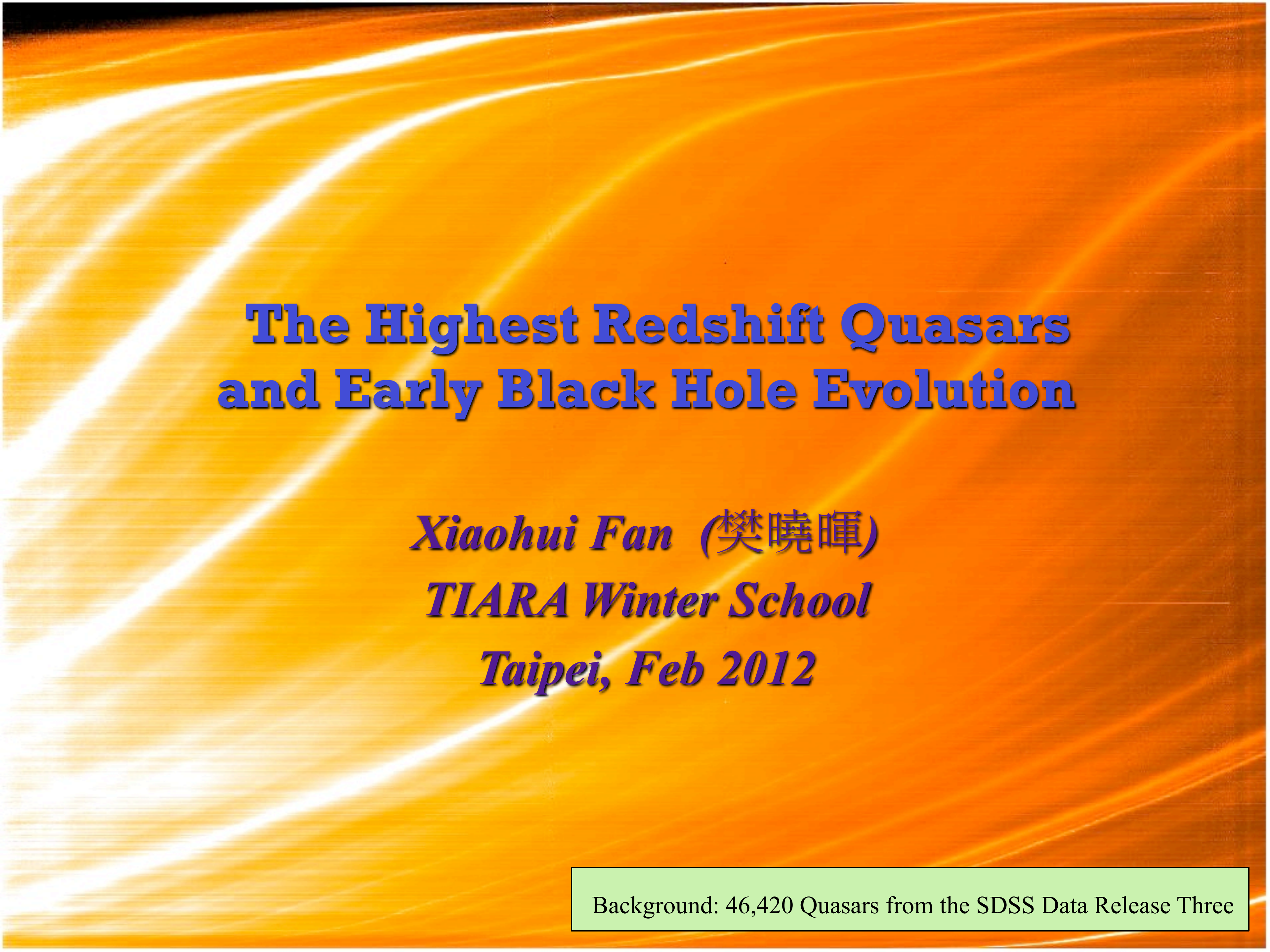


The Highest Redshift Quasars and Early Black Hole Evolution

Xiaohui Fan (樊曉暉)

TIARA Winter School

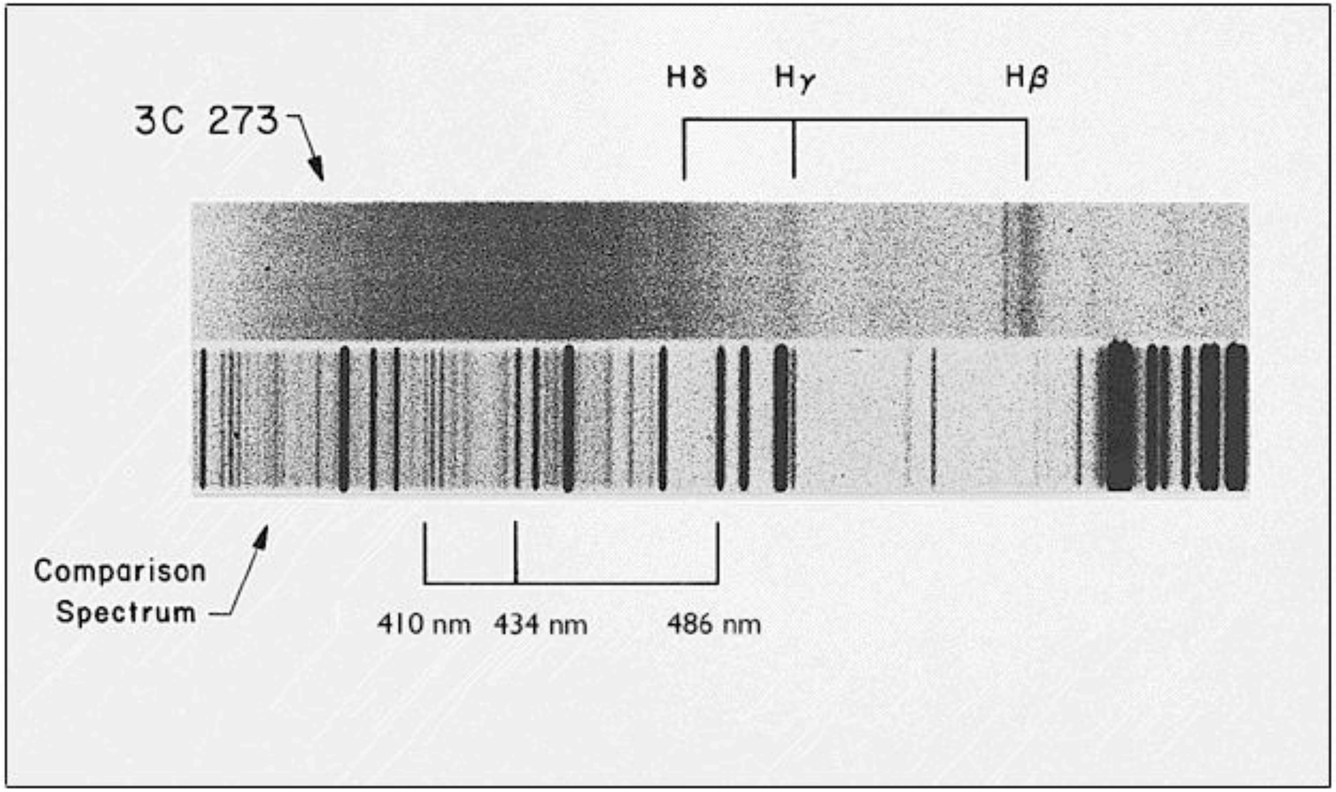
Taipei, Feb 2012

Background: 46,420 Quasars from the SDSS Data Release Three

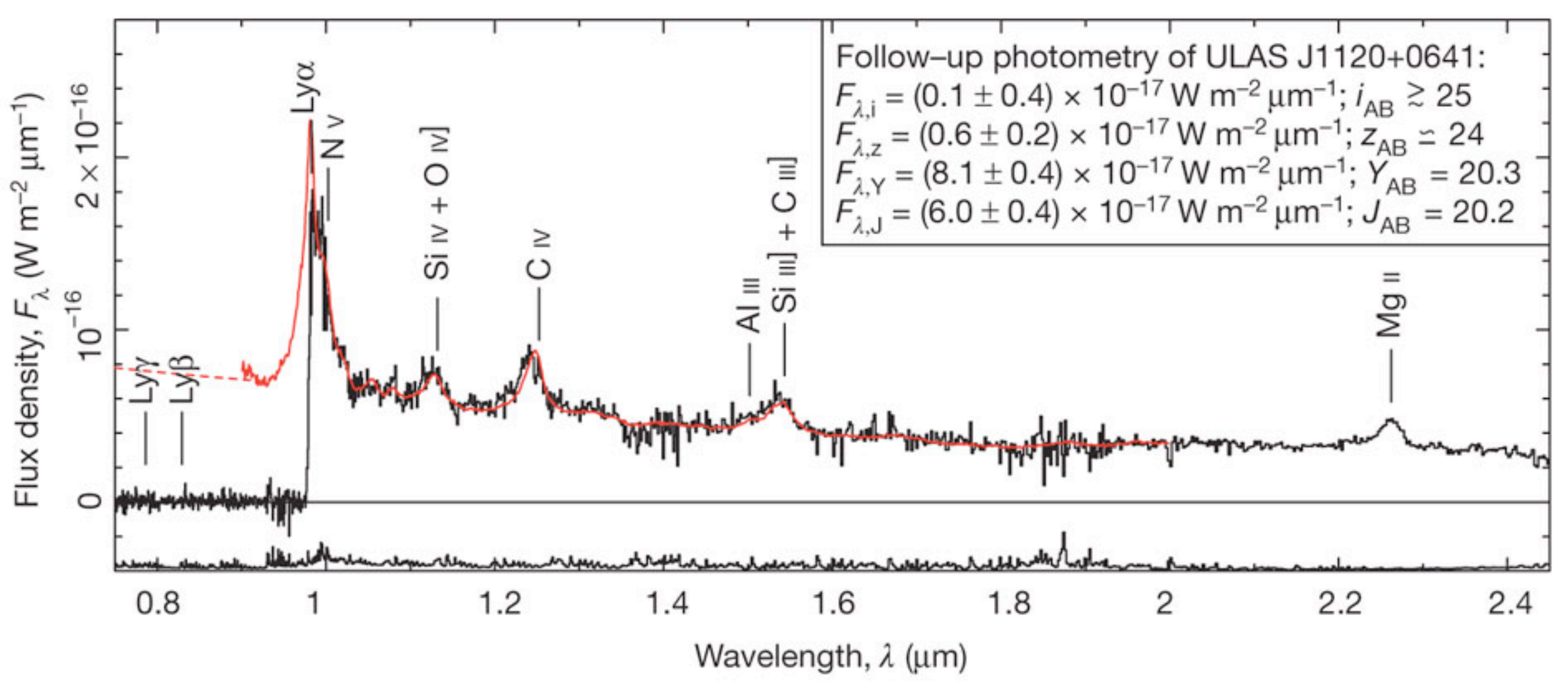

EXPLORING THE EDGE OF THE UNIVERSE
TIME
THE WEEKLY NEWSMAGAZINE
ASTRONOMER
MAARTEN SCHMIDT

1963

The First Quasar Discovered
$z=0.158$



The New Highest Redshift Quasar
z=7.085



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Goals of High-z Quasar Studies

