Grow Supermassive Black Holes in the Early Universe

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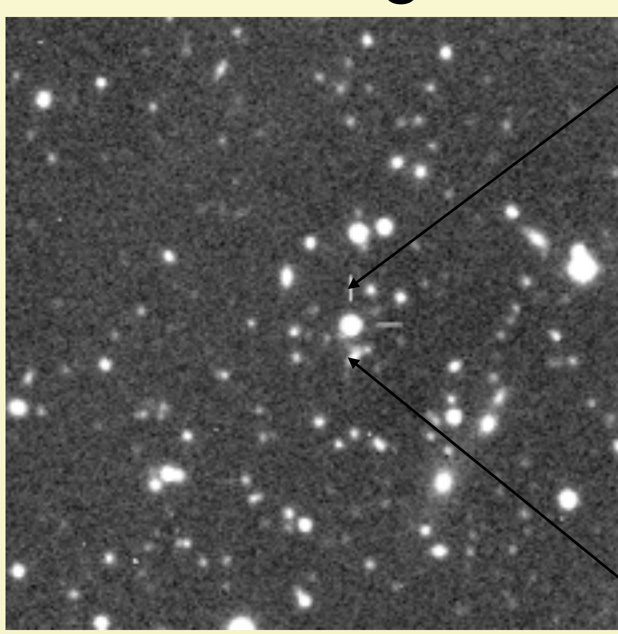
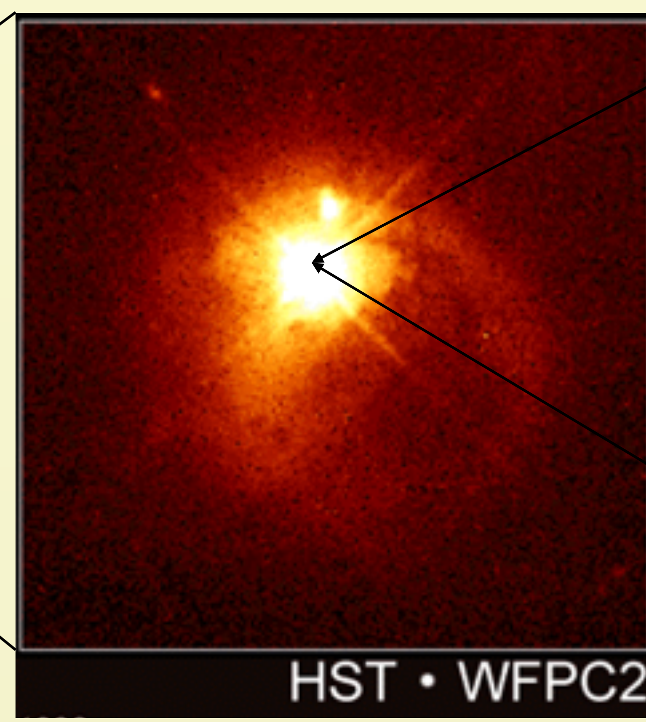
3C273: the first quasar (1963)

What is a Quasar?

- Quasar – Quasi-Stellar Object (QSO)
  - Compact, active nucleus at the center of distant galaxy
  - Very luminous (100 – 1000 brighter than Milky Way)
  - Powered by super-massive black holes (millions - billions solar masses)
  - Radiation from hot gas falling into BH
  - Among the most distant objects in the universe



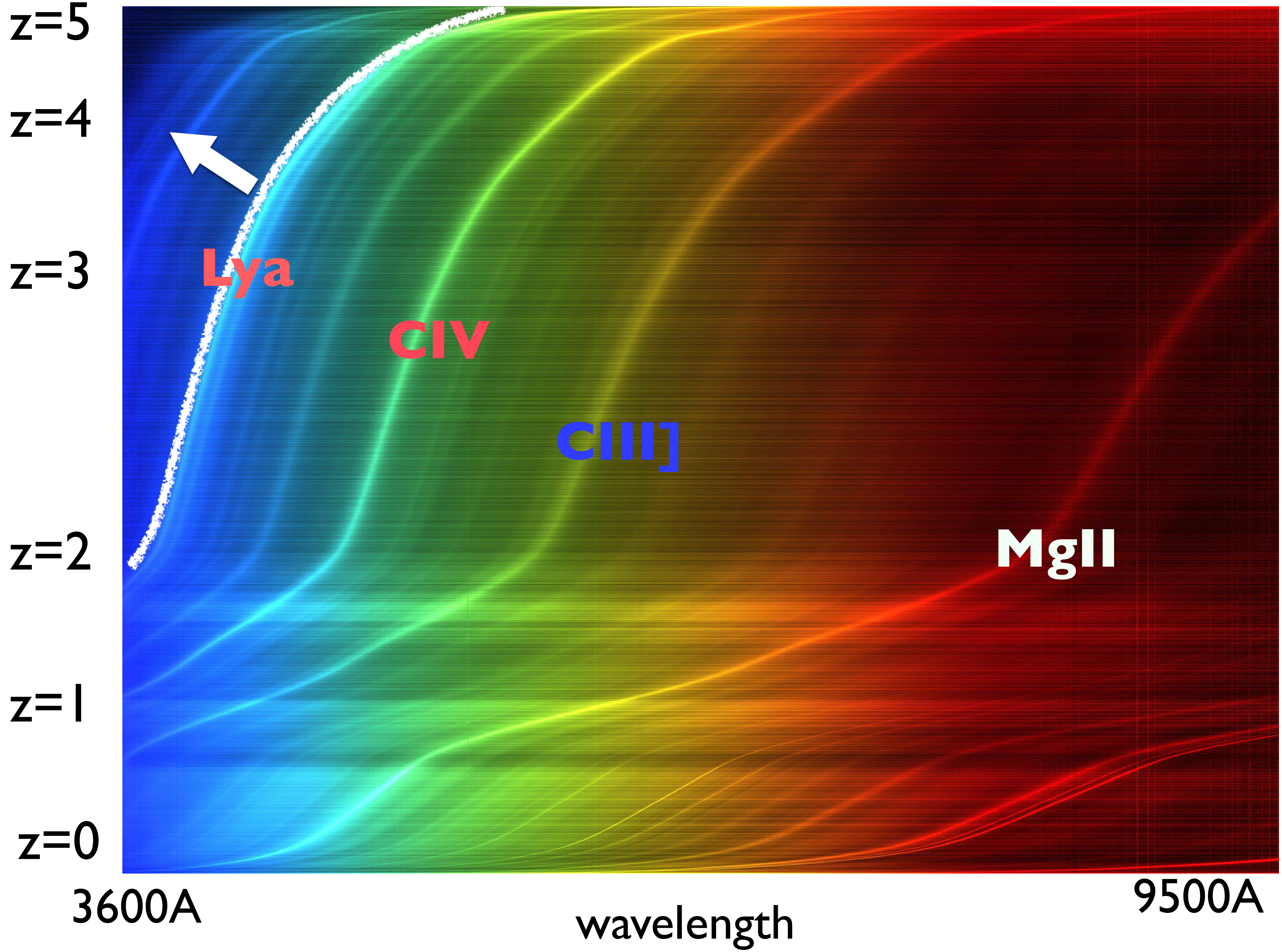
Ground-based
Image: stellar



At the center of galaxy

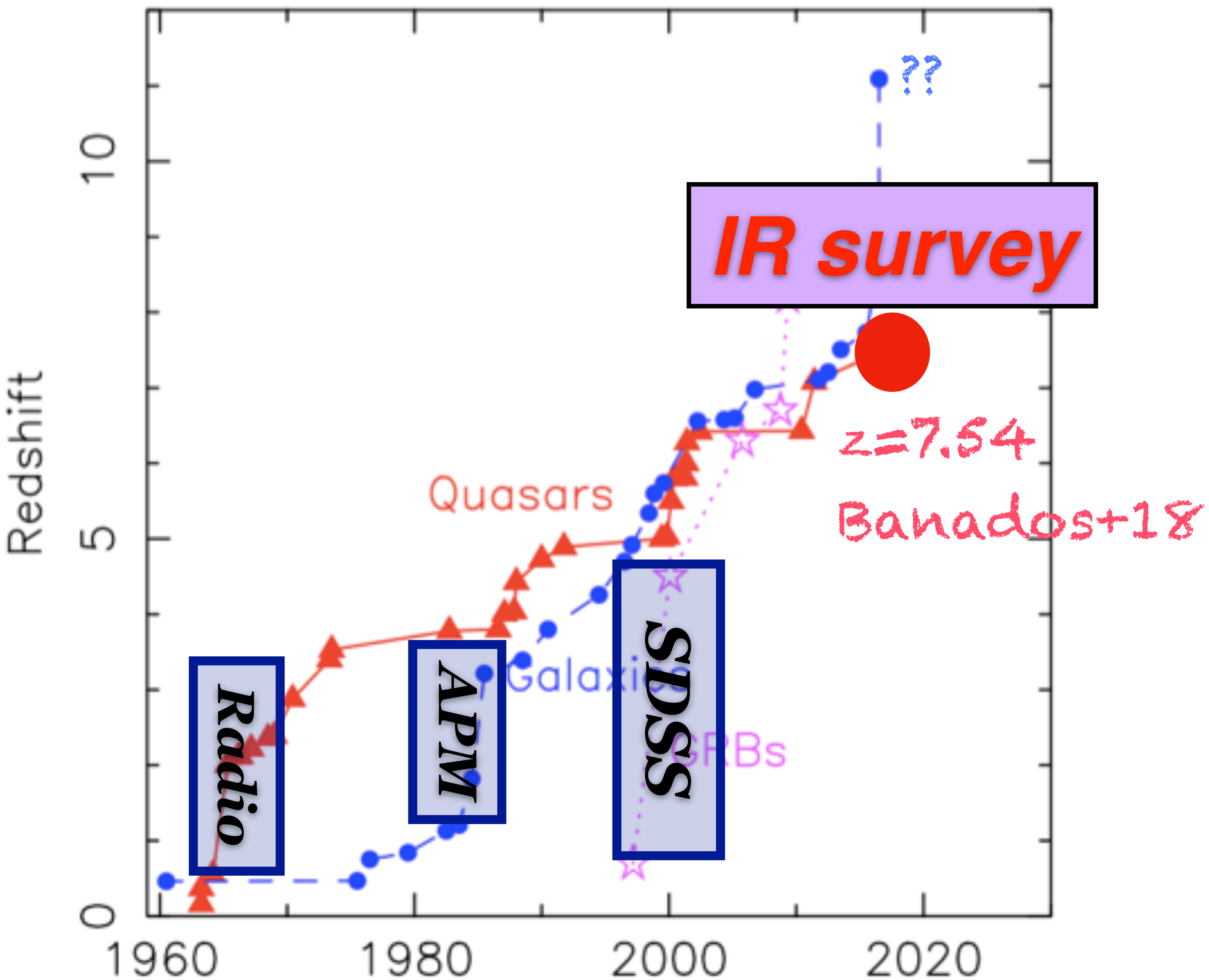
Gas and dust surrounding
The central BH

SDSS DR12 (2016) : 300,000 quasars



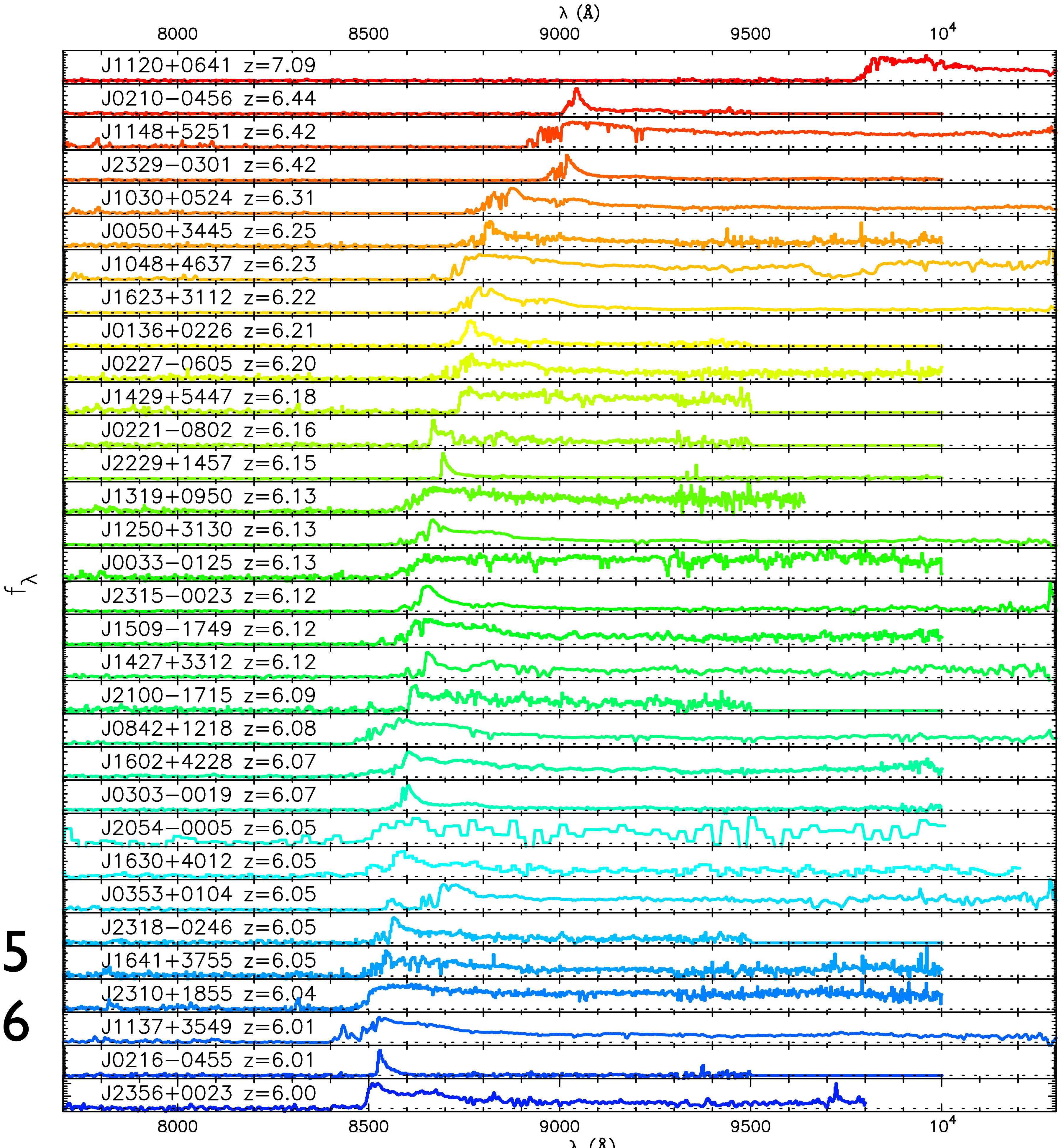
Credit: Franco Alberti

The highest redshift frontier now



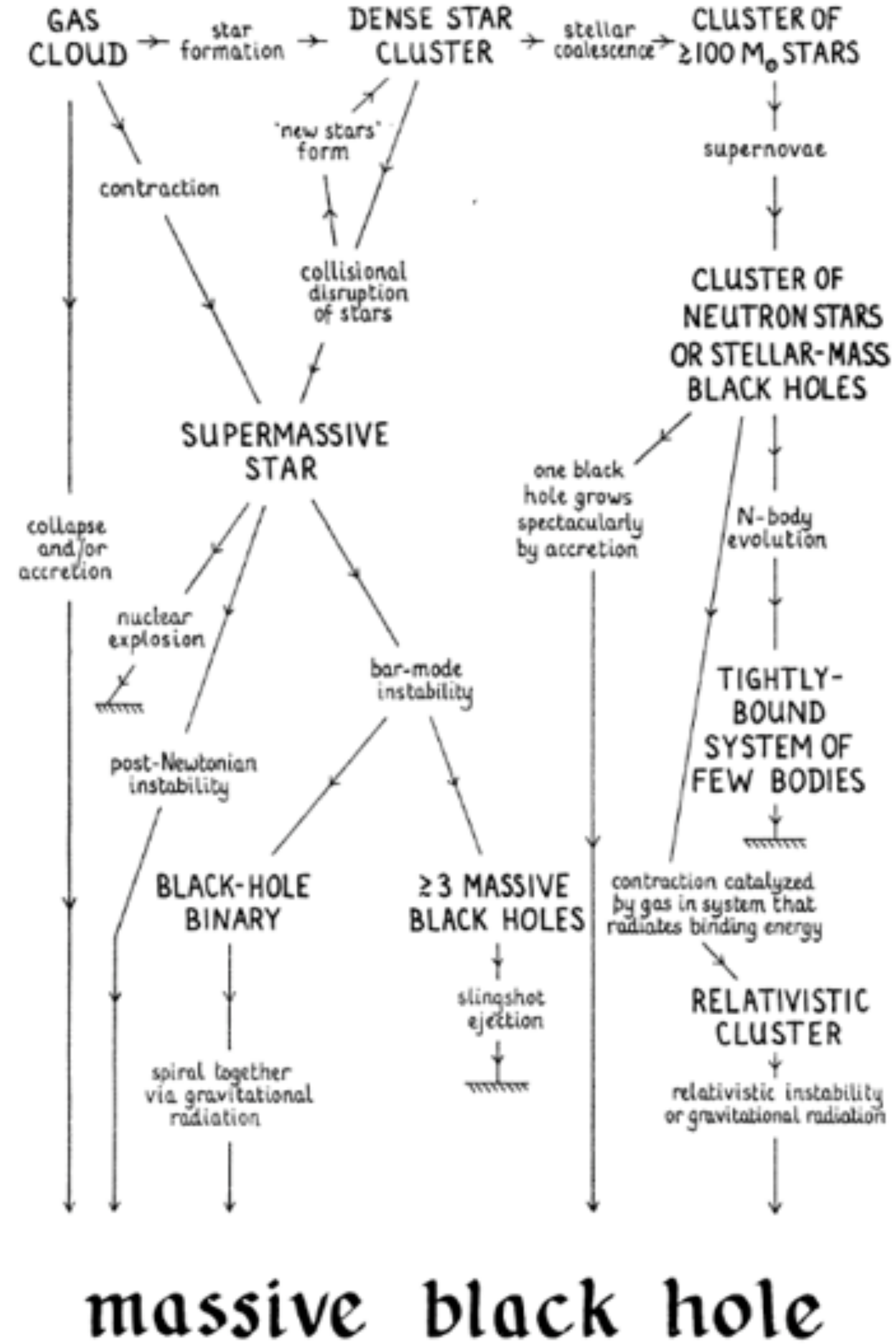
It might yet prove possible to account for the observed high-redshift (z~4) quasar populations with ... conventional cosmic structure formation theory

