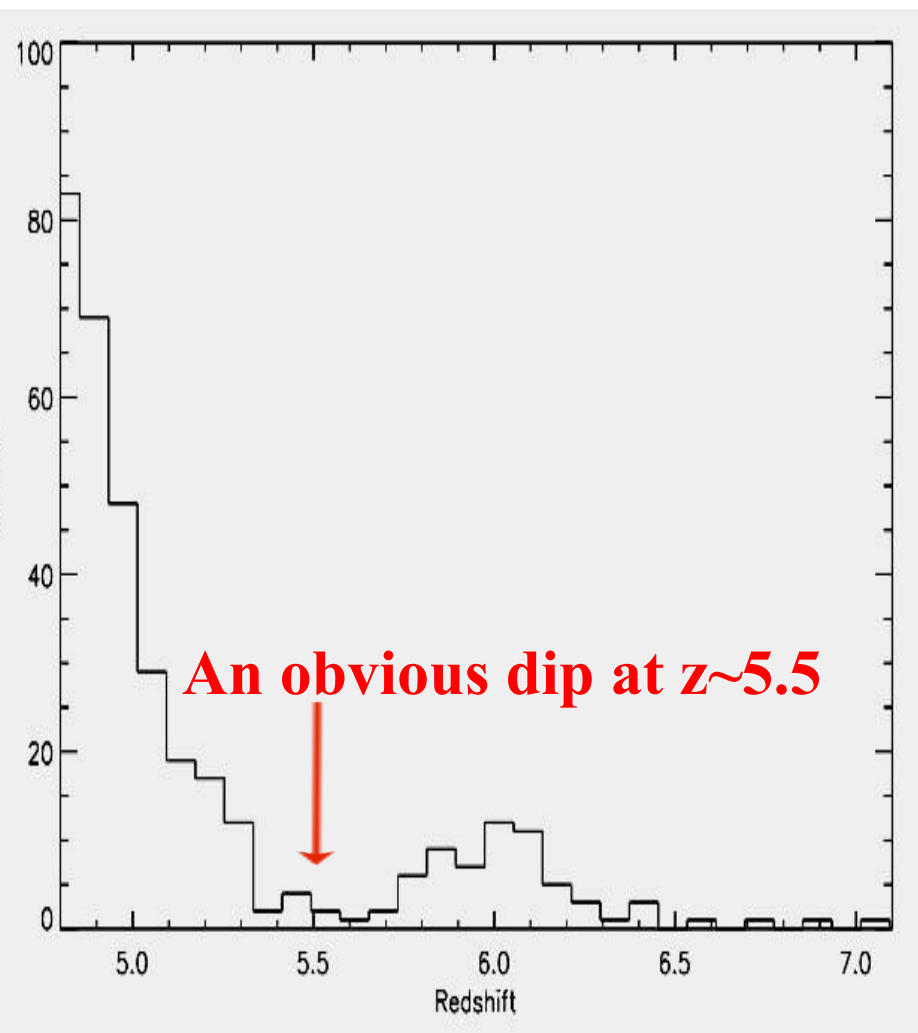
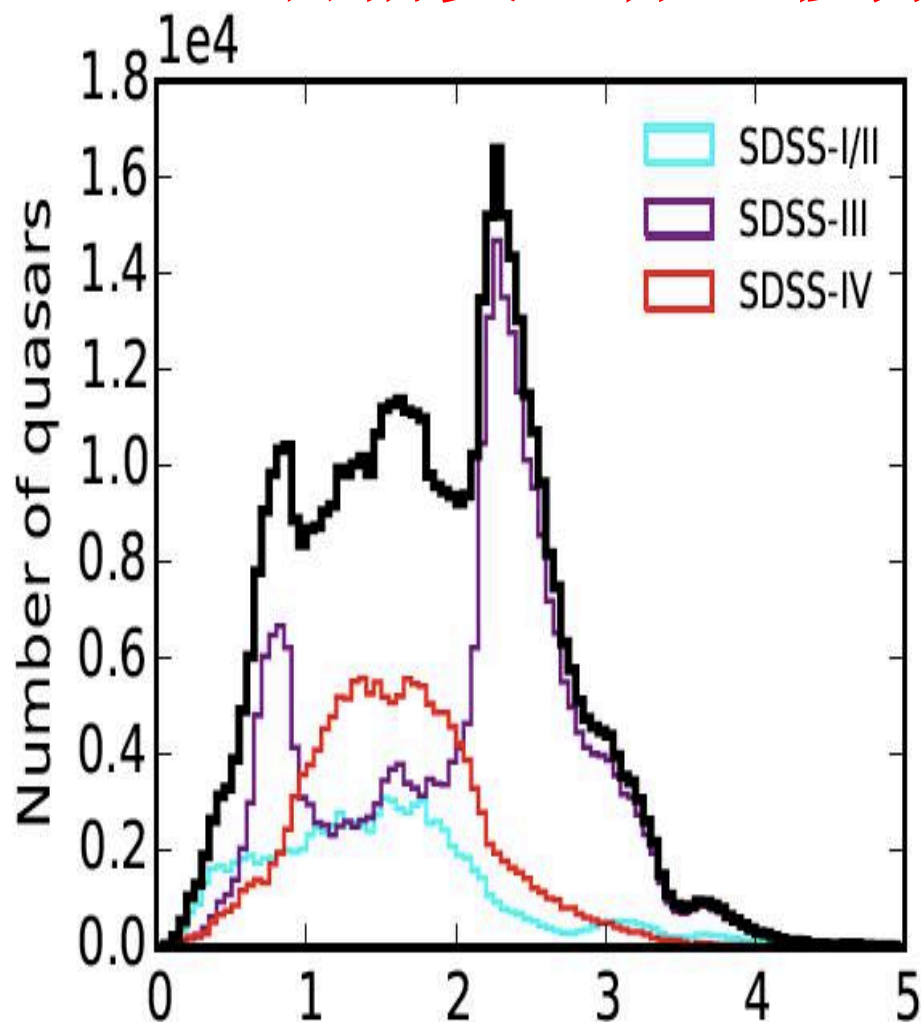
(Banados et al. 2018, Nature)



遥远类星体的中心黑洞质量

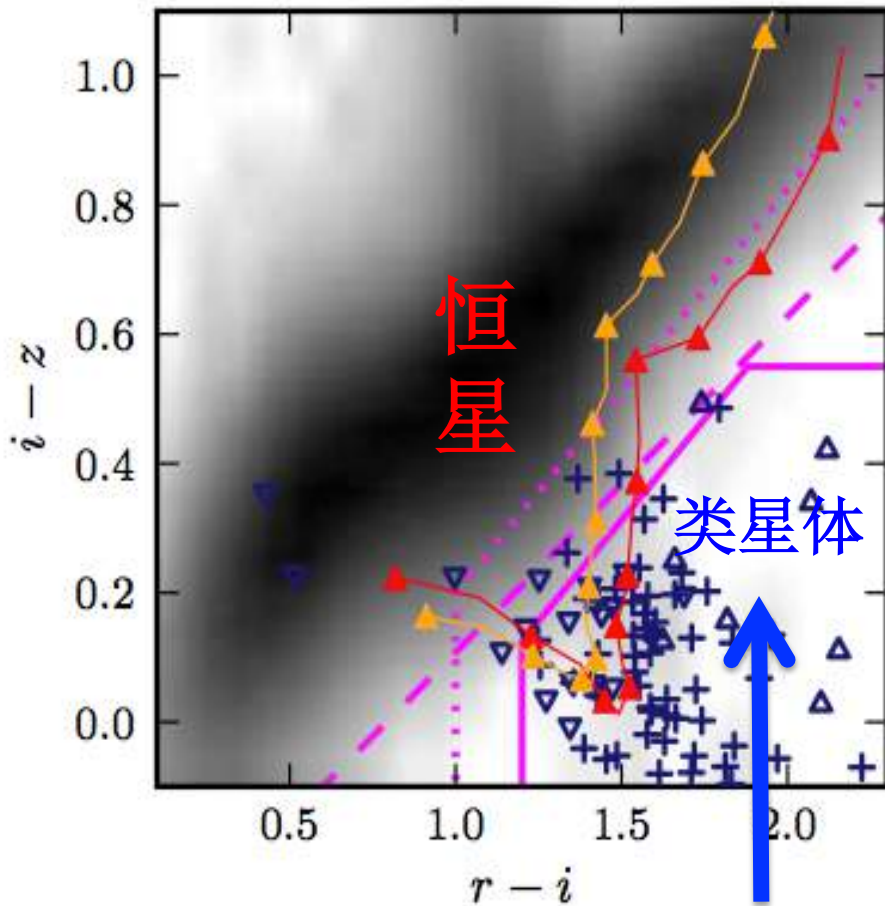
- 类星体中心黑洞质量可以由一些经验关系得到 ($M \propto V^2 R \propto V^2 L^{1/2}$, V 和 L 可由光谱中谱线宽度和连续谱光度给出)
- 红移 $z=6-7$ 类星体的黑洞质量估计为10亿 ($1E9$) 太阳质量, 那时的宇宙年龄小于10亿年, 如何在早期宇宙的短时间内让黑洞增长到质量如此之大, 成为一大理论难题

目前类星体红移分布(高红移奇缺!)

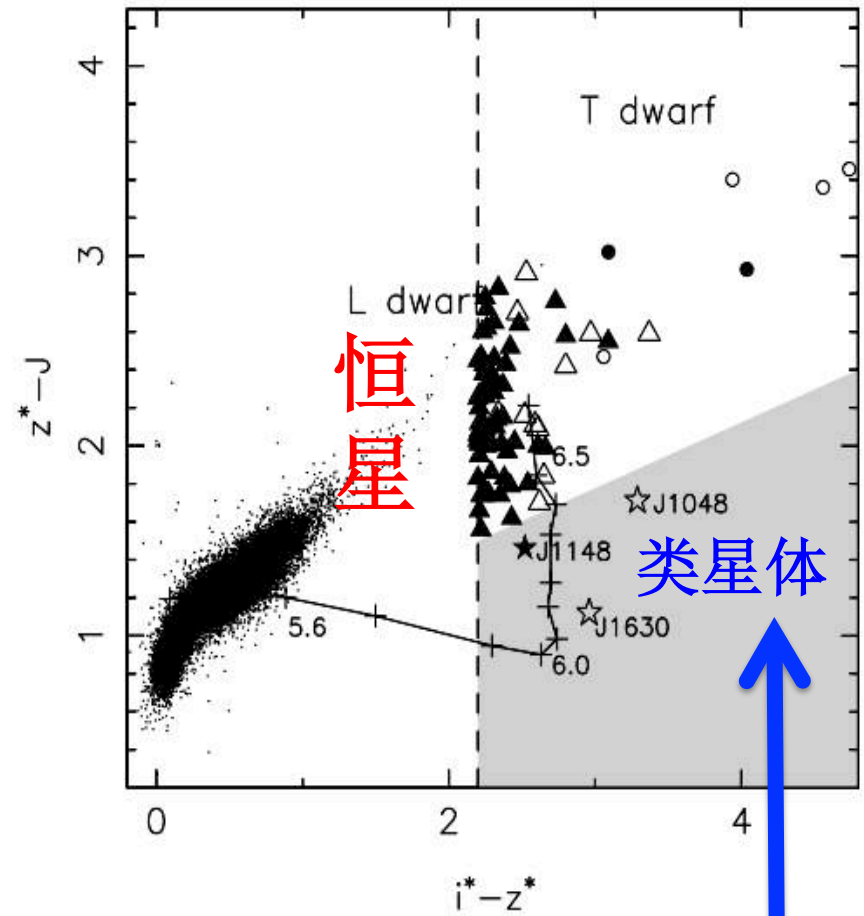


50万已知类星体中，红移大于5的只有300多个，大于6的只有120多个，大于7的只有4个

为何发现红移5.5左右的类星体非常困难？ (颜色-颜色图上的比较 -> 严重的恒星污染！)

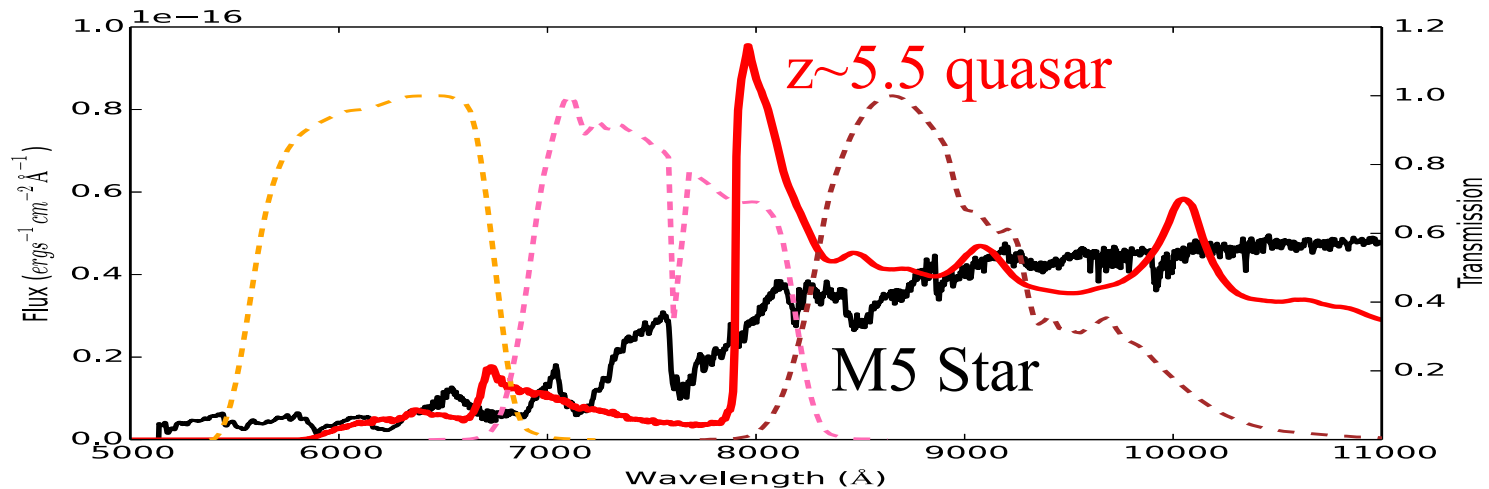
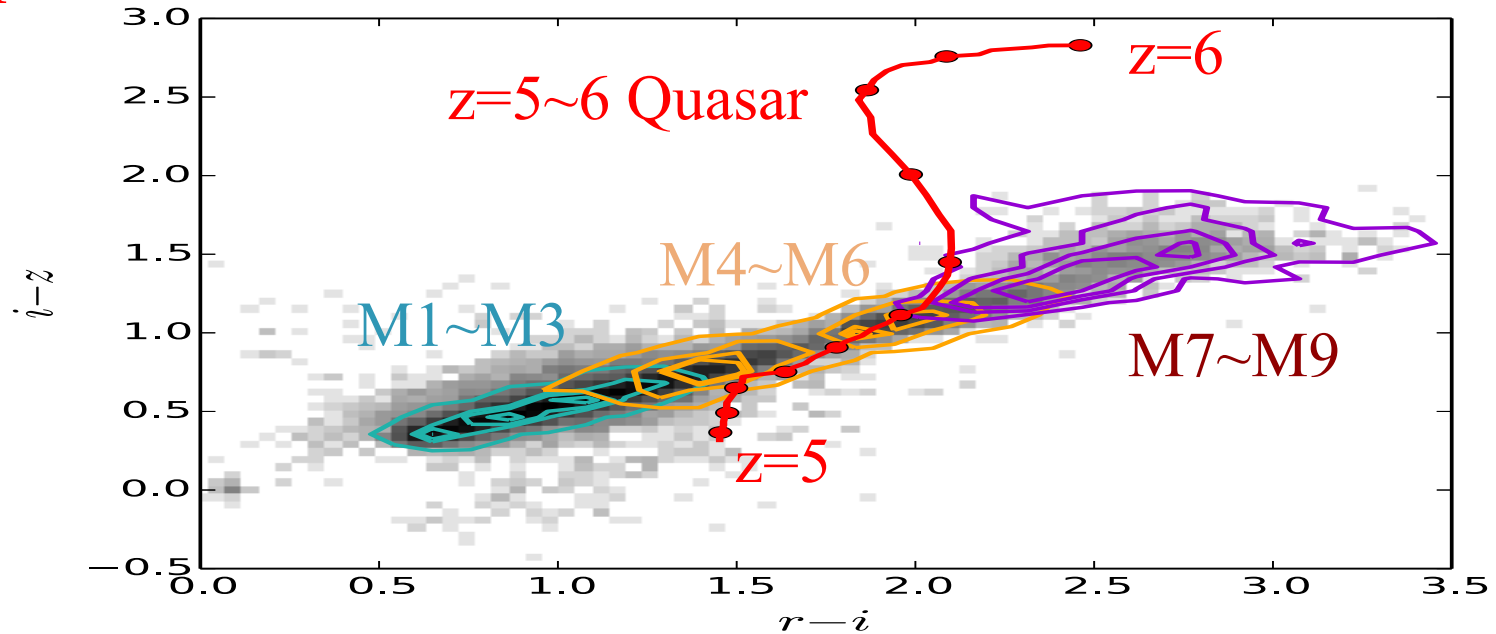


McGreer et al. 2013; Effective:
 $4.7 < z < 5.1$

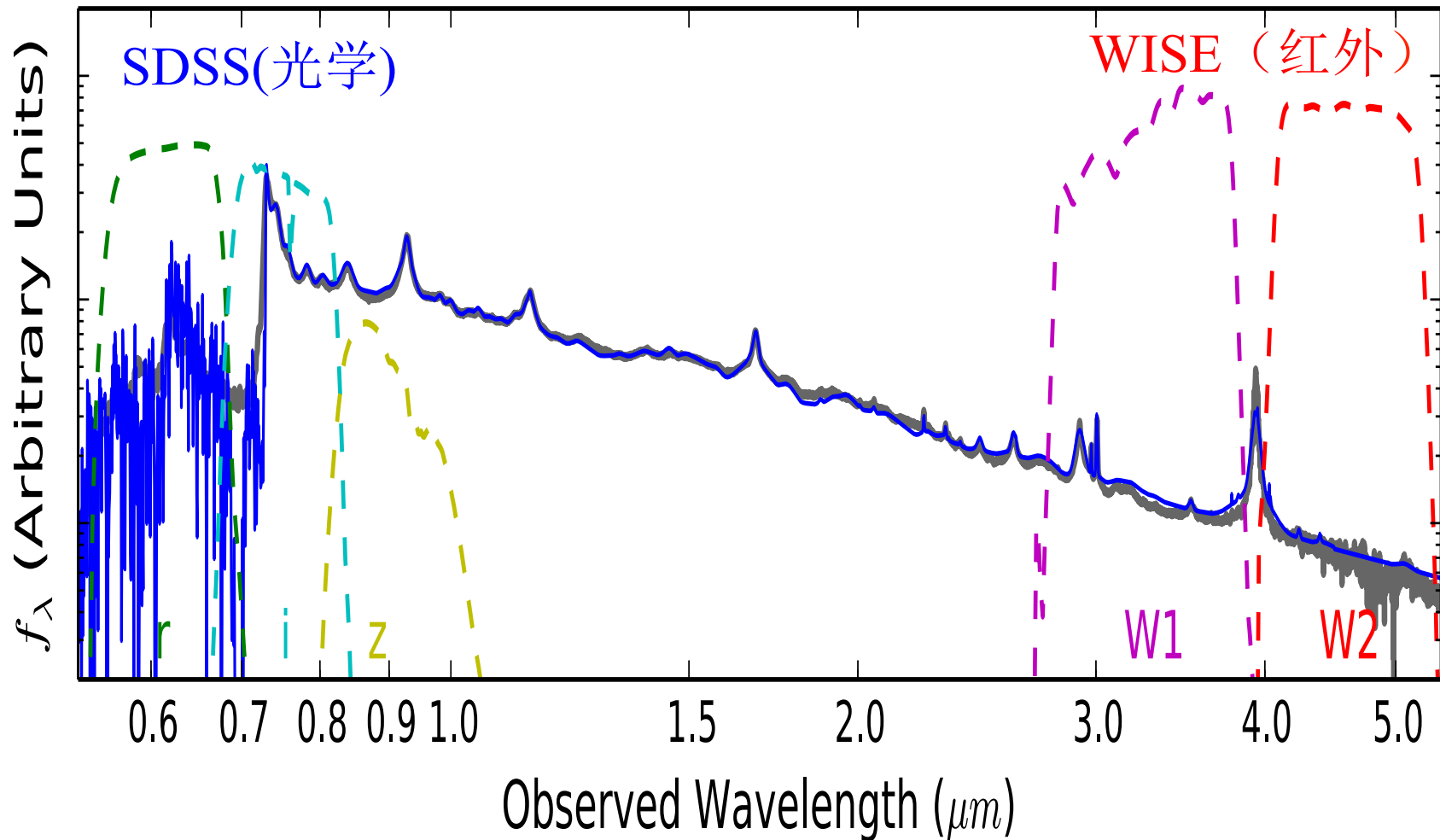


Fan et al. 2001, 03, 04, 06
Jiang et al. 2008, 09;
Effective: $z > 5.8$

Using optical colors can hardly separate $z \sim 5.5$ quasars from M stars (Yang, Fan, Wu, et al., 2016)