- Accretion History of BHs
  - How do BHs grow in the Universe
- Accretion and BH Physics
  - How do BHs get fueled by the host environment and how to use constrain BH properties
- Roles of AGNs/quasars in galaxy formation
  - How do BH activities affect the host galaxy and vice versa

Summary of high-z quasar studies

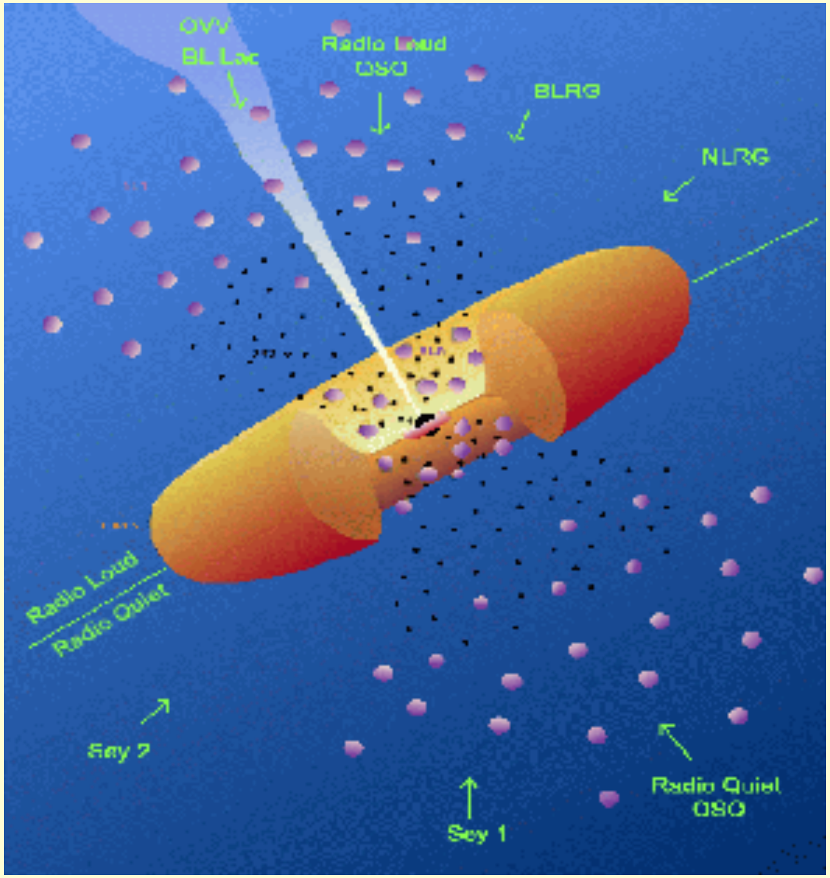
- Billion solar mass BHs at z>7
  - rapid BH growth after reionization
  - challenges to standard BH growth model
- z>6 quasars reside in dusty, metal-enriched env with intense star formation
  - early BH growth and early galaxy growth go hand-in-hand?
- z>6 quasars live in host galaxies with modest mass
  - strong evolution in M-sigma relation?

Quasar Basics

- Properties of quasars and AGNs
  - how to find quasars
- Characteristics of BH growth
  - timescale of BH growth

Challenge I: quasars are multi-wavelength, multi-scale phenomena

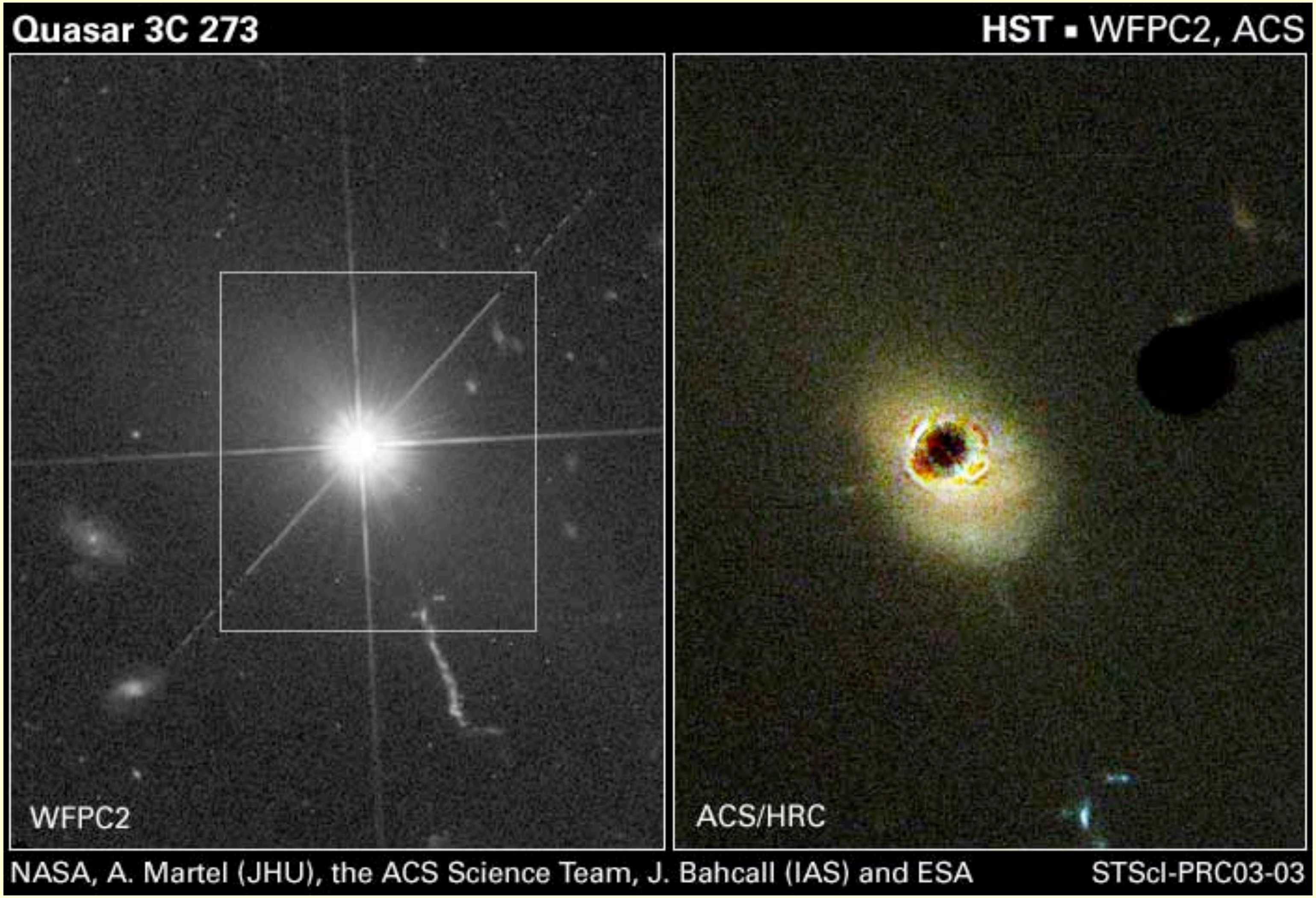
Challenge II: We do not observe the central engine



“Sometimes you can’t stick your head in the engine, so you have to examine the exhaust”

-- D. E. Osterbrock

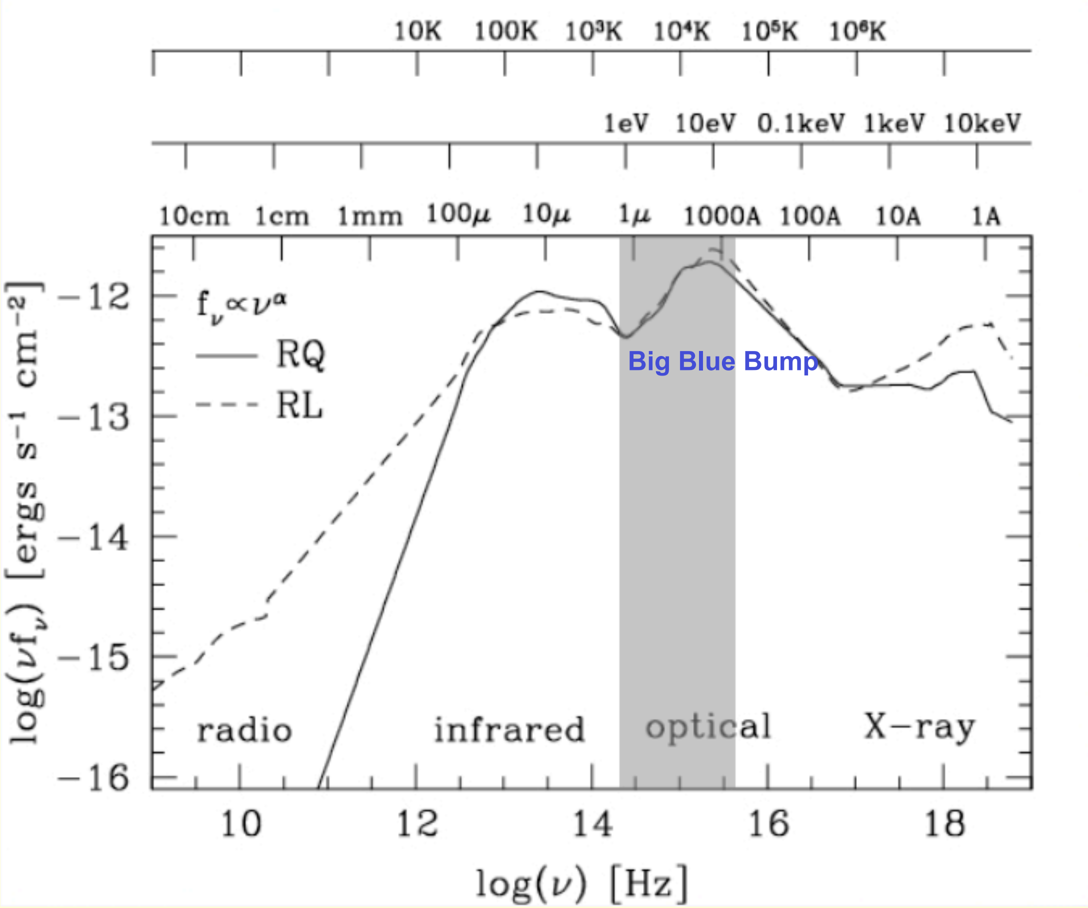
Challenge III: Quasars outshine their host galaxies by large factor



Observational Properties of AGNs

- Textbook definition
  - Small angular sizes (compact)
  - Cosmological distance
  - High luminosity?
  - Broad-band continuum emission
  - Emission Lines indicative of hard ionizing source
  - Variability
  - Polarization (subset)
- AGN surveys utilize one or more of these properties

The Spectral Energy Distribution of AGNs



- 1 micron - .2 keV: Thermal emission from optically thick accretion disk
- X-rays: Synchrotron, Inverse Compton, Hot corona + reflection
- Mm-1 micron: Dust emission
- Radio: Synchrotron (relativistic electrons in B-field)