--- Ed Turner 1991



Quasars
>200 at z>5
>100 at z>6
3 at z>7

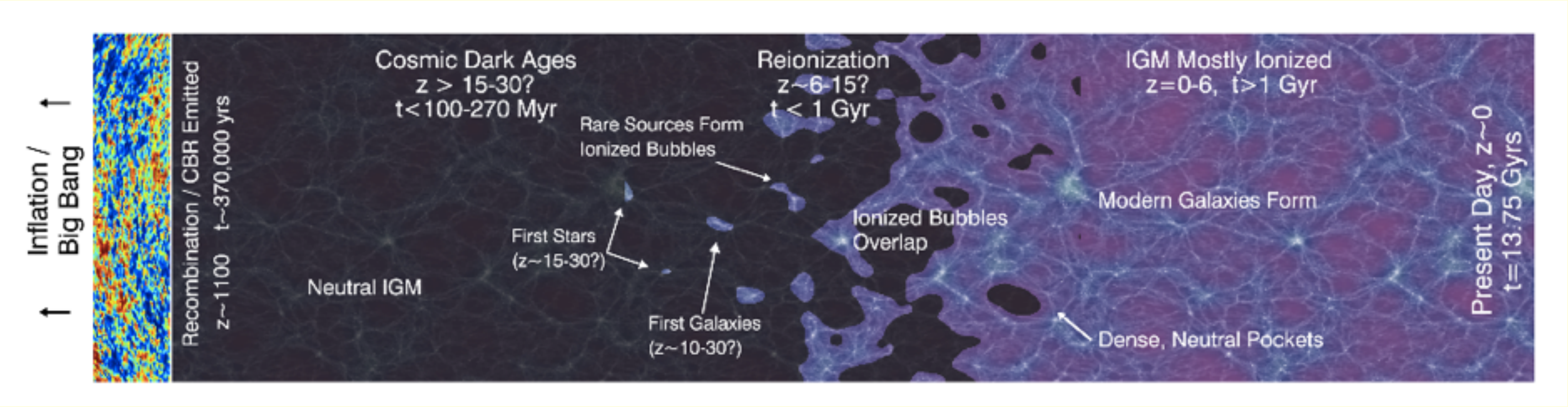
Fan 2013

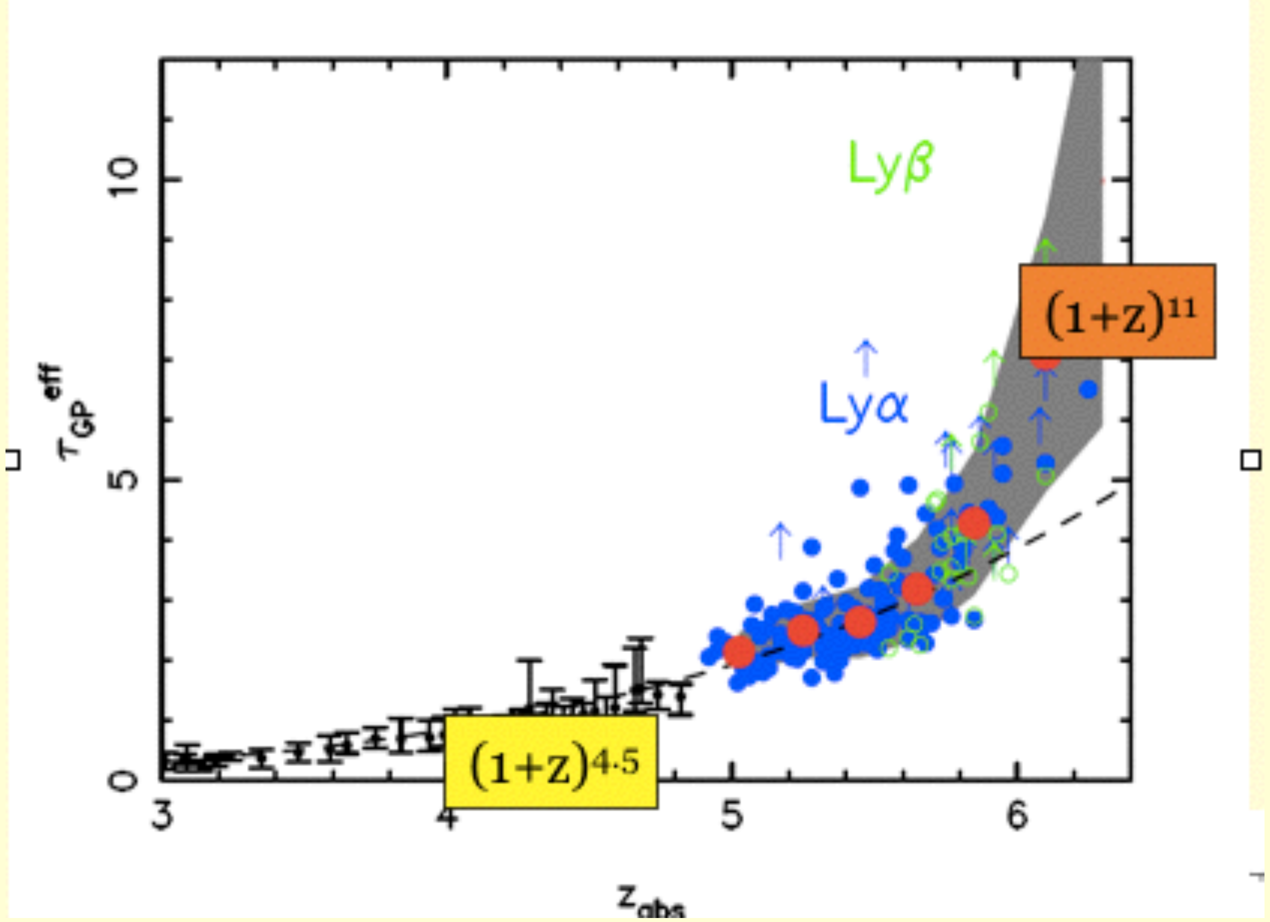


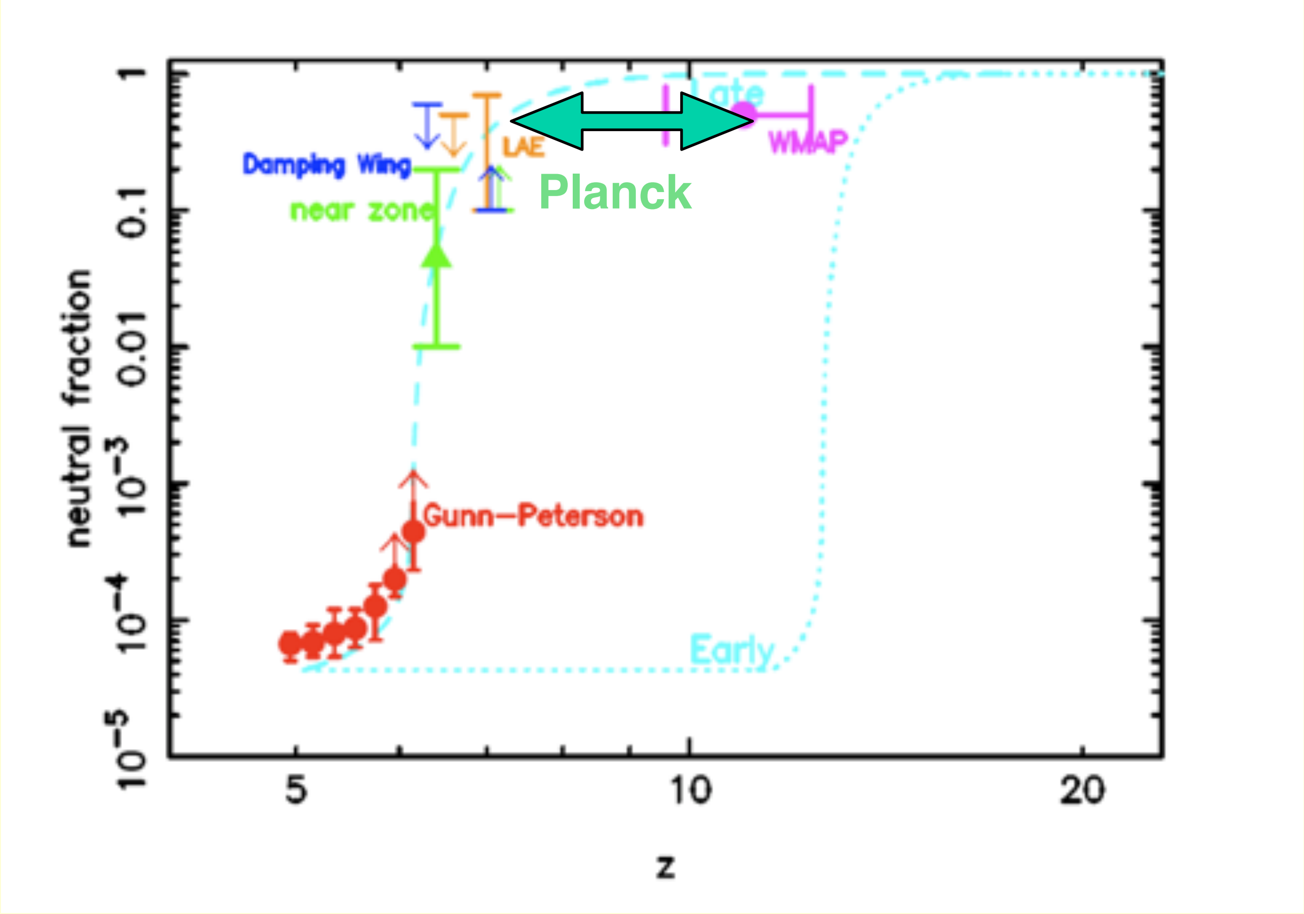
--- Martin Rees 1978

The study of distant quasars, and attempts to detect even larger redshifts, are thus crucially important for the study of galactic evolution. All the problems are so interrelated that we will not understand the dynamics or kinematics of the cosmos until we have a clearer perception of galactic evolution, and of what happens in active nuclei. Therefore, observations must be pursued on a broad front, in the hope that all issues will gradually clarify concurrently.

End of Cosmic Reionization







Fan et al. 2006

Next Generation Quasar Surveys

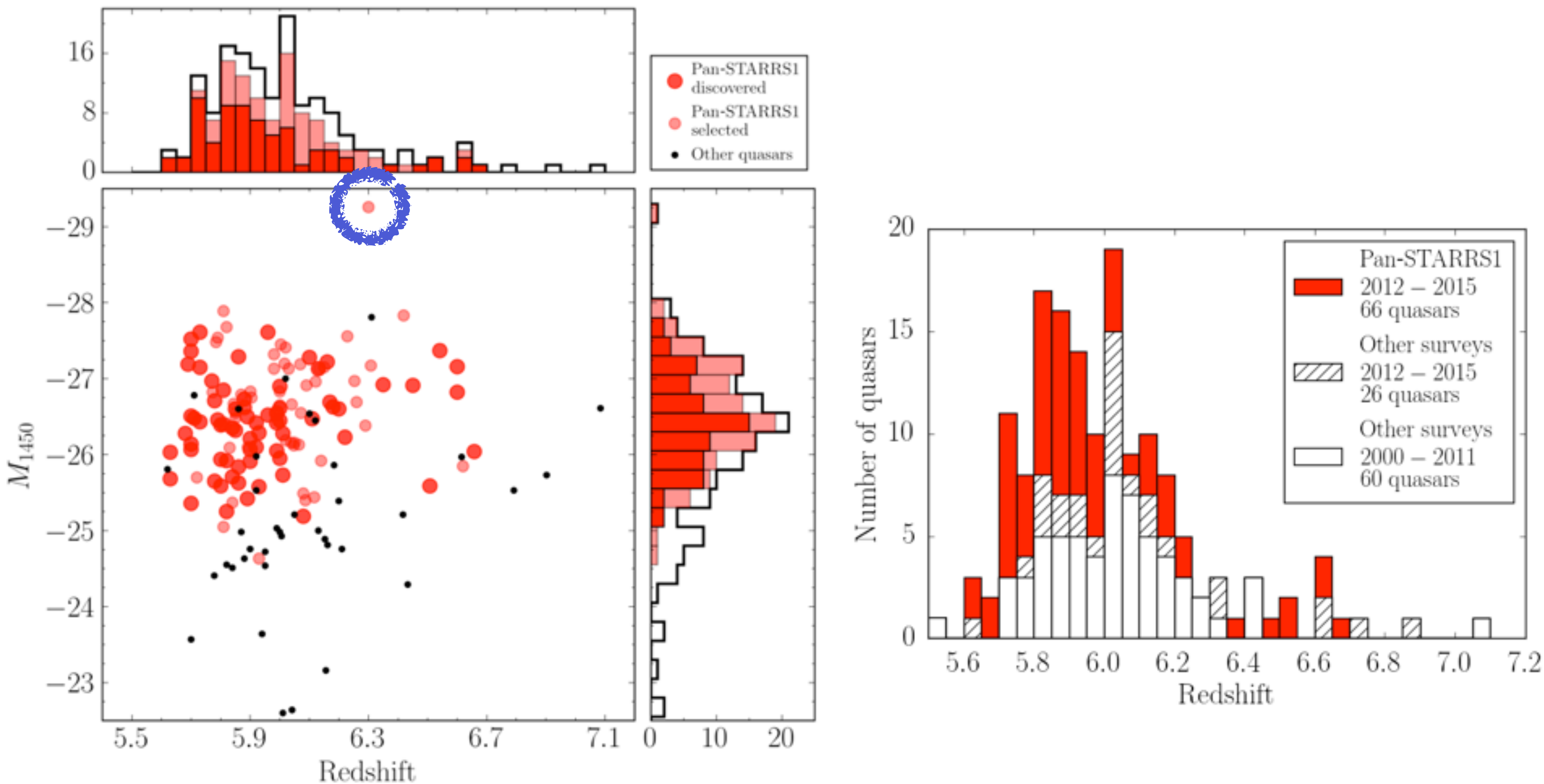
- Optical surveys (SDSS):
  - limited to z<6.5 (Ly alpha > 9000A)
- New generations of red-sensitive CCD devices (z<7.5)
  - Improved QE at 1 micron (Y band)
  - SUBARU/HSC (2014+): a few hundred deg, Y<25
  - **Pan-Starrs** (2009+): 3π: Y<21.4
  - **DESI Legacy Imaging Survey**: 14000 deg^2, z<22.5
  - **DES** (2013+): 5000 deg^2, Y<21.7
  - LSST (2018+): 3π: Y< 25
- New generation of Near-IR surveys (z=8-10)
  - **UKIDSS** (2005 - 2013): 4000 $deg^{2:}$ J_{AB}<21
  - **UHS/VHS** (2010+): 30000 $deg^{2:}$ J_{AB}<21
  - ECULID/WFIRST: 20,000 sq. deg, J_AB ~ 24

Questions

- The most massive black holes in the early Universe
  - Formation of seed black holes?
- The most distant quasars
  - History of Cosmic Reionization