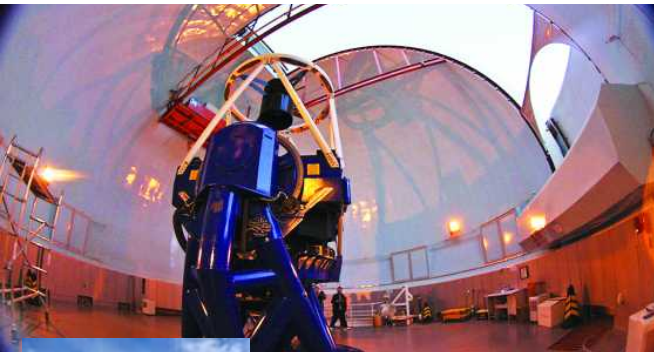
红移~5 的类星体光谱



把光学波段和红外波段数据结合起来
寻找高红移类星体更有效！

2、发现红移5以上的类星体

我们用到的望远镜



2.4-m
telescope,
Lijiang,
Yunnan, China

2.16-m
telescope,
Xinglong/
NAOC,
China



Bok 2.3-m,
Kitt Peak
USA



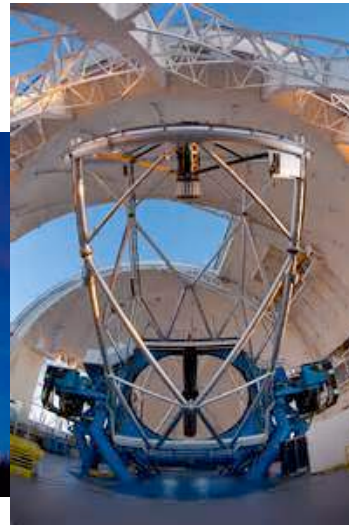
ANU 2.3-m,
Australia



MMT(6.5-m)



LBT(2*8.4-m)



Gemini-N(8.1-m)

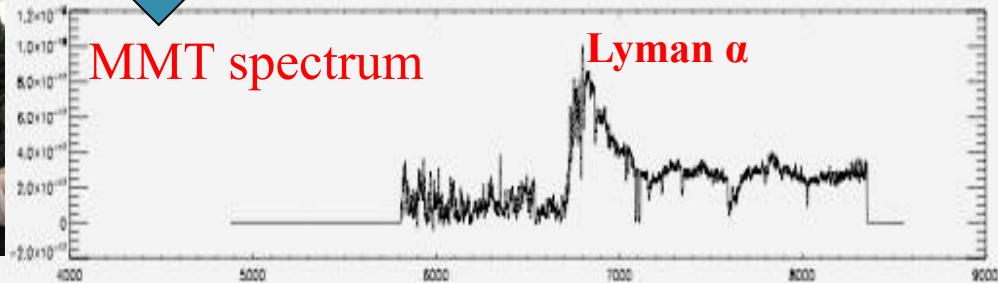
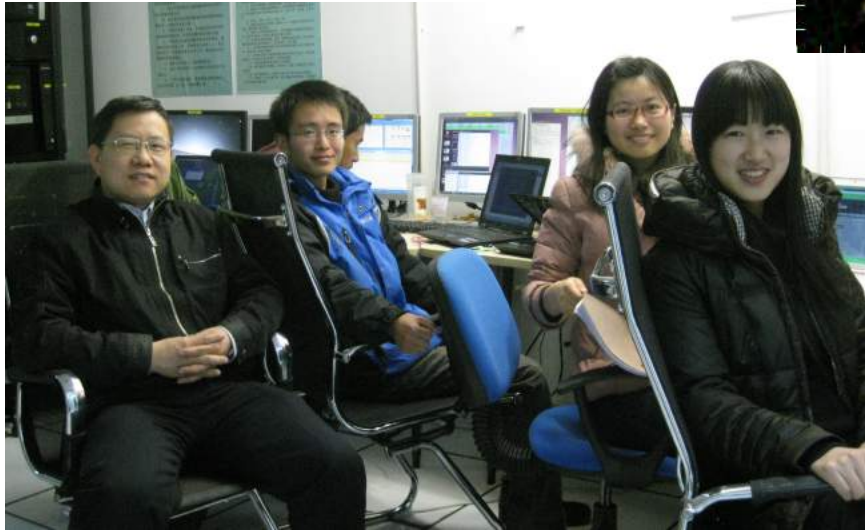
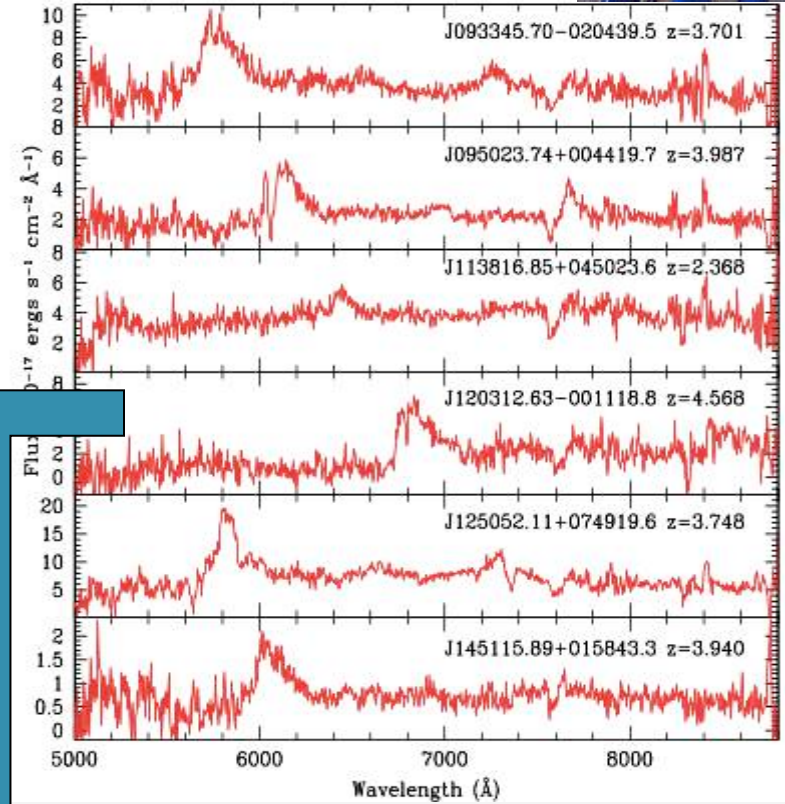
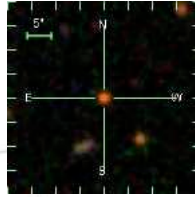


Magellan(6.5-m)

利用国内2米望远镜发现遥远类星体

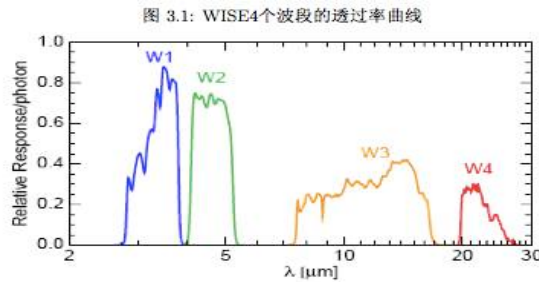
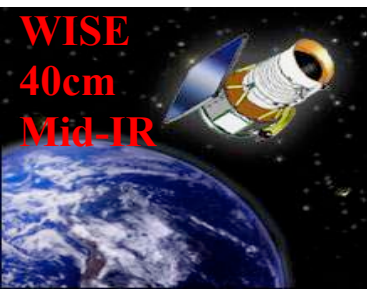
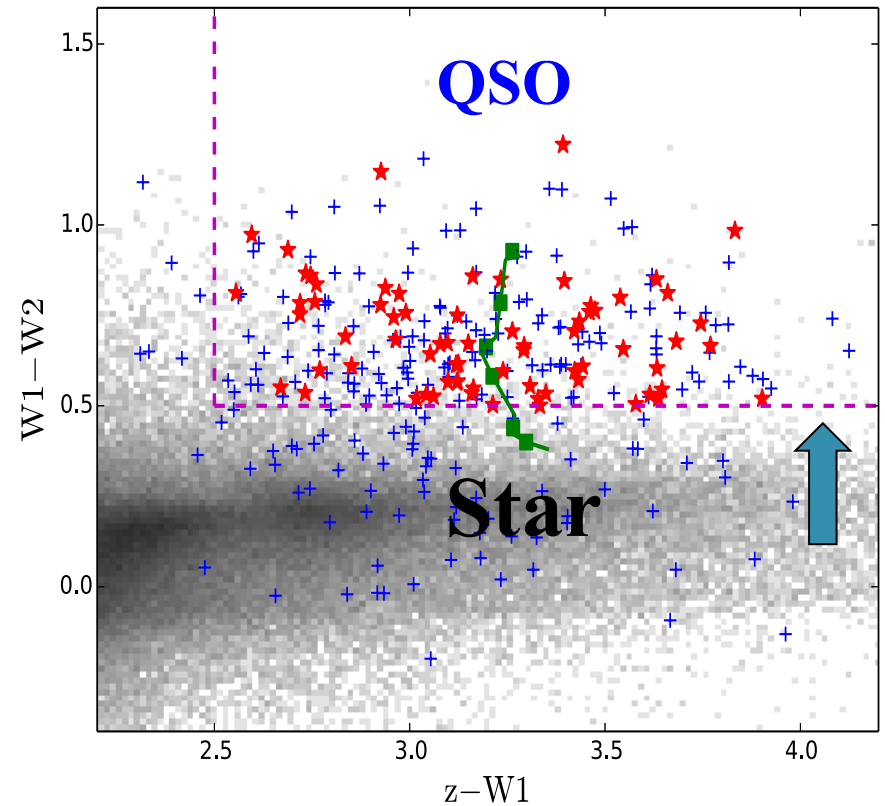
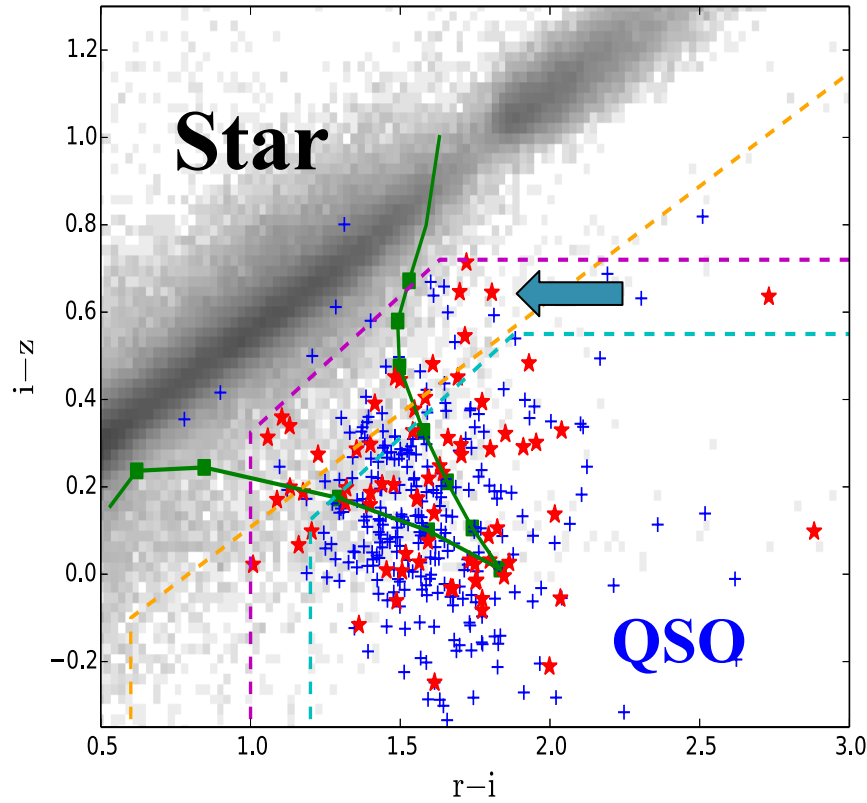


- 2012年在国内发现第一个高红移类星体(光学+近红外UKIRT选源; $z=4.6$)
- 2012年2月28日用2.4米望远镜发现
- 被中科大同事用美国6.5米MMT望远镜观测核实



Select high- z quasar candidates with SDSS-WISE

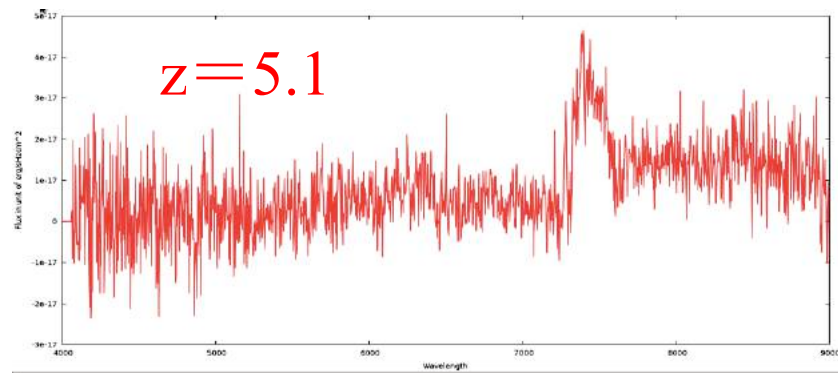
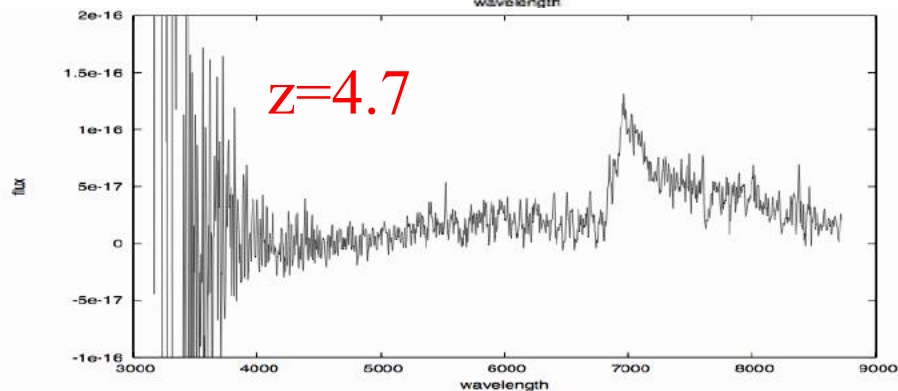
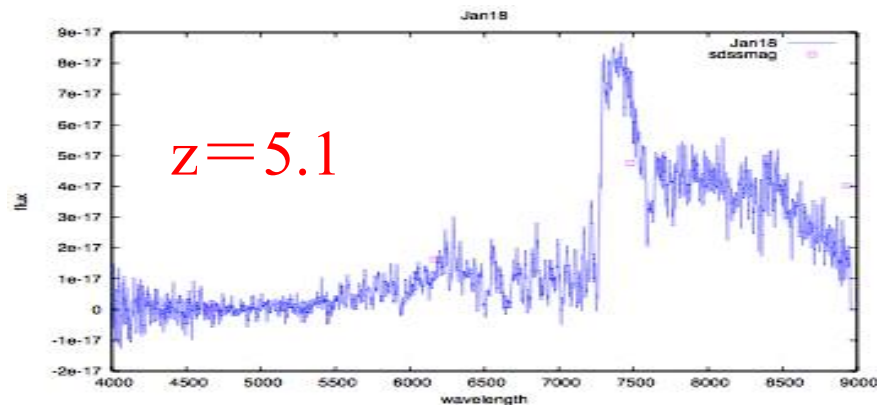
Because WISE detection rate of $z > 4.5$ quasars is 70%, using WISE can help find $z \sim 5$ quasars if the revised selection criteria adopted



(Wang F., Wu, X.-B., et al. 2016, ApJ, 819, 24)

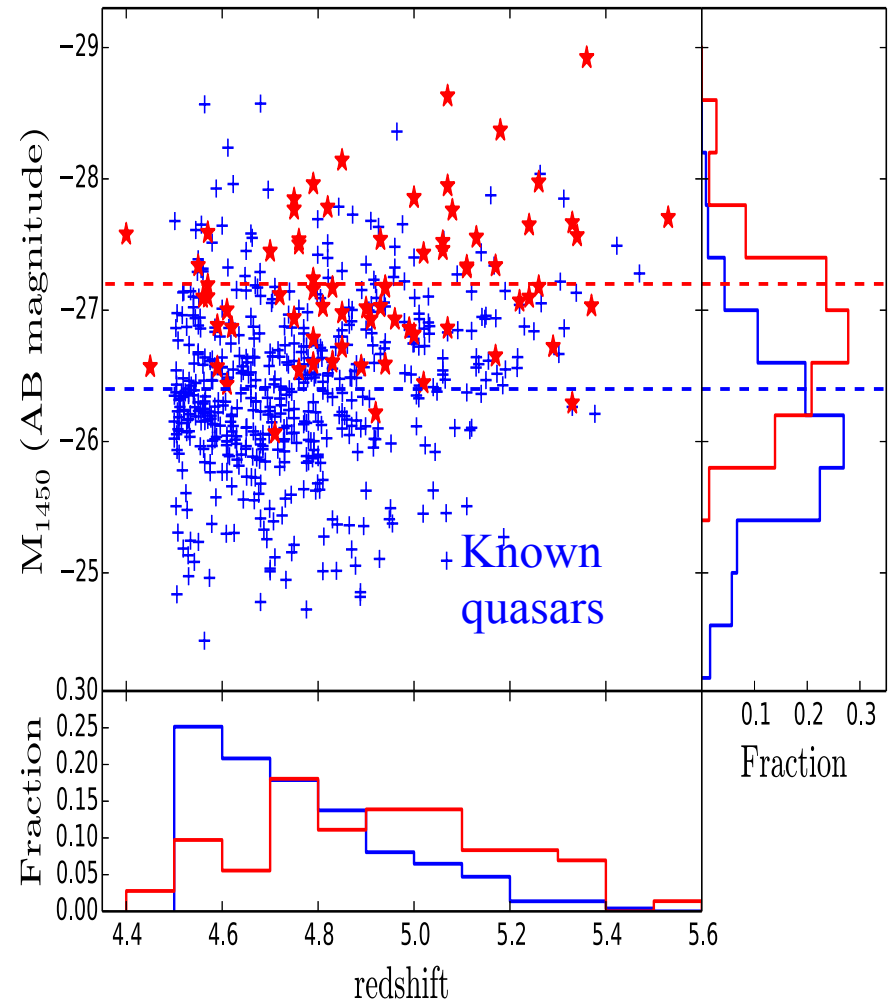
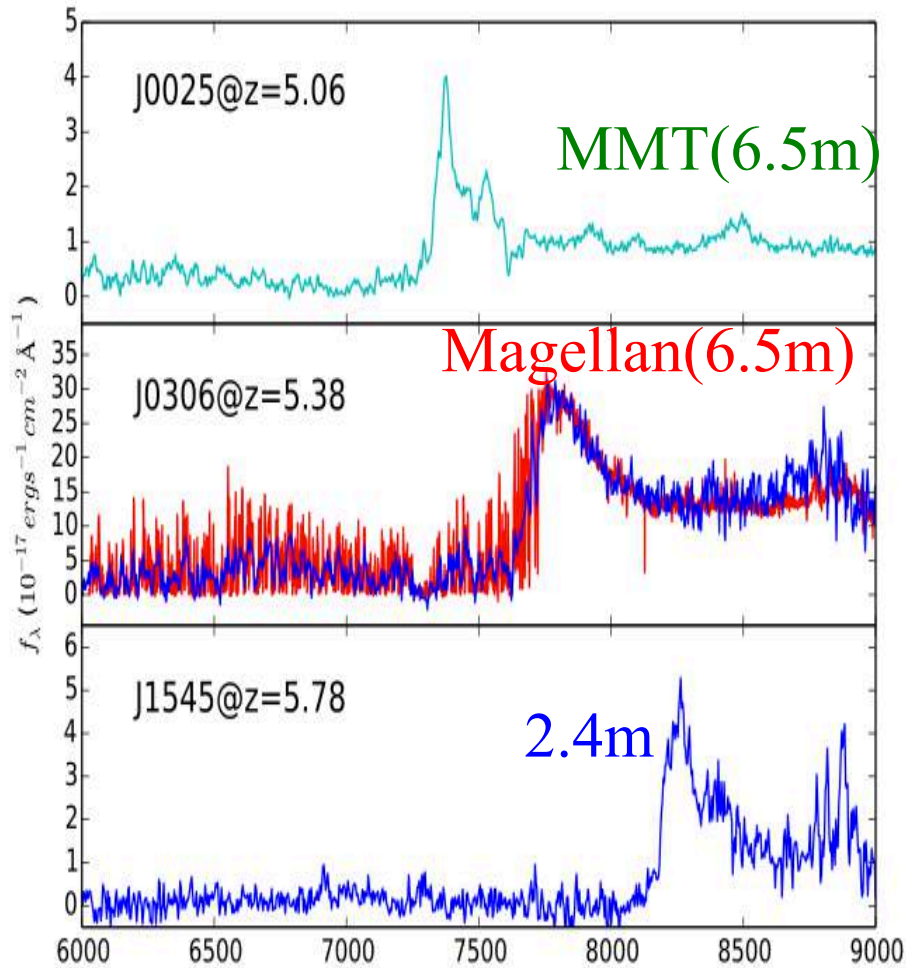
2013年我们再次刷新国内记录

