The physics and demography of supermassive black holes

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Outline

The role of supermassive black holes in galaxy evolution

Ubiquity and importance of SMBHs
Dormant and active SMBHs
Feedback

How does a BH grow?

Accretion and Active Galactic Nuclei
The central engine

AGN demography

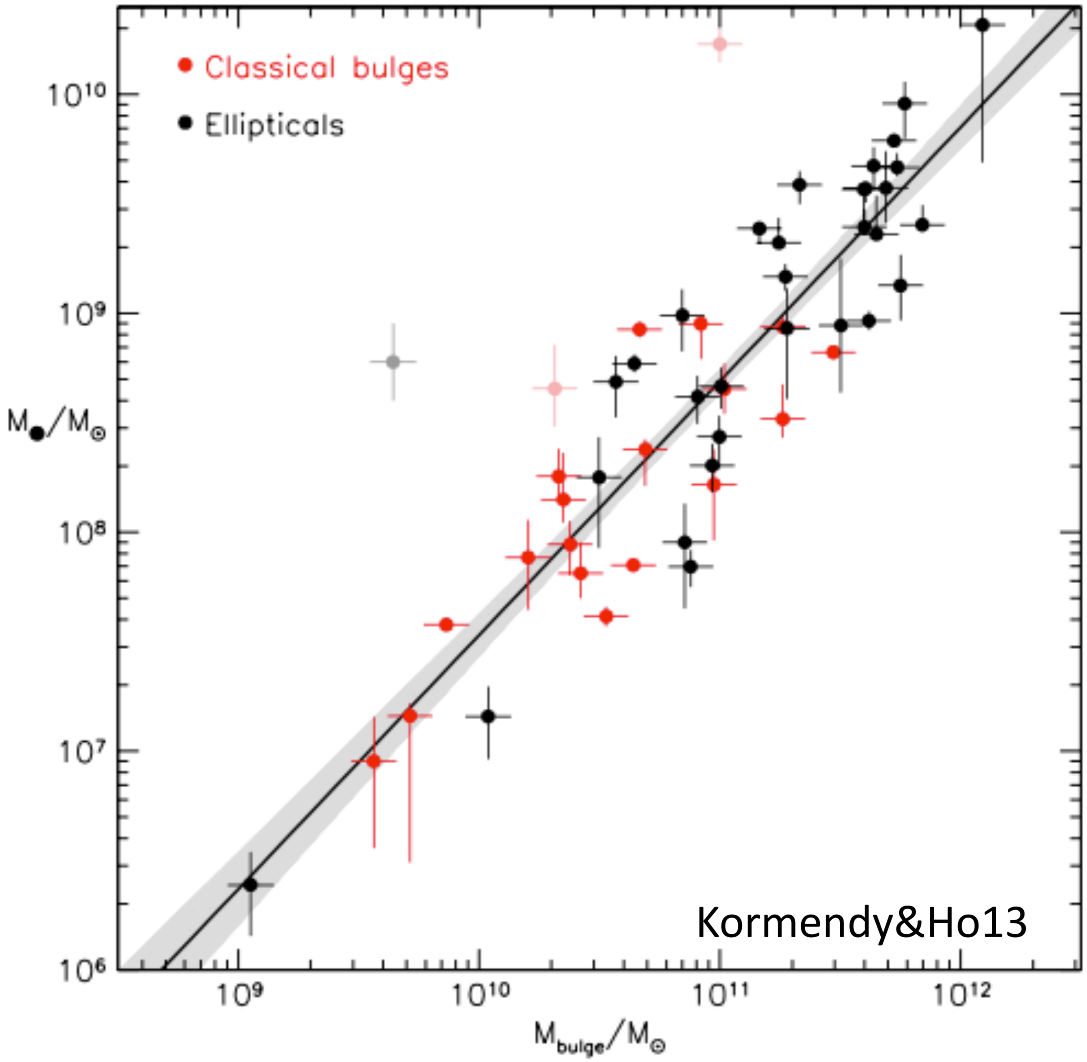
Obscured and unobscured AGN, the unified model
Cosmic evolution
The X-ray background

The first black holes

Demography of high-z QSOs
How do early BHs form?