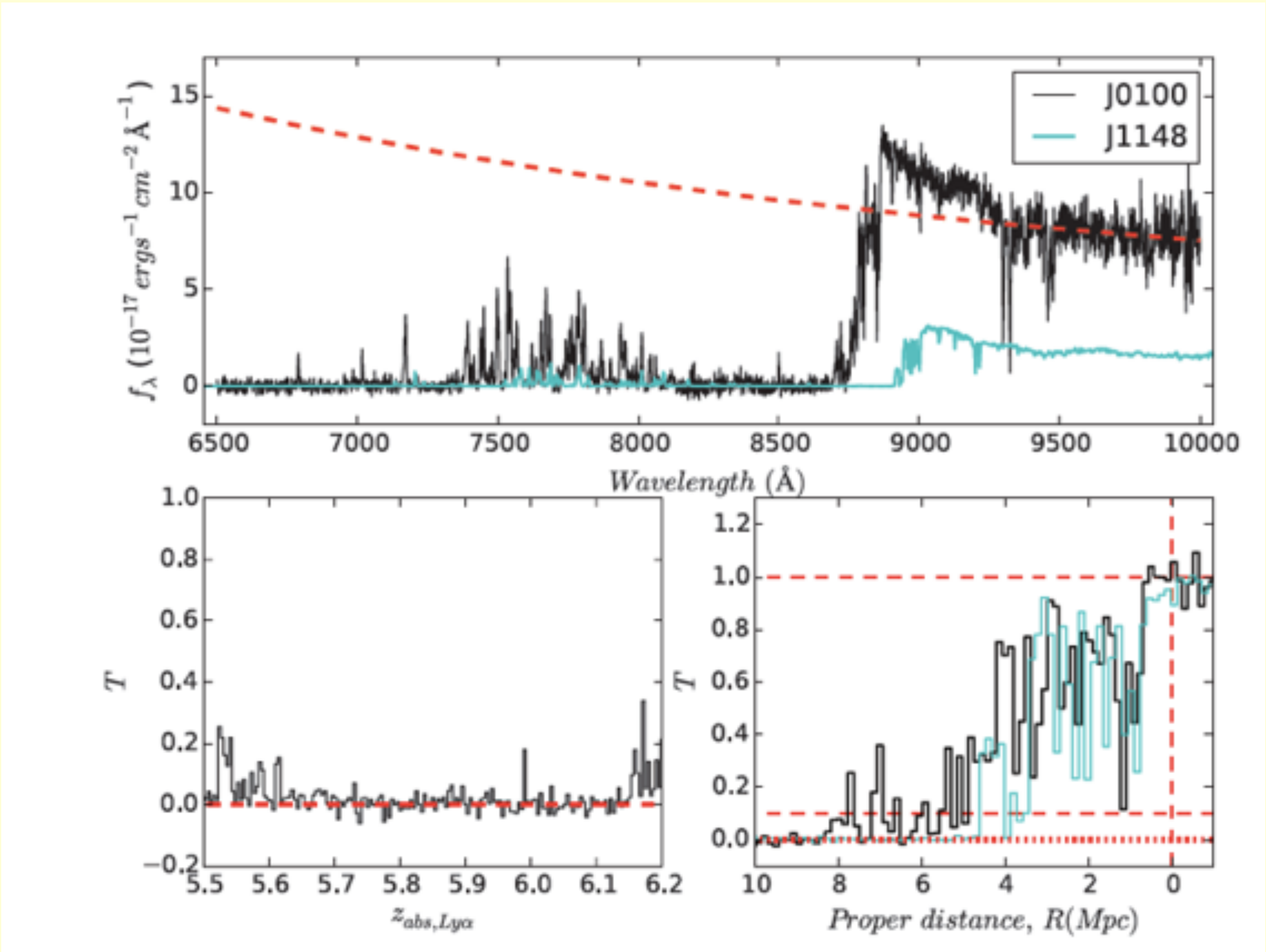

I.
II.
I. The Most Massive Black Hole
in the Early Universe

New Surveys: Expanding High-Redshift Frontier



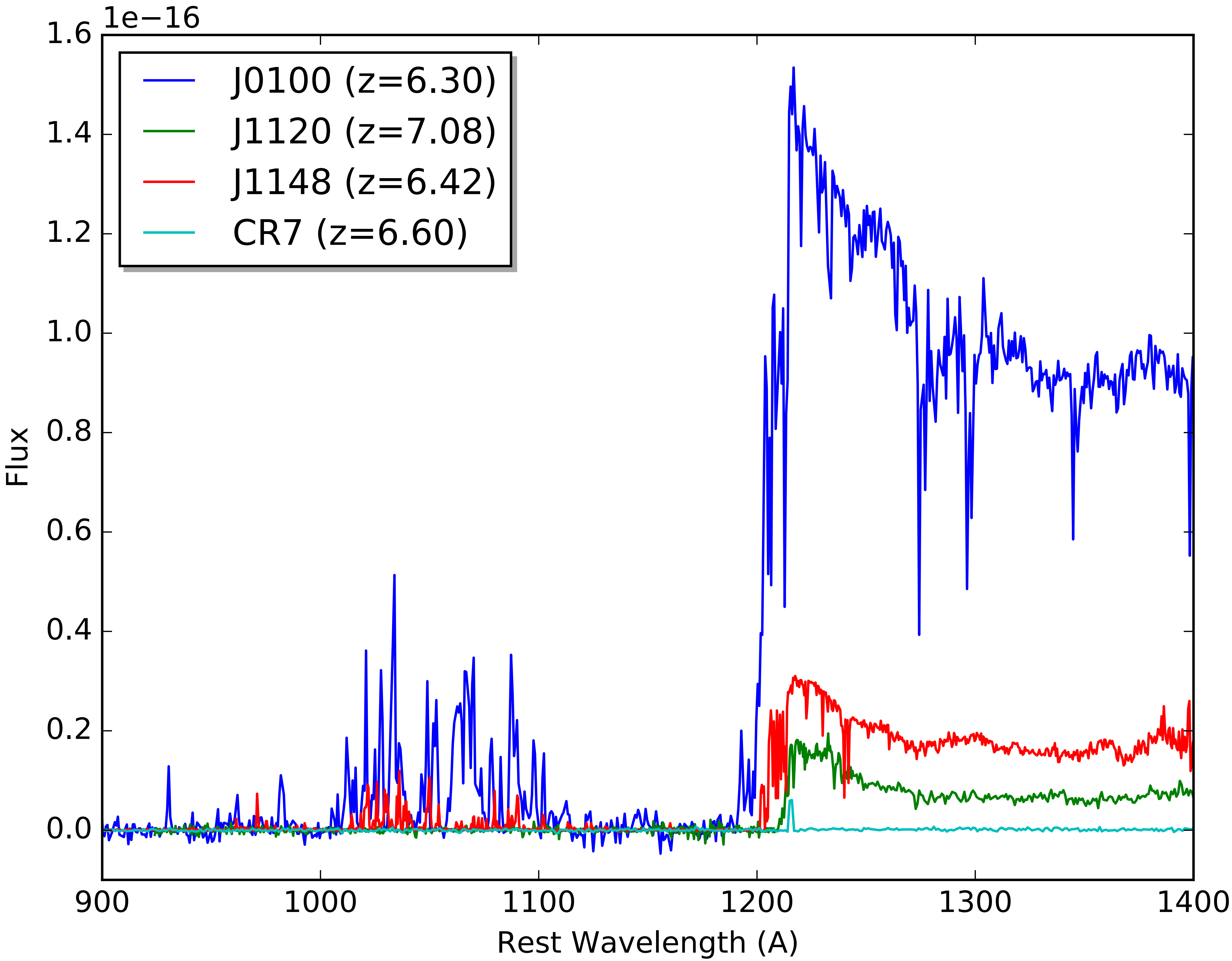
credit: Eduardo Banados

J0100: An Ultra-Luminous Quasar at z=6.3



Wu, Wang, Fan et al. 2015
LBT/MODS spectrum

- SDSS+WISE Selection
  - z_{AB}=18.3, K=15.2 (2MASS = 8 sec exposure on 1.3m telescope)
  - the most luminous object in the observable universe at z>5
  - $L_{bol} = 4x10^{14} L_{sun}$
  - five times more luminous than previous record-holder J1148
  - deep Gunn-Peterson trough and large ionizing zone



1e−16
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Flux
J0100 (z=6.30)
J1120 (z=7.08)
J1148 (z=6.42)
CR7 (z=6.60)
900
1000
1100
1200
1300
1400
Rest Wavelength (A)

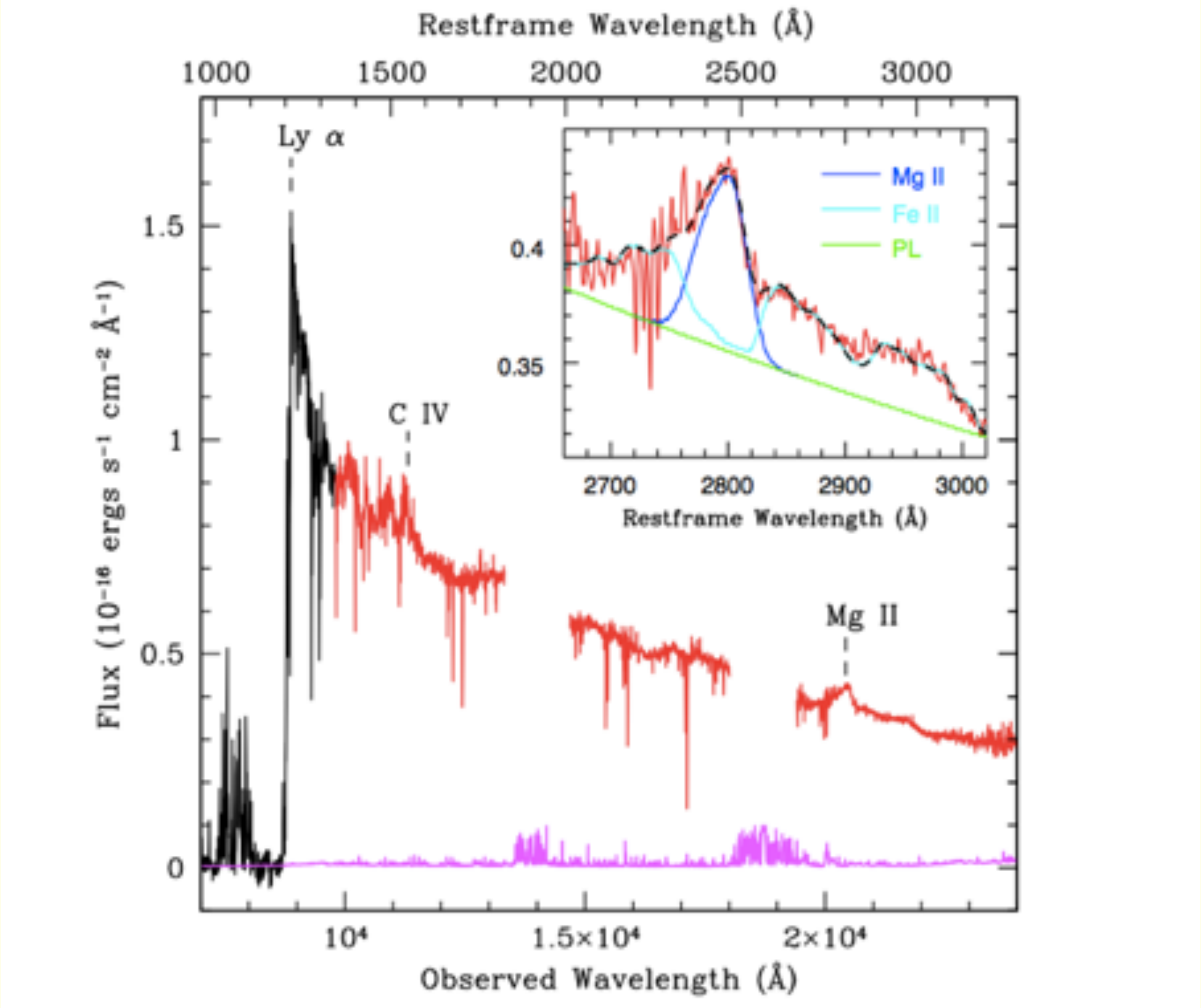
It would … asn't
selected … earches
describe … the i-z
colour o … have
passed t