- 2013年1月，利用丽江2.4米望远镜发现 $z=5.1$ 类星体
- 2013年3月，利用兴隆2.16米望远镜发现 $z=4.7$ 类星体
- 2013年8月，利用丽江2.4米望远镜再次发现 $z=5.1$ 类星体



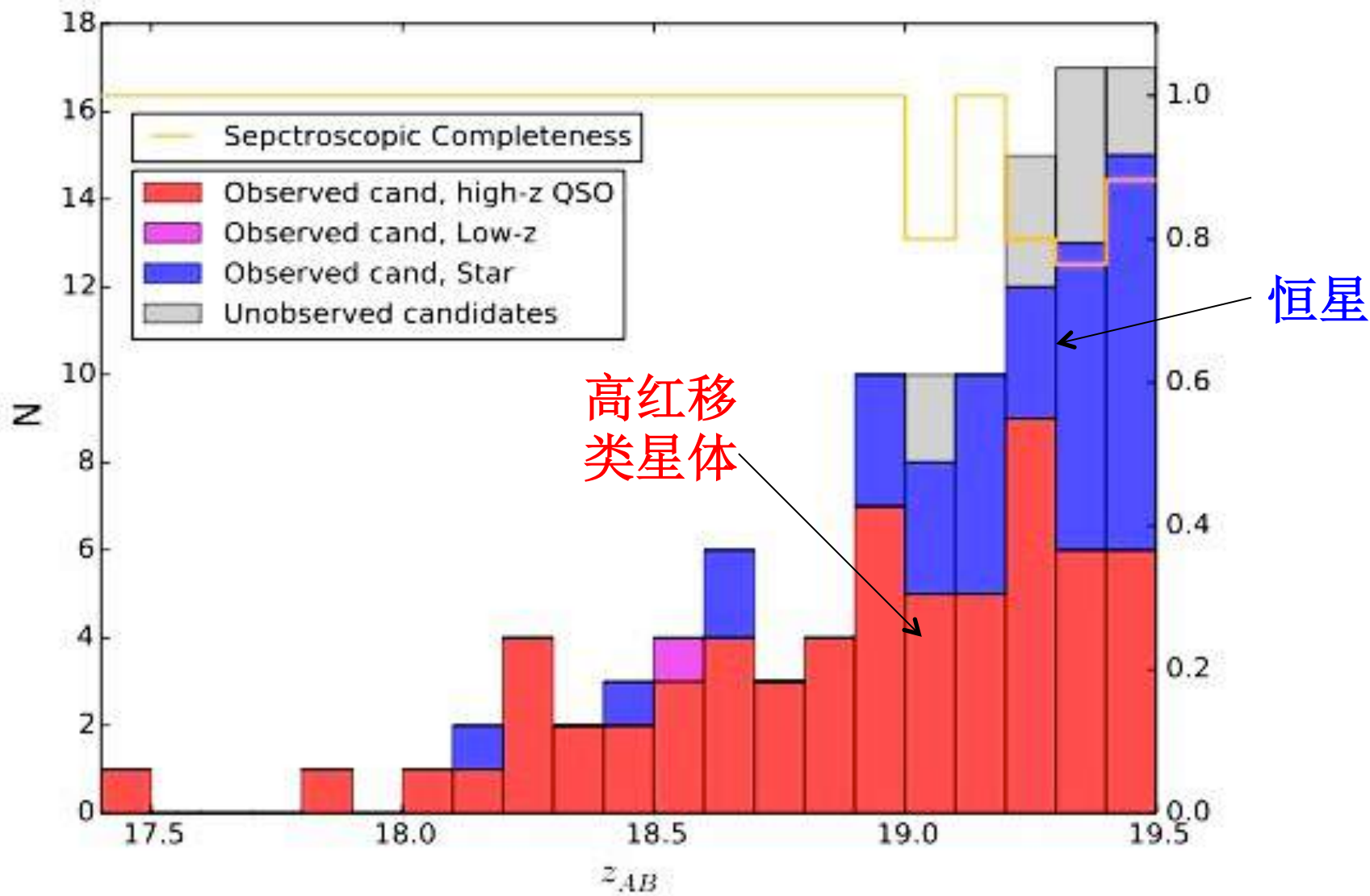
SDSS-WISE High-z Quasars

-->76 new luminous quasars at $4.4 < z < 5.6$



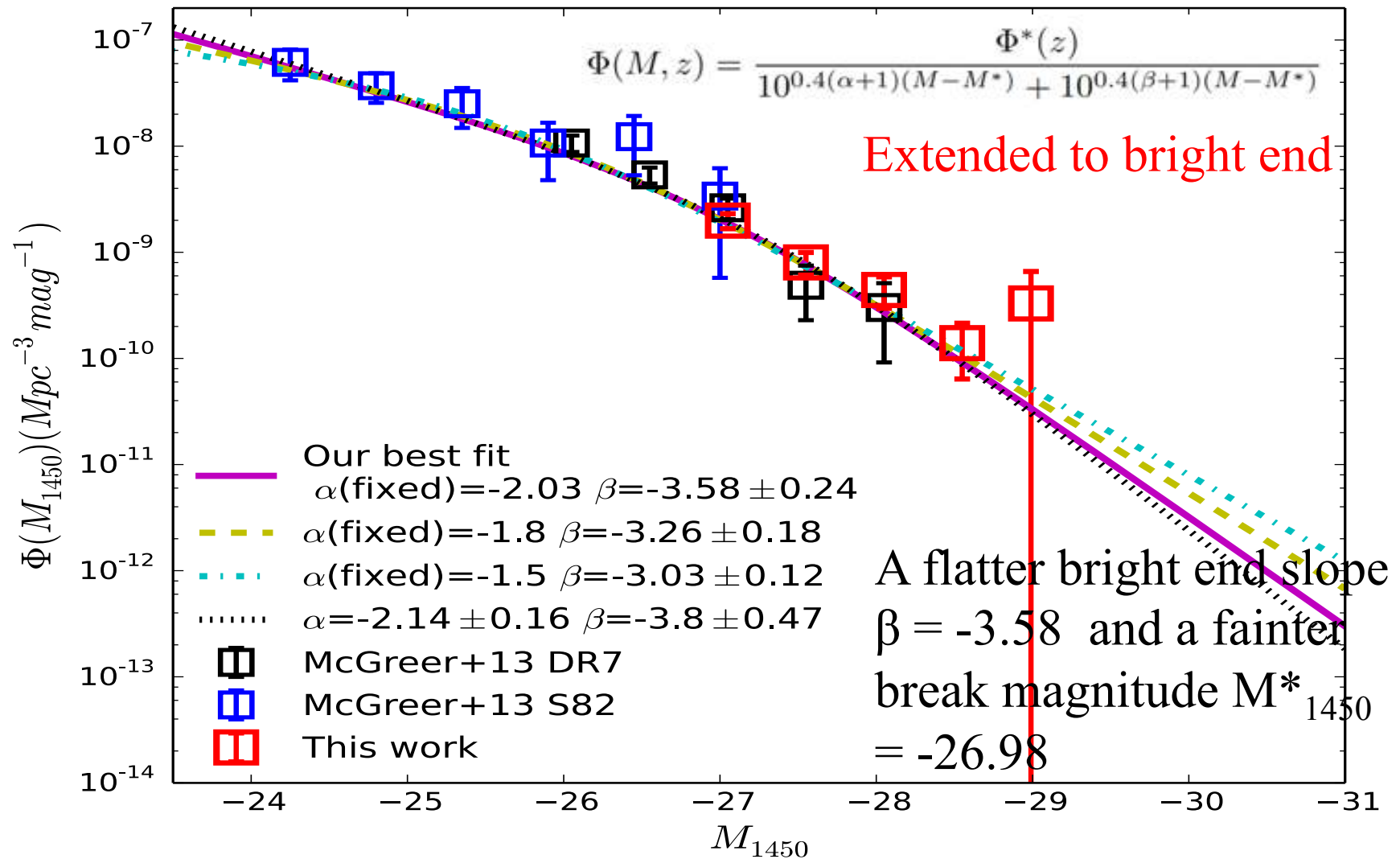
(Wang F. et al. 2016, ApJ, 819, 24)

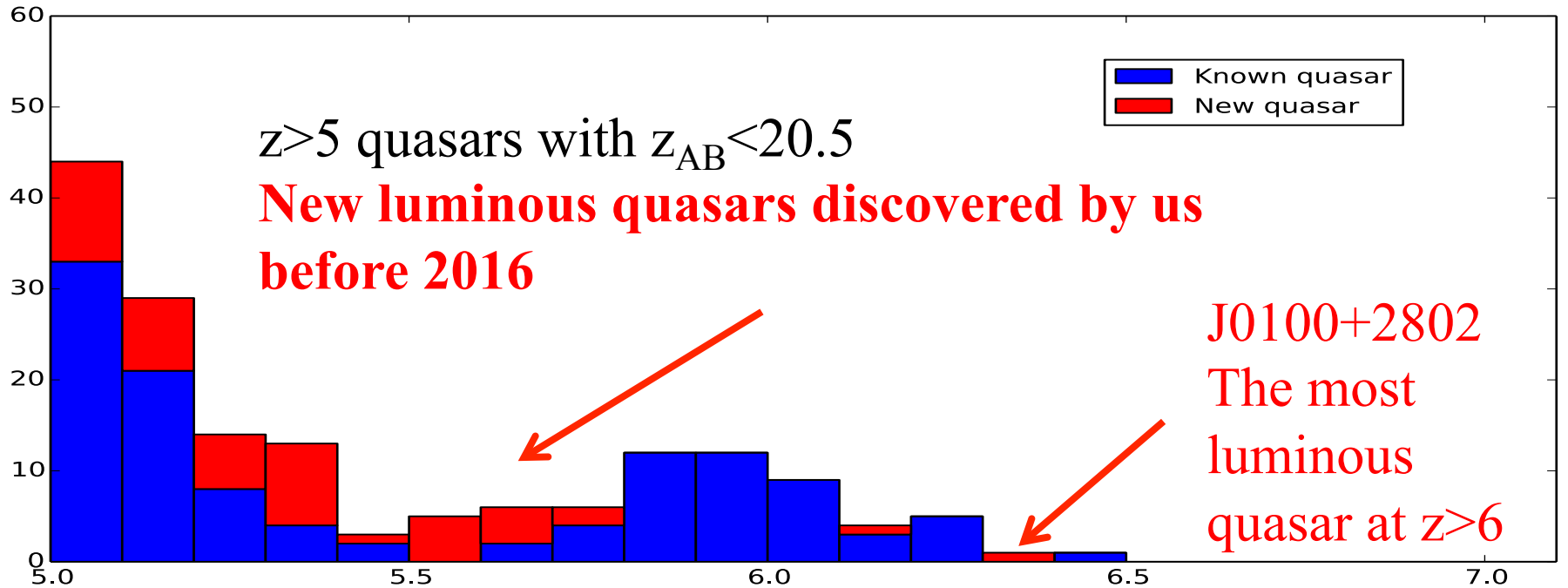
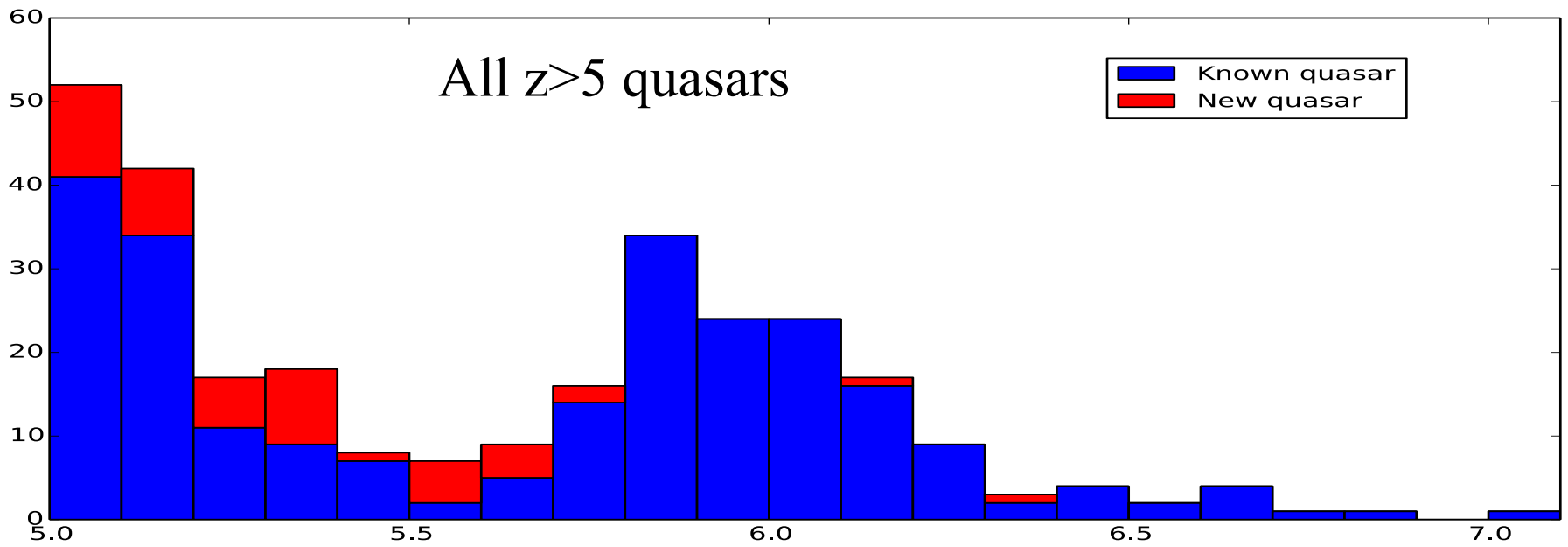
2013-2016年对110个候选体的观测 发现70多个高红移类星体



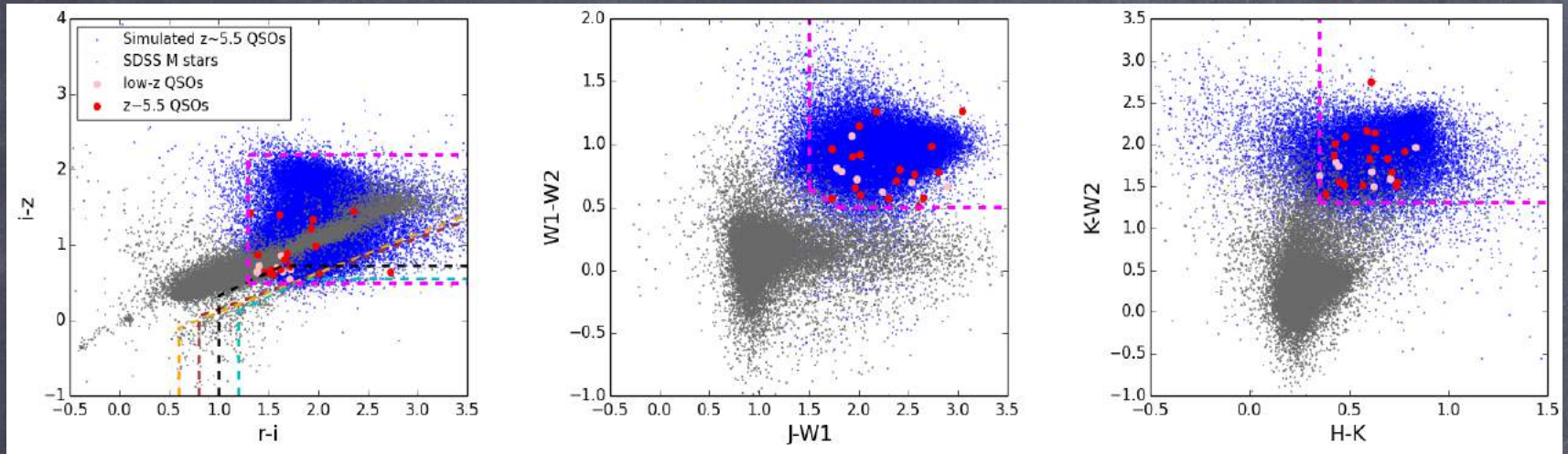
Quasar Luminosity Function at $z \sim 5$