Ubiquity and importance of SMBHs

Fundamental scaling relations observed in the local Universe between M_{BH} and structural properties of the host galaxy (e.g. bulge L, σ, M*)

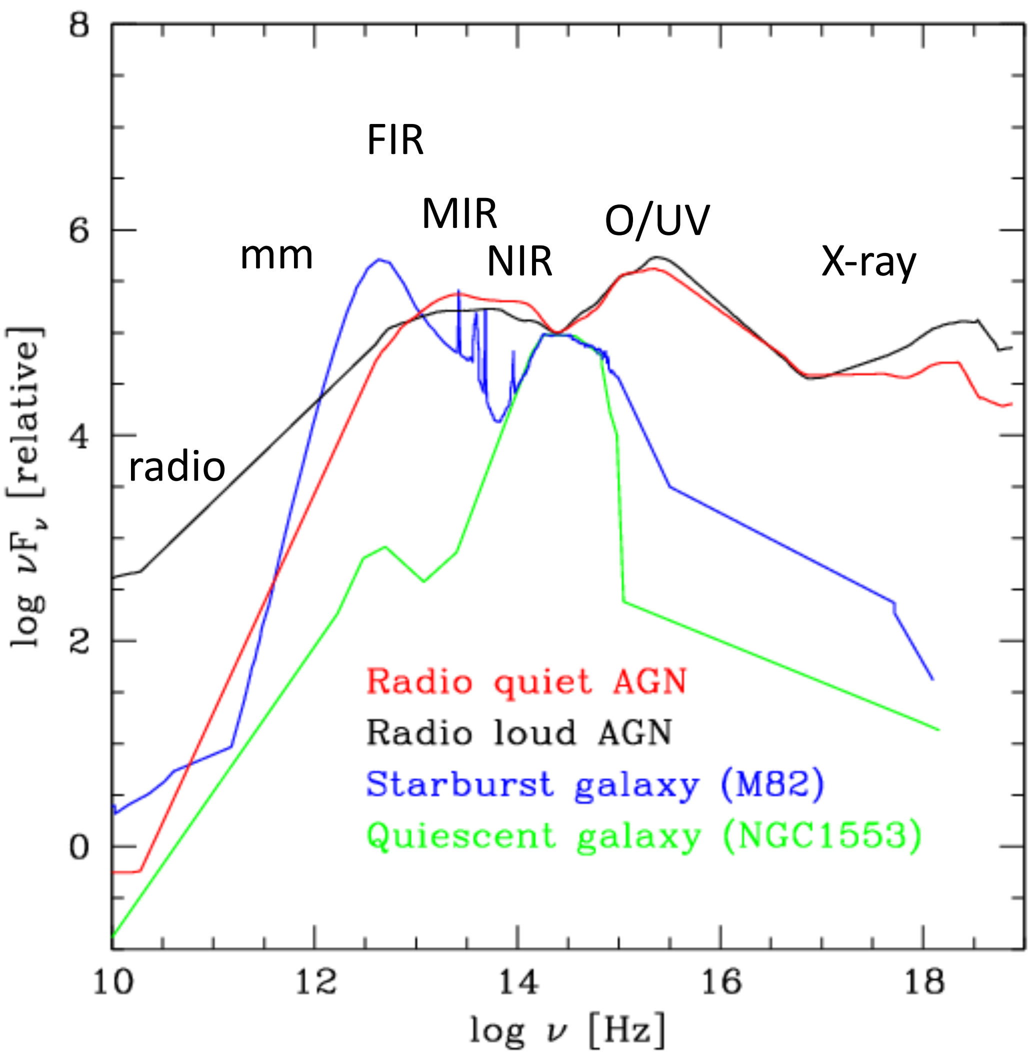


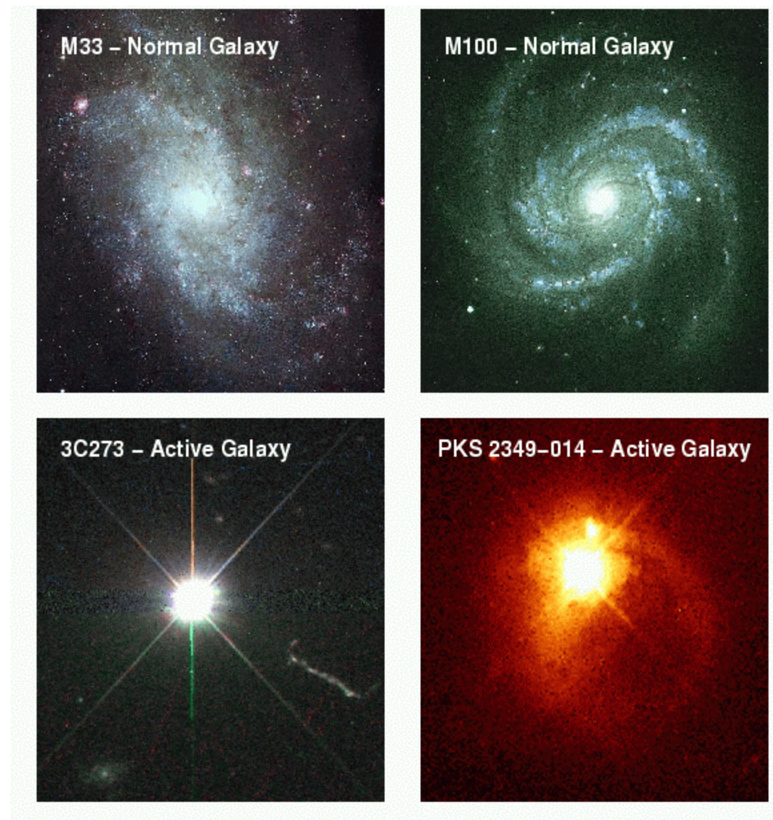
M_{BH}~10^6-10^{10} M_{sun}

M_* ~ 200-500 M_{BH}

Ferrarese&Merritt00
Marconi&Hunt03
Sani+11
....

Dormant and active SMBHs (Active Galactic Nuclei, AGN)