Observational Properties of AGNs

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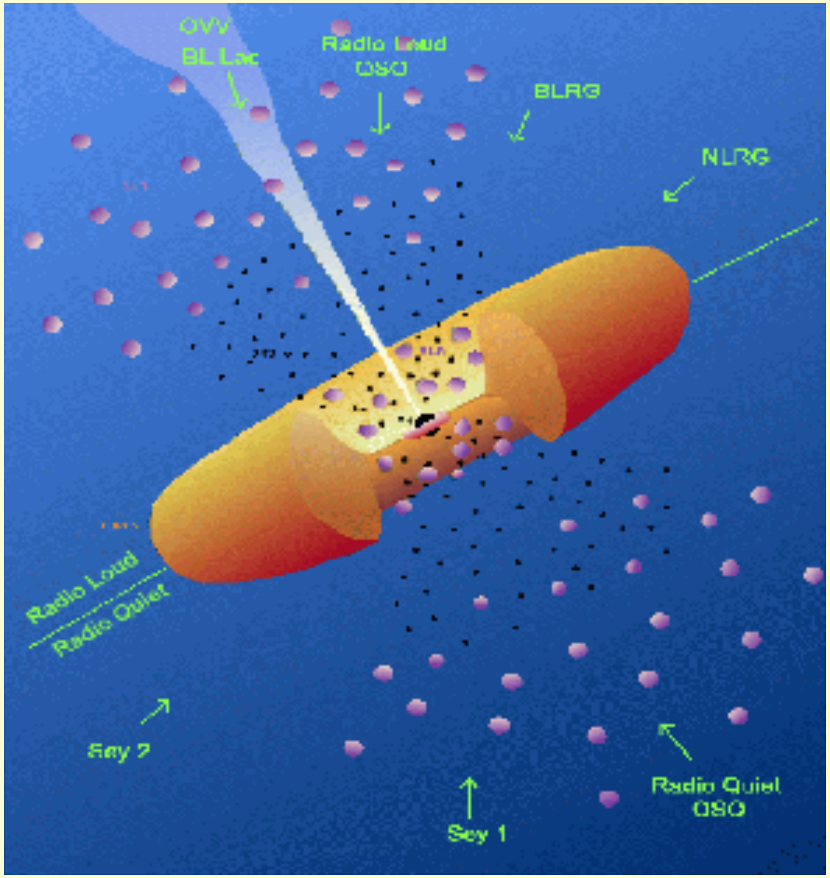
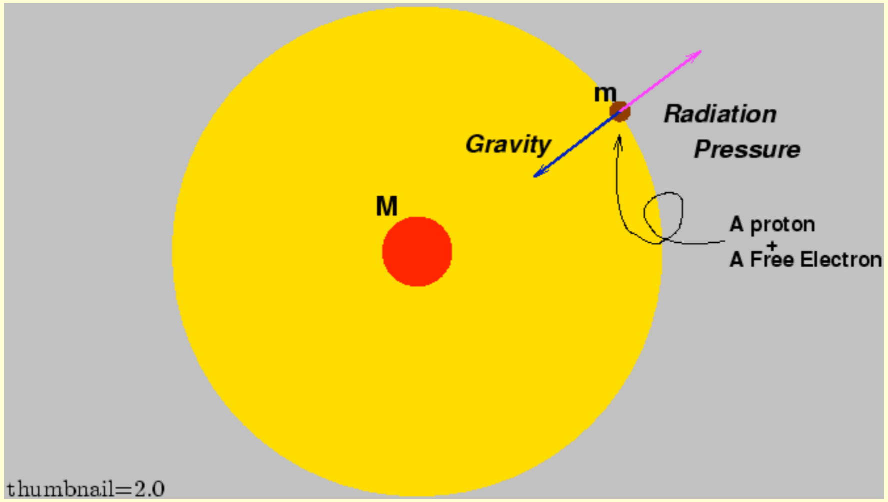
AGN Unification



Eddington Limit



$$F_{rad} \leq F_{grav},$$

$$\frac{\sigma_T L}{4\pi c r^2} \leq \frac{GMm_p}{r^2}.$$

$$L_E = \frac{4\pi GMM_p c}{\sigma_T} \sim 3 \times 10^4 \frac{M}{M_\odot} L_\odot \sim 1.26 \times 10^{38} \frac{M}{M_\odot}.$$

- quasar: L~10^44
- BH mass: 10^8 M_sun

Radiative Efficiency

- Luminosity

$$L = dE/dt = \eta \dot{M} c^2.$$

- Energy Conversion

$$L = |d(PE)/dt| = GM/R\dot{M}$$

- Schwarzschild radius

$$R_s = 2GM/c^2$$

- Last stable orbit: a few R_s

$$\eta \sim 0.1.$$

Eddington Timescale

$$L_E = \eta \dot{M} c^2,$$

$$L_E = \frac{4\pi G c m_p}{\sigma_T} M = \eta \dot{M} c^2.$$

$$\dot{M} \sim 2.2 \times 10^{-8} M \mathrm{yr}^{-1} = (\mathrm{M/t_E}),$$

$$M = M_0 \exp(t/t_E).$$

Eddington timescale = 4.4×10^7 years if η is 0.1

Virial Mass Estimates

$$M_{BH} = v^2 R_{BLR}/G$$

- Reverberation Mapping: $R_{BLR}=c\tau$, v_{BLR}
- **Radius – Luminosity Relation:** **$R \sim L^{\beta}$**
- Scaling Relationships:

$$M_{BH} \propto FWHM^2 \; L^{\beta}$$

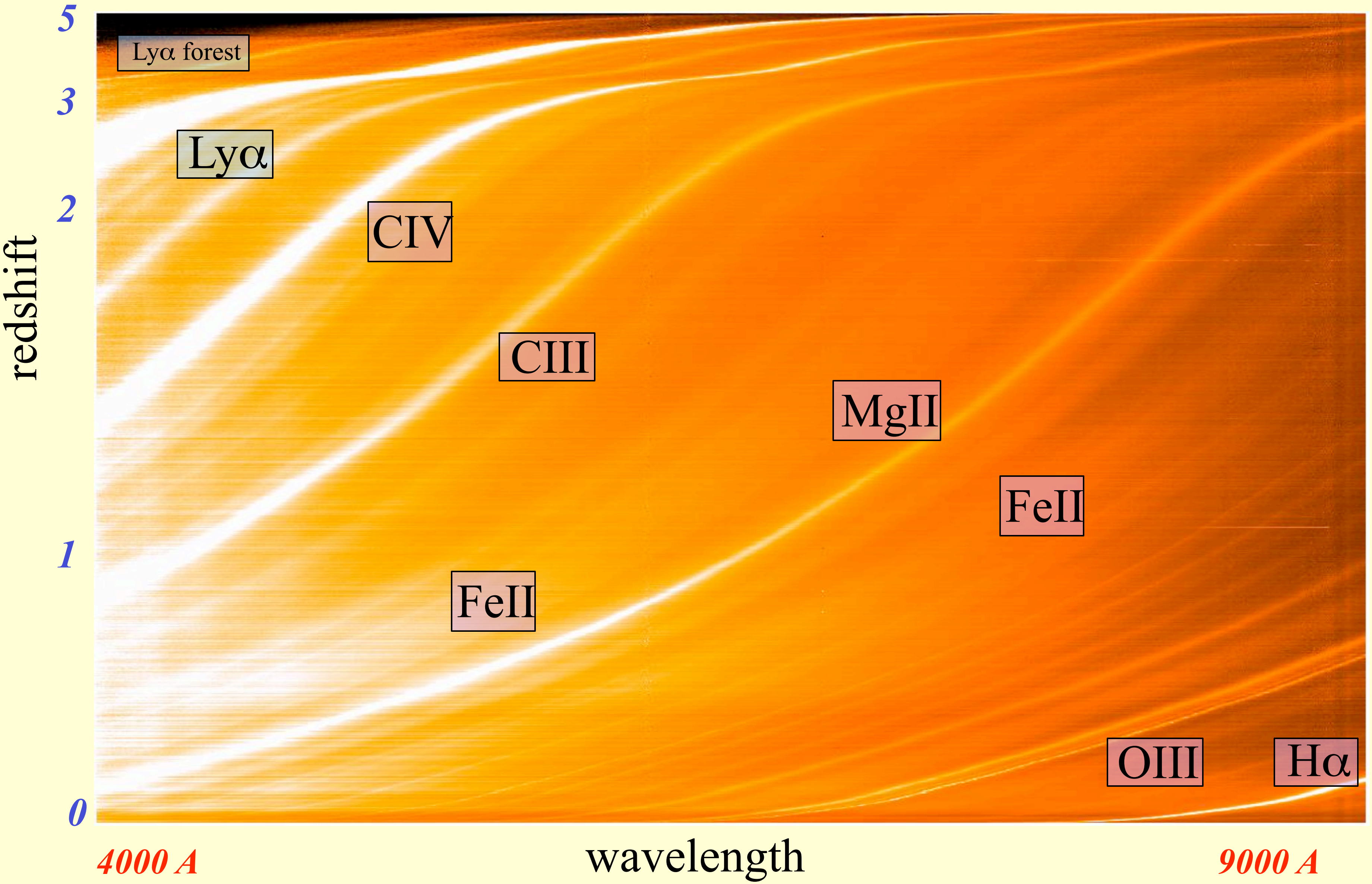
  - **Single epoch spectroscopy sufficient**
  - **But what is β?**
    - **Photoionization predicts: $R \sim L^{1/2}$**

Typical Quasar

- Luminosity 10^44 erg/s
- BH mass 10^8 M_sun
- Accreting : few M_sun per year
- Mass doubling time: few tens of million years

- High-redshift?

46,420 Quasars from the SDSS Data Release Three



Putting things together: Soltan's argument

- Soltan's argument: QSO luminosity function $\Psi(L,t)$ traces the accretion history of local remnant BHs (Soltan 1982), if BH grows radiatively

$$\int_0^\infty M n_M(M,t_0)\,dM = \int_0^{t_0} \mathrm{d}t \int_0^\infty \mathrm{d}L \, \frac{(1-\varepsilon)L_{\mathrm{bol}}}{\varepsilon c^2} \psi(L,t);$$

local accreted

$n_M(M,t_0)$: local BH mass function,

$\psi(L,t)$: QSO luminosity function,

ε : efficiency, $\dot{M} = \frac{(1-\varepsilon)L_{\mathrm{bol}}}{\varepsilon c^2}$.