Yang J., Wang, F., Wu, X.-B. et al. 2016, ApJ, 829, 33





New method by adding Near-IR, Mid-IR photometric data

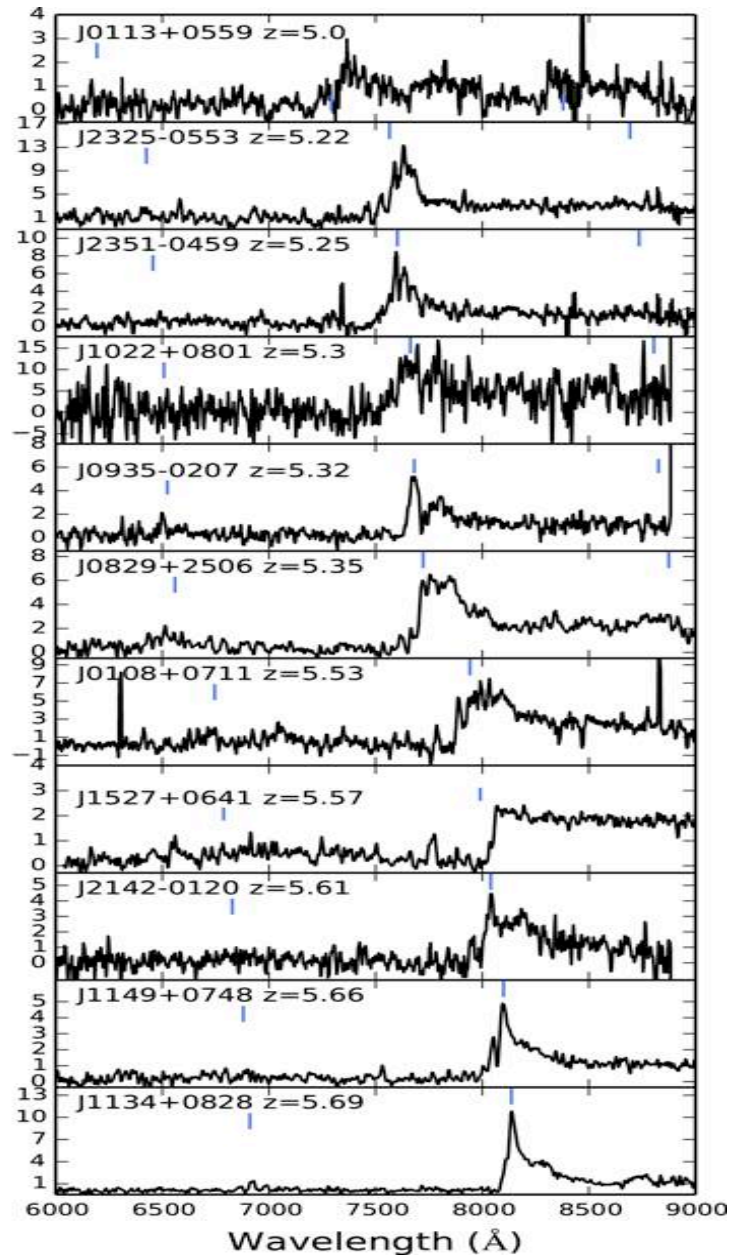
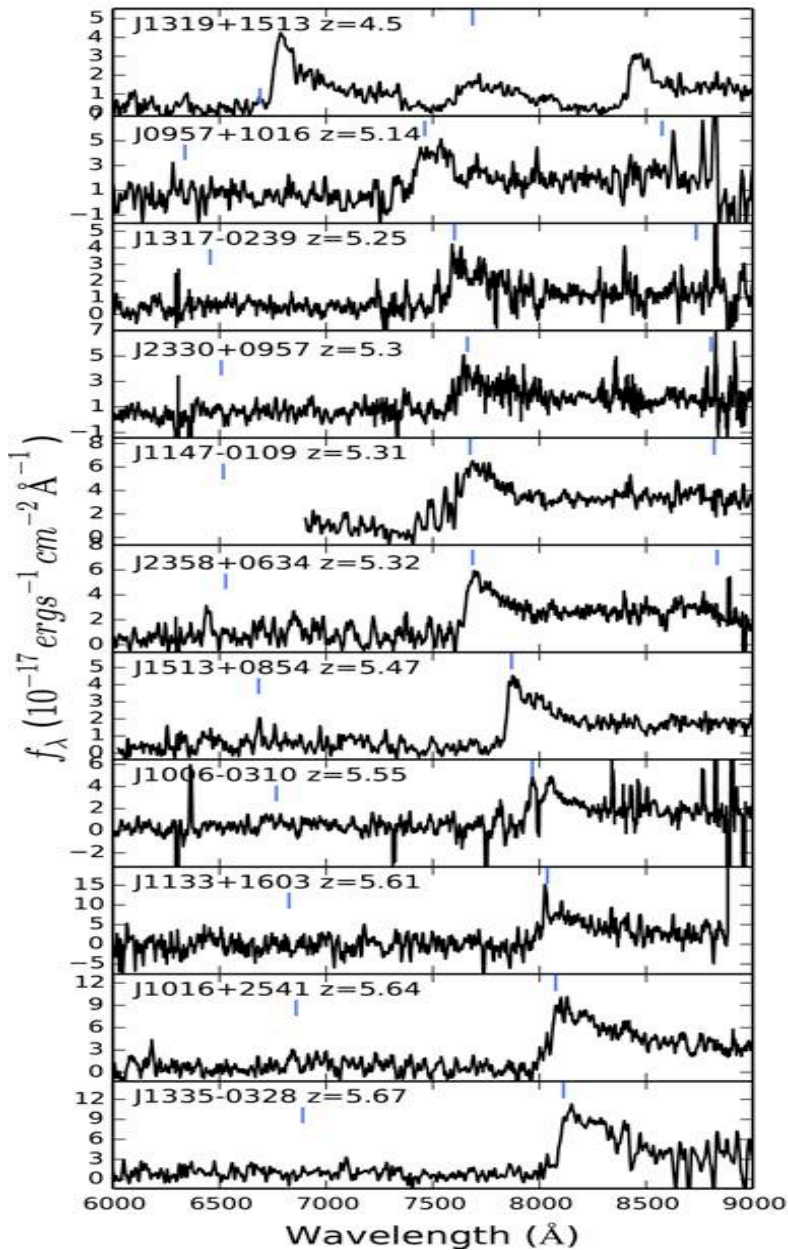


A survey based on SDSS-ULAS/VHS-ALLWISE
in a ~ 5000 square degree field, $z < 20.5$ mag

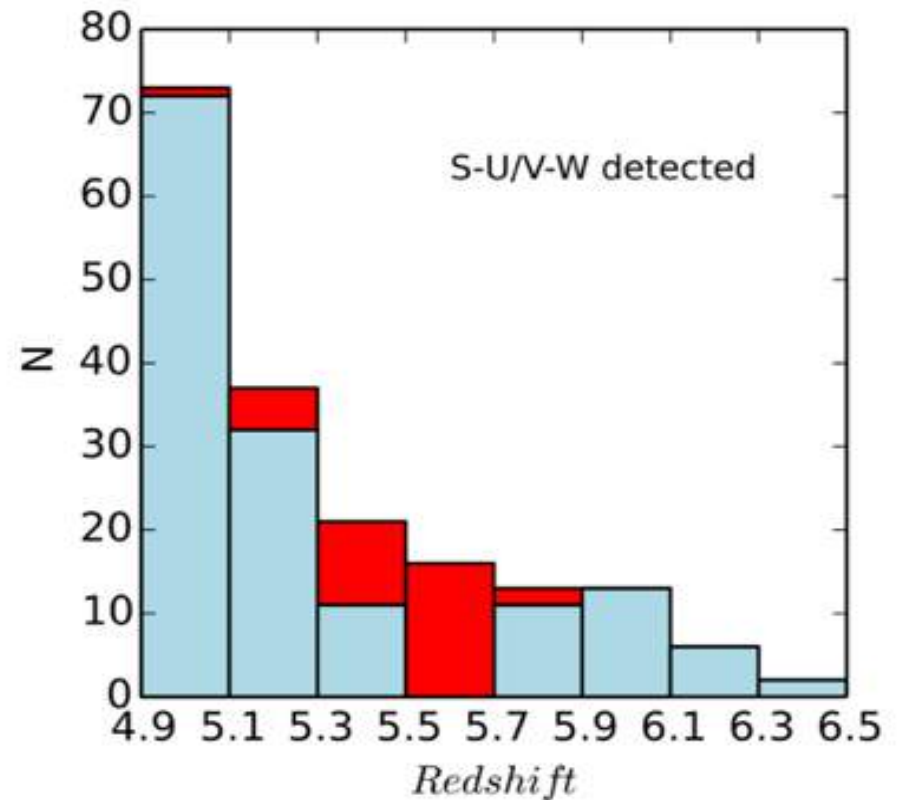
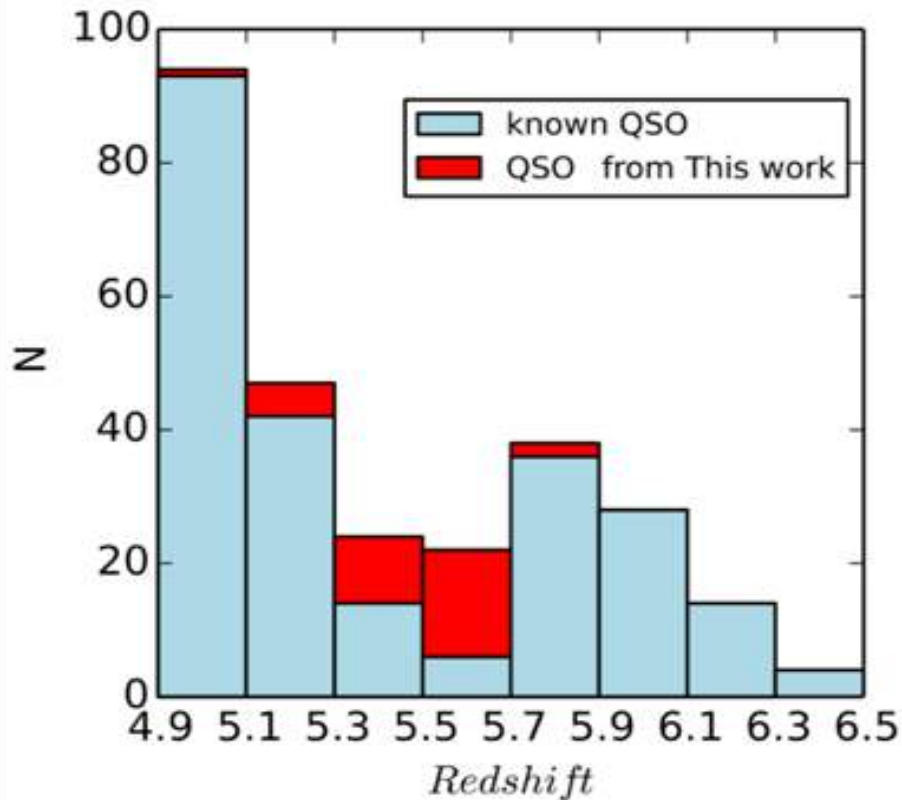
UKIRT InfraRed Deep Sky Surveys - Large Area Survey
VISTA Hemisphere Survey

A **new** $z \sim 5.5$ quasar survey based on **SDSS-ULAS/VHS/UHS-WISE**

- In a ~ 5000 square degree field, $z < 20.5$ mag; SDSS; **UKIRT InfraRed Deep Sky Surveys - Large Area Survey(ULAS); VISTA Hemisphere Survey(VHS); WISE**
- Extended sample
 - in **UKIRT Hemisphere Survey (UHS, J-band)** area; SDSS - UHS $\sim 8000 \text{ deg}^2$; + **Pan-STARRS1 (PS1)** data
- We have discovered **31 new $z \sim 5.5$ quasars** in total, forming the first uniform quasar sample at $z \sim 5.5$



Identifications with Palomar P200, MMT 6.5m and ANU 2.3m



The $z \sim 5.5$ gap is filled well now if considering only $z_{AB} < 20.5$ sources with SDSS, NIR(ULAS,UHS,VHS) and WISE detections

HIGHLIGHTS



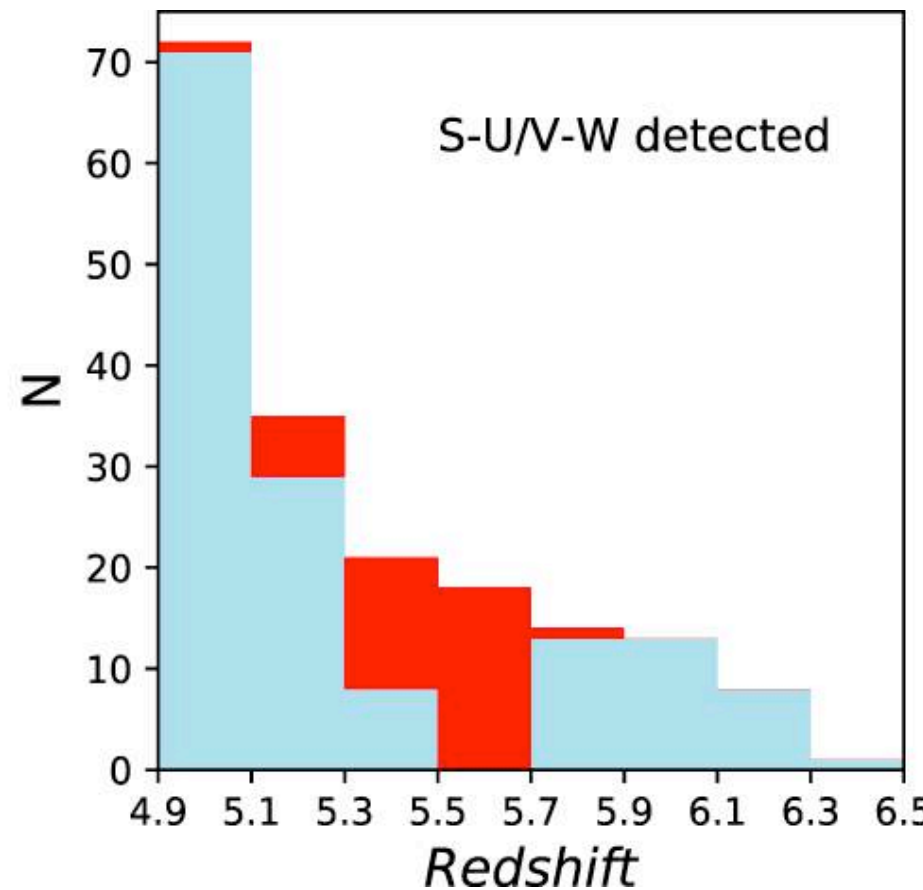
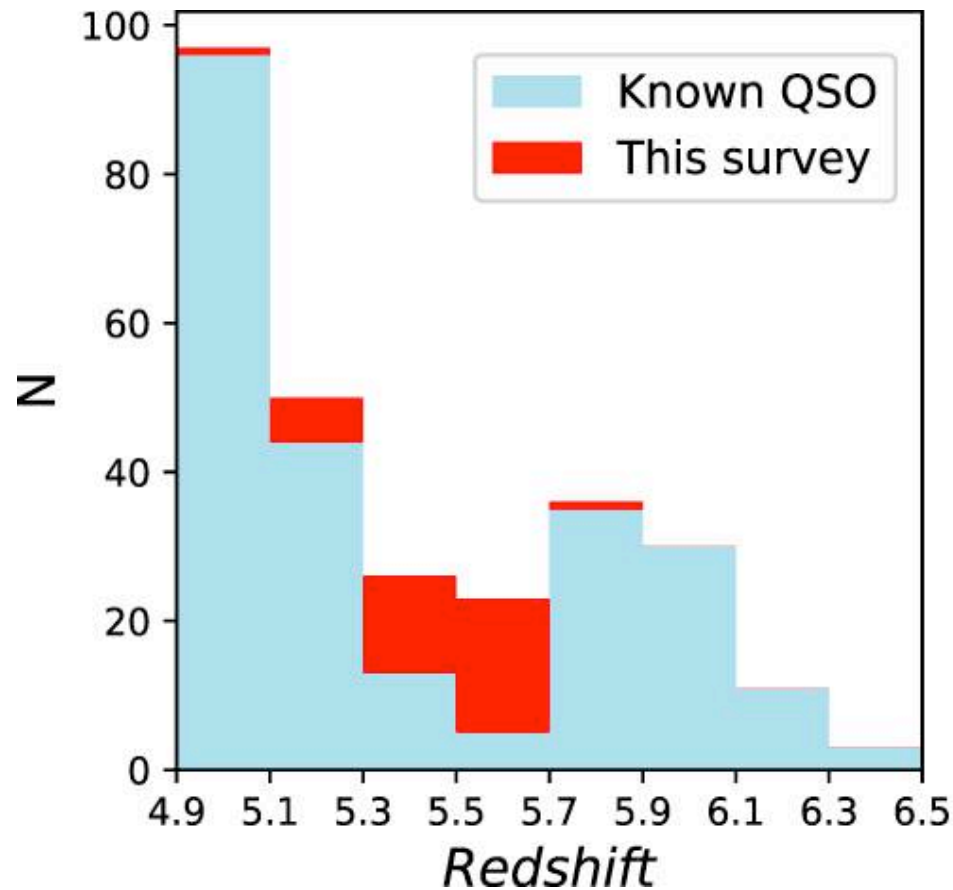
12 April 2017 **FEATURES**

New Discoveries Fill the Quasar Gap

Quasars are cleverly camouflaged at some high redshifts, making them tough to spot. Now there's a way to detect these distant monsters in spite of their disguise.

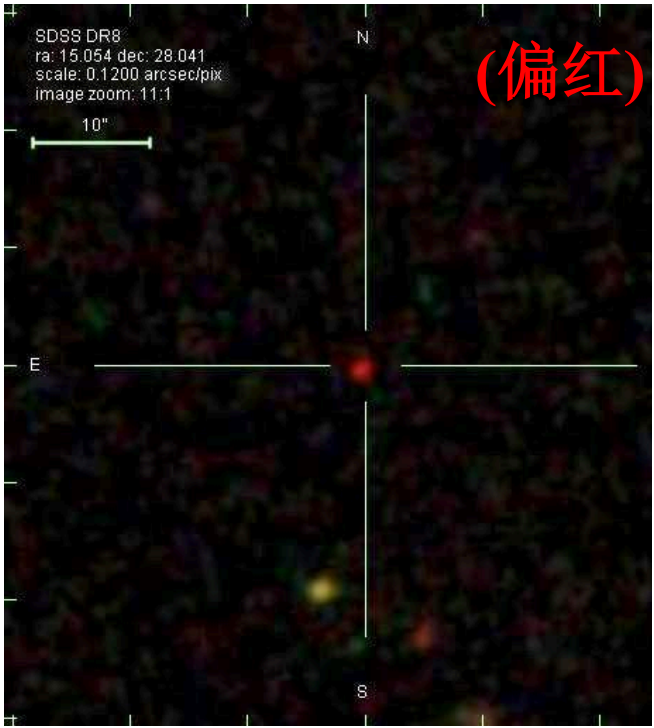
Complete survey for $z \sim 5.5$ quasars at $z_{AB} < 20.5$ (100+ $z > 5$ quasars found)

(SDSS–PS1–ULAS/VHS/UHS–*WISE* color–color selection)