-

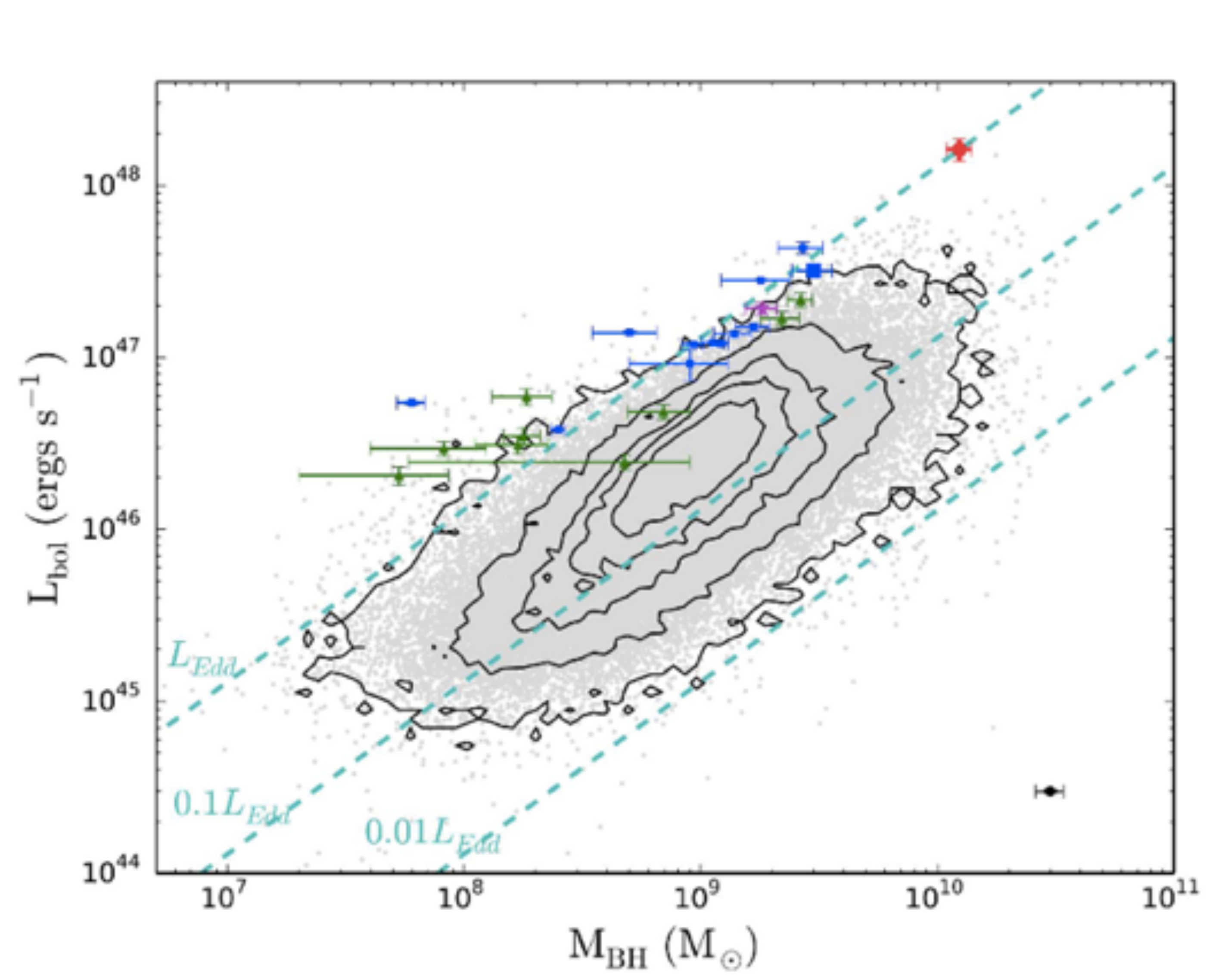
Courtesy of Arizona graduate students

Too Bright: 2MASS sources ignored by selection

A Twelve Billion Solar Mass Black Hole at the End of Reionization

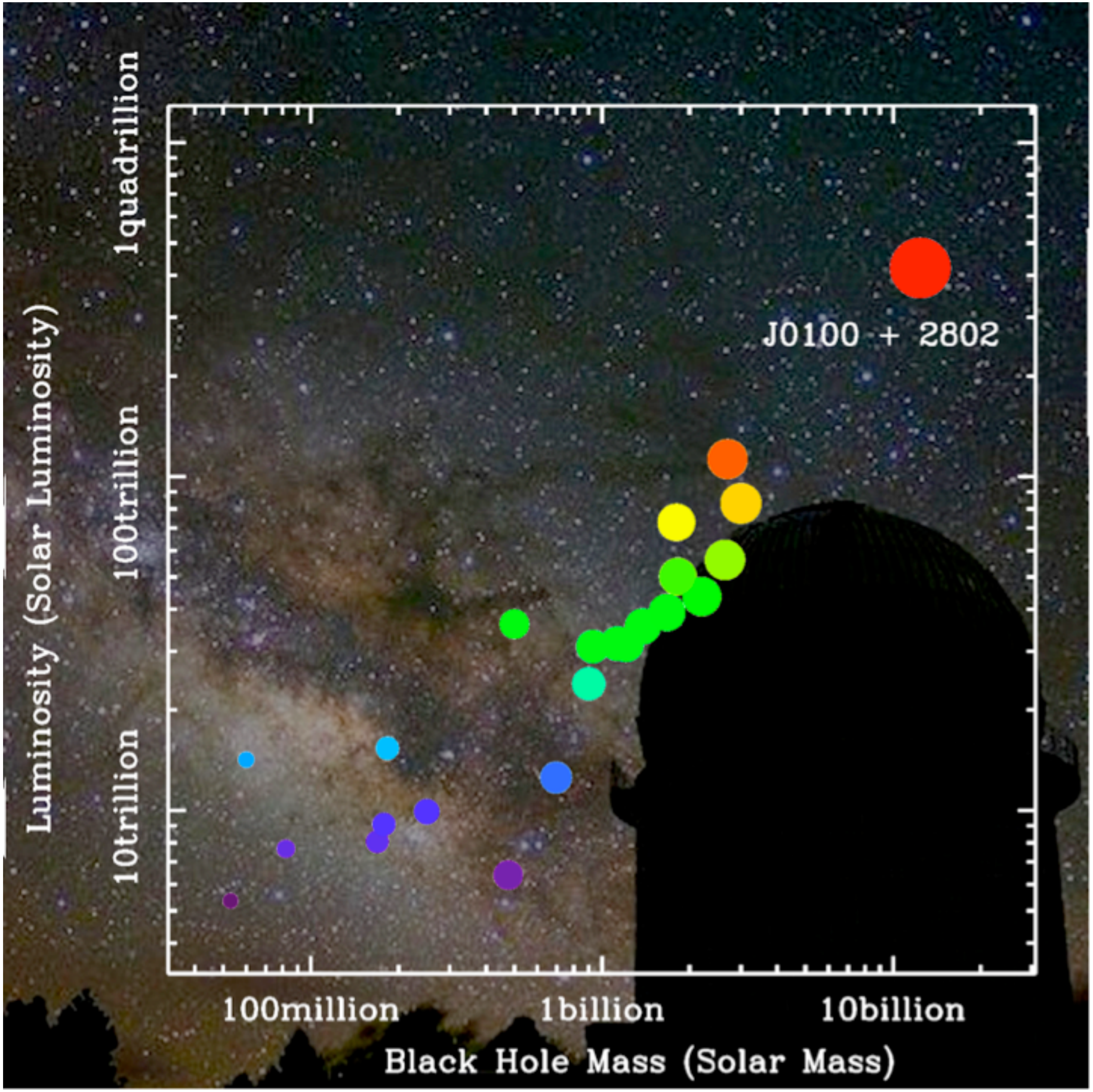


Magellan/FIRE spectrum

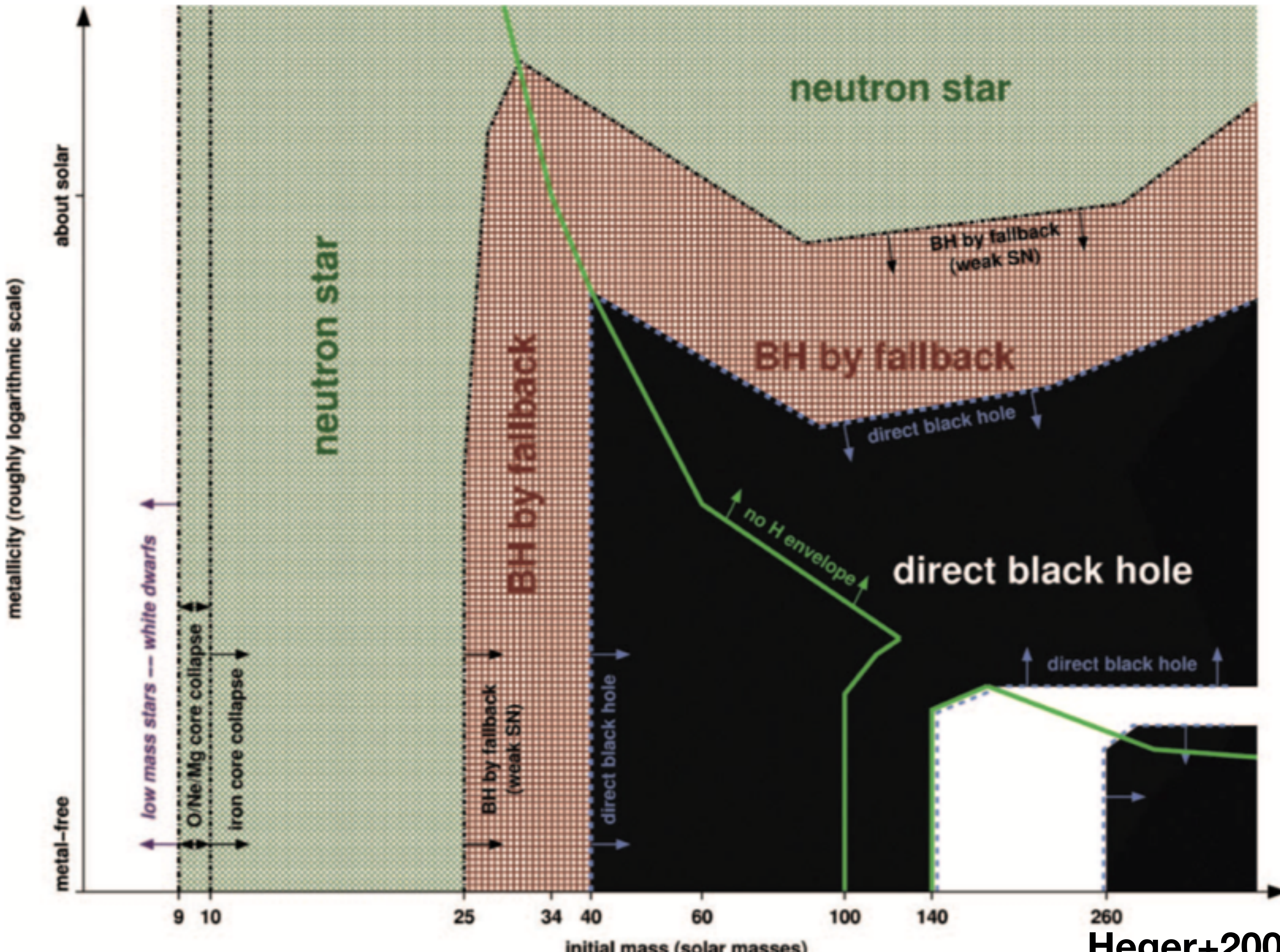


- BH mass ~12 billion solar masses
- emitting at Eddington limit
- comparable to the most massive BH in the local universe, at z=6.3!!
- Challenge to BH formation and growth

Wu et al. 2015, Nature

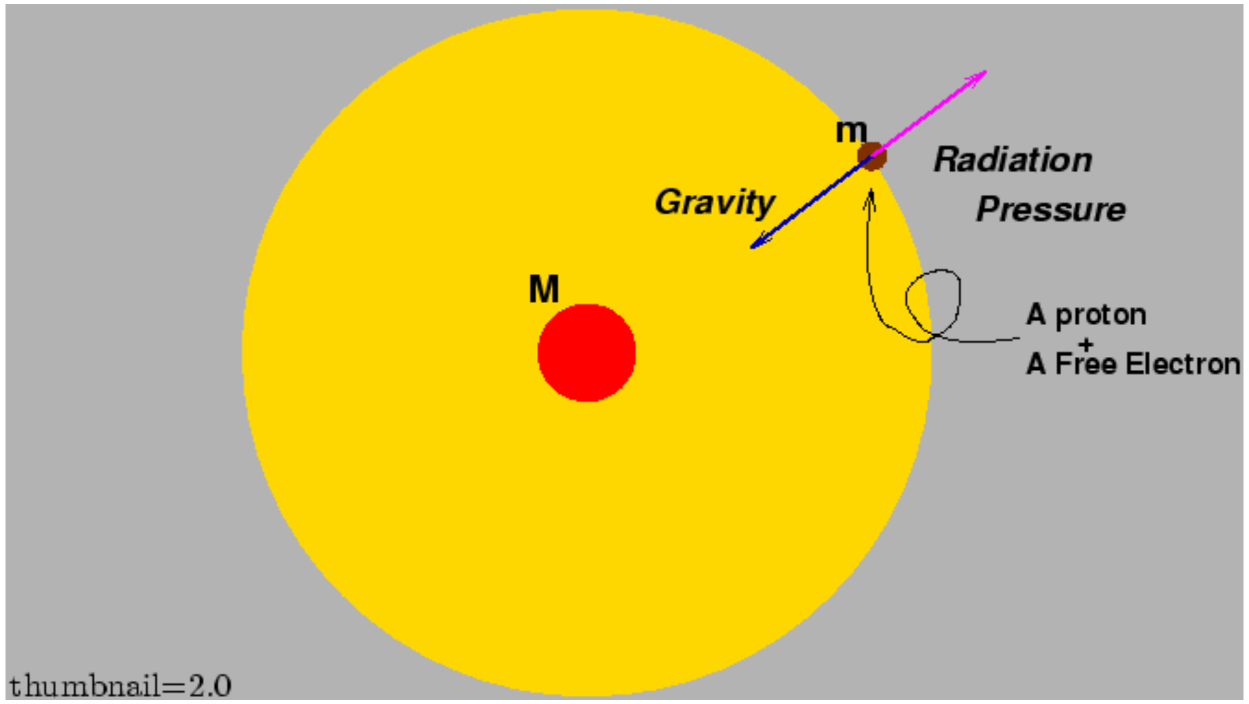

J0100 + 2802
1quadrillion
100trillion
10trillion
Luminosity (Solar Luminosity)
100million
1billion
10billion
Black Hole Mass (Solar Mass)

Fate of the first stars: first BH seed



Heger+2002

Eddington Limit of BH Growth



- balance of radiation pressure and gravity
- e-folding time of BH growth ~40 Myrs, assuming radiative effective accretion (~0.1)

How to form 12 billion solar mass BH at z=6.3?

- Black Holes do not grow arbitrarily fast
  - Accretion onto BHs dictated by Eddington Limit
  - E-folding time of **maximum** supermassive BH growth: 40 Myr
  - At z=6.3: age of the universe: 880 Myr = **maximum** 20 e-folding
- 12 Billion solar mass BH at z>6
  - Non-stop, maximum accretion from 100 solar mass BHs at z~30 (collapse of first stars in the Universe?)
  - **Theoretically difficult for formation of 12 billion solar mass BHs by z=6**
  - possibilities?
    - Direct collapse of "intermediate" mass BHs (10^{4-5} M_{sun})?

Direct Collapse Black Holes (DCBHs) as Seeds of the Most Massive SMBHs in the Early Universe?

- Supermassive stars can form via atomic hydrogen cooling
  - Agarwal, Begelman, Johnson, Latif, Omukai, Regan, Volonteri, etc.

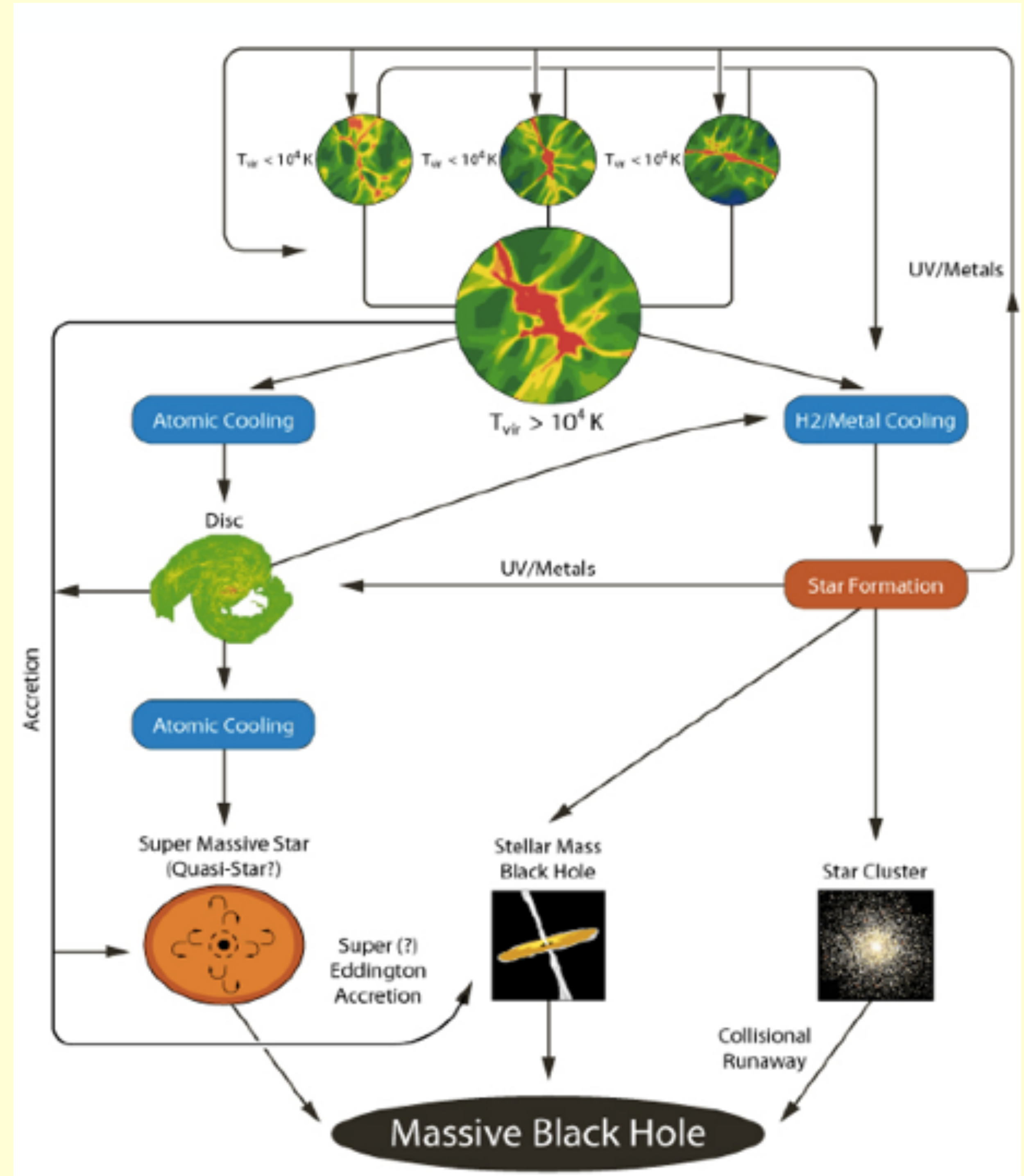
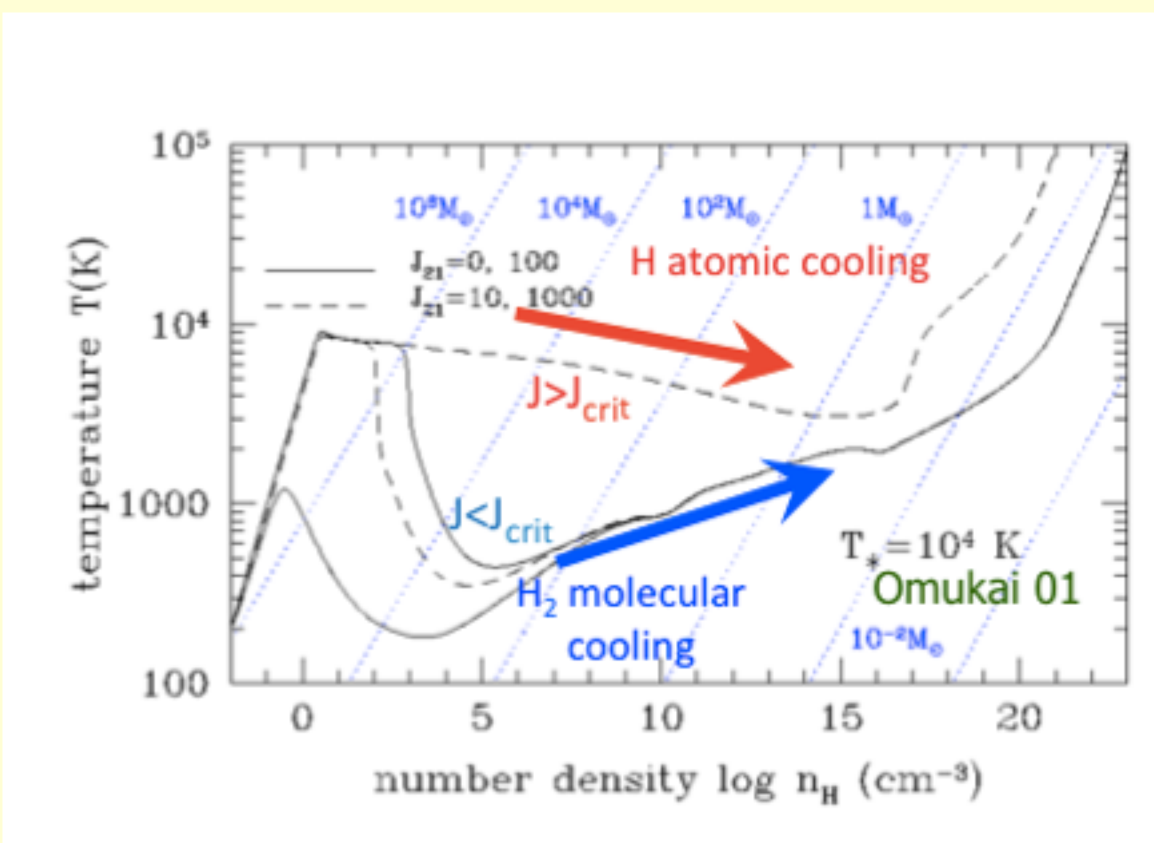
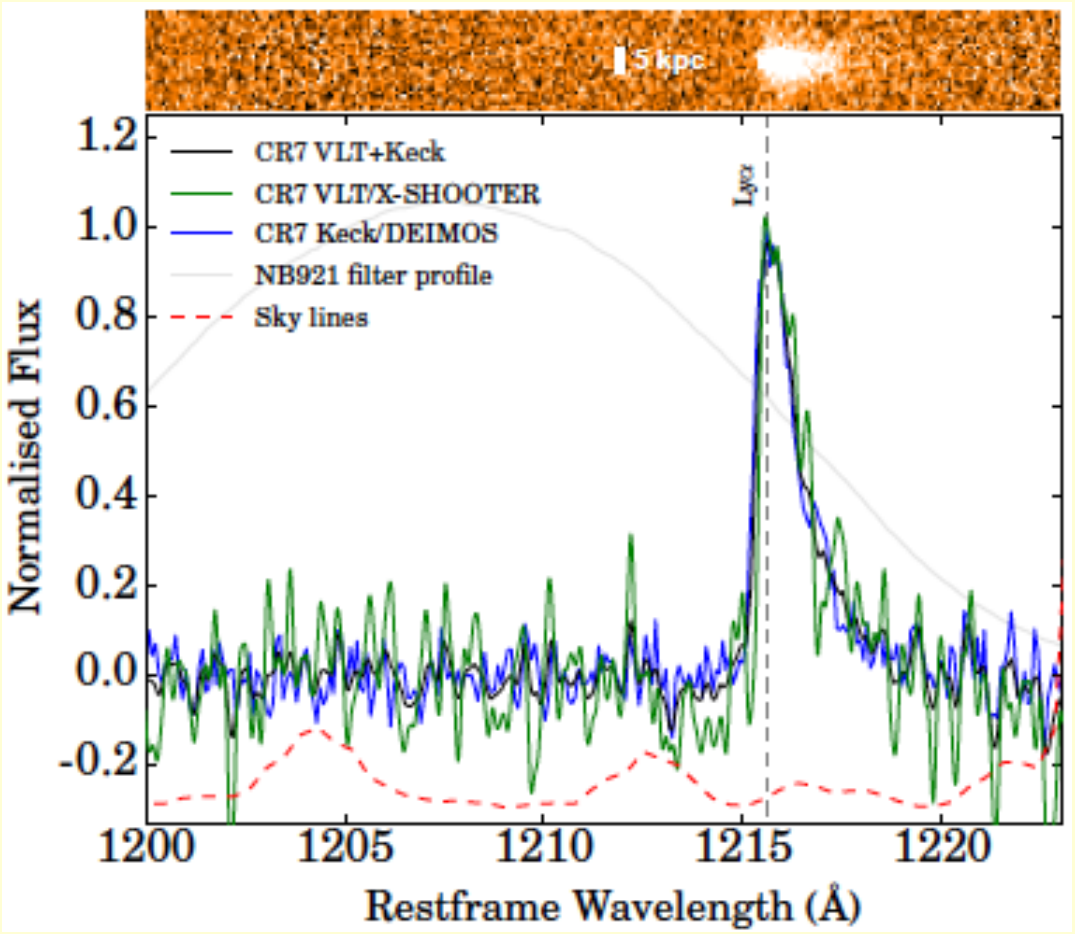