Total mass density accreted = total local BH mass density

New estimates of BH mass densities

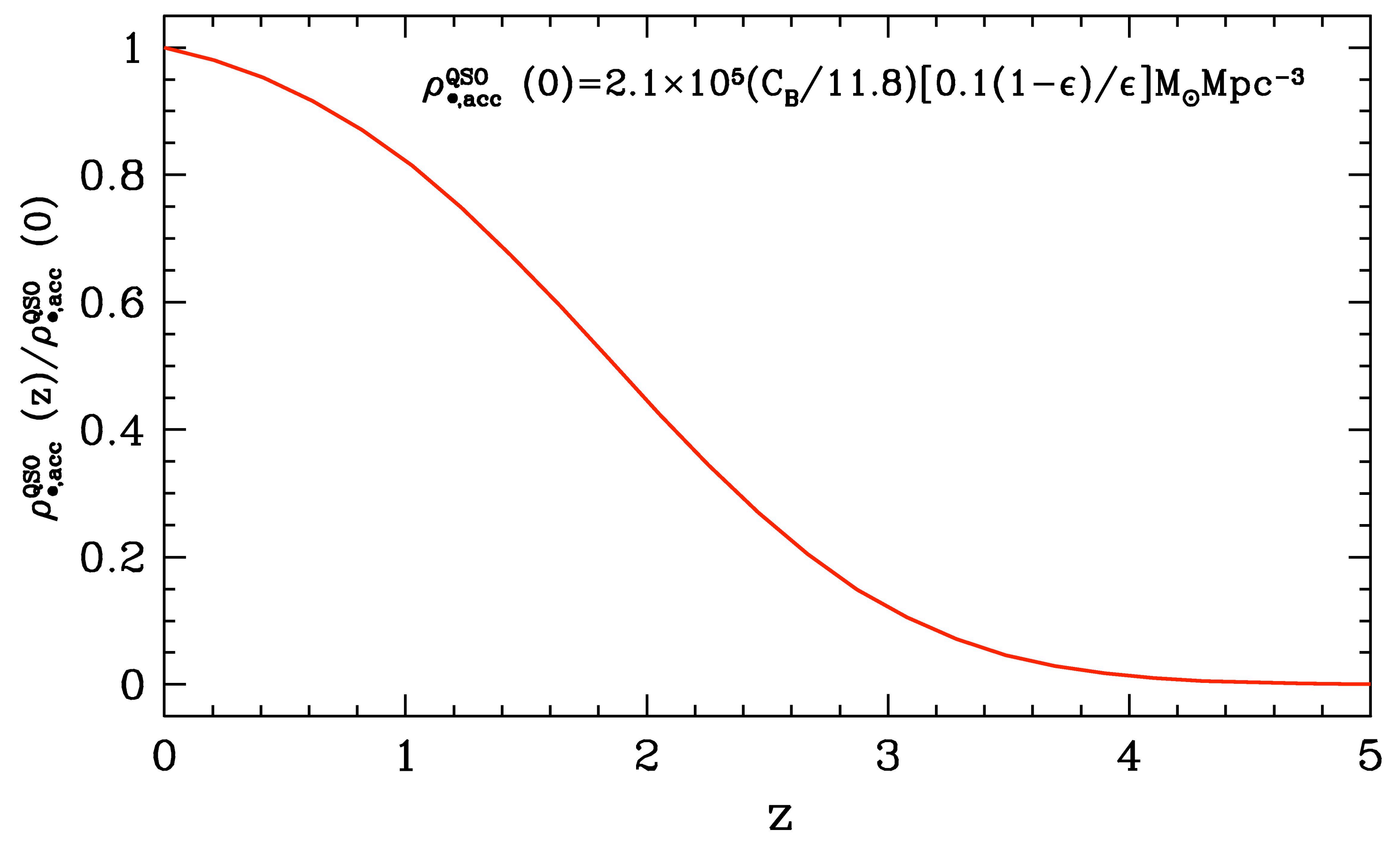
- Total local BH mass density:
  - local BH mass function $n_M(M,t_0)$:
    - SDSS early-type galaxy sample $n_\sigma(\sigma,t_0)$ (Bernardi et al. 2001)
    - the tight $M_\bullet$–σ relation (Tremaine et al. 2002)
  - $\rho_{\bullet,\mathrm{local}}=(2.5\pm0.4)\times10^5\ M_\odot/\mathrm{Mpc}^3$ (h=0.65) (Yu & Tremaine 2002)

- BH mass density accreted due to optically bright QSO phases:
  - $\Psi(L,t)$: 2dF QSO Redshift survey (Boyle et al. 2000)
  - $\rho_{\bullet,\mathrm{acc}}=2.1\times10^5[0.1(1-\varepsilon)/\varepsilon]\ M_\odot/\mathrm{Mpc}^3$ (Yu & Tremaine 2002)

$$\rho_{\bullet,\mathrm{local}} \approx \rho_{\bullet,\mathrm{acc}} \quad \text{if} \quad \varepsilon \approx 0.1$$

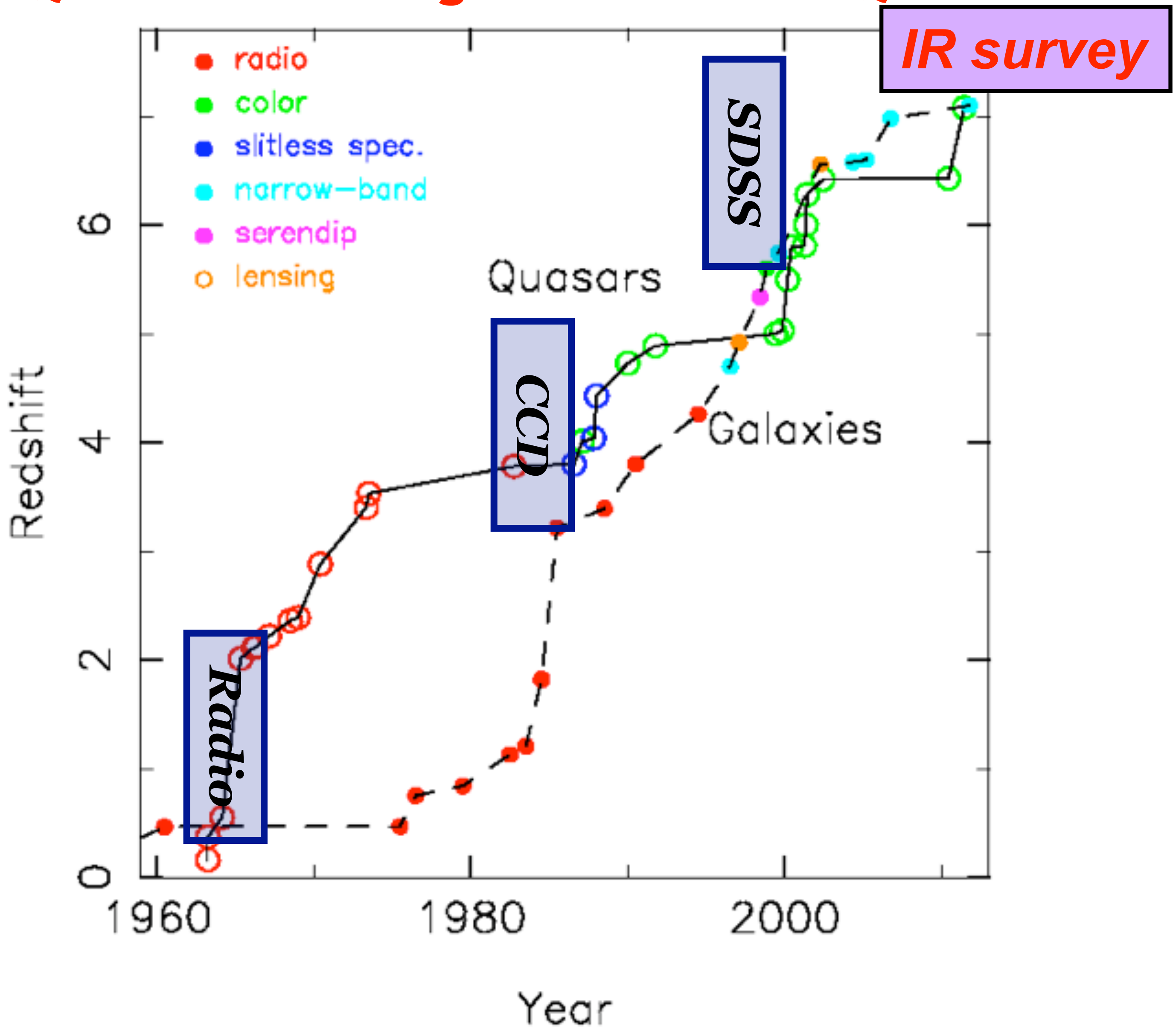
- Bright quasar phase can account for most of the BH mass growth; low efficiency accretion and obscured AGN not very important

The history of BH mass density accreted



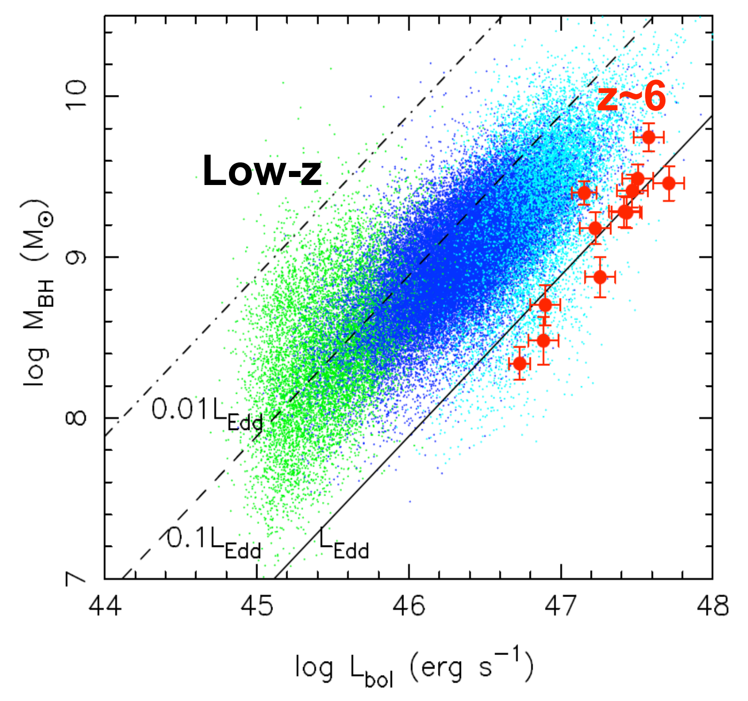
Yu and Tremaine 2002

Quest to the Highest Redshift Quasars



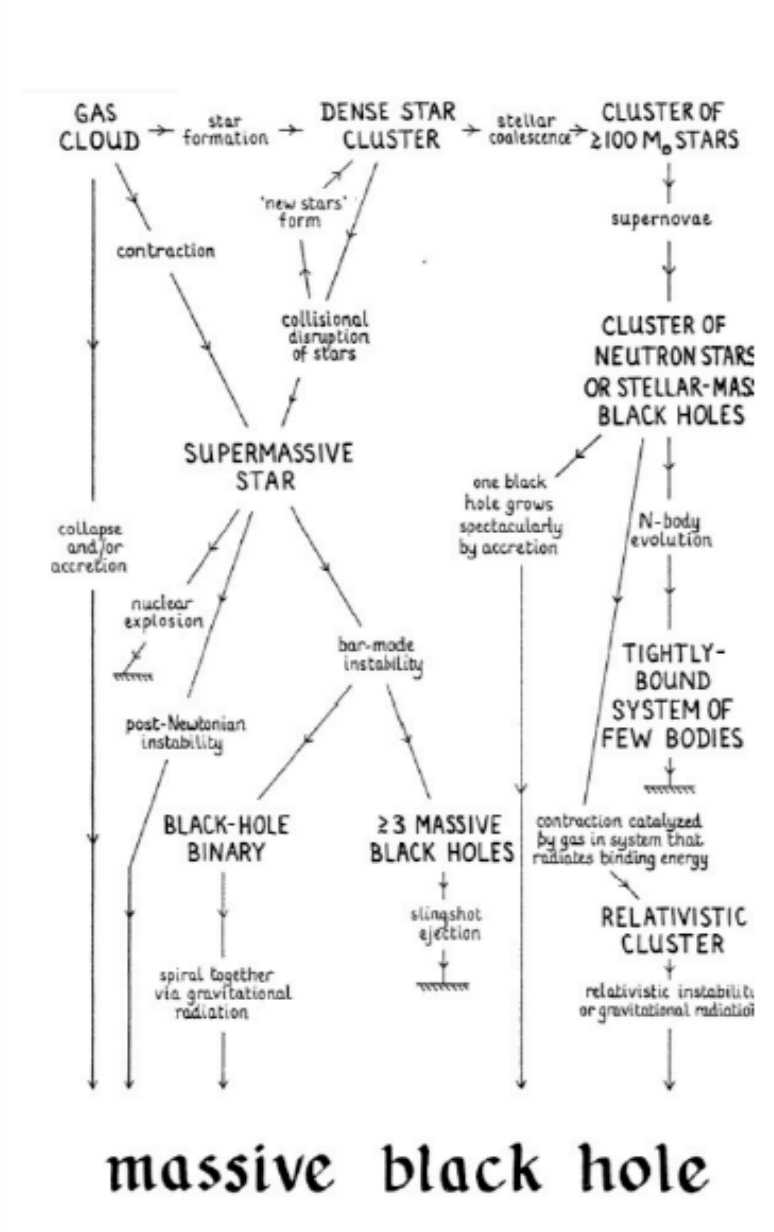
Quasar Evolution at z~6

- Black hole mass measurements
  - ***M_{BH}~$10^{9\text{-}10}$ M_{sun}***
  - $M_{halo} \sim 10^{12\text{-}13}$ M_{sun}
  - rare, 5-6 sigma peaks at z~6 (density of 1 per $\mathrm{Gpc}^{3)}$
- *Quasars accreting at maximum rate*
  - *Quasar luminosity consistent with Eddington limit*
  - *How to form these BHs???*