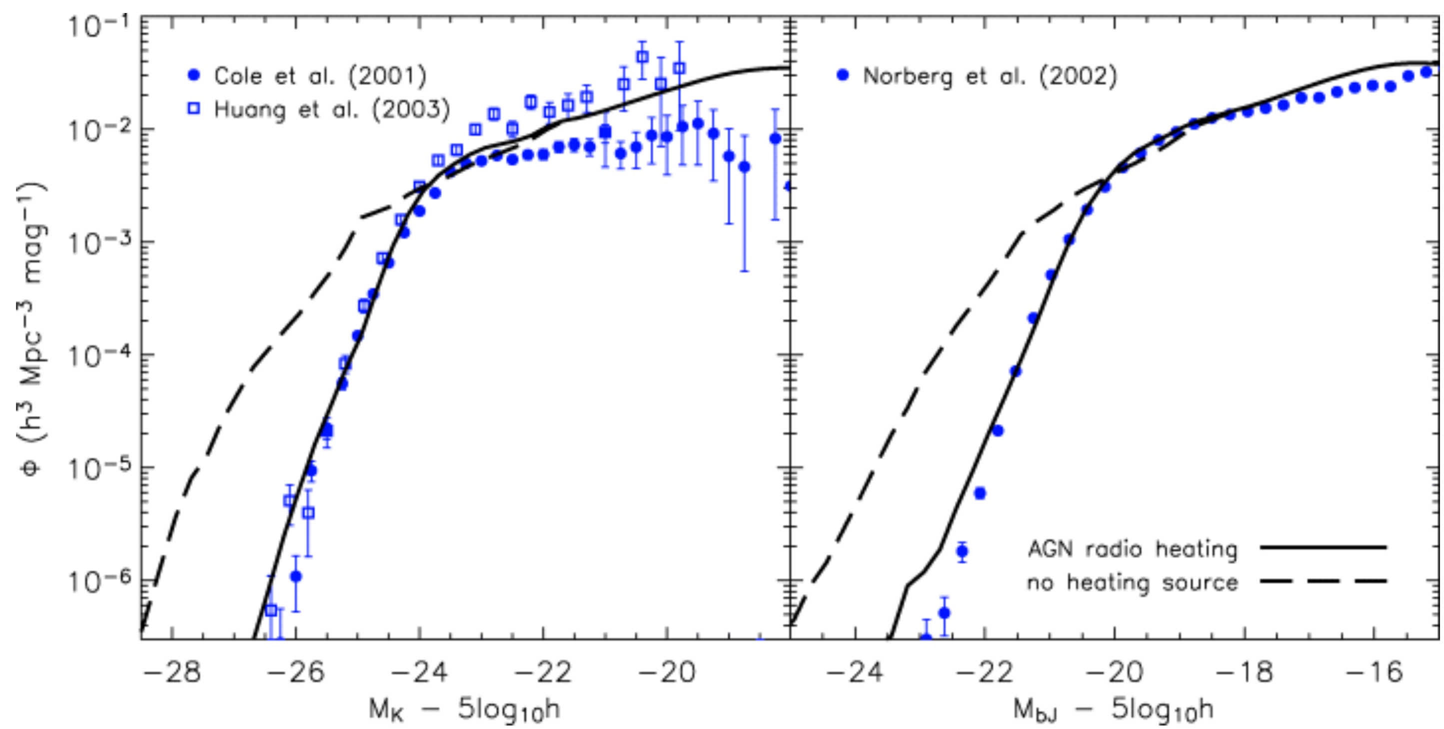


about 1-10% of galaxies are AGN

t_{AGN}~$10^{7\text{-}9}$ yr

Importance of AGN for galaxy evolution

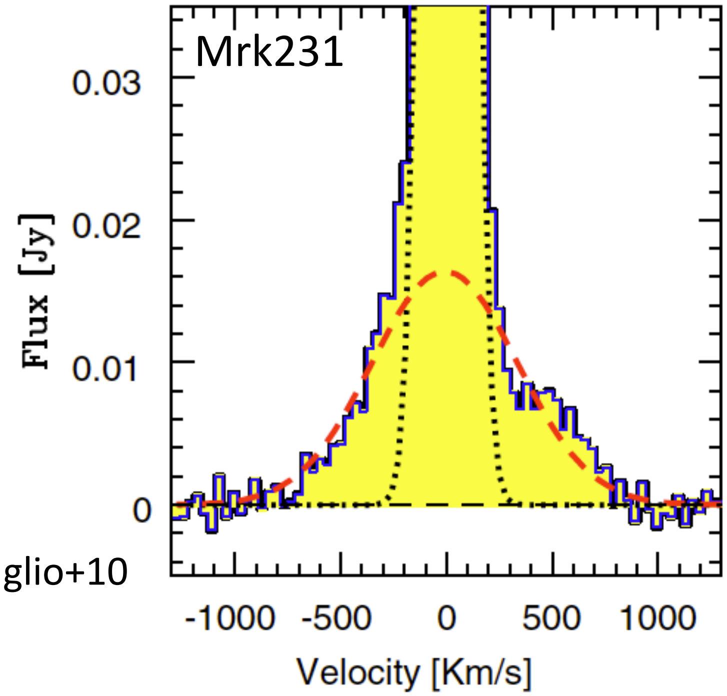
Croton+06



AGN feedback (radiative, kinetic) introduced ad hoc by semi-analytic models to expel or heat the gas, halt star formation