Image credit Regan et al 2009



DCBH detected?

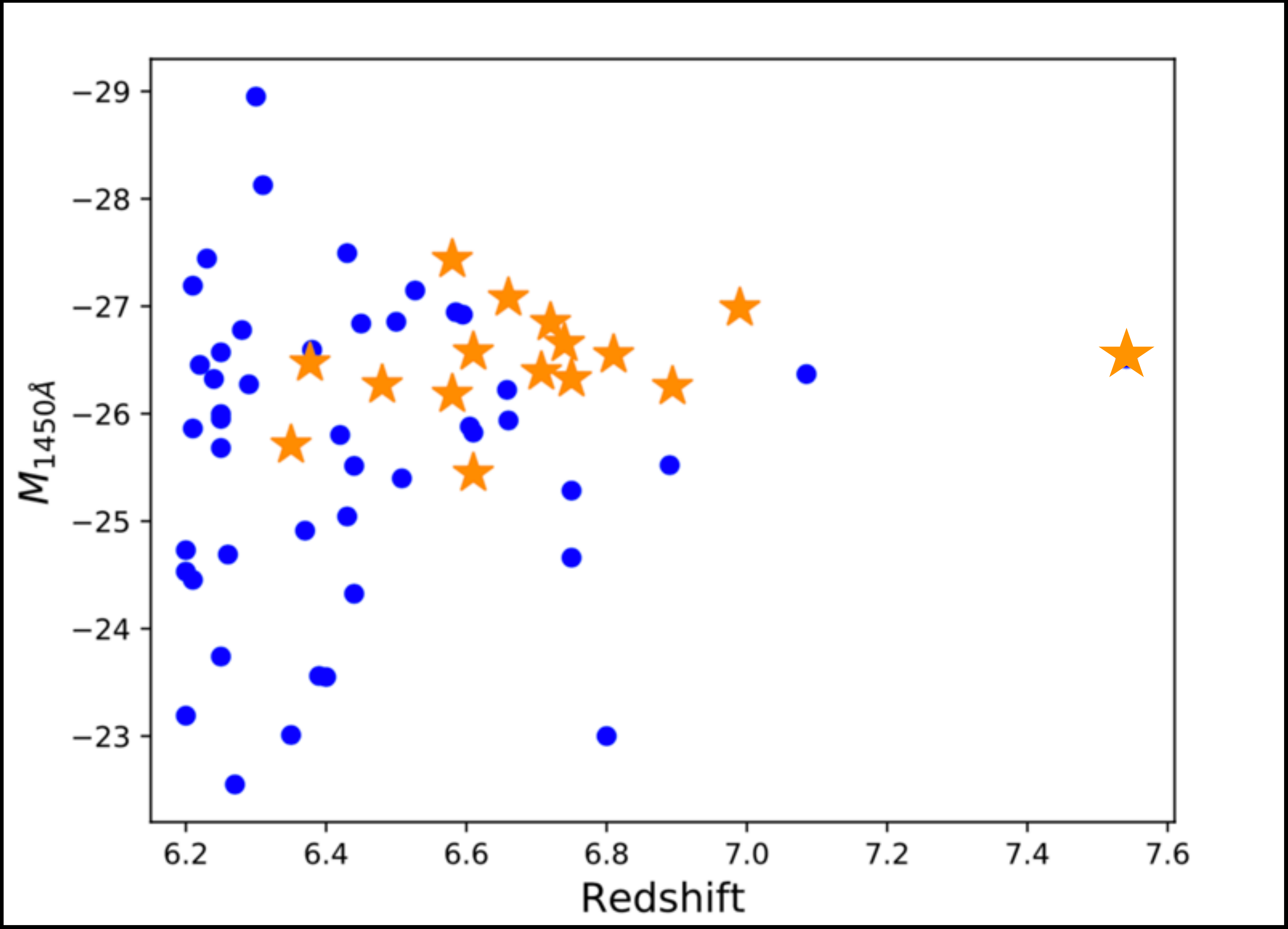


- CR7:
  - brightest known Lyman alpha emitter
  - strong HeII line, no metal lines
  - Pallottini et al. 2015 and others: Pop III galaxy or DCBH?
- Implications:
  - DCBH needs special environment in the early universe
  - low occupation of dark matter halos
  - what does this mean for host galaxy/environment of the most luminous quasars?

II. The highest redshift quasar

New quasar discoveries in the last two years

Wang et al. 2018, in prep



Eduardo Banados March 10, 2017 at 3:22 AM

To: Fabian Walter, Venemans Bram, Roberto Decarli, Chiara Mazzucchelli, Xiaohui Fan, Feige Wang, and 2 more...

pisco sour quasar

EB

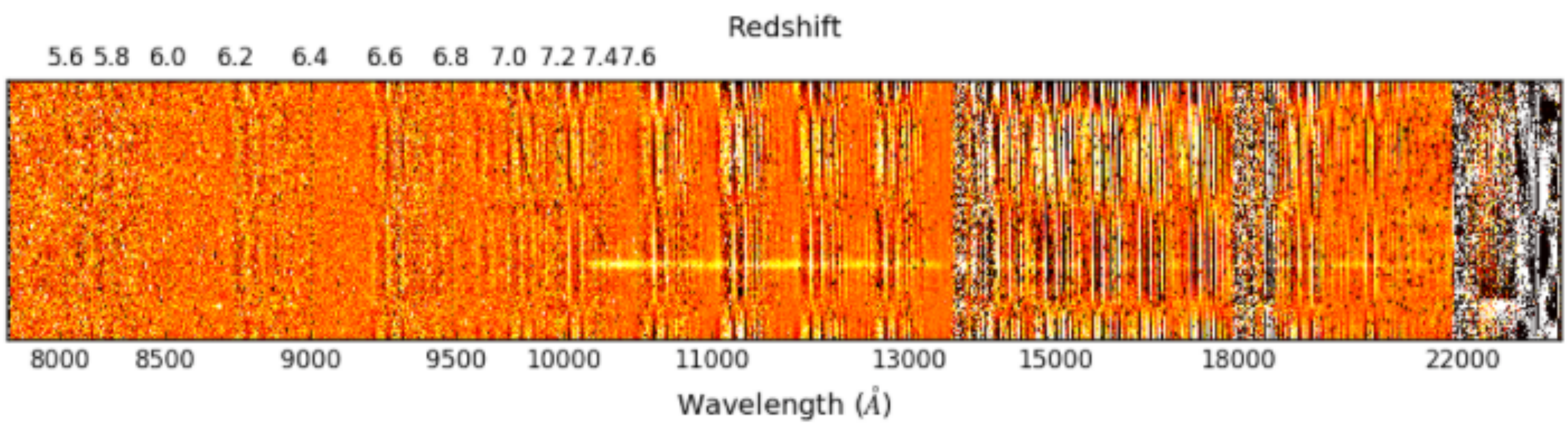
Dear all,

We are concluding the last night at Magellan. We observed more than 100 objects and we are happy to tell you that we have a winner! See attached the 'pisco sour' z>7.2 quasar.

Now is pisco sour time.

Cheers,

Eduardo & Dan



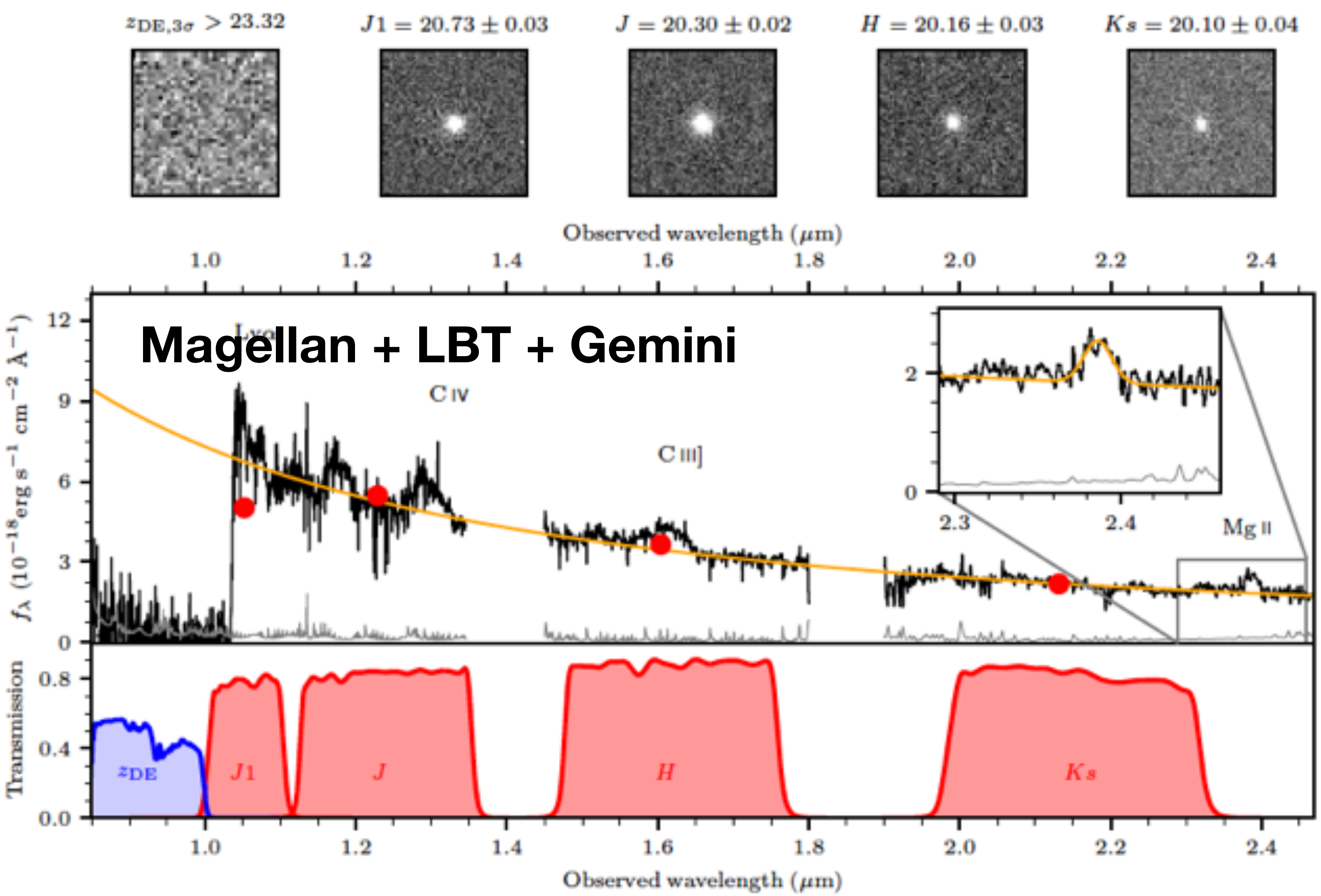
What does it takes to make a pisco sour

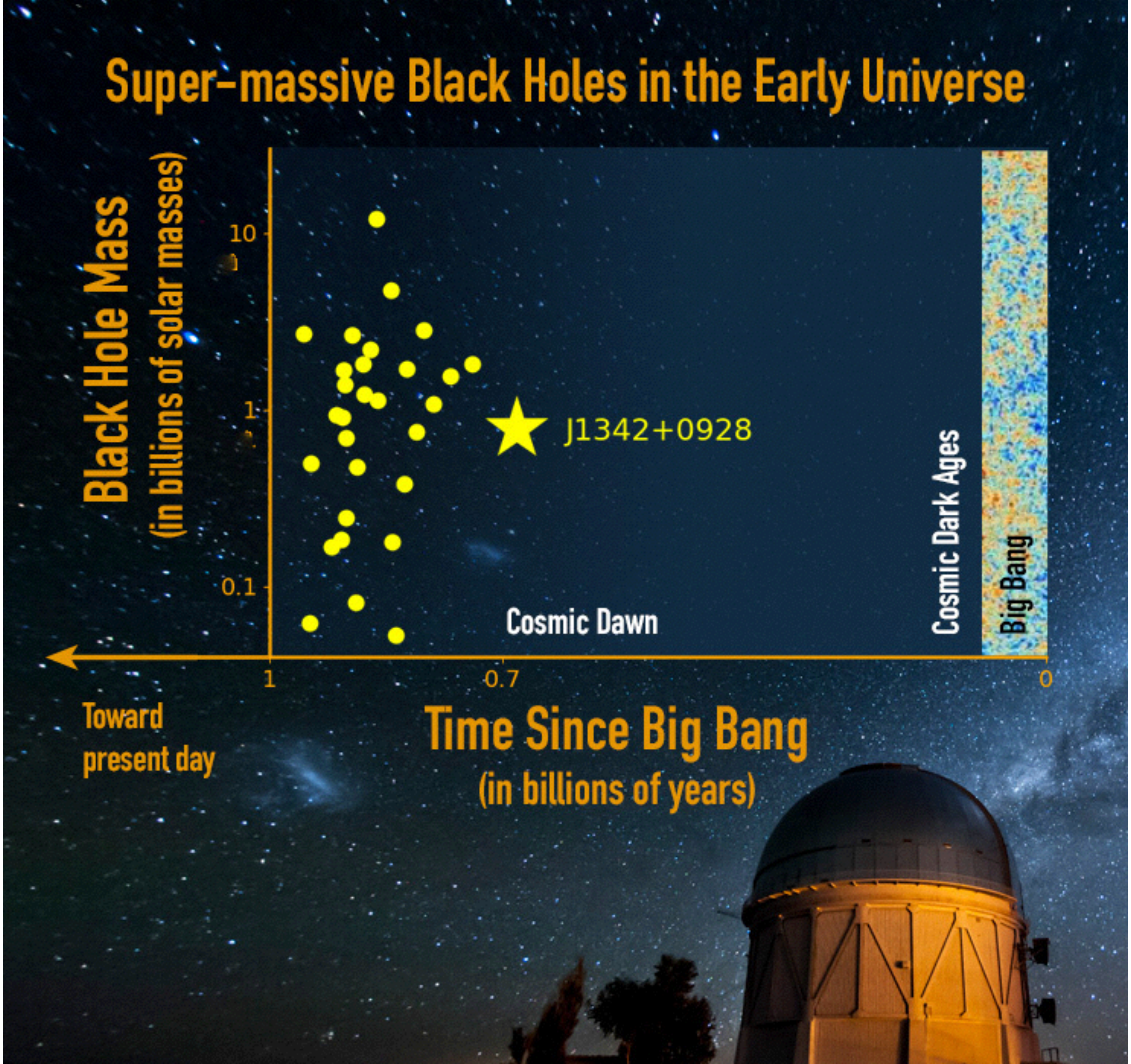
(1) photometric selection

Survey	AB magnitudes	
DECaLS	$z_{DE,3\sigma} > 23.32$	
UKIDSS	$Y = 21.47 \pm 0.19$	$J = 20.75 \pm 0.11$
	$H = 20.02 \pm 0.02$	$K = 20.03 \pm 0.12$
WISE	$W1 = 20.17 \pm 0.15$	$W2 = 20.11 \pm 0.29$