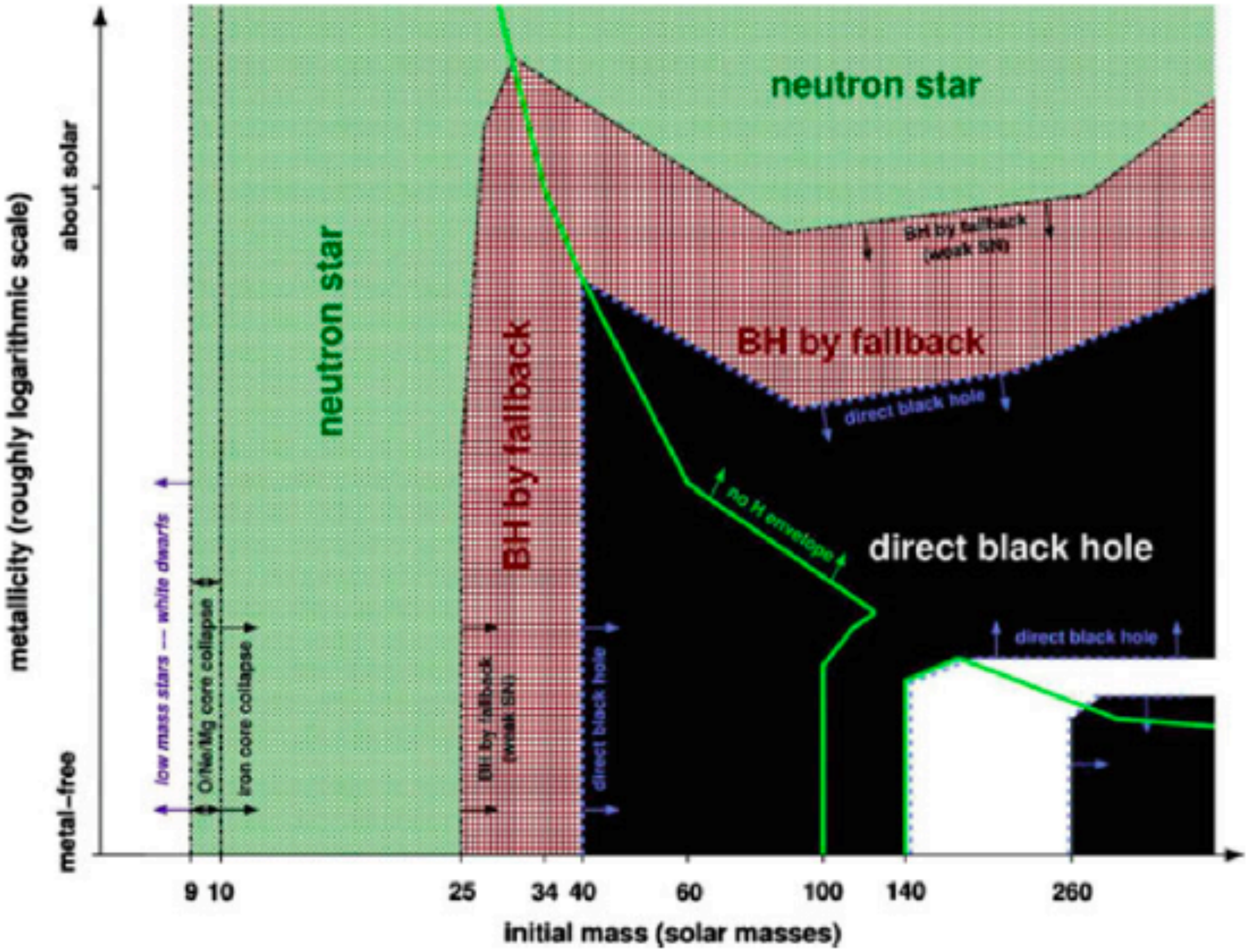


Fan et al. 2006, 2010

BH growth

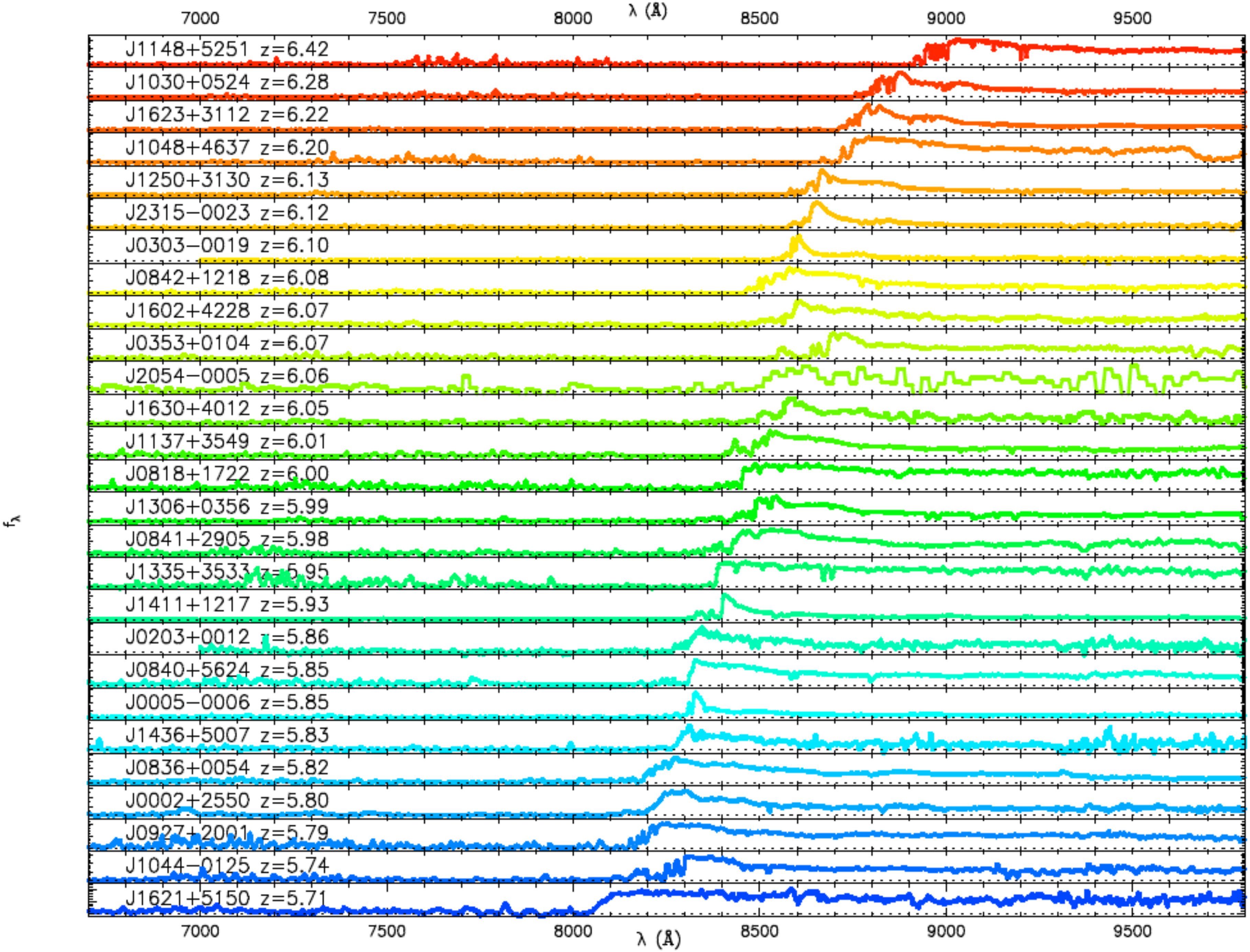

GAS CLOUD
star formation
DENSE STAR CLUSTER
stellar coalescence
CLUSTER OF ≥100 M☉ STARS
'new stars' form
contraction
supernovae
collisional disruption of stars
CLUSTER OF NEUTRON STARS OR STELLAR-MAS BLACK HOLES
SUPERMASSIVE STAR
one black hole grows spectacularly by accretion
N-body evolution
collapse and/or accretion
nuclear explosion
bar-mode instability
TIGHTLY-BOUND SYSTEM OF FEW BODIES
post-Newtonian instability
BLACK-HOLE BINARY
≥3 MASSIVE BLACK HOLES
contraction catalyzed by gas in system that radiates binding energy
slingshot ejection
RELATIVISTIC CLUSTER
spiral together via gravitational radiation
relativistic instabilit or gravitational radiatio
massive black hole