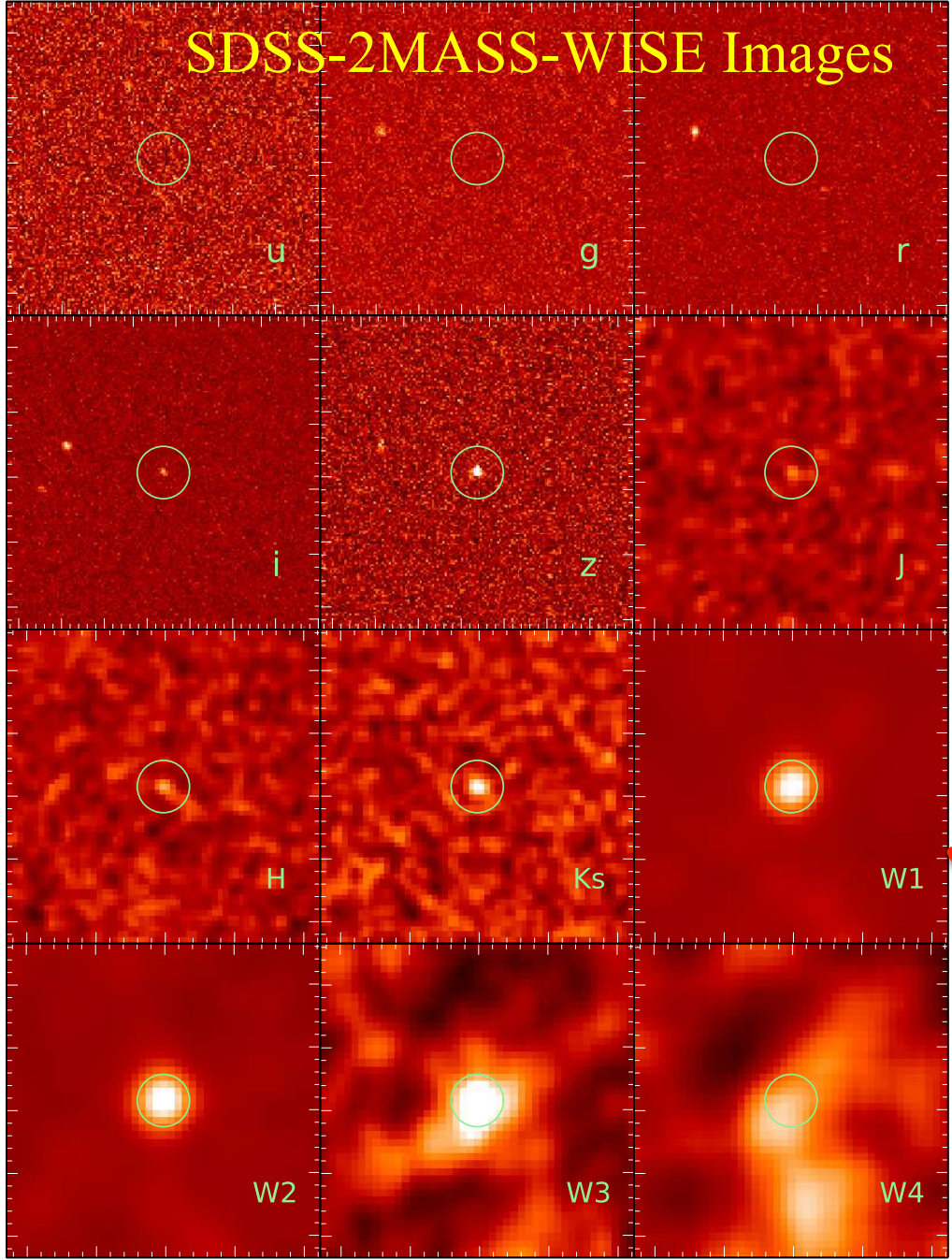


3、发现宇宙早期的超级黑洞

One interesting target

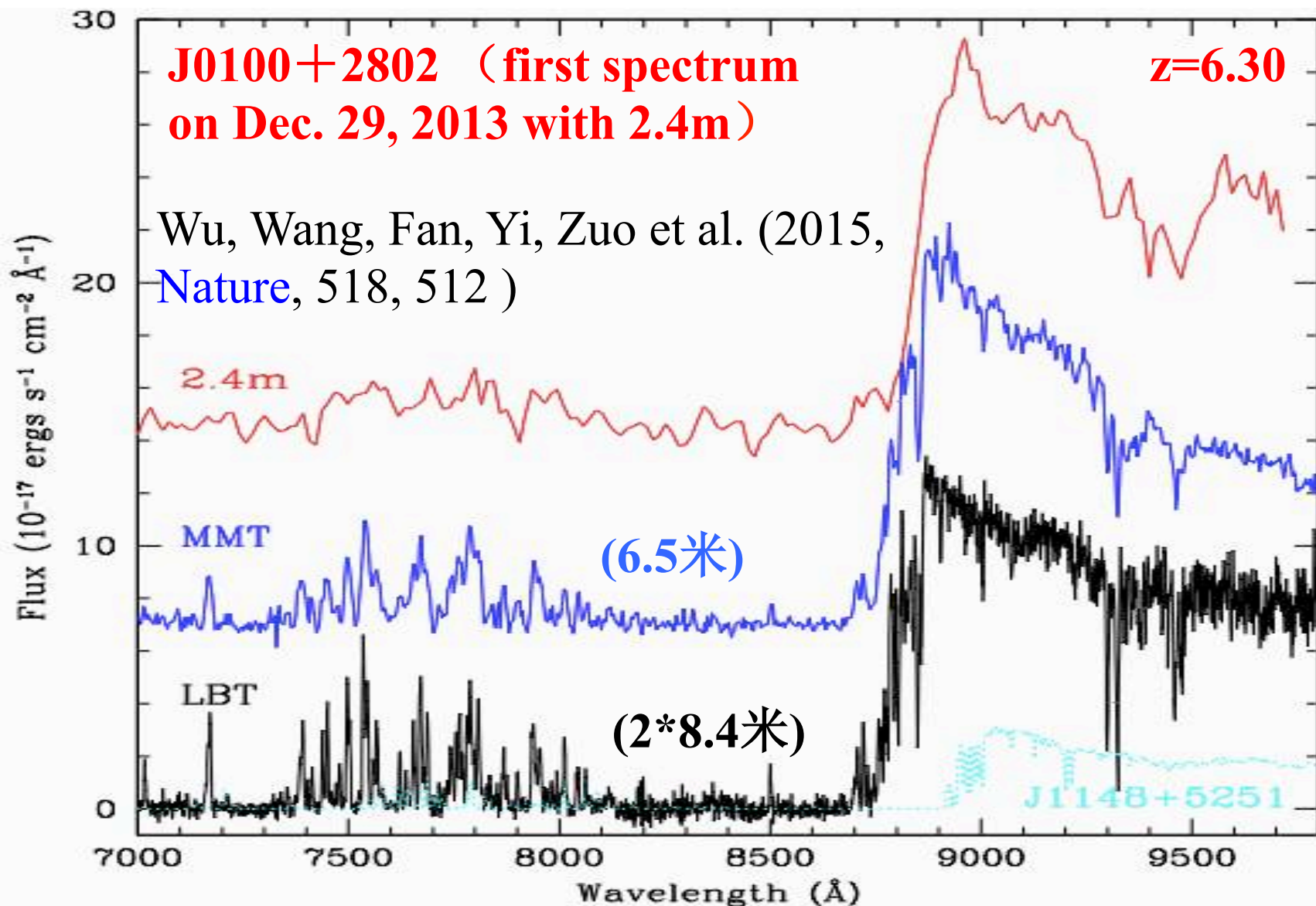


$i=20.84$ $z=18.33$
 $J=17.00$ $H=15.98$
 $K_s=15.20$
 $W1=14.45$ $W2=13.63$
 $W3=11.71$ $W4=8.98$
测光红移 $\sim 6.3!$



波长由短到长

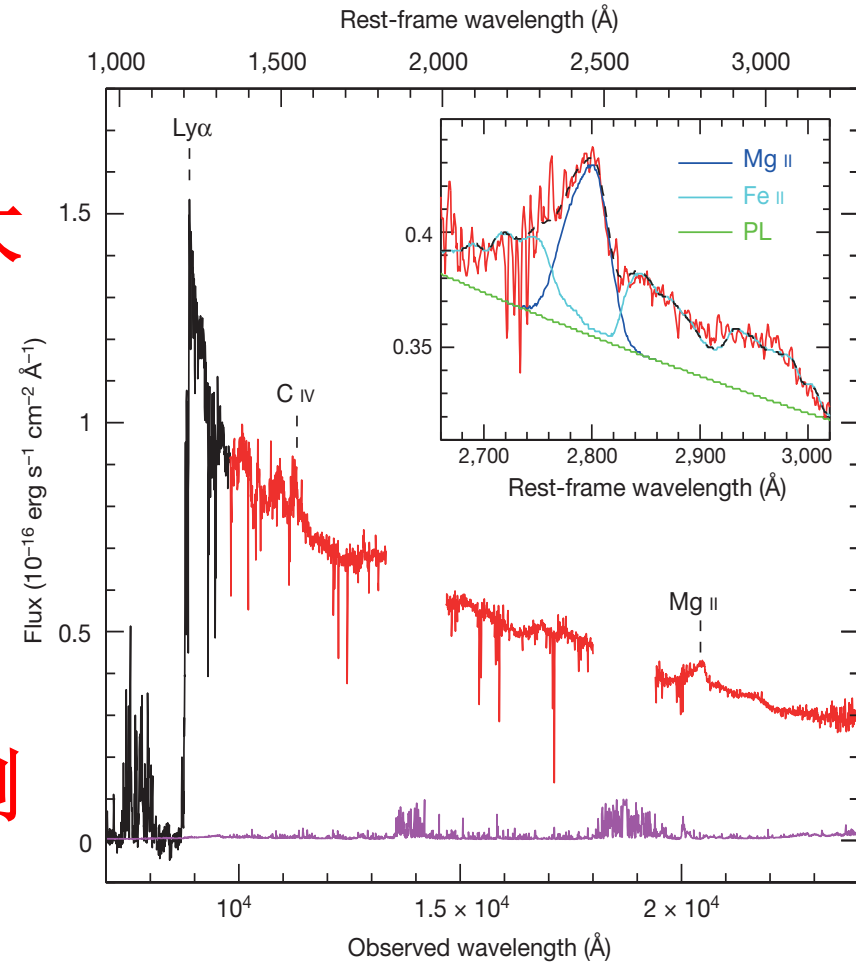
利用国内丽江2米4望远镜发现的最高红移类星体



一波三折的红外光谱观测



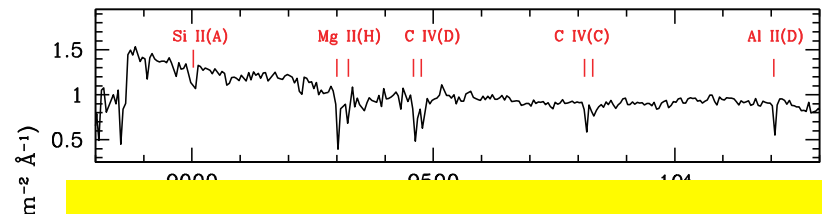
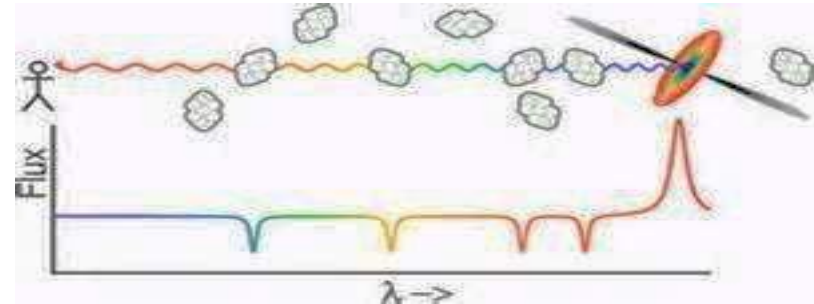
- 2014年1月2日和8月20日，美国大双筒望远镜(LBT, $2 * 8.4$ 米)红外观测，**噪音大**
- 2014年8月6日，美国双子座望远镜(Gemini, 8.4米)，**不理想**
- 2014年10月2-3日，智利麦哲伦望远镜(Magellan, 6.5米)，下雨，多云，**无法观测**
- 2014年10月7日，麦哲伦望远镜工程时间(engineering time)一小时曝光，**观测成功**



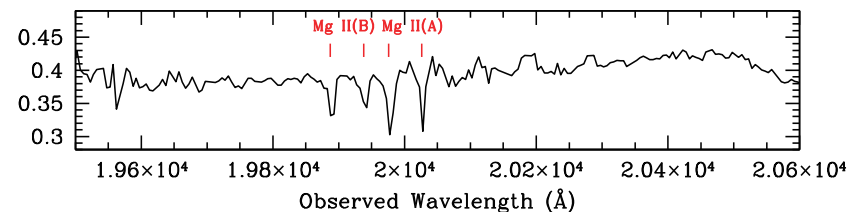
利用谱线宽度和连续谱强度，得出黑洞质量为120亿太阳质量！

最亮的遥远类星体可帮助研究早期宇宙

- 最亮的类星体就像宇宙里最亮的**灯塔**，可提供我们了解以前无法了解的早期宇宙信息
- 类星体光谱中吸收谱线是沿途宇宙物质留给我们的**脚印信息**
- 利用最亮类星体的光谱，我们已了解从红移6.1到2.3的**物质分布**情况
- 这是**以前无法做到的**

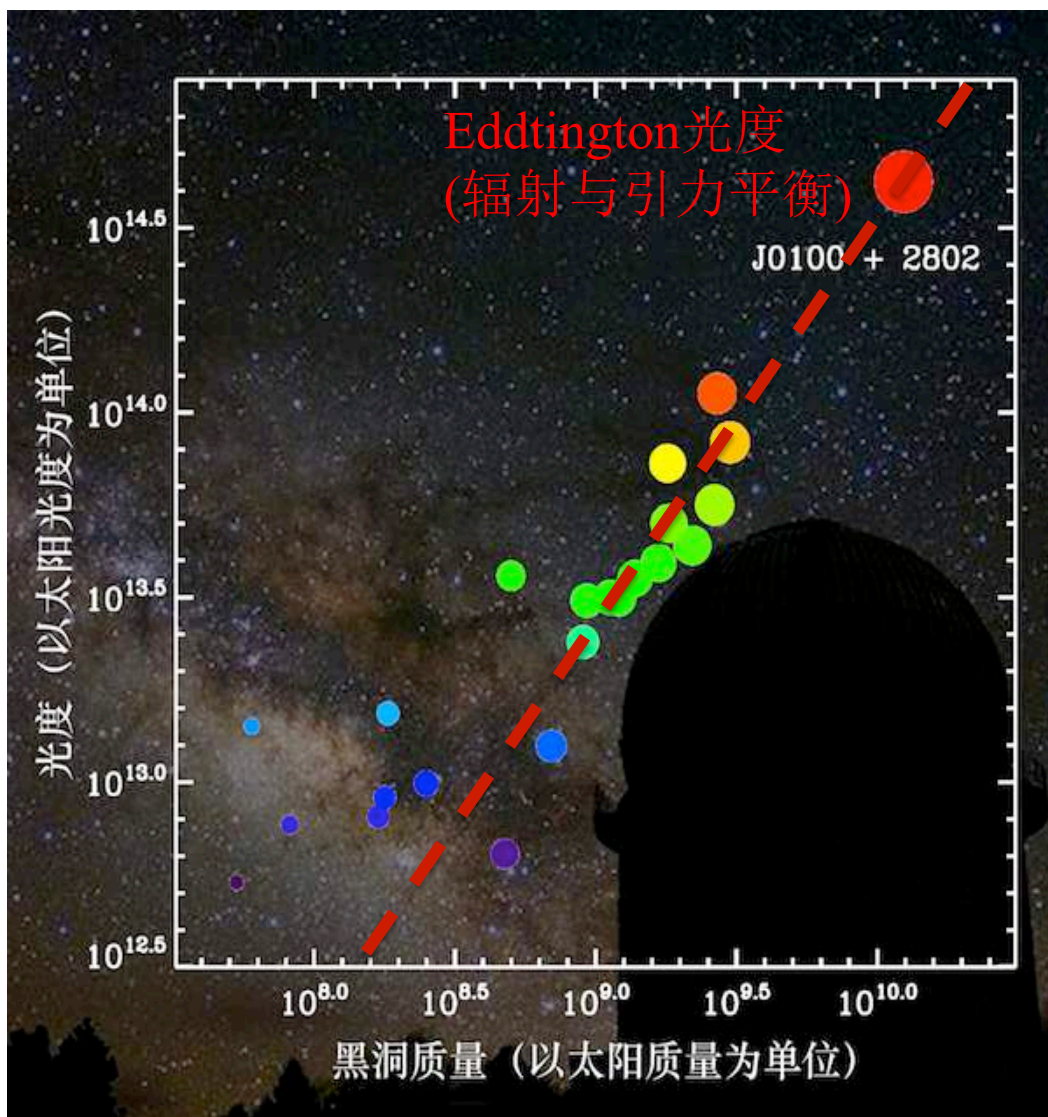


Best example for using distant quasars to probe the structure of the early Universe!



宇宙早期黑洞质量最大的最亮类星体

- 与其它宇宙早期的类星体相比
 - J0100+2802 黑洞质量最大(120亿倍太阳质量)
 - J0100+2802 发光最强(430万亿倍太阳光度)
- 它是宇宙早期的**超级黑洞和最亮天体**！挑战现有理论
- 唯一用**2米级**的望远镜发现的一颗宇宙早期类星体





TIME

SCIENCE ASTRONOMY

Scientists Find a Black Hole 12 Billion Times More Massive Than the Sun

Helen Regan @hcregan | Feb. 26, 2015

It's discovery appears to confound current theories about how black holes are created

A team of international astronomers has discovered a black hole of almost unimaginable proportions.

At 12 billion times more massive than the sun, it challenges current cosmological



NASA/JPL-Caltech/Handout/Reuters
An artist's illustration shows a supermassive

科技部发布2015年度中国科学十大进展 科学家发现超亮类星体

2015年度中国科学十大进展分别为

- 1 实现单光子多自由度量子隐形传态
- 2 理论预言并实验验证外尔半金属的存在
- 3 揭示埃博拉病毒演化及遗传多样性特征
- 4 实现对反物质间相互作用力的测量
- 5 探测到宇宙早期最亮中心黑洞质量最大的类星体
- 6 发现东亚最早的现代人化石
- 7 揭示人类原始生殖细胞基因表达与表观遗传调控特征
- 8 解析细胞炎性坏死的关键分子机制
- 9 研制出碳基高效光解水催化剂
- 10 实现对单个蛋白质分子的磁共振探测

资料来源：科技部 新华社发（大巢制图）



SMBH formation at early Universe

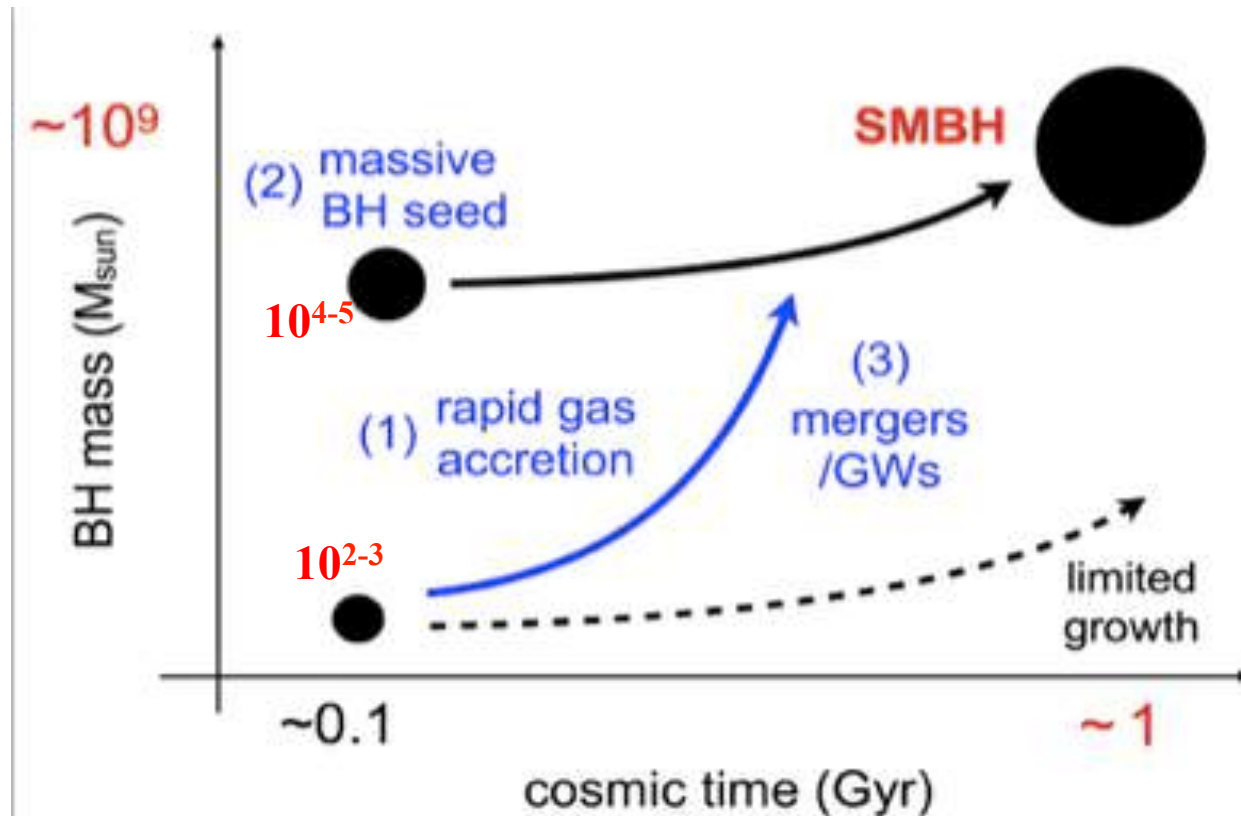
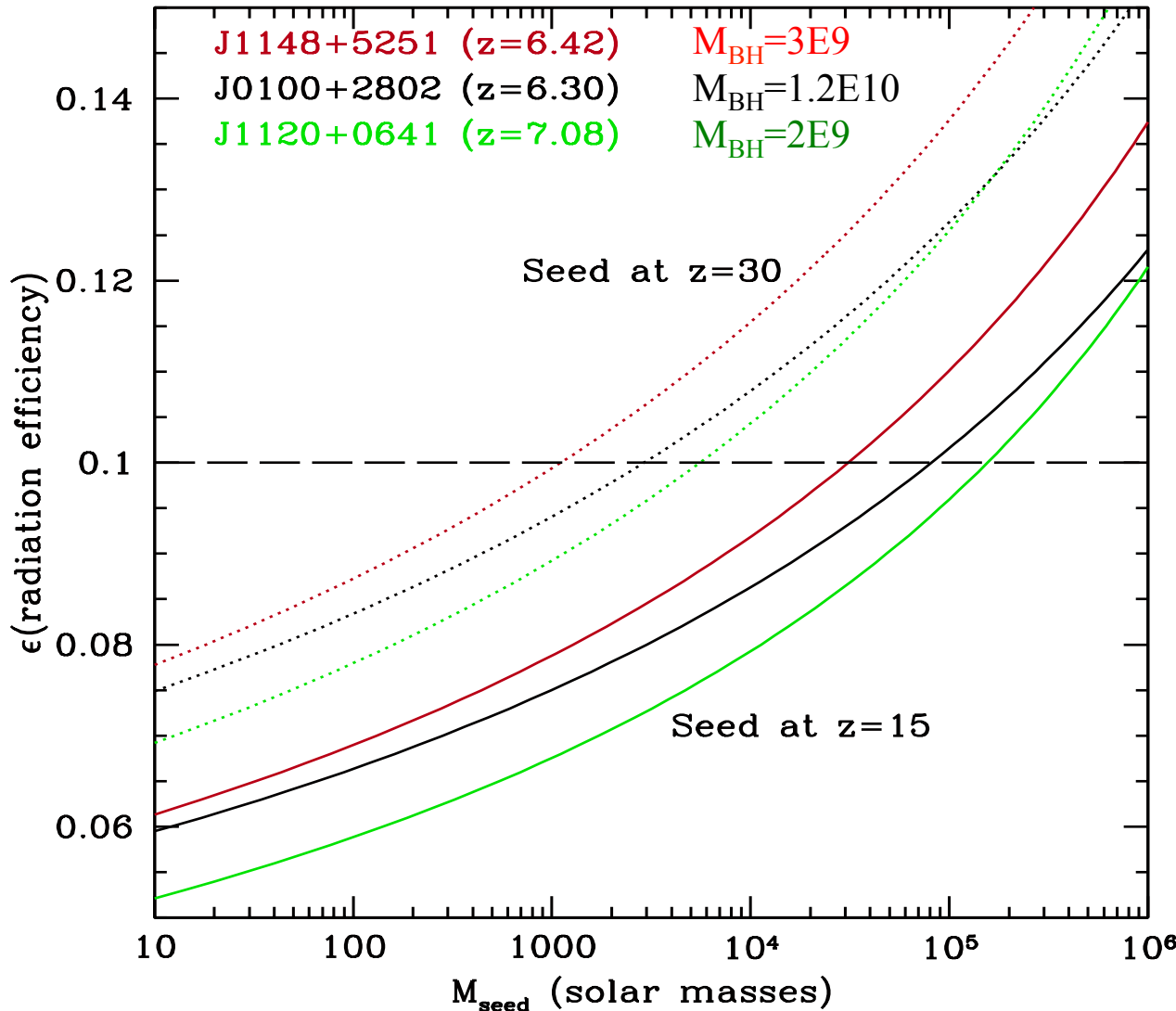


Fig. 1: Formation scenarios of SMBHs in the early universe, requiring their rapid gas accretion, massive seed formation and frequent BH mergers.