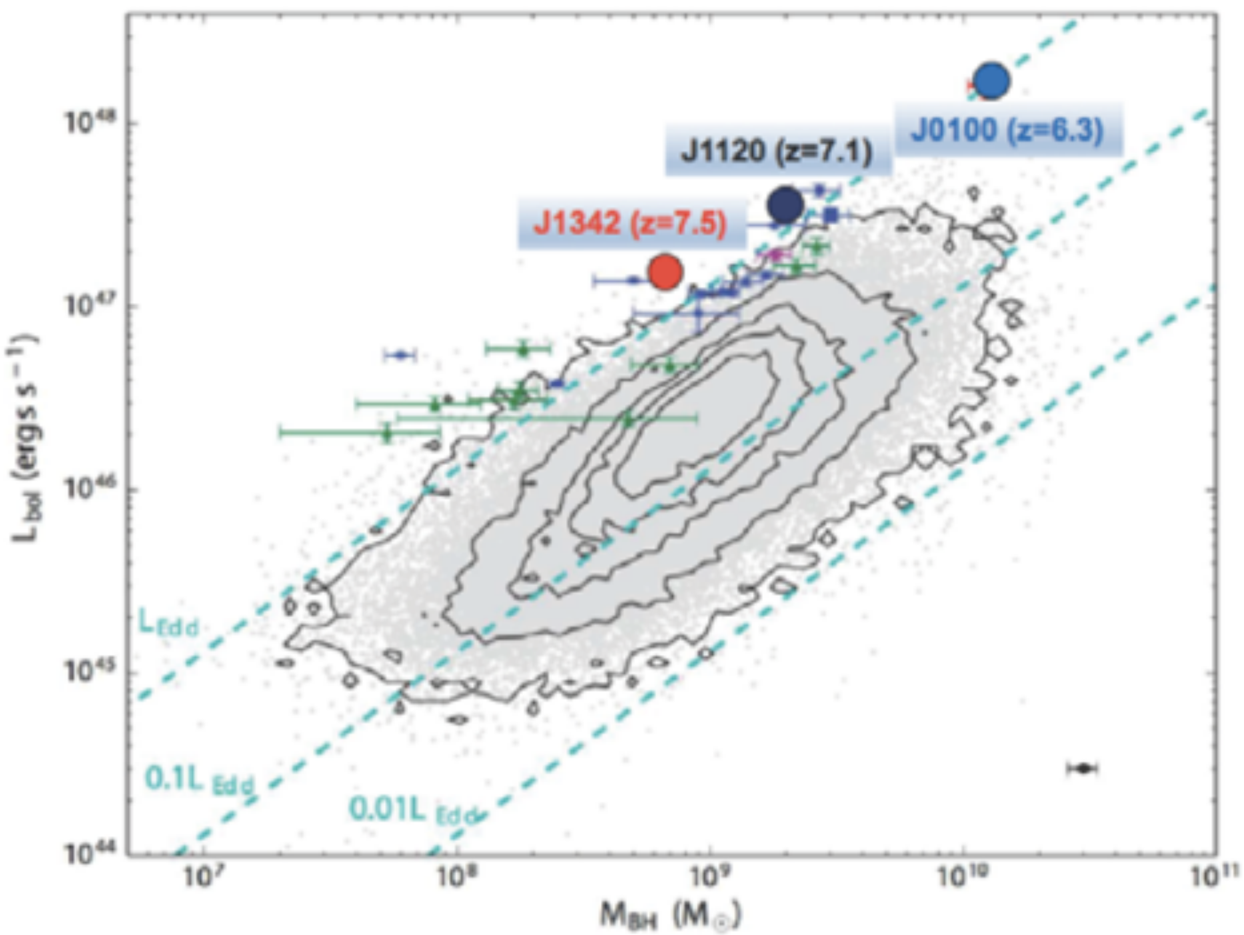
(3) redshift determination: z=7.54 from millimeter observations of C[II]

(2) spec identification

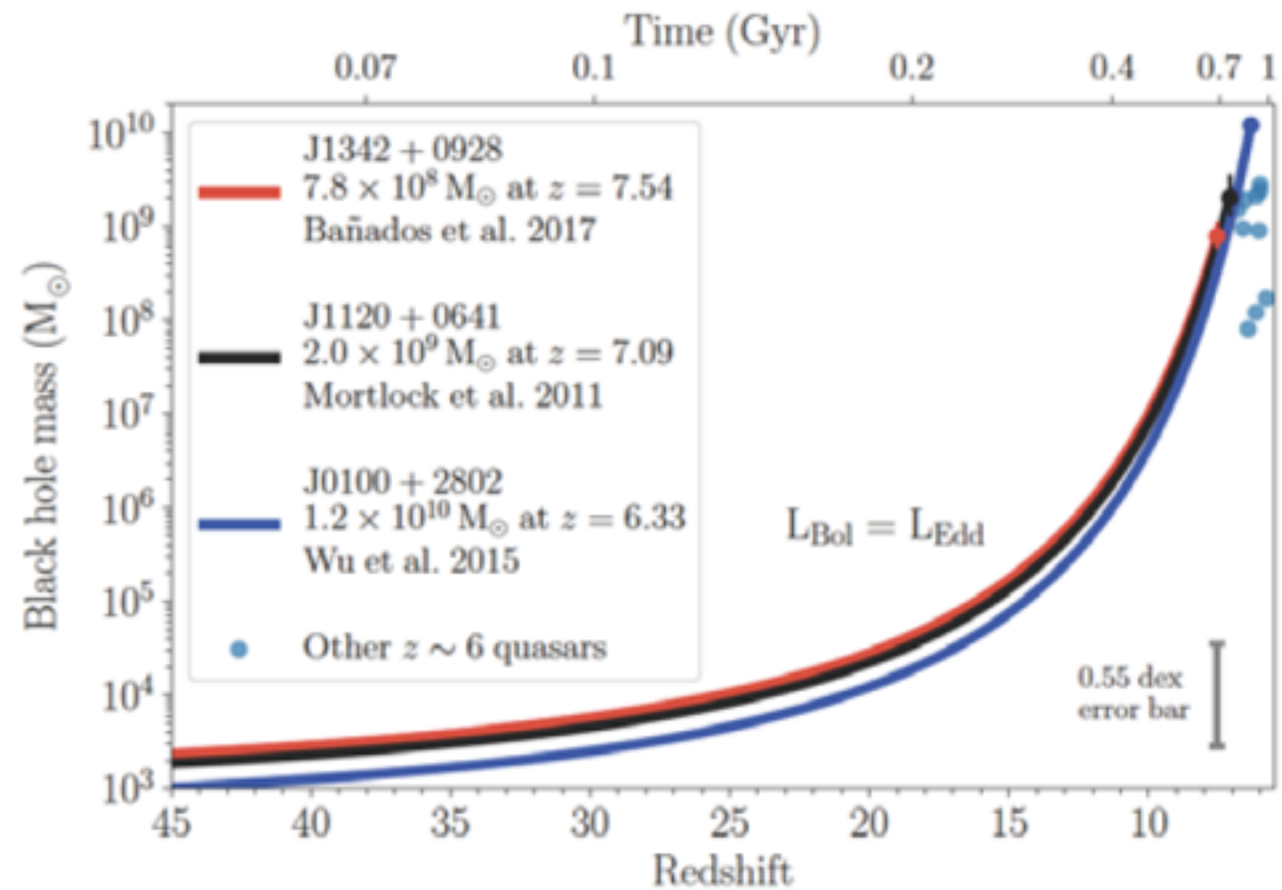




Super-massive Black Holes in the Early Universe
Black Hole Mass
(in billions of solar masses)
10
1
0.1
J1342+0928
Cosmic Dawn
Cosmic Dark Ages
Big Bang
1
0.7
0
Toward present day
Time Since Big Bang
(in billions of years)

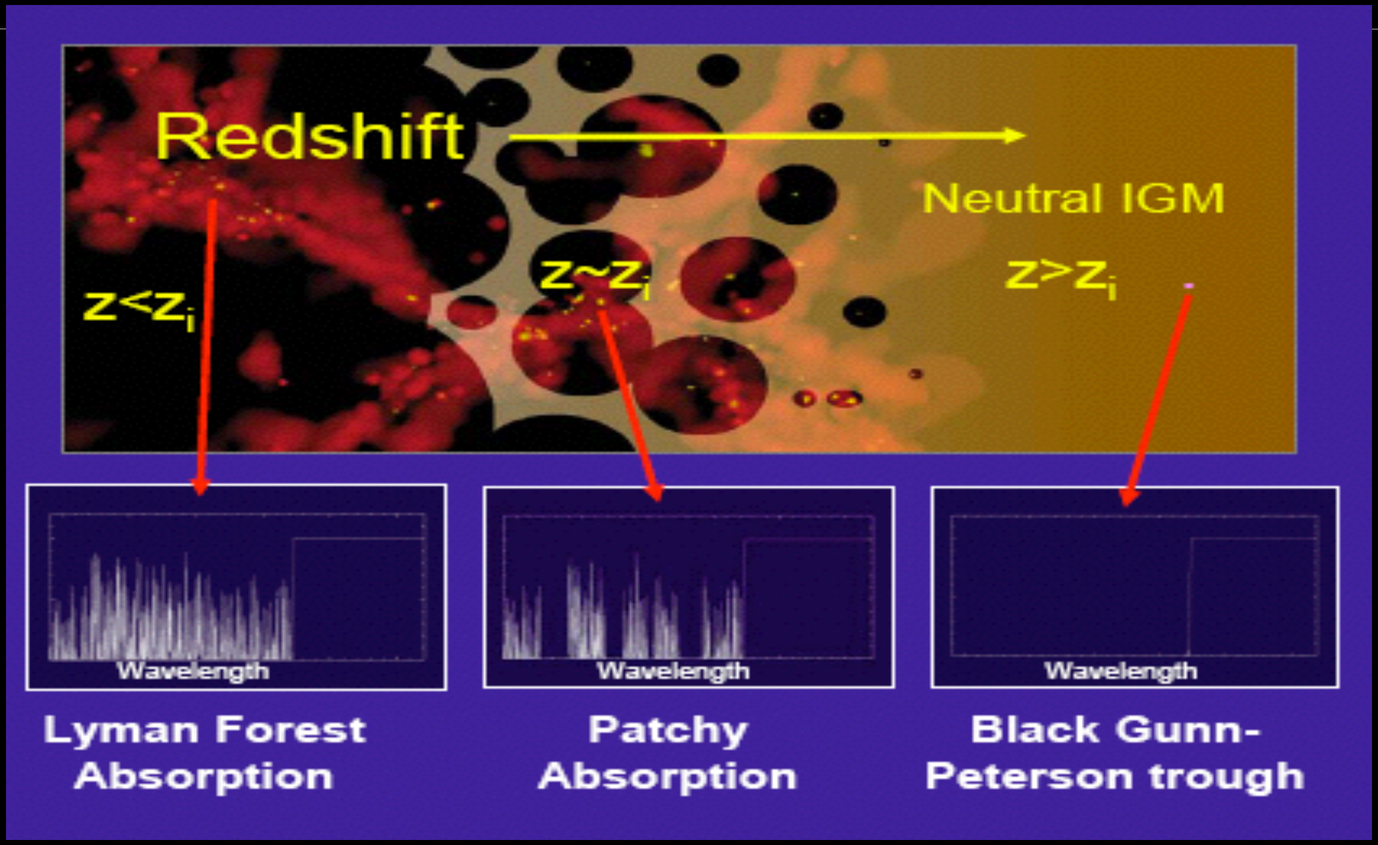


J0100 (z=6.3)
J1120 (z=7.1)
J1342 (z=7.5)
L_{Edd}
$0.1L_{Edd}$
$0.01L_{Edd}$
L_{bol} (ergs s^{-1})
M_{BH} ($M_\odot$)



Time (Gyr)
0.07
0.1
0.2
0.4
0.7
1
J1342 + 0928
$7.8 \times 10^8\ M_\odot$ at $z = 7.54$
Bañados et al. 2017
J1120 + 0641
$2.0 \times 10^9\ M_\odot$ at $z = 7.09$
Mortlock et al. 2011
J0100 + 2802
$1.2 \times 10^{10}\ M_\odot$ at $z = 6.33$
Wu et al. 2015
Other $z \sim 6$ quasars
$L_{Bol} = L_{Edd}$
0.55 dex error bar
Black hole mass ($M_\odot$)
Redshift