First BH Seeds

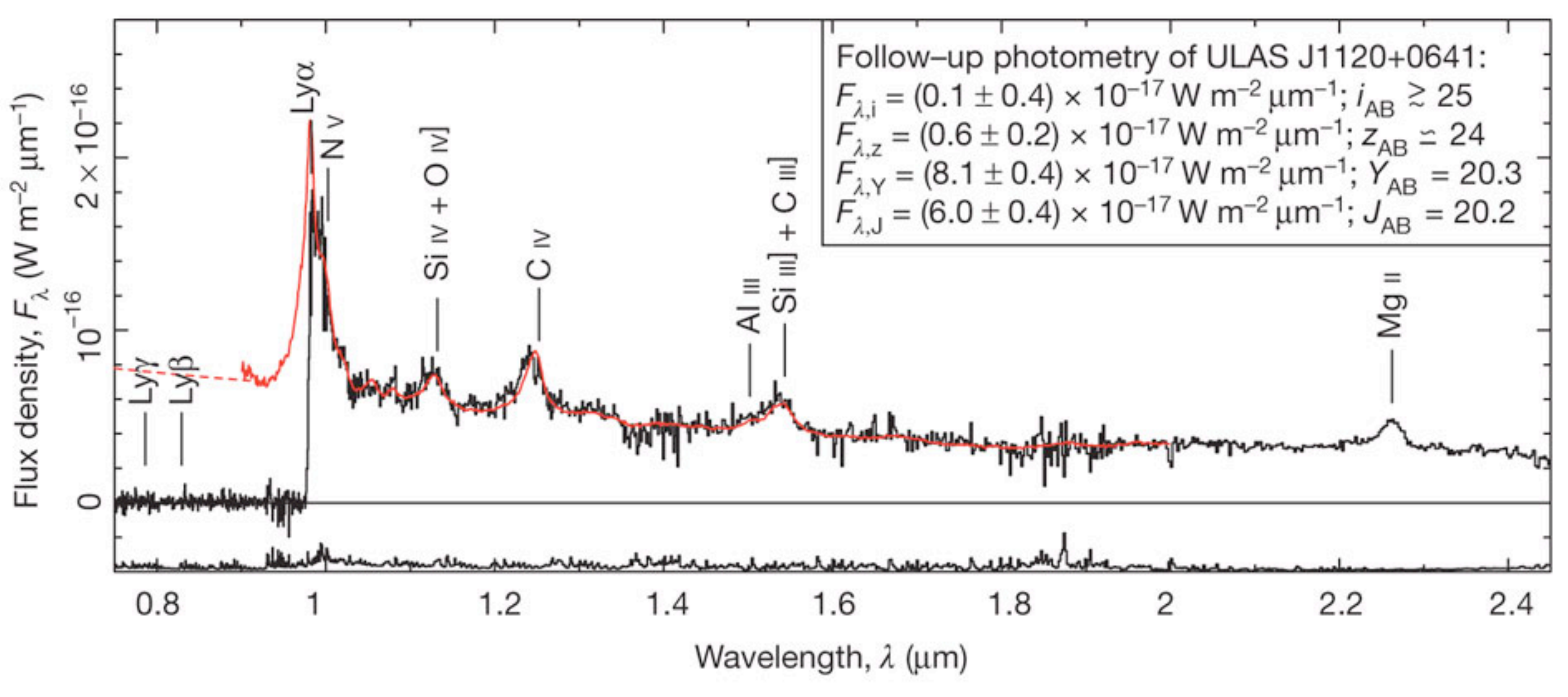


Puzzle 1:
Are there luminous quasars at z>>7

- Black Holes do not grow arbitrarily fast
  - Accretion onto BHs dicitated by Eddington Limit
  - E-folding time of **maximum** supermassive BH growth: 40 Myr
  - At z=7: age of the universe: 800 Myr = **maximum** 20 e-folding
- Billion solar mass BH at z>7
  - Non-stop, maximum accretion from 100 solar mass BHs at z=15 (collapse of first stars in the Universe)
  - **Theoretically difficult for formation of z>7 billion solar mass BHs**
  - What if we find them:
    - Direct collapse of "intermediate" mass BHs?
    - More efficient accretion model "super-Eddington"?


λ (Å)
7000
7500
8000
8500
9000
9500
J1148+5251 z=6.42
J1030+0524 z=6.28
J1623+3112 z=6.22
J1048+4637 z=6.20
J1250+3130 z=6.13
J2315−0023 z=6.12
J0303−0019 z=6.10
J0842+1218 z=6.08
J1602+4228 z=6.07
J0353+0104 z=6.07
J2054−0005 z=6.06
J1630+4012 z=6.05
J1137+3549 z=6.01
J0818+1722 z=6.00
J1306+0356 z=5.99
J0841+2905 z=5.98
J1335+3533 z=5.95
J1411+1217 z=5.93
J0203+0012 z=5.86
J0840+5624 z=5.85
J0005−0006 z=5.85
J1436+5007 z=5.83
J0836+0054 z=5.82
J0002+2550 z=5.80
J0927+2001 z=5.79
J1044−0125 z=5.74
J1621+5150 z=5.71
f_λ
7000
7500
8000
8500
9000
9500
λ (Å)

The Highest Redshift Quasar



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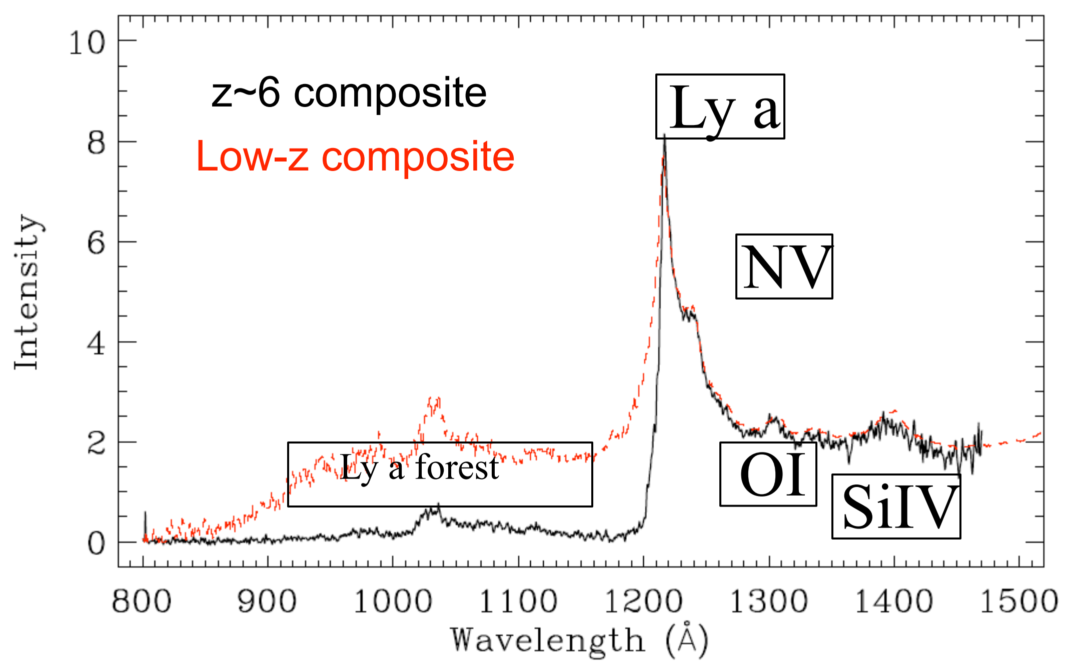
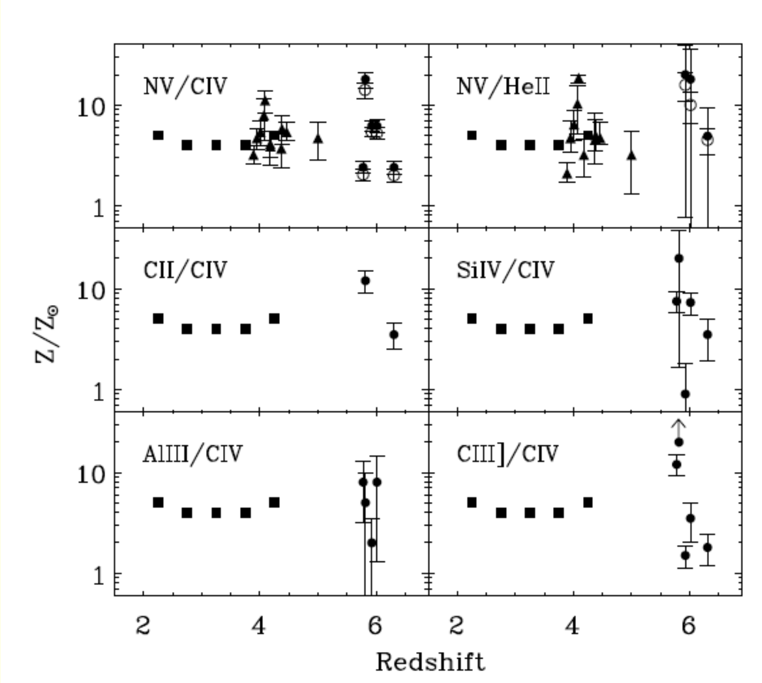
Puzzle 2: non-evolution of quasar (black hole) emission



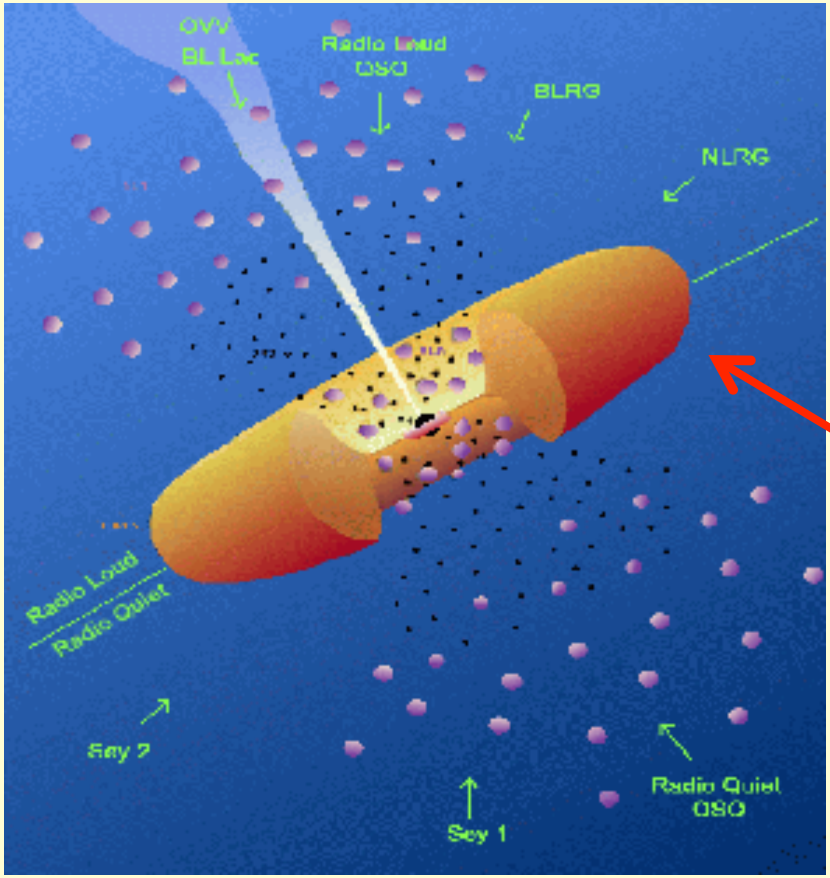
XF et al. 2010



Jiang, XF et al. 2008

- Rapid chemical enrichment in quasar vicinity
- Quasar env has supersolar metallicity : no metallicity evolution
- High-z quasars are ***old,* not yet first quasars, and live in metal enriched env similar to centers of massive galaxies**

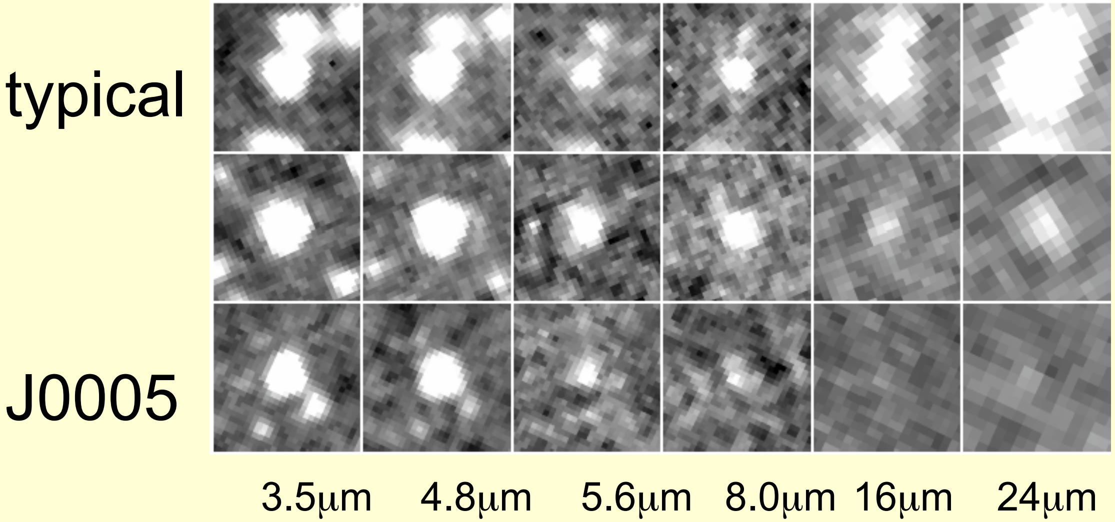
When did the first quasar form?