黑洞增长：对种子黑洞质量的限制

$$M(t) = M(0) \exp\left(\frac{1-\epsilon}{\epsilon} \frac{t}{t_{\text{Edd}}}\right) \quad t_{\text{Edd}} = 0.45 \text{ Gyr}$$



Assumptions:

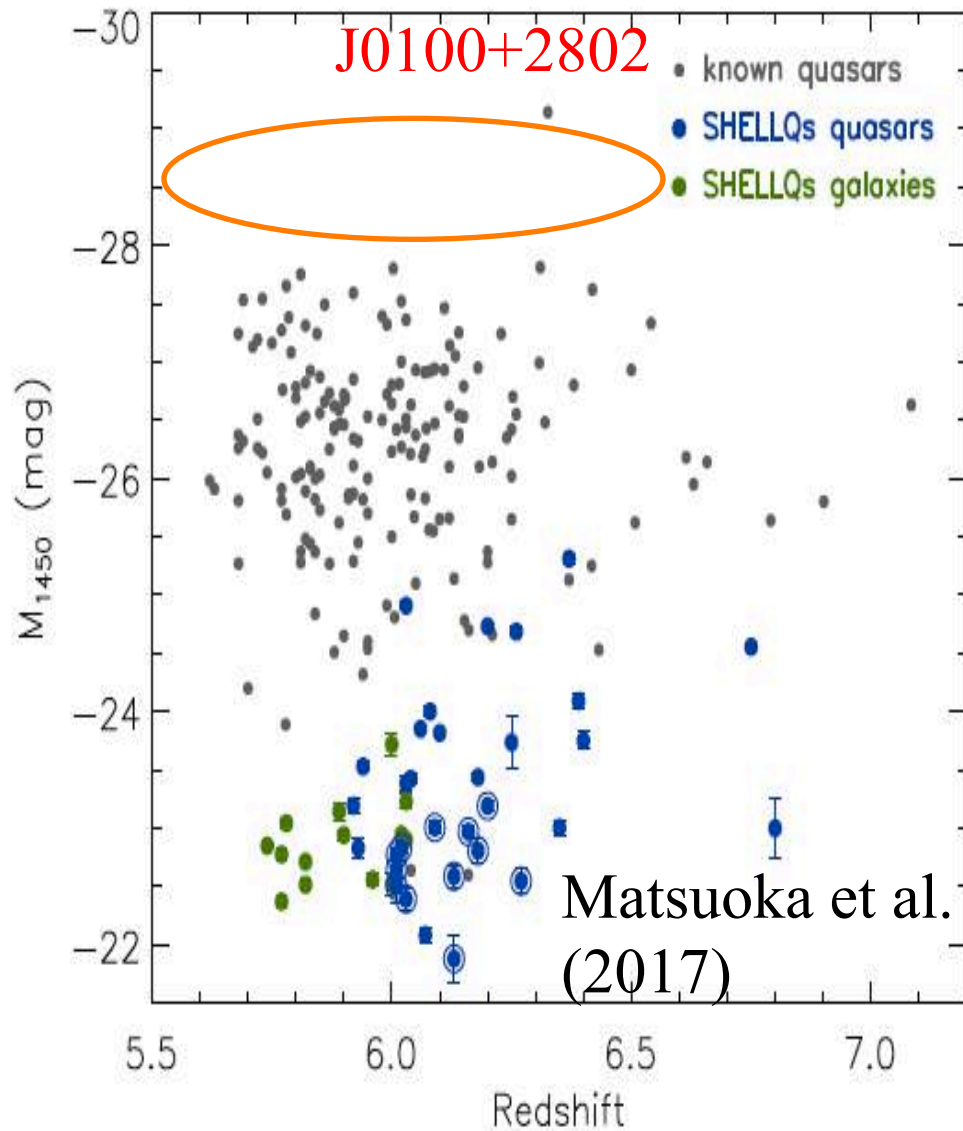
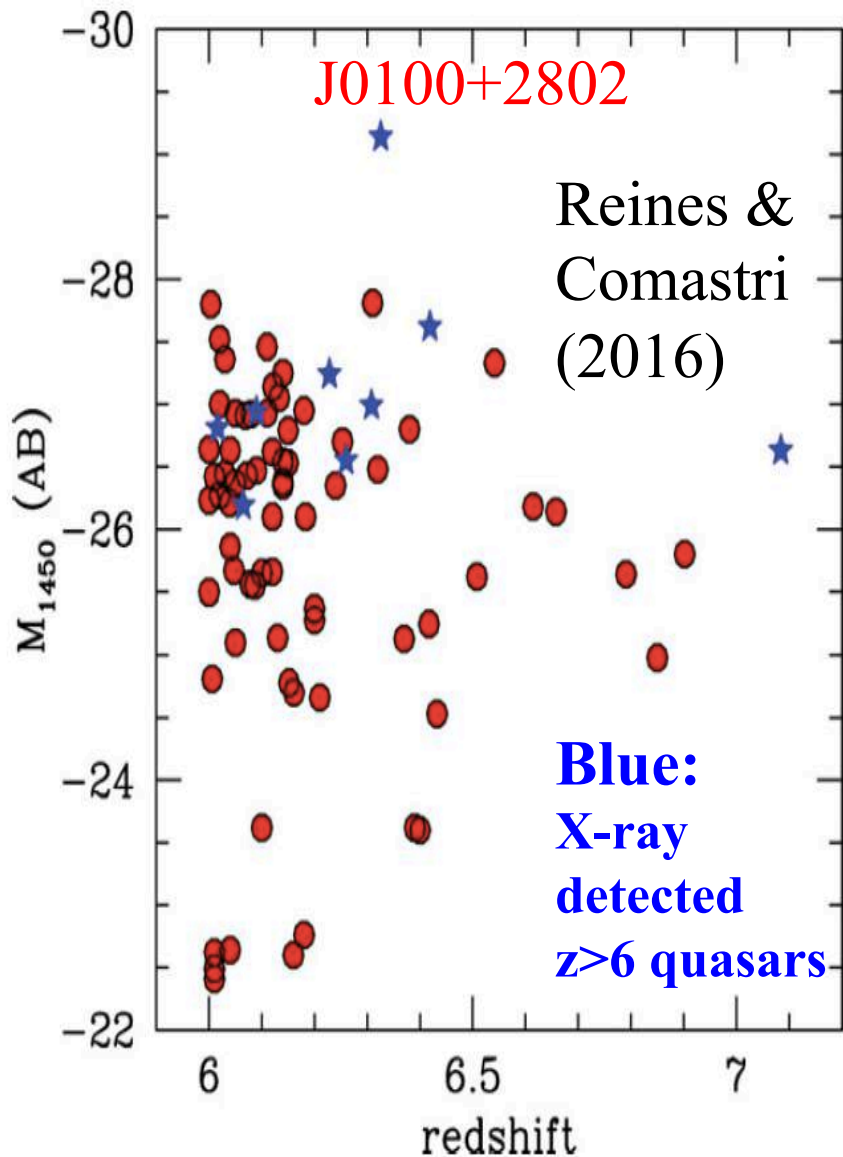
**Eddington accretion;
Duty cycle=1**

**Seed BH mass $>10^5$
solar masses!**

**Direct collapse?
(Latif & Volonteri
2015)**

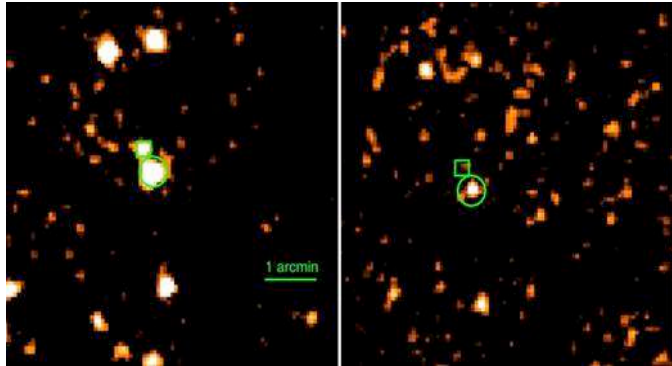
**Or super(hyper)-
Eddington
accretion ?
(Inayoshi, Haiman
& Ostriker 2016)**

至今仍保持最亮的高红移类星体纪录！



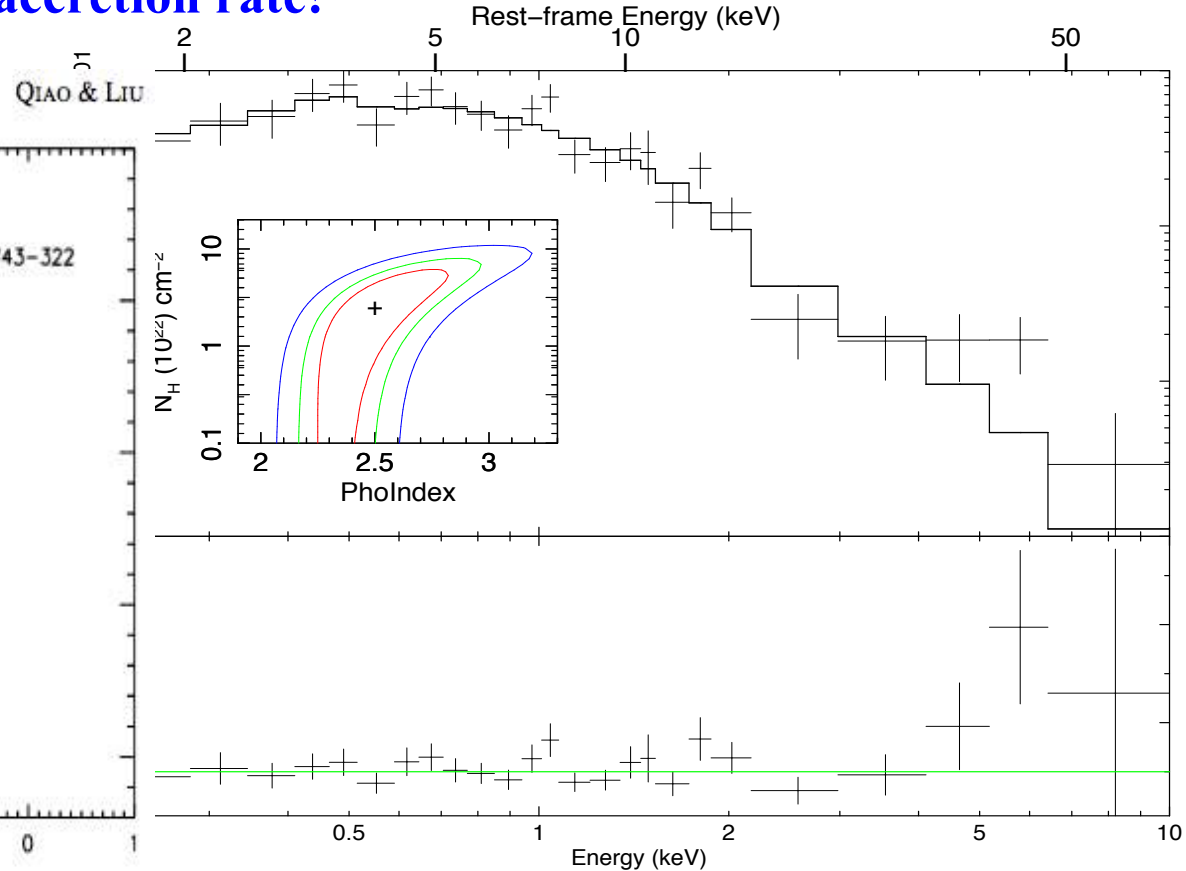
XMM-Newton Observation on J0100

65ks on June 29, 2016 (~500photons)

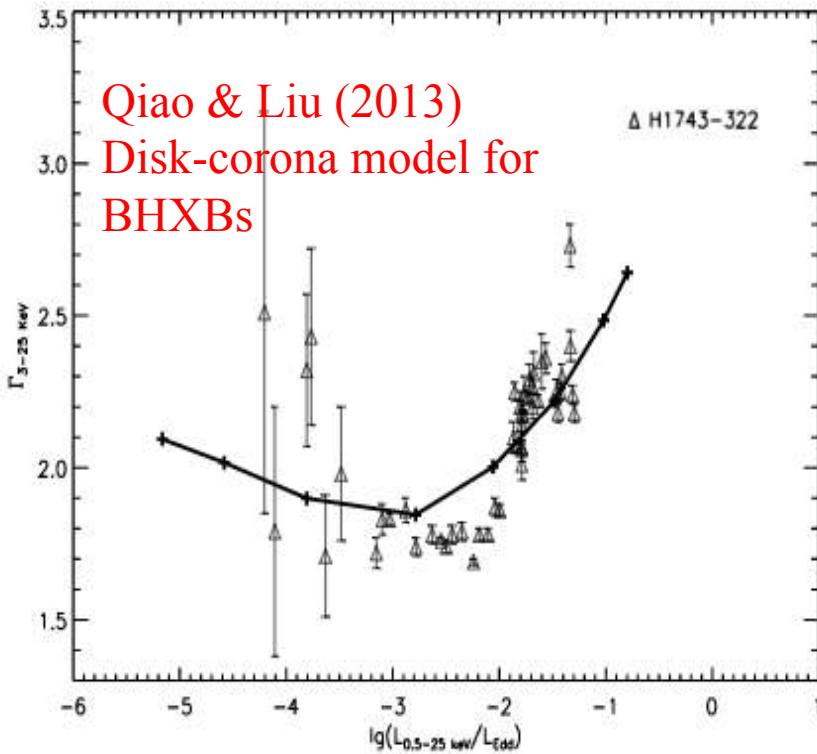


Photon index $\Gamma=2.30\pm 0.10$, $L_{2-10\text{ keV}} = 3.1E45\text{ ergs/s}$

Softer X-ray spectrum consistent with the higher accretion rate!



Qiao & Liu (2013)
Disk-corona model for
BHXBs

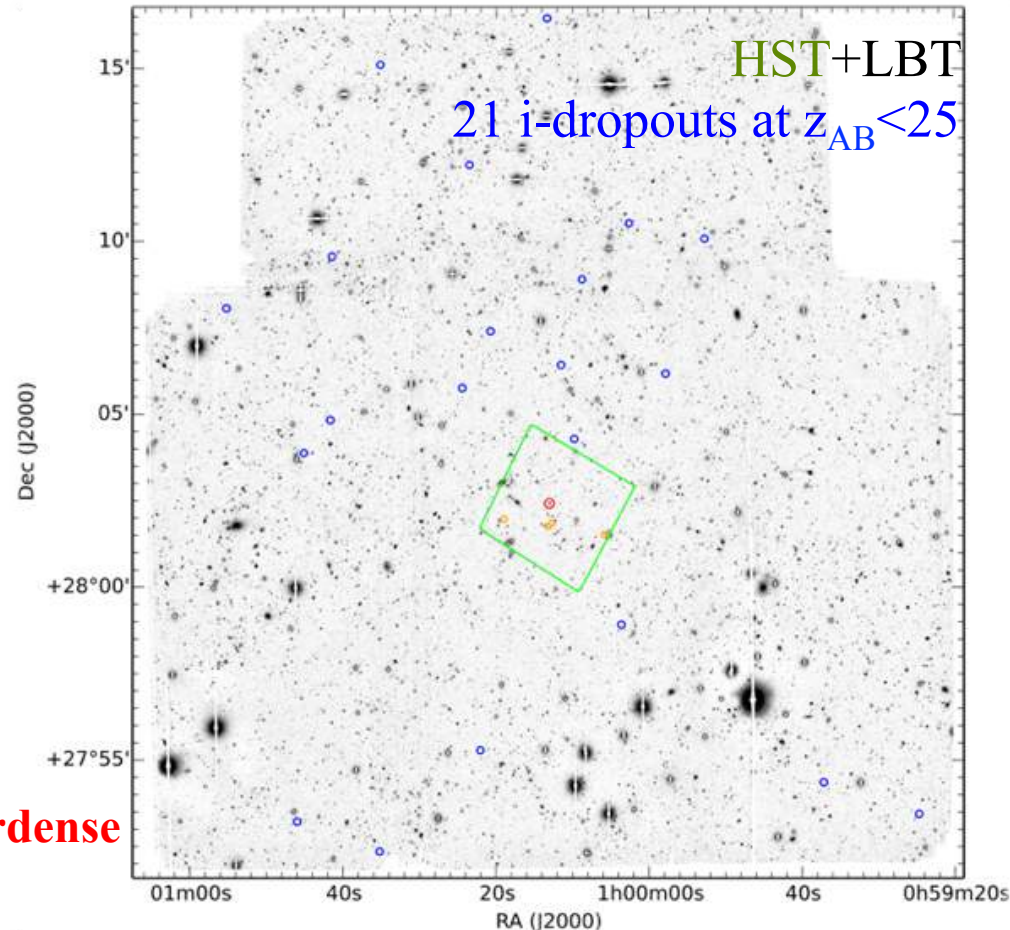
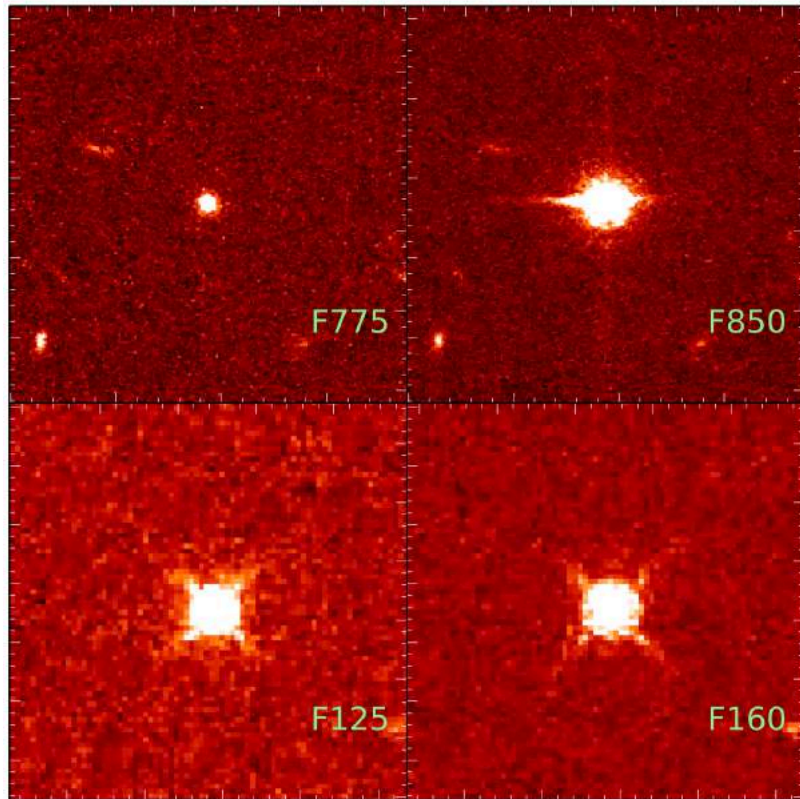