Gunn-Peterson Test

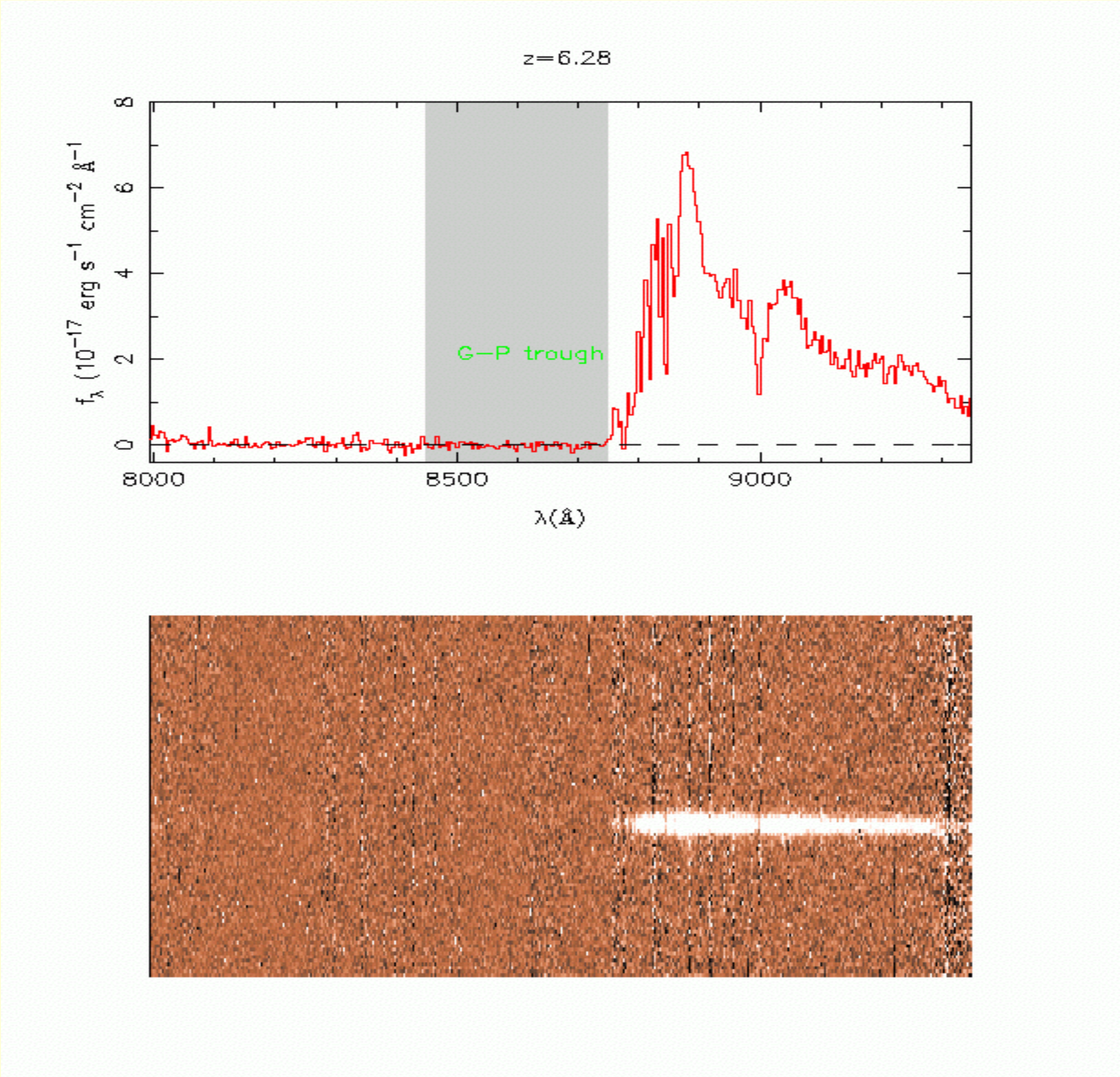


- Classic G-P (1965) effect:

$$\tau_{GP} \sim 10^5 (n_{HI} / n_H)$$

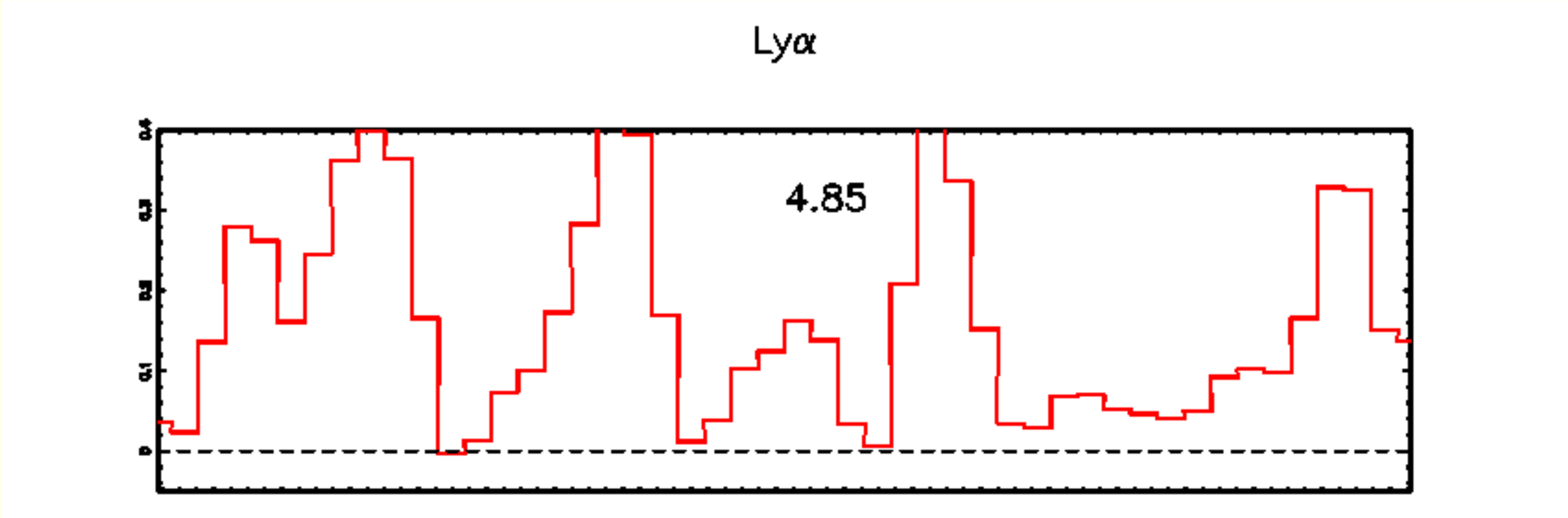
  – Saturates at low neutral fraction

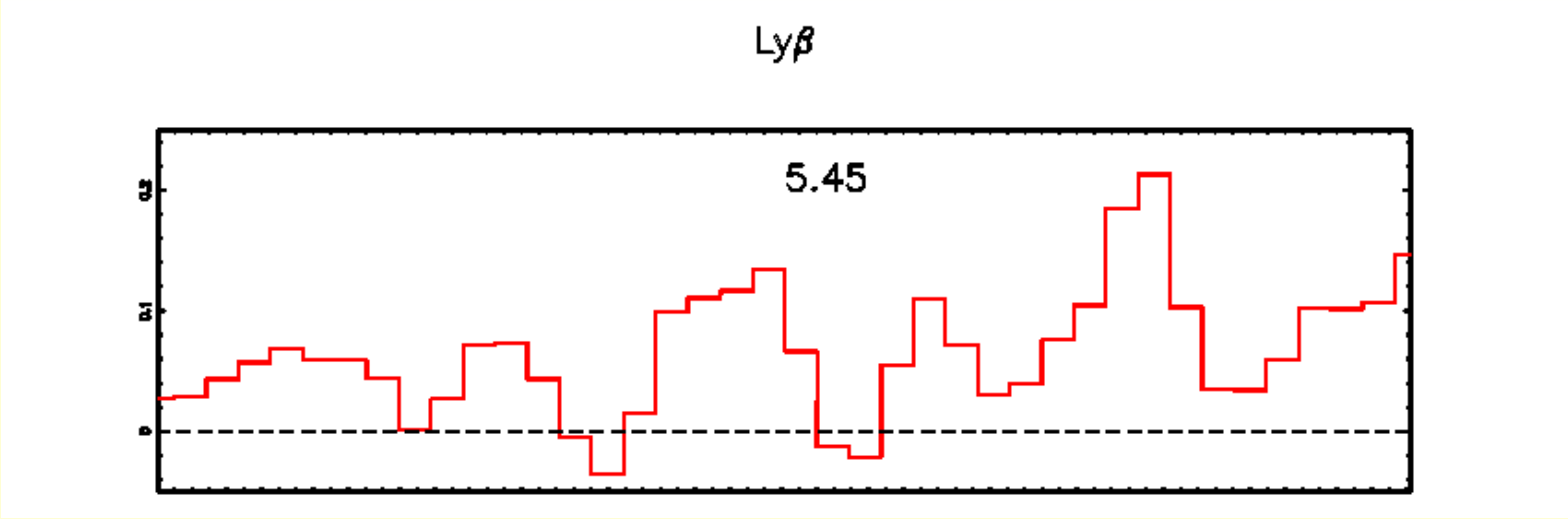
First detection of Gunn-Peterson Effect



Fan+2002

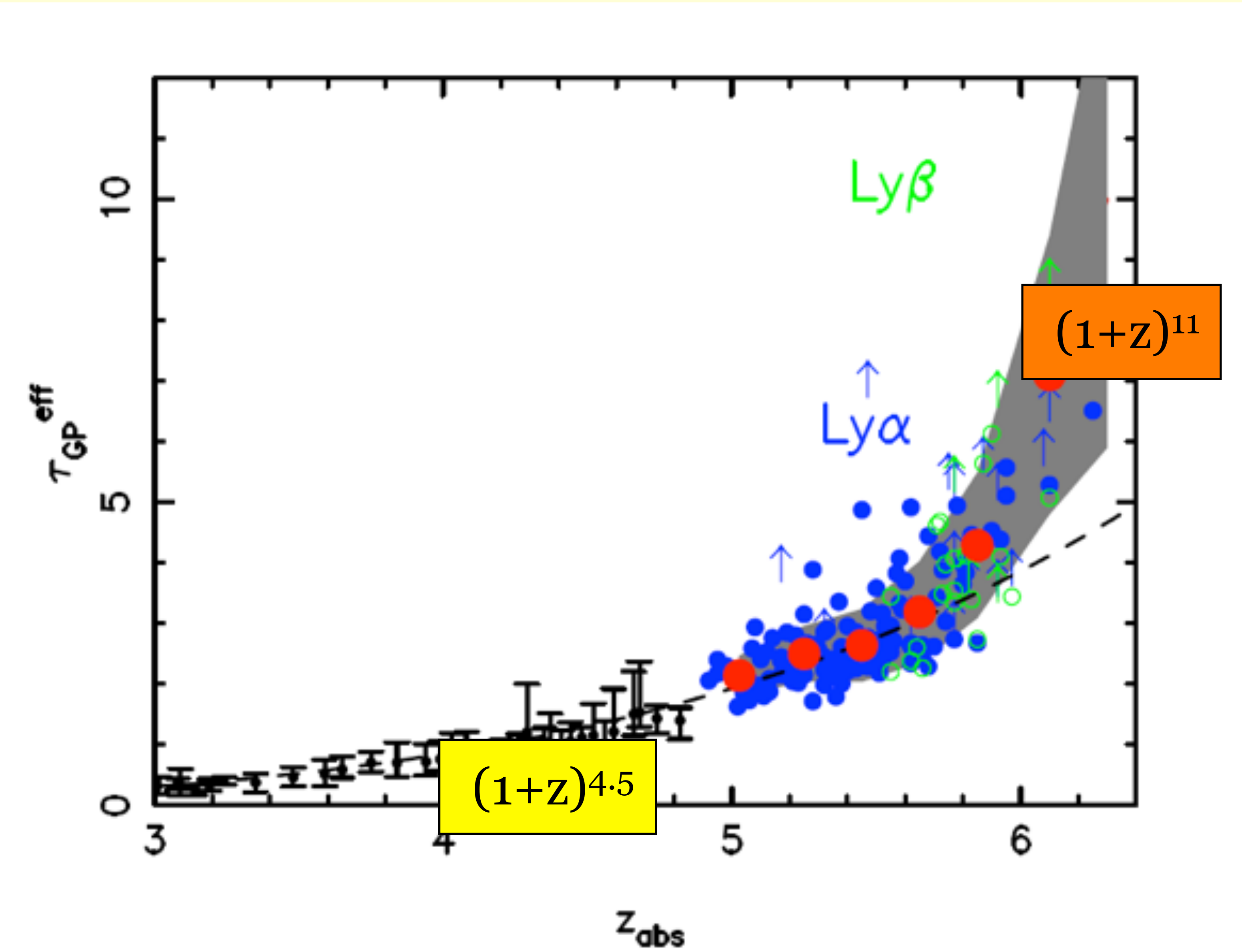
Evolution of Lyman Absorptions at z=5-6





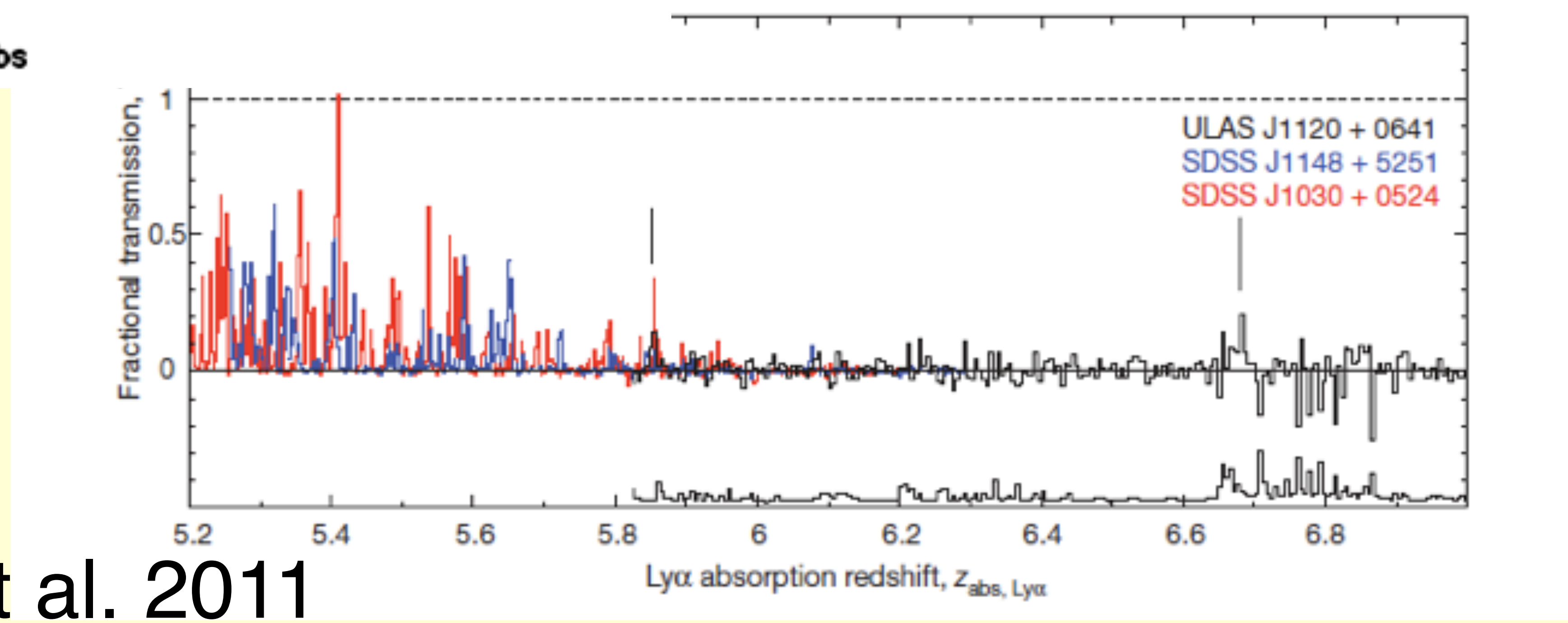
$\Delta z = 0.15$

Accelerated Evolution at z>5.7



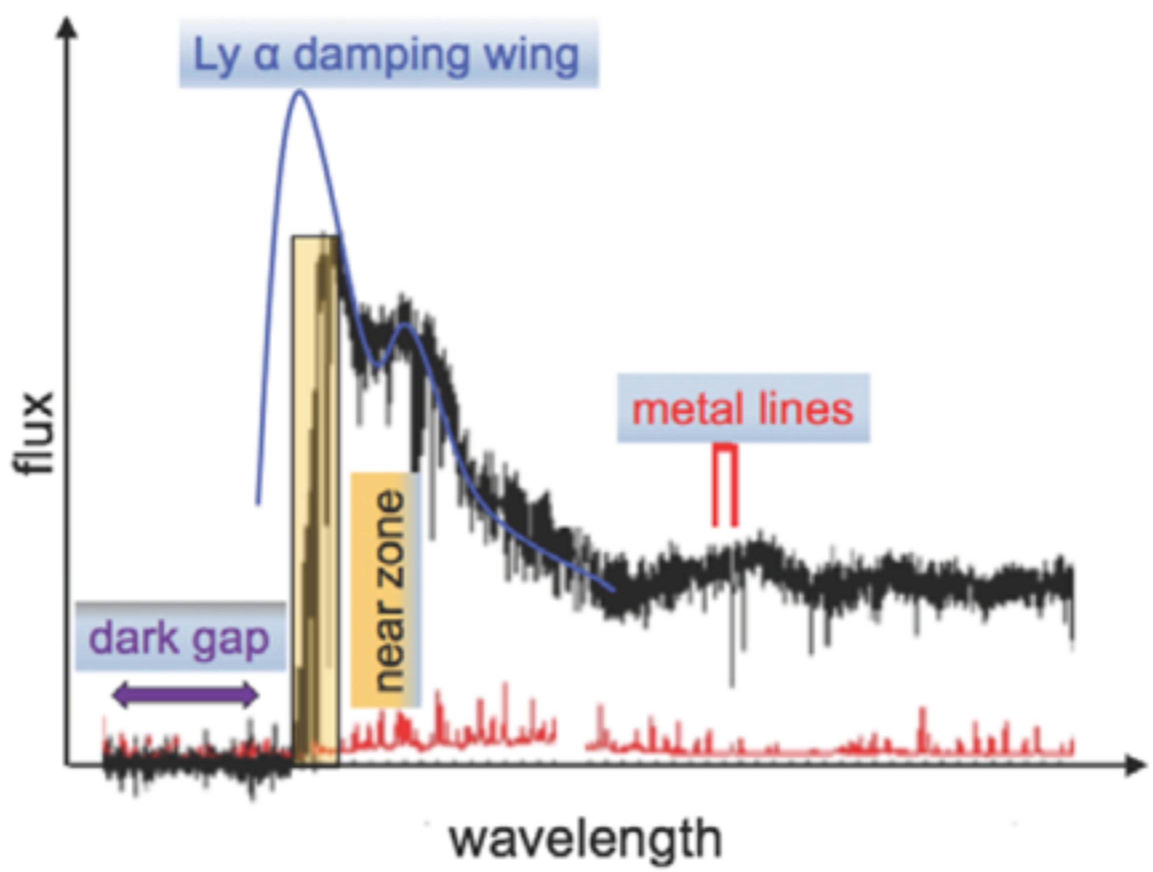
XF et al. 2006

- *Optical depth evolution accelerated*
  - z<5.7: $\tau \sim (1+z)^{4.5}$
  - z>5.7: $\tau \sim (1+z)^{>11}$
  - ***End of reionization?***