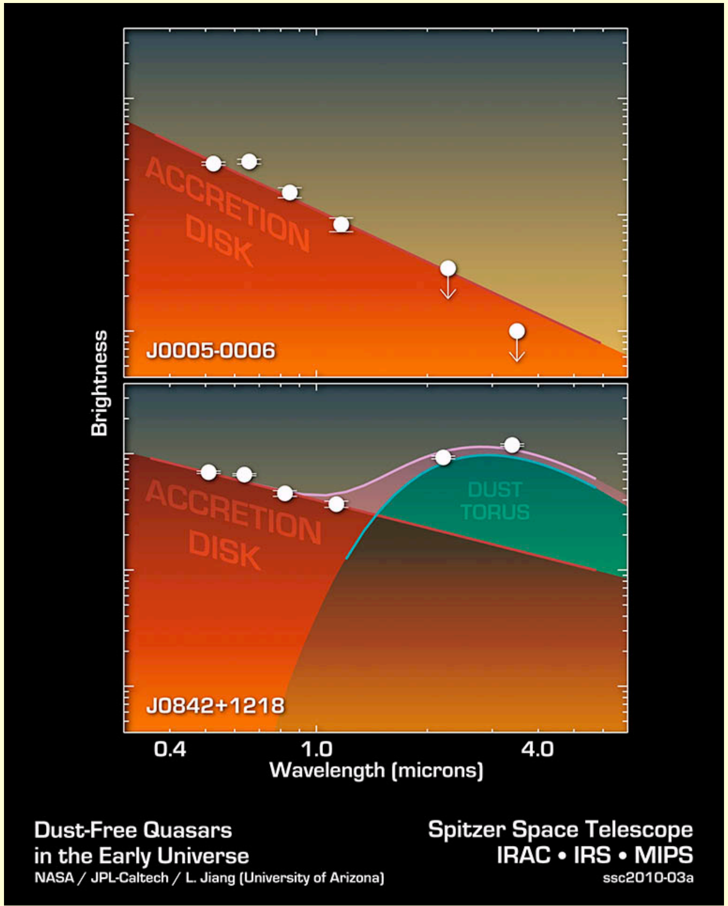
Dust: emitting in infrared

radiation from X-ray to radio as a result of black hole accretion and growth

Disappearance of Dust Torus at z~6?

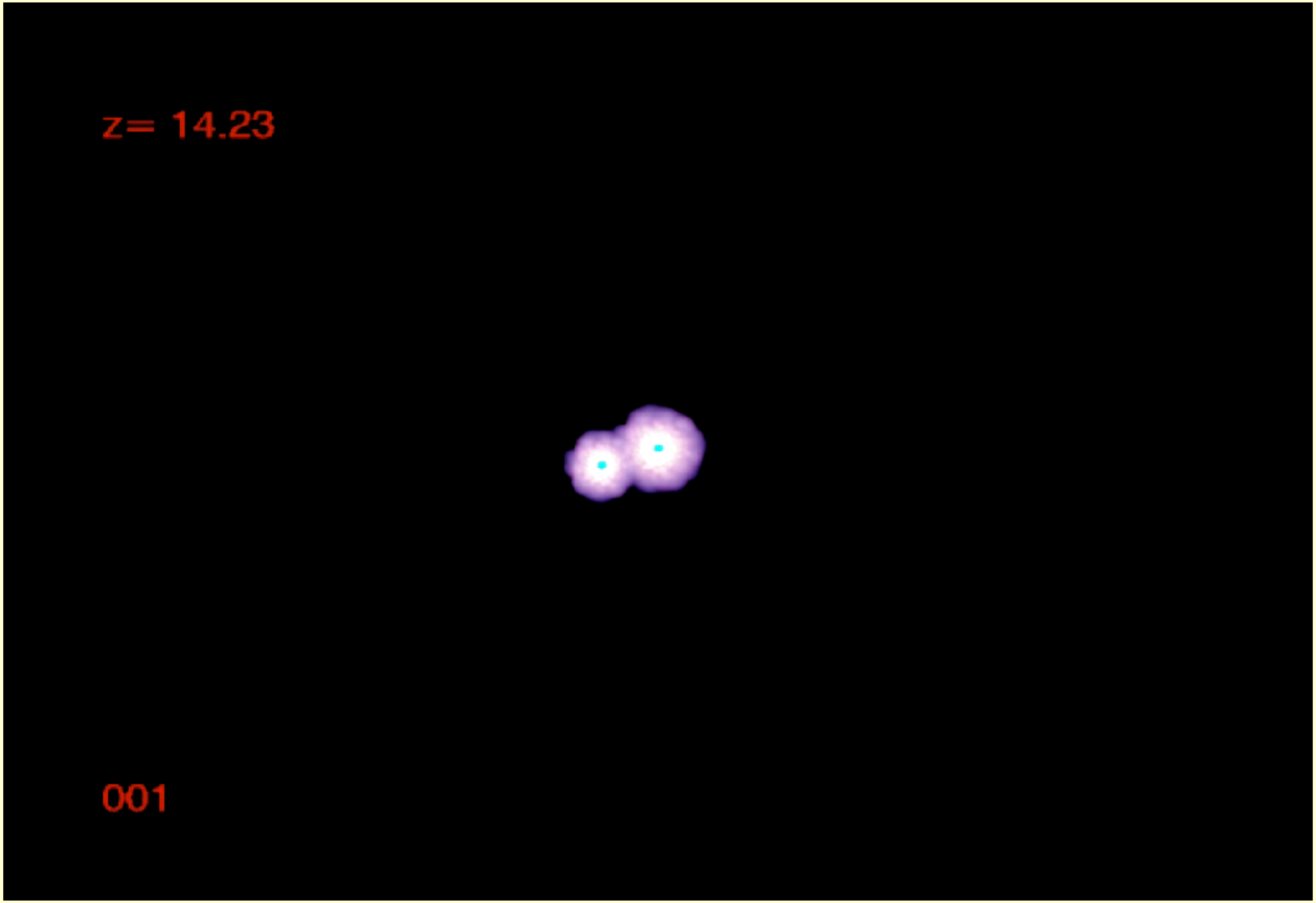


- ***quasars with no hot dust***
  - Spitzer SEDs consistent with disk continuum only
  - ***No similar objects known at low-z***
  - ***no enough time to form hot dust tori? Or formed in metal-free environment?***

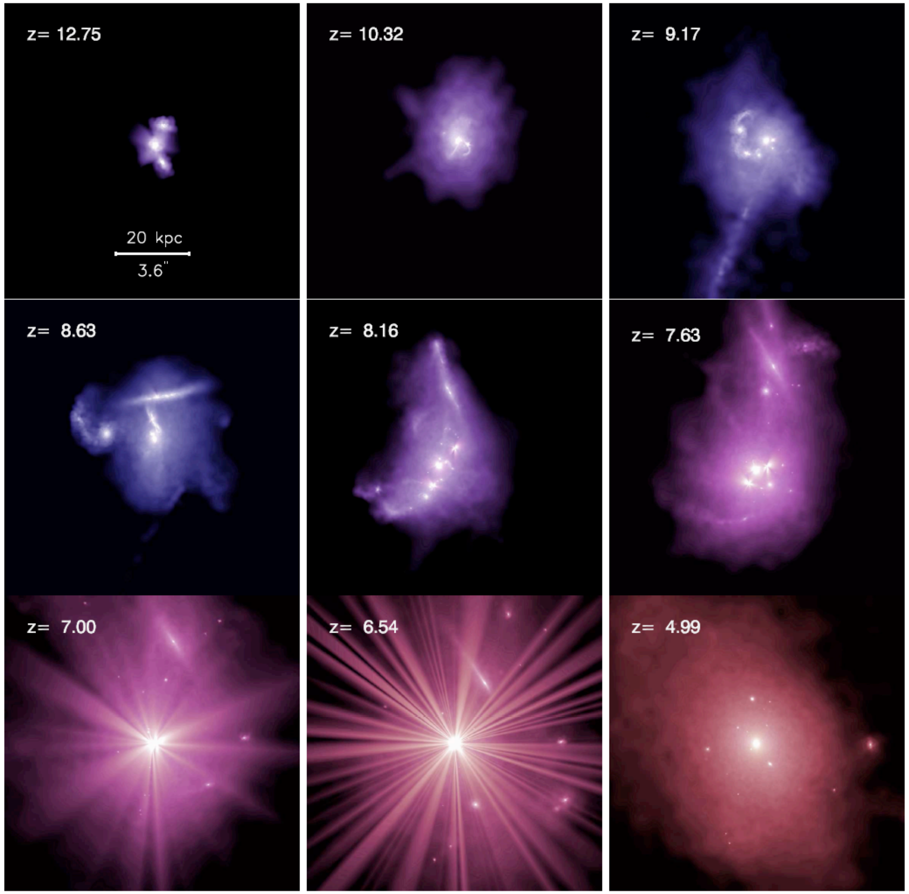


Jiang, XF et al. 2010

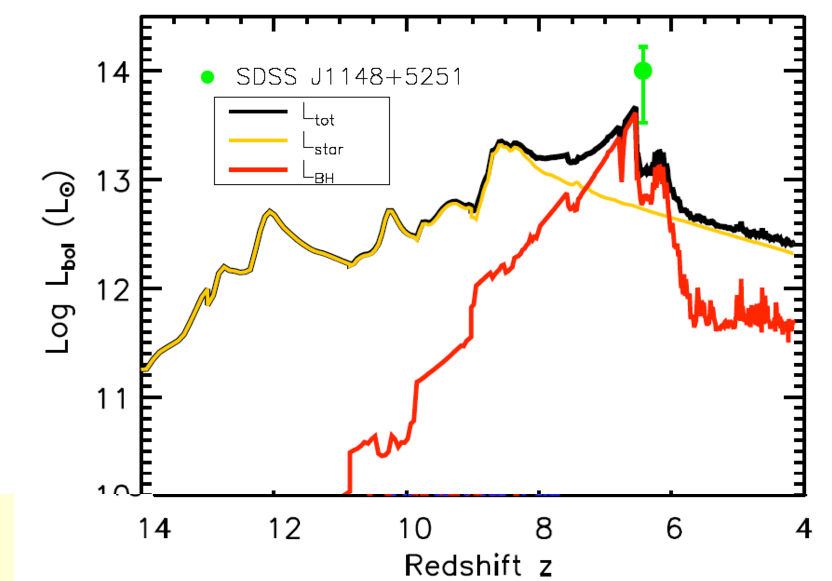
Simulation of high-z quasar formation



Co-formation of BH/Galaxy at high-z



- Host galaxies of z~6 quasars should have ULIRG properties
  - Star formation rate?
  - Mass of host galaxies?
  - evolution of M-sigma relation?