HST Observation on J0100

(Preliminary! Wang F. et al, in prep)

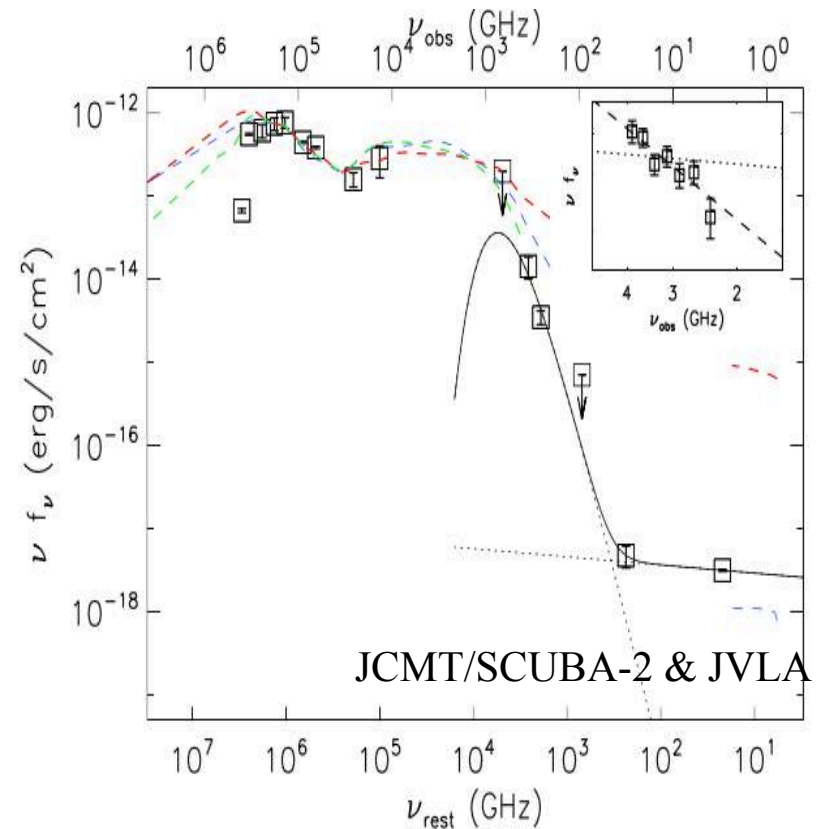
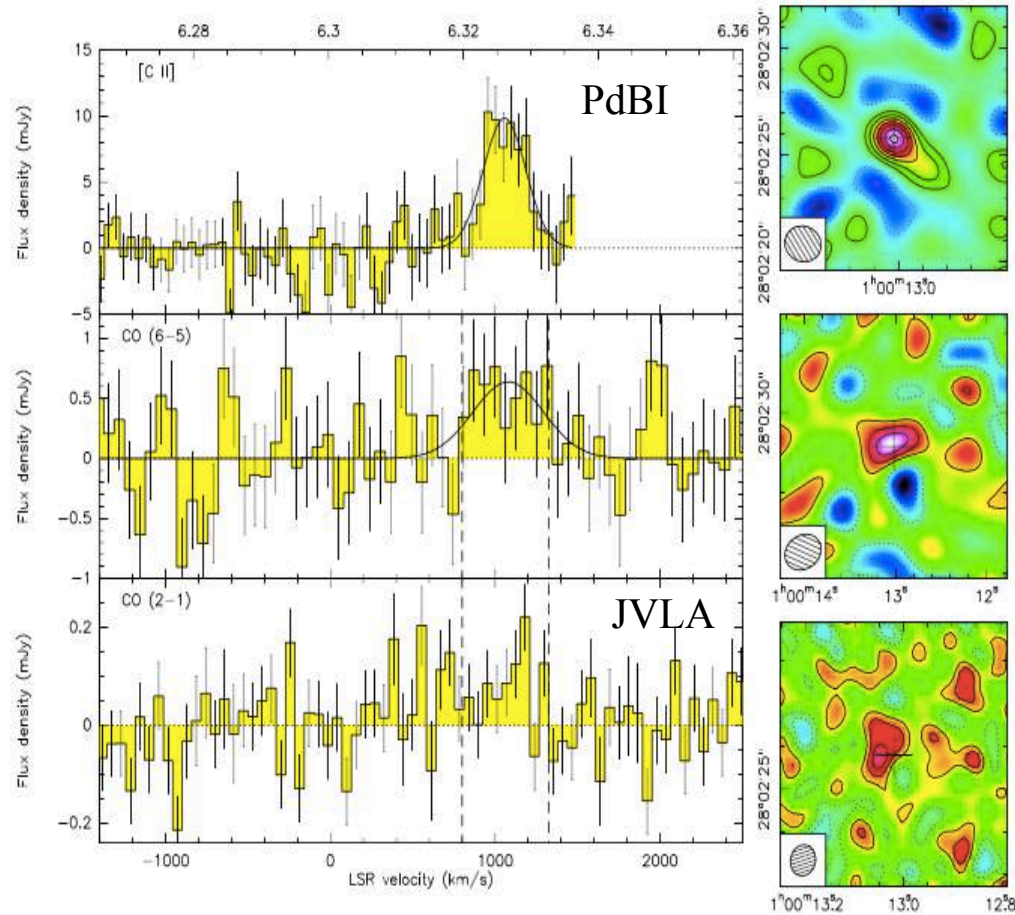
Not a lensed object!

We find the significance of overdensity at physical scale of $8 \times 8 \text{ Mpc}^2$!



Most massive BHs situated in the most overdense regions! (Simulations by Costa et al. 2014)

mm/radio observations on J0100+2802 (IRAM/PdBI, JCMT/SCUBA-2, JVLA)

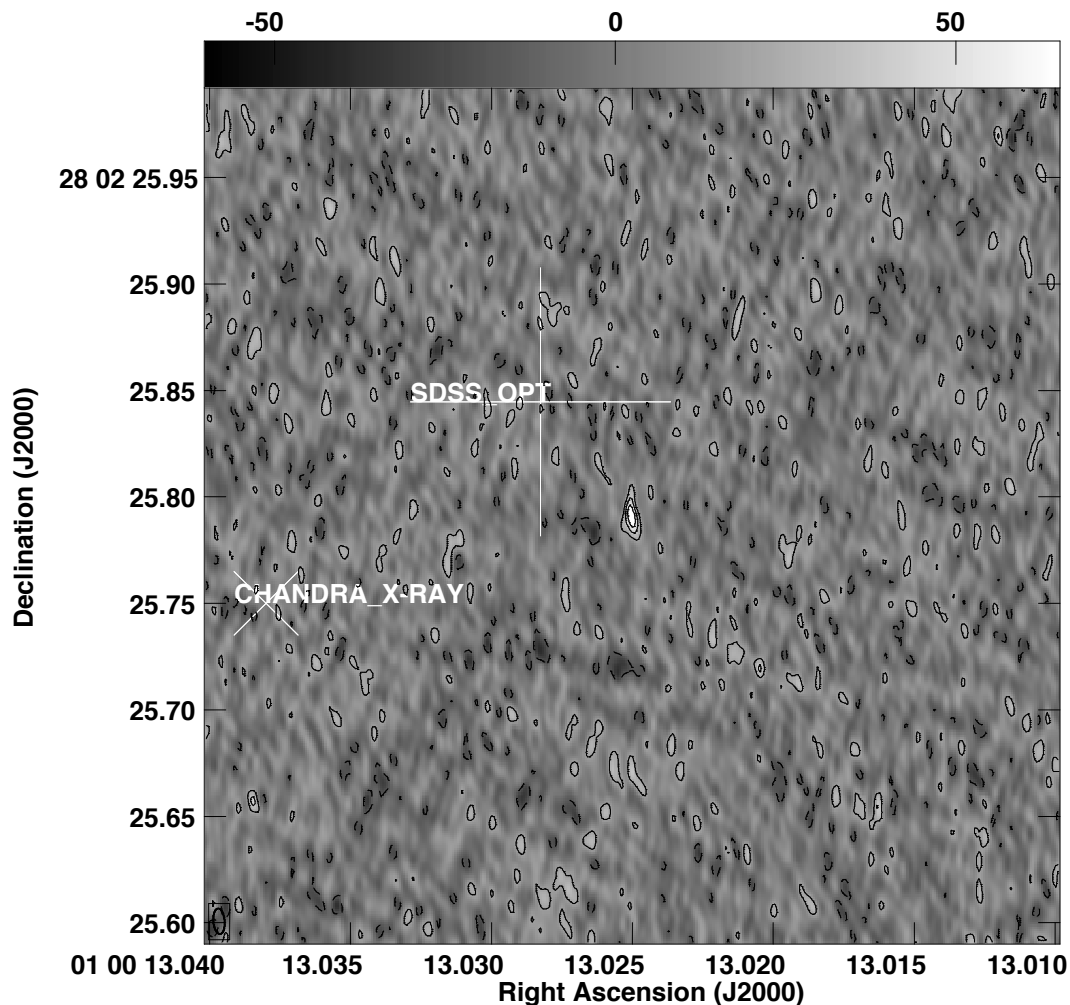


Wang R. et al. 2016, ApJ

Detect the [C II] 158 μm fine structure line and molecular CO(6-5) line and continuum emission at 353 GHz, 260 GHz, and 3 GHz \rightarrow **active star formation!**

Milli-arcsecond VLBA Imaging

(Wang, R. et al., 2017, ApJ, 835, L20)



0.4'' × 0.4'', 1.5GHz

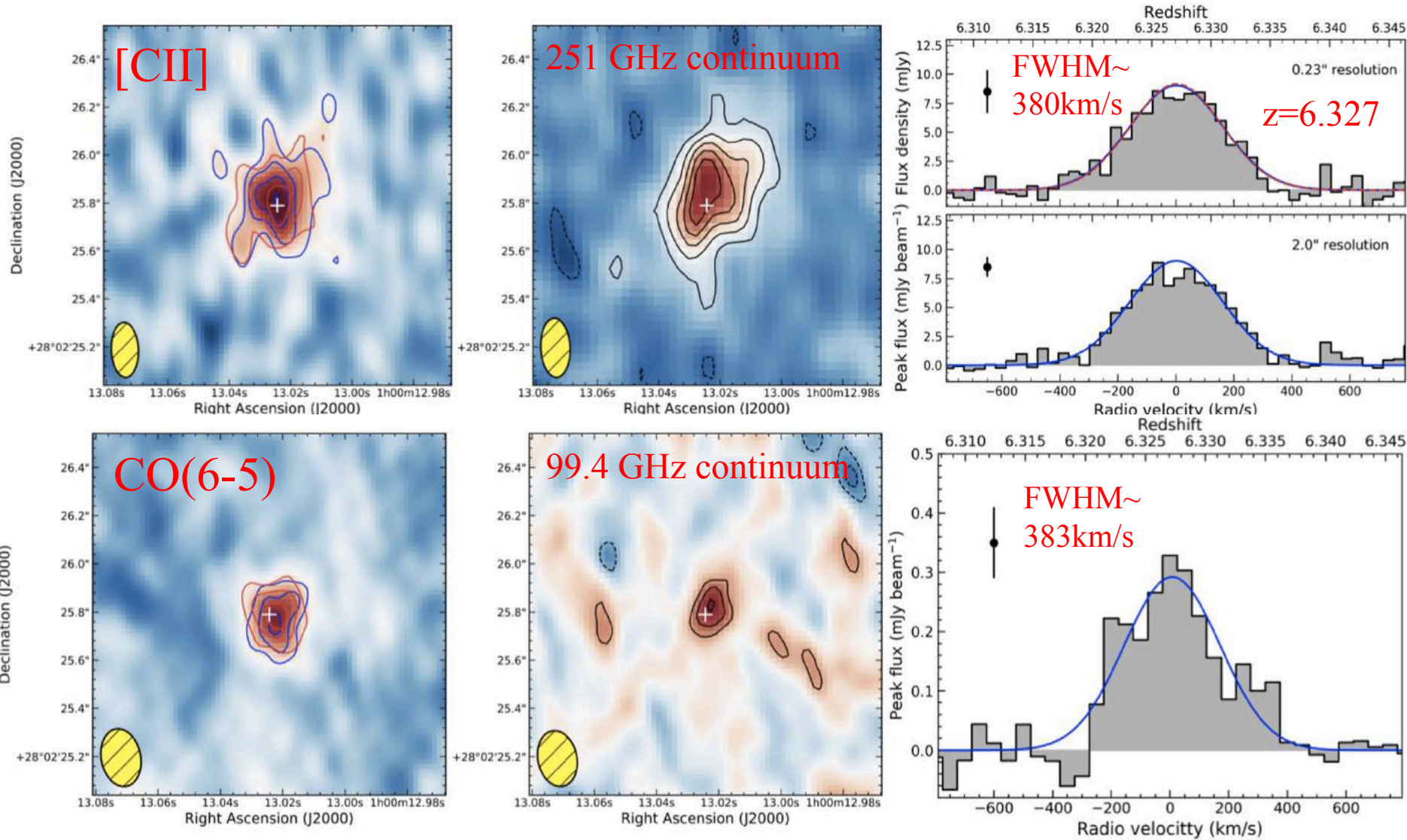
Detected the radio continuum emission from J0100 with a peak surface brightness of $64.6 \pm 9.0 \mu\text{Jy beam}^{-1}$ and a total flux density of **$88 \pm 19 \mu\text{Jy}$** .

The position of the radio peak is consistent with that from SDSS in the optical and Chandra in the X-ray.

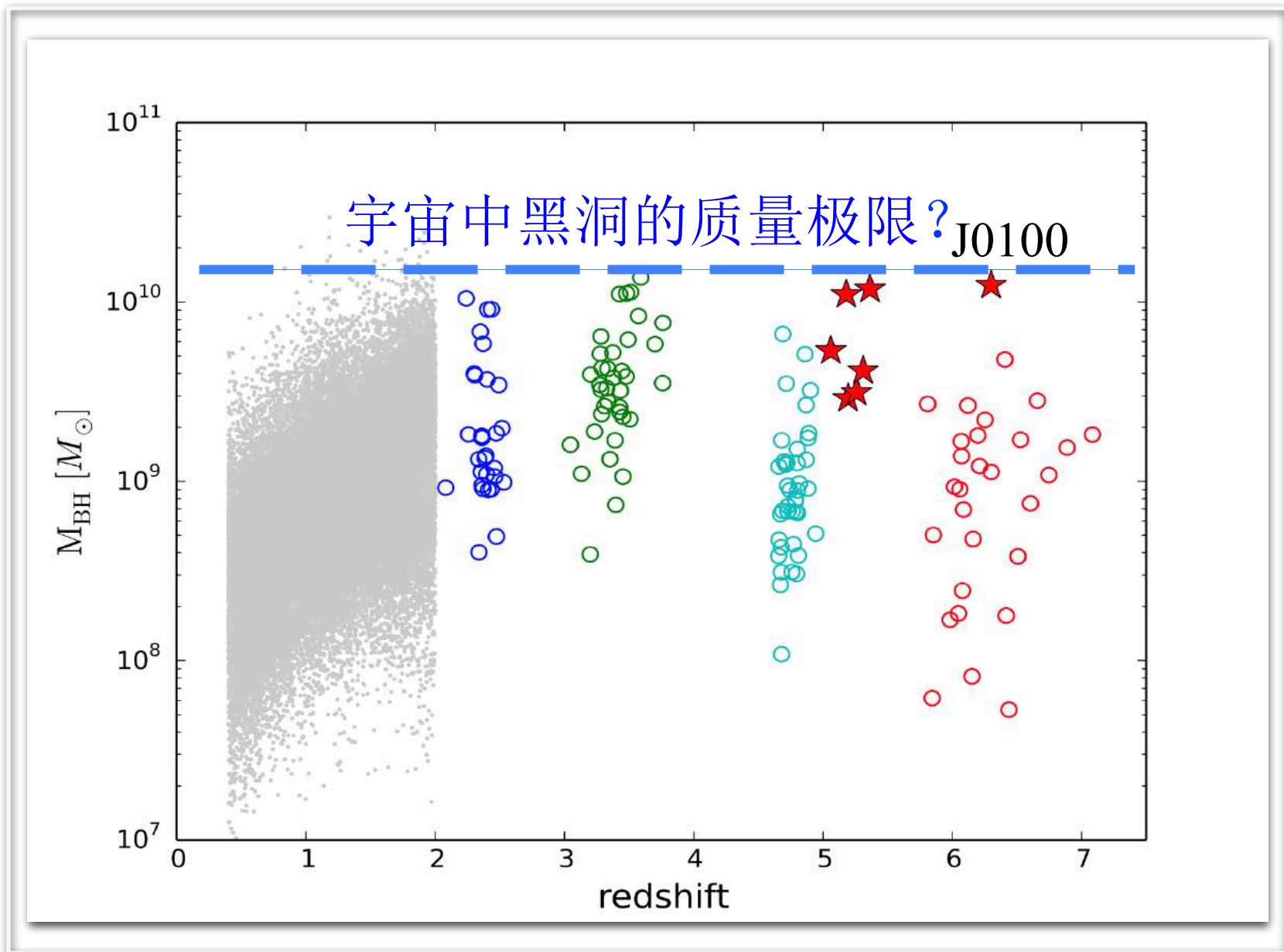
The intrinsic brightness temperature is $1.6 \times 10^7 \text{ K}$, significantly higher than the maximum value in normal star forming galaxies, indicating an **AGN origin for the radio continuum emission.**

Multi-band ALMA Observations

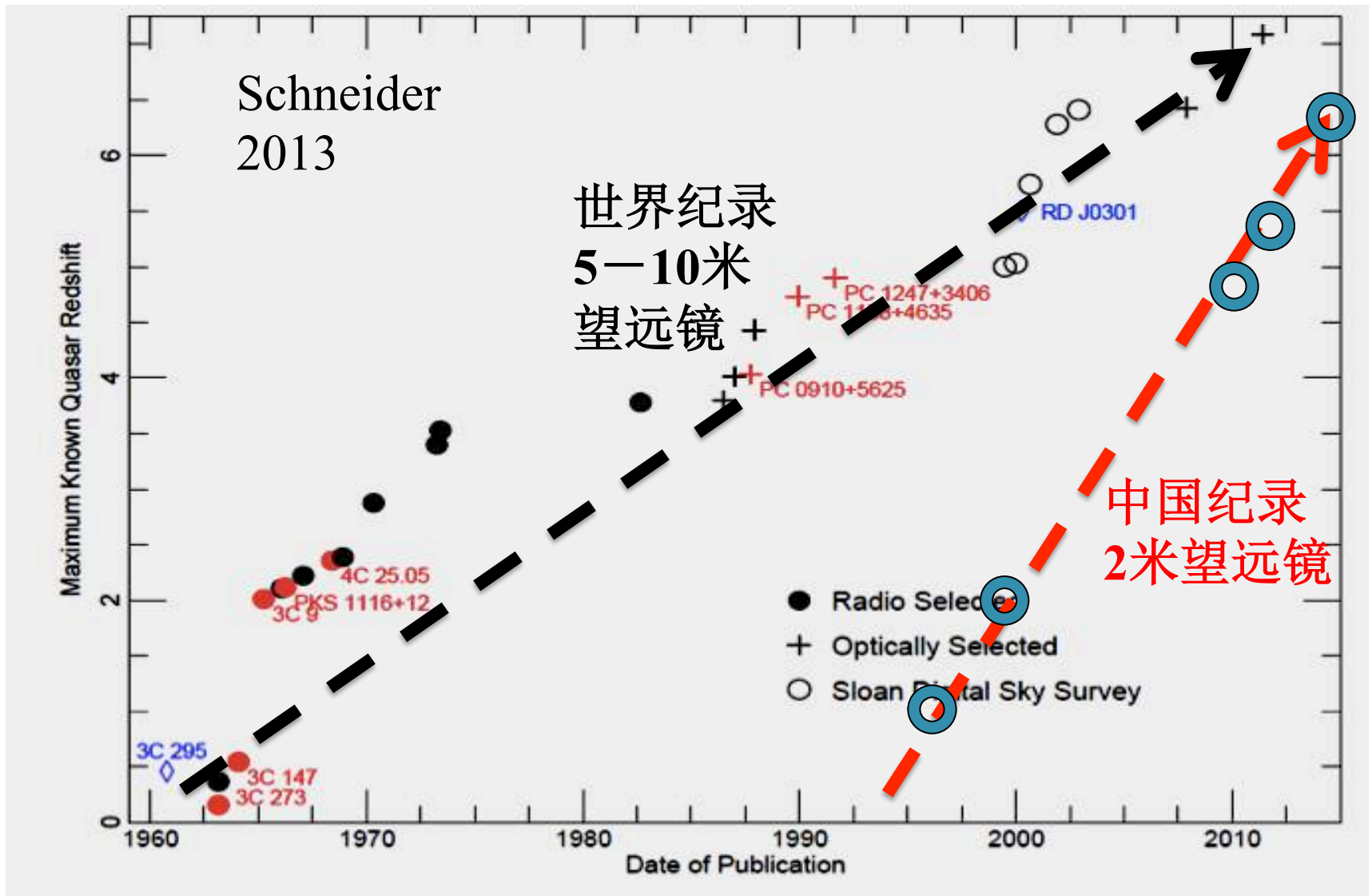
(Wang F., Wang R., Fan X., Wu, X.-B. et al., 2019, ApJ)