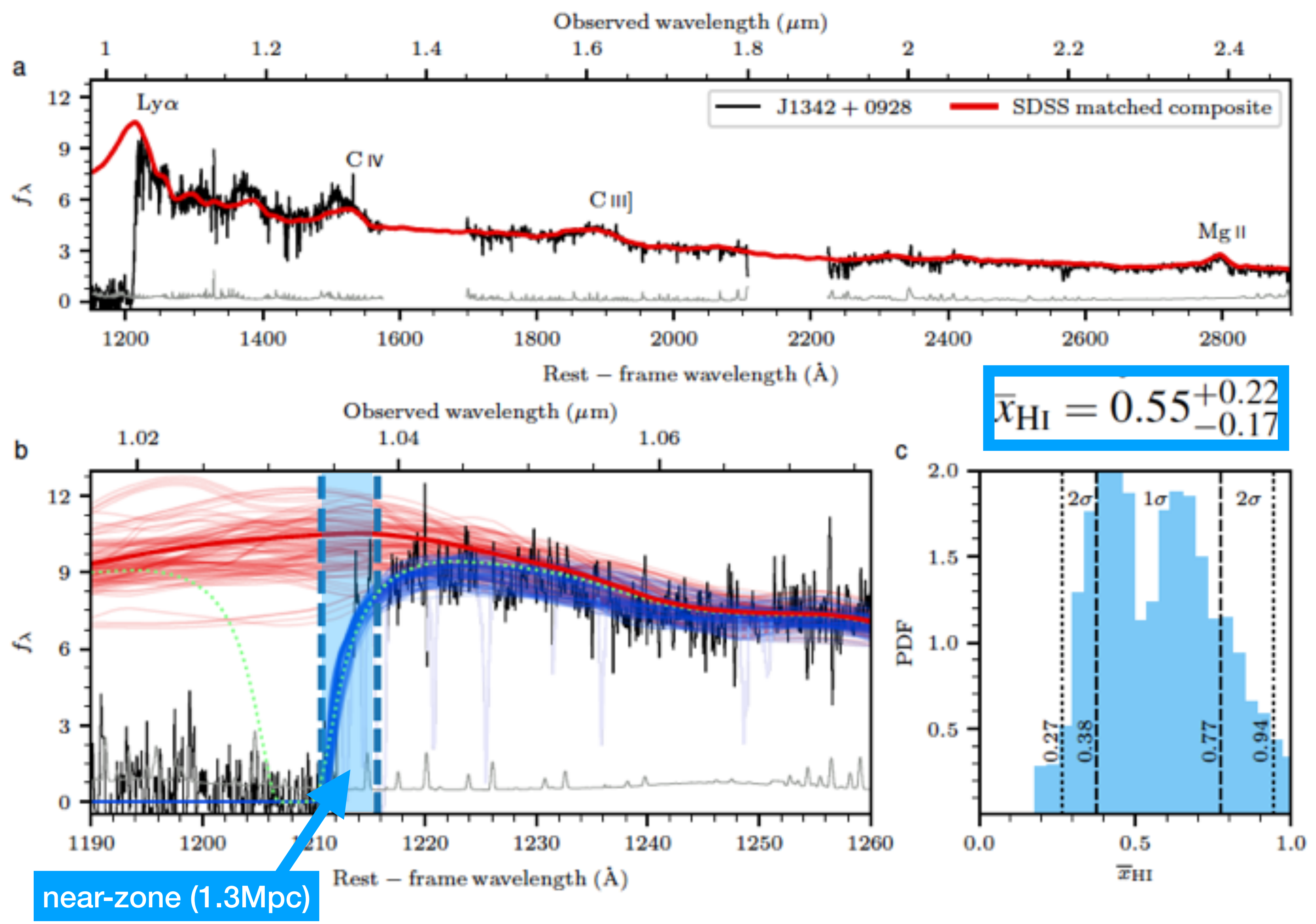
Mortlock et al. 2011

Reionization Probes with Quasar Ly α absorption



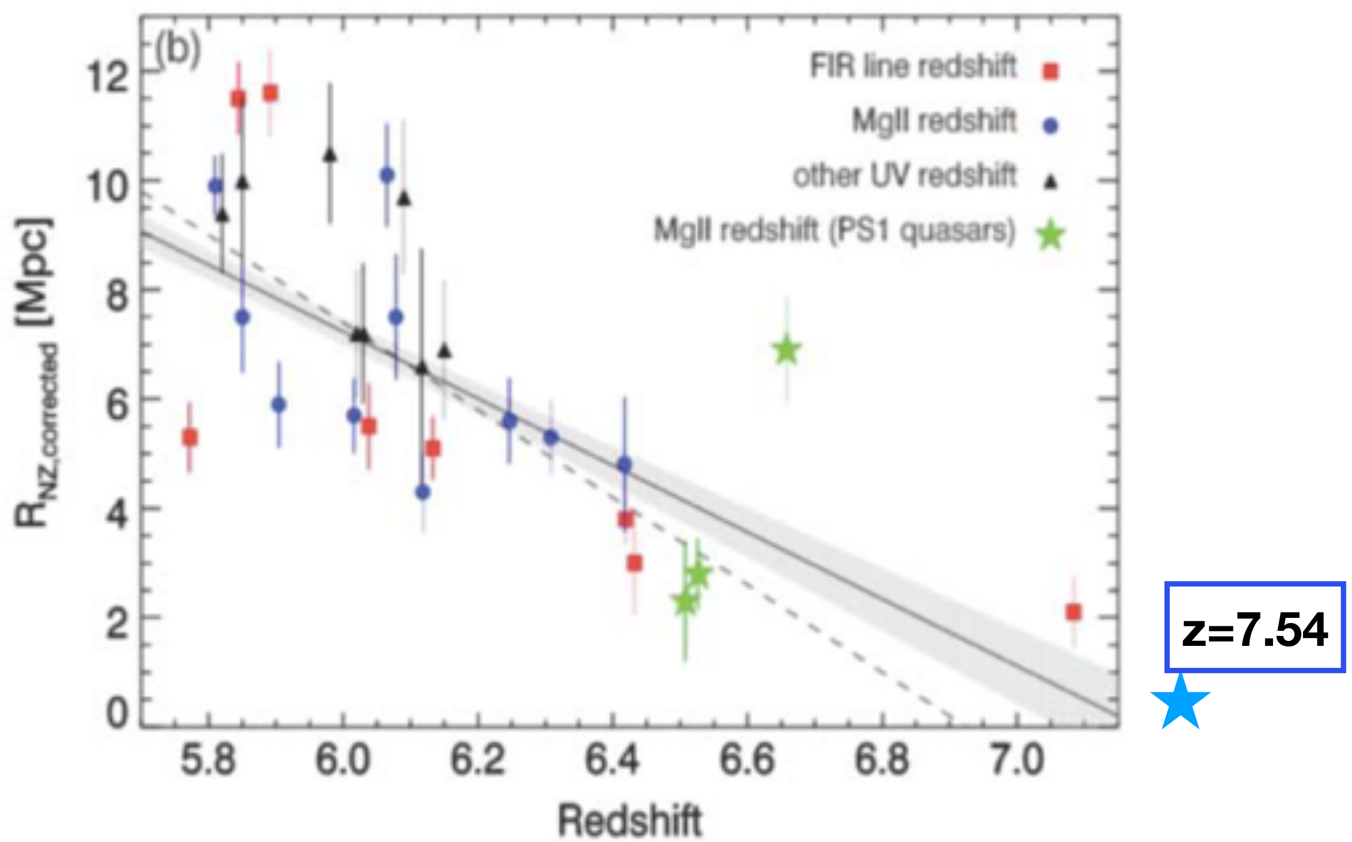
Feature	Strength	Limitation
Dark gap	Secure upper limit of neutral fraction, few assumptions	Not sensitive to high neutral fraction
Gunn-Peterson optical depth PDF	Easy to interpret, sensitive to ionizing background fluctuations	Saturates at high neutral fraction
Ly α damping wing	Sensitive to high neutral fraction	Requires accurate modeling of intrinsic quasar spectrum
Near zone size	Sensitive to high neutral fraction, can be applied to moderate S/N data	Strong dependence on quasar model and viewing angle, large scatter

Gunn-Peterson Damping Wing
in z=7.54 Quasar

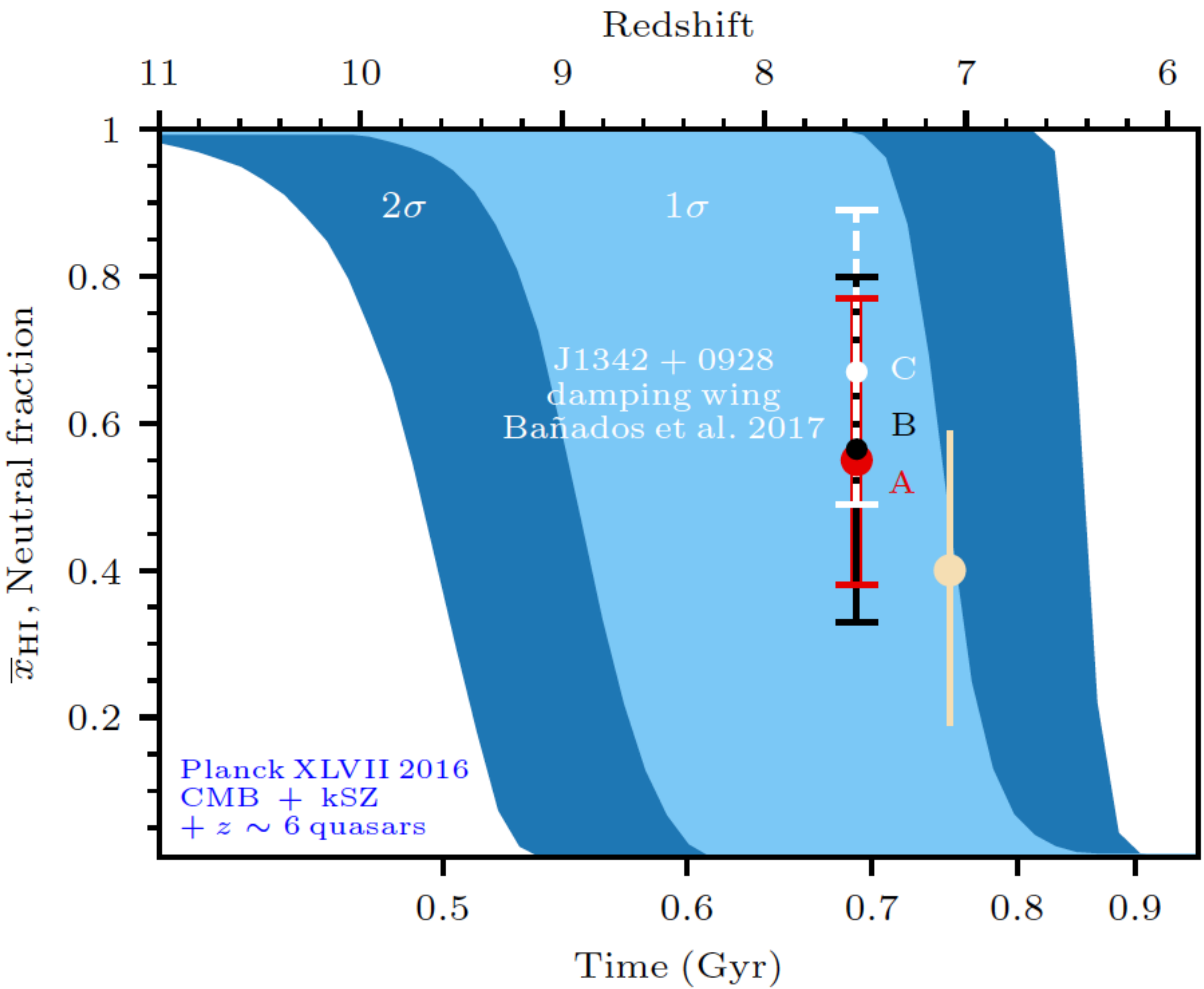


Banados+17

near-zone size measurement



Venemans+15



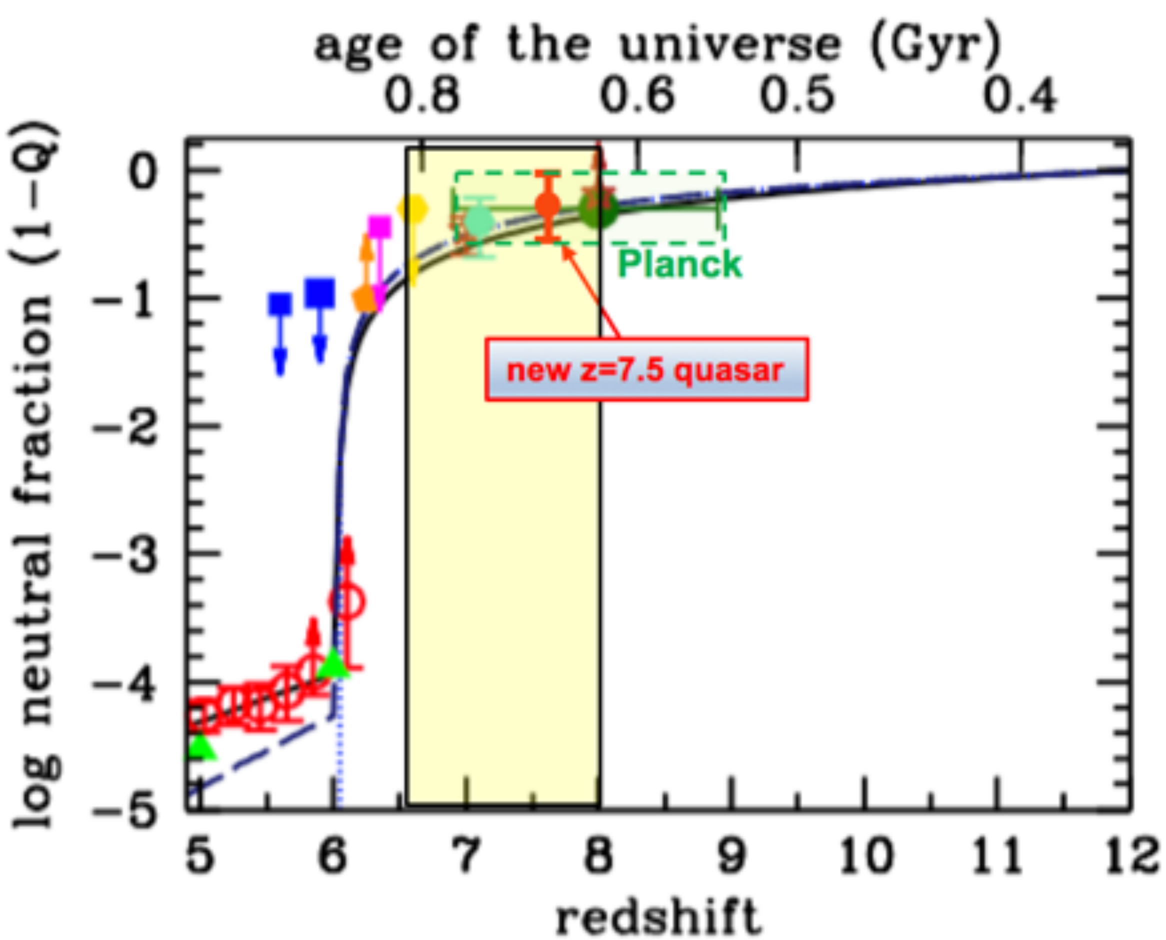
Redshift
11
10
9
8
7
6
1
0.8
0.6
0.4
0.2
$\overline{x}_{\mathrm{HI}}$, Neutral fraction
2σ
1σ
J1342 + 0928
damping wing
Bañados et al. 2017
C
B
A
Planck XLVII 2016
CMB + kSZ
+ z ∼ 6 quasars
0.5
0.6
0.7
0.8
0.9
Time (Gyr)

Summary

- Ten billion solar mass black holes at the end of reionization: direct collapse of large mass seed black holes in early universe

- Combination of deep optical, near-IR and mid-IR photometric selection allows the first systemic surveys of luminous quasars at z>=7, with a recent record-breaking discovery of a z=7.5 quasar

- Detection of Gunn-Peterson damping wings suggests a high IGM neutral fraction at z>7, and a rapid reionization at z=6-8



Madau17