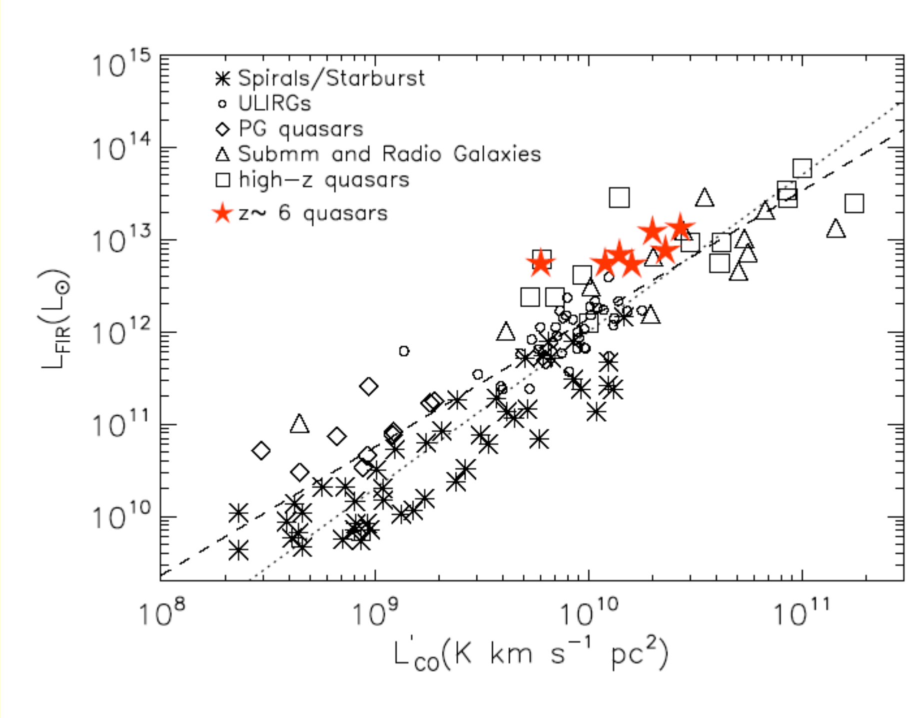
Li et al. 2007

Sub-mm and Radio Observation of High-z Quasars

- Probing dust and star formation in the most massive high-z systems
- Advantage:
  - No AGN contamination
  - Negative K-correction for both continuum and line luminosity at high-z
  - Give measurements to
    - Star formation rate
    - Gas morphology
    - Gas kinematics

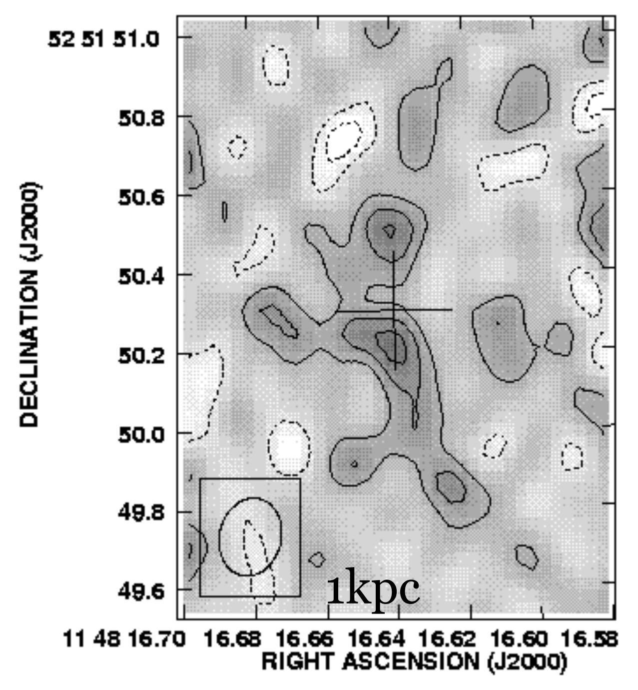
Star Formation in z~6 Quasars

- 30% of z~6 quasars detected at 1mJy level in 1-mm ->
  - $L_{FIR}\sim 10^{13}L_{sun}$
  - T~50K
  - **SFR~1000 $M_{sun}yr^{-1}$** (if dust heated by SB)
- New CO observations
  - eight quasars detected in CO
  - Probing ISM properties and host galaxy masses



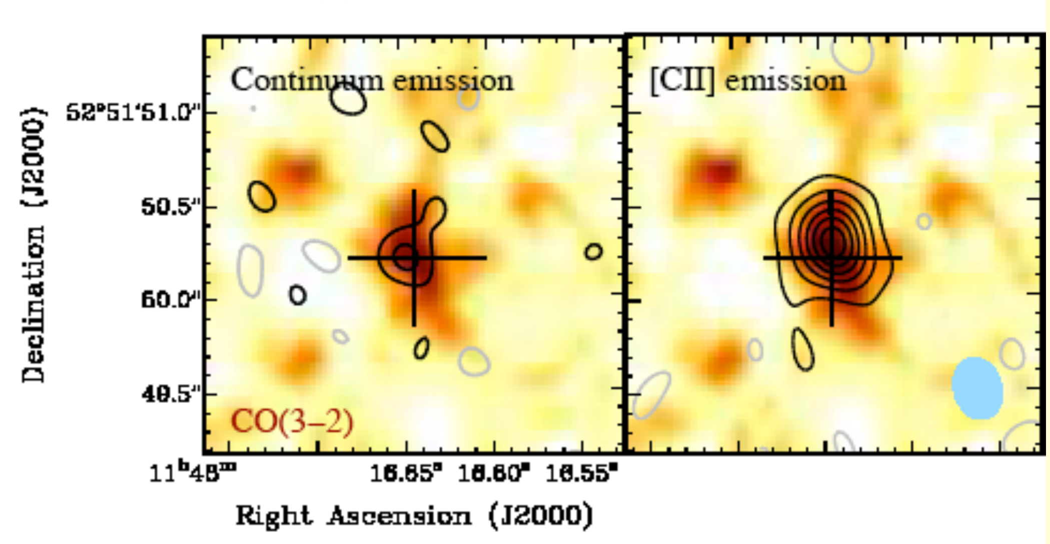
Wang et al. 2008, 2009

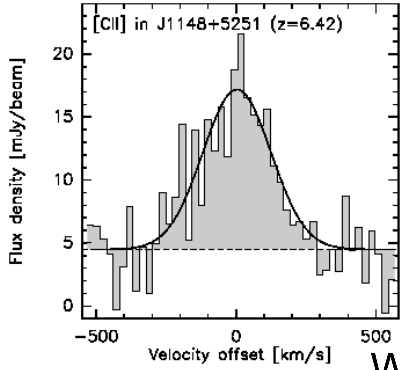
Maximum starburst in z=6.4 quasar ?



Walter et al. 2004

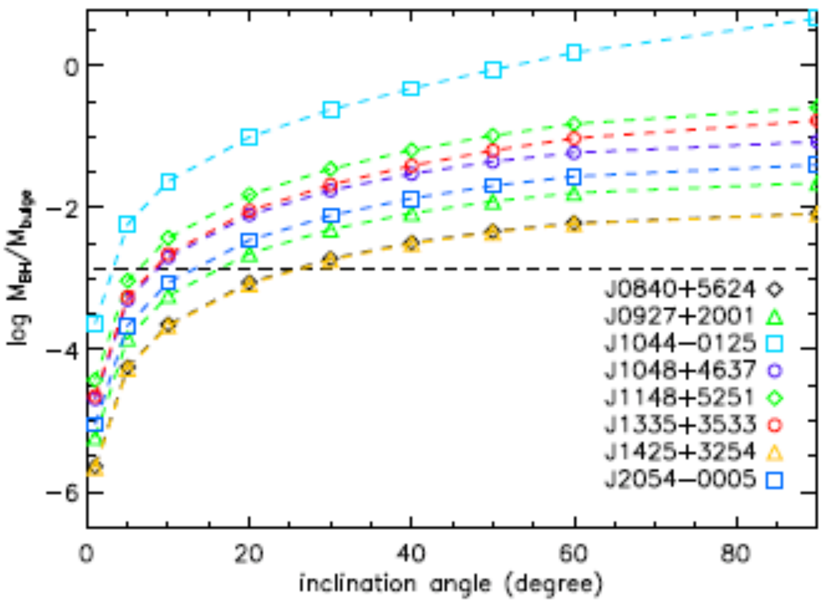
- Spatially resolved CO and [CII] emissions:
  - Size: ~1.5 kpc from [CII] (0.3")
  - Continuum has >50% extended component: SB heating?
  - Star formation rate of: $\sim 1000\ M_{sun} yr^{-1} kpc^{-2}$
    - Eddington limited maximum star formation rate (Thompson et al.)?
    - Gas supply exhaused over a few t_{dyn}
  - Similar SF intensity to Arp 200 but 100 times larger!
- Dynamical mass:
  - CO/CII line width ~300km/s
  - Dynamical mass $\sim 10^{11} M_{sun?}$

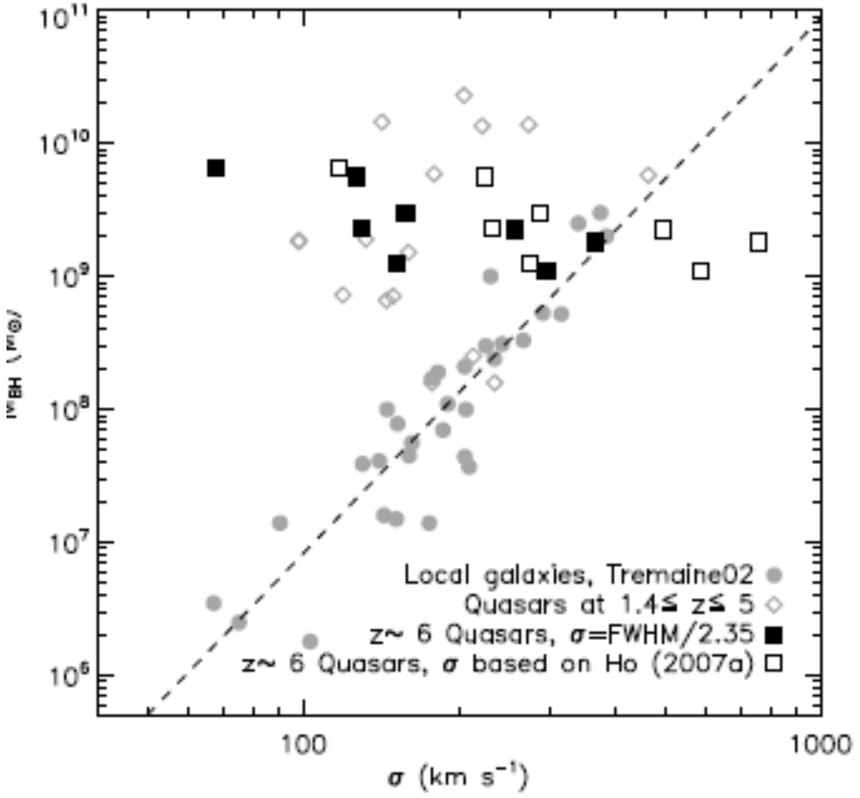




Walter et al. 2009

Evolution of M-sigma Relation?





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