不同红移的类星体黑洞质量的比较



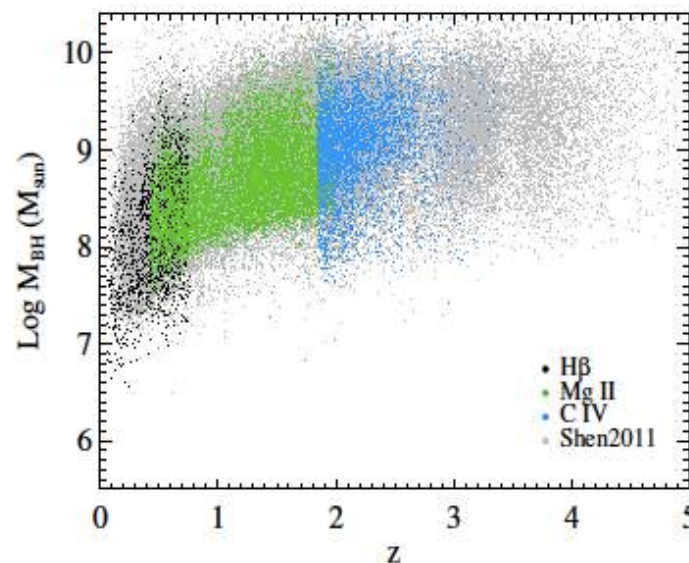
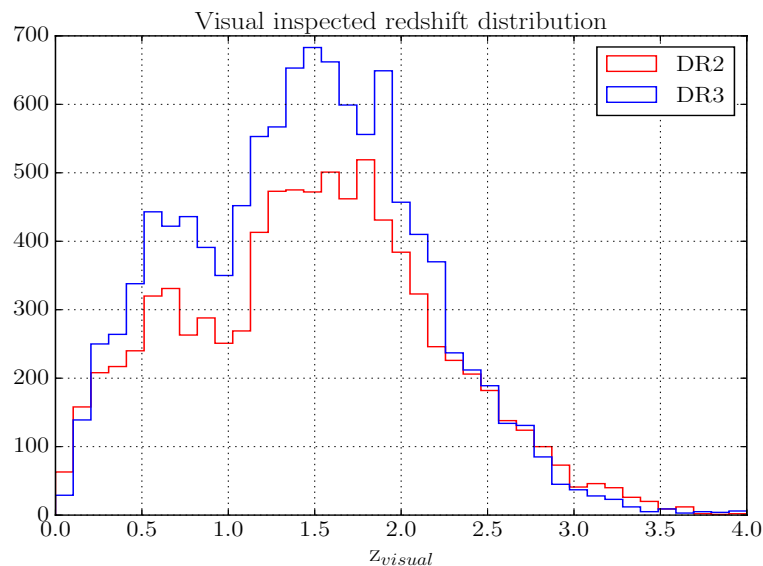
不同时间发现的最高红移类星体



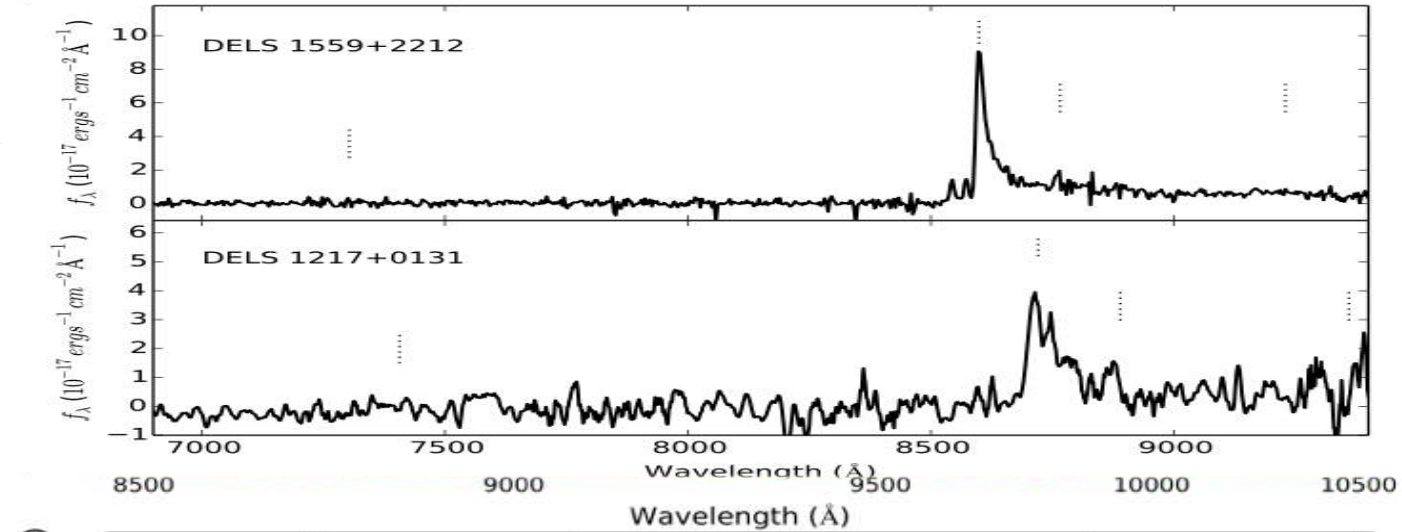
郭守敬望远镜 (LAMOST) 类星体巡天



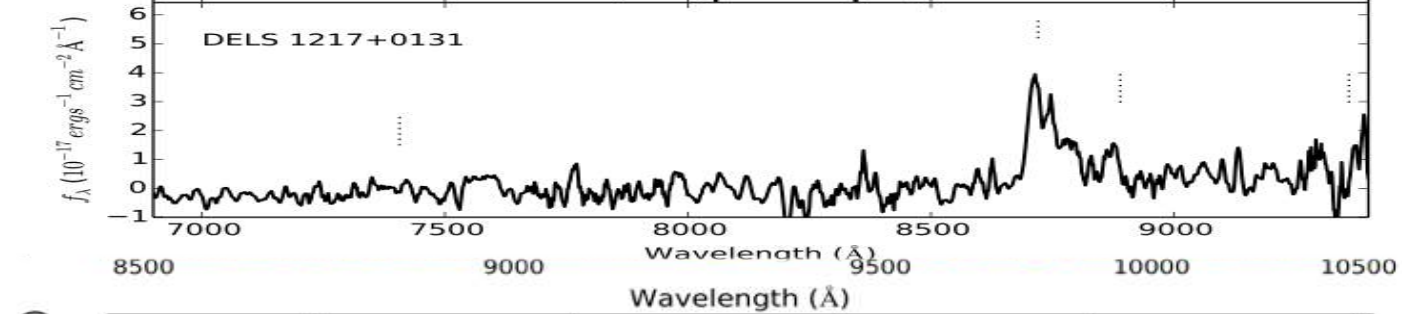
- 现状：证认43000个类星体，24700个为独立发现，17100个为新发现。
 - DR1: 证认4080个类星体，1180个新发现
 - DR2&DR3: 证认19939个类星体，8100个新发现
 - DR4&DR5: 证认19253个类星体，8162个新发现



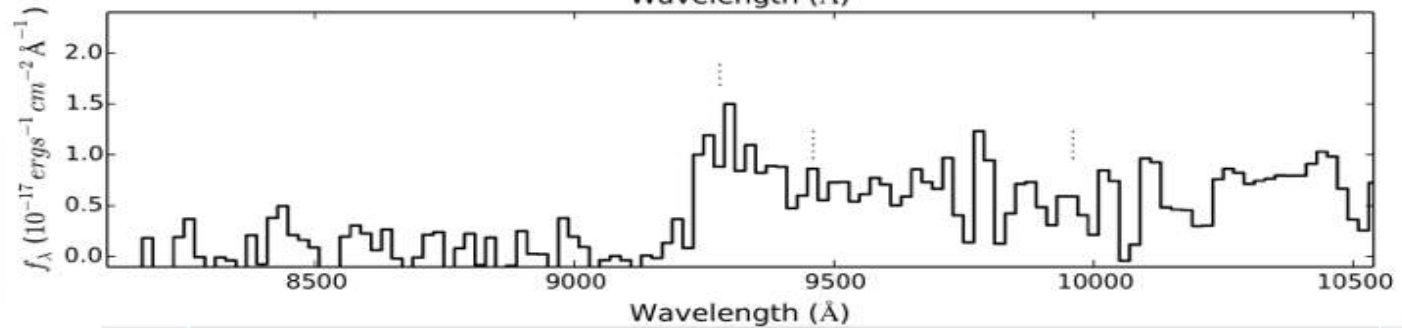
更多发现: New $z > 6$ Quasars found with Magellan(智利6.5米) & Hale(美国5米)!



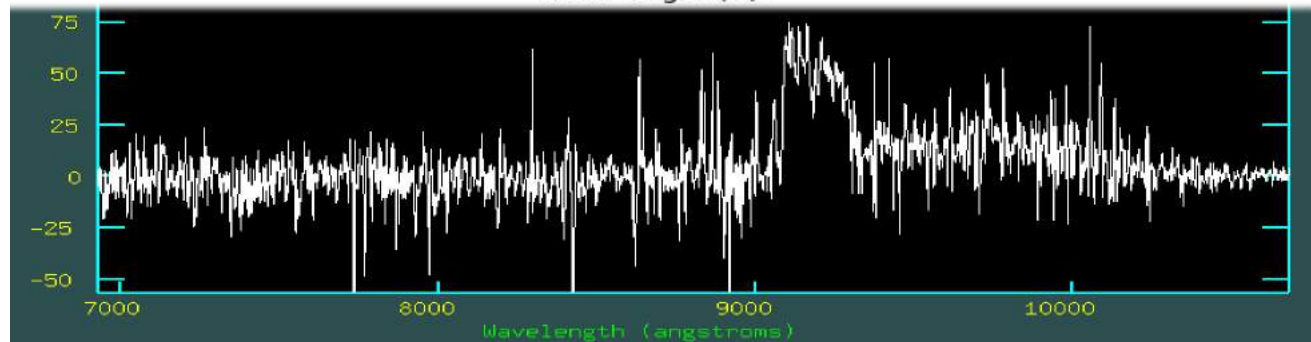
$z=6.1$



$z=6.2$



$z=6.6$



$z=6.5$

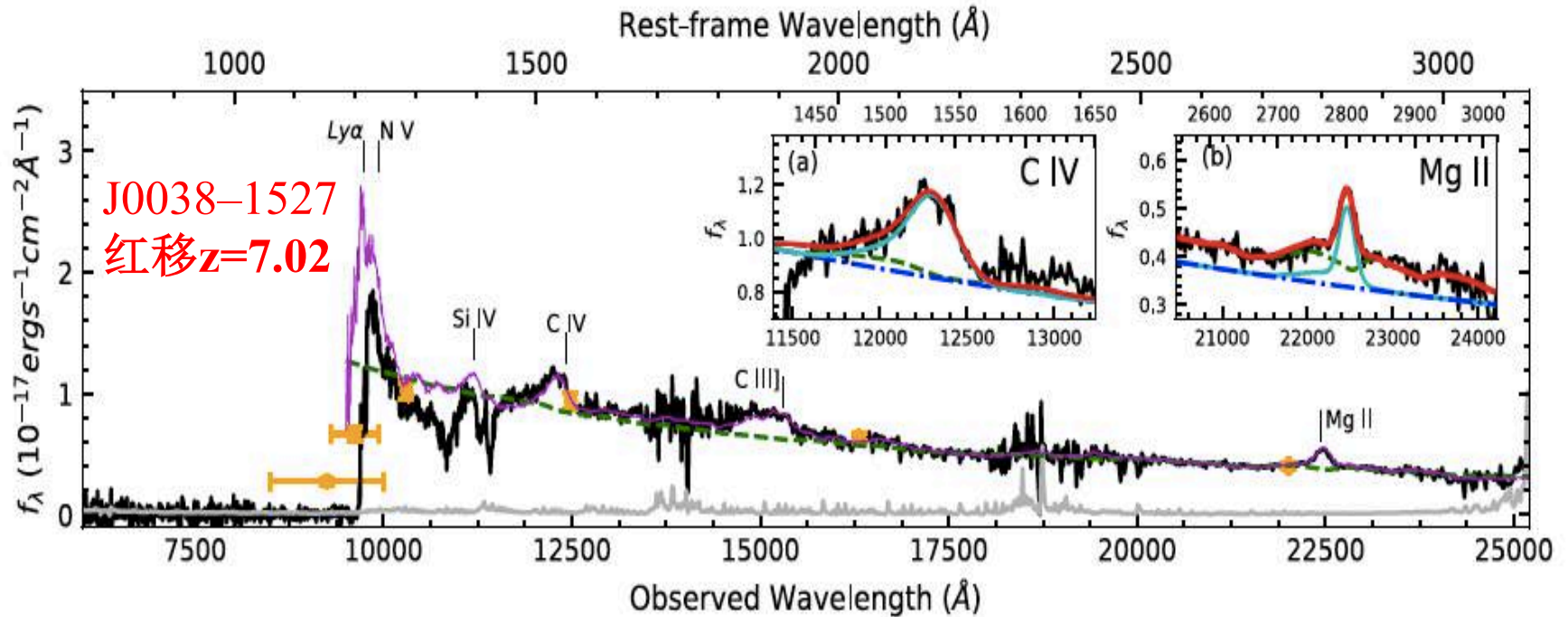


Figure 1. Final calibrated spectrum of J0038-1527. The black and gray lines represent the Galactic extinction corrected spectrum and error vector. The thin magenta line denotes the quasar composite spectrum constructed with ~ 200 Sloan Digital Sky Survey (SDSS) quasars with large C IV blueshifts. The green dashed line denotes the pseudo-continuum, which includes power-law, Fe II emission, and Balmer continuum. The orange circles are flux-density converted from galactic extinction corrected magnitudes listed in Table 1. The x -axis error bars of the two leftmost orange circles denote the FWHMs of z_{DELS} and y_{ps1} filter curves. Two inner plots show spectral fitting of C IV (a) and Mg II (b) regions, respectively. The blue dotted-dashed line denotes the best-fit power-law continuum, the green dashed line denotes the best-fit pseudo-continuum. The cyan line denotes fitted C IV and Mg II emission lines plus power-law continuum, and the red line denotes the total fitted flux.

$$z_{\text{AB}} = 21.65, y_{\text{AB}} = 20.61$$

$$W1_{\text{VEGA}} = 16.80, W2_{\text{VEGA}} = 16.08$$

Spectra taken at MMT(6.5m),
Magellan (6.5m), VLT/X-
Shooter (8.2m), and Gemini
(8.1m) in 2018.

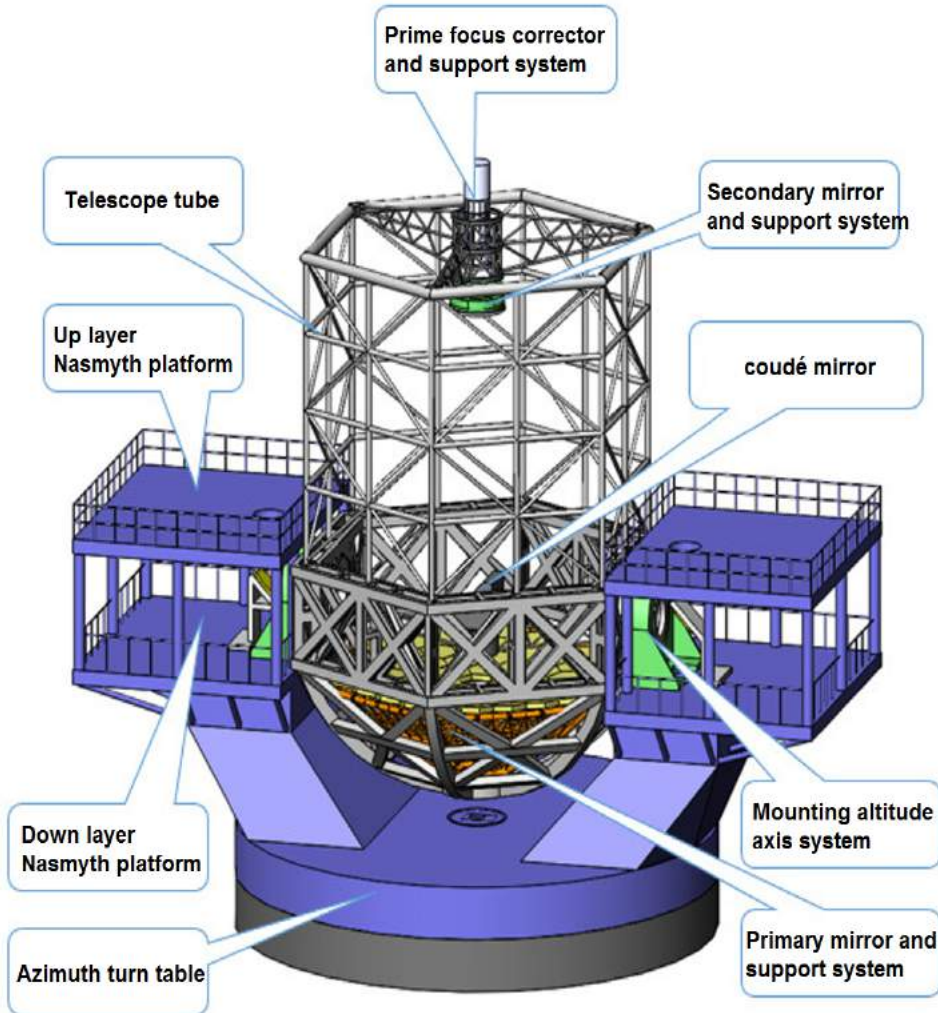
Collecting Area of Large Telescopes



未来中国的光学红外大望远镜

大型光学望远镜LOT(12米)

6.5米望远镜



4、总结与展望

- **类星体**是中心具有**超大质量黑洞**且能量极大的遥远天体，**高红移**类星体是研究遥远宇宙的宝贵探针。发现更多的高红移类星体对研究宇宙的演化非常重要。
- 基于我们从光学-红外测光巡天数据选取类星体候选体的新方法，利用国内外中大型光学红外望远镜发现了**100多个红移5以上的类星体**。填补了类星体在红移5.5左右的“**红移沙漠**”，为研究高红移类星体的演化提供了重要样本。
- 利用丽江2.4米望远镜首先观测和国外望远镜后续观测，发现了一个**红移6.3**、亮度是太阳光度的430万亿倍、中心为**120亿倍太阳质量**黑洞的极亮类星体，为研究宇宙早期的黑洞增长和结构形成提供了难得的机遇。
- 希望我国建成**更大口径的光学 / 红外望远镜**，发现更多宇宙中最遥远的类星体和黑洞。