and hence prevent the assembly of (too many) massive galaxies

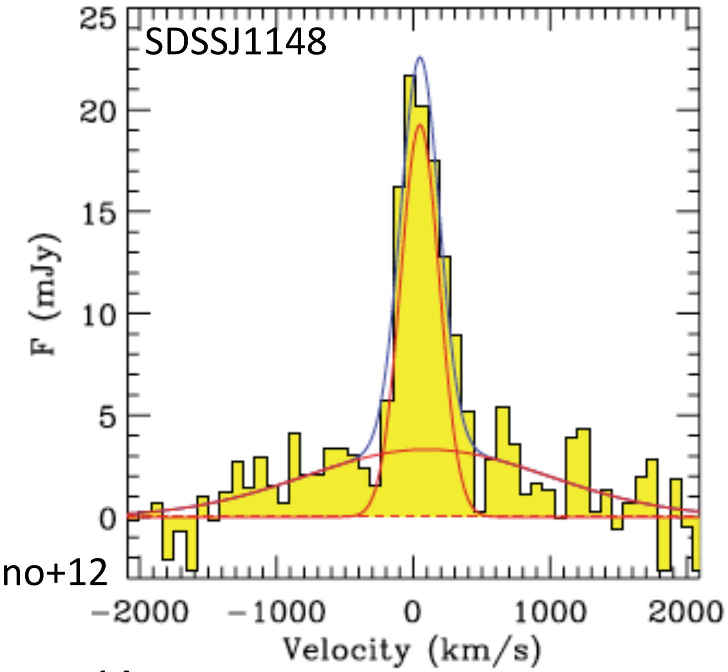
Observational evidences of AGN feedback

CO data (trace molecular gas)



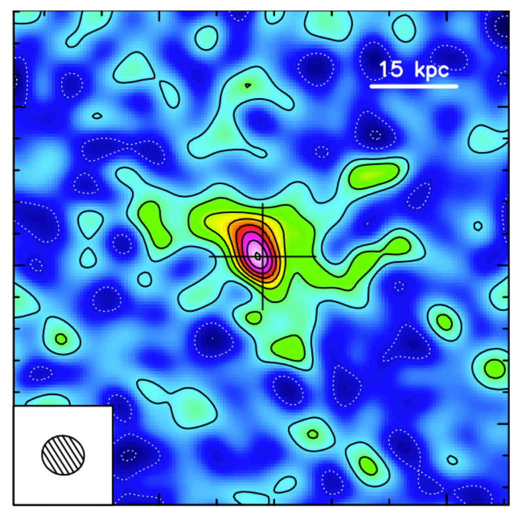
Feruglio+10

[CII] data (trace atomic gas)



Maiolino+12

Cicone+14



Molecular and atomic gas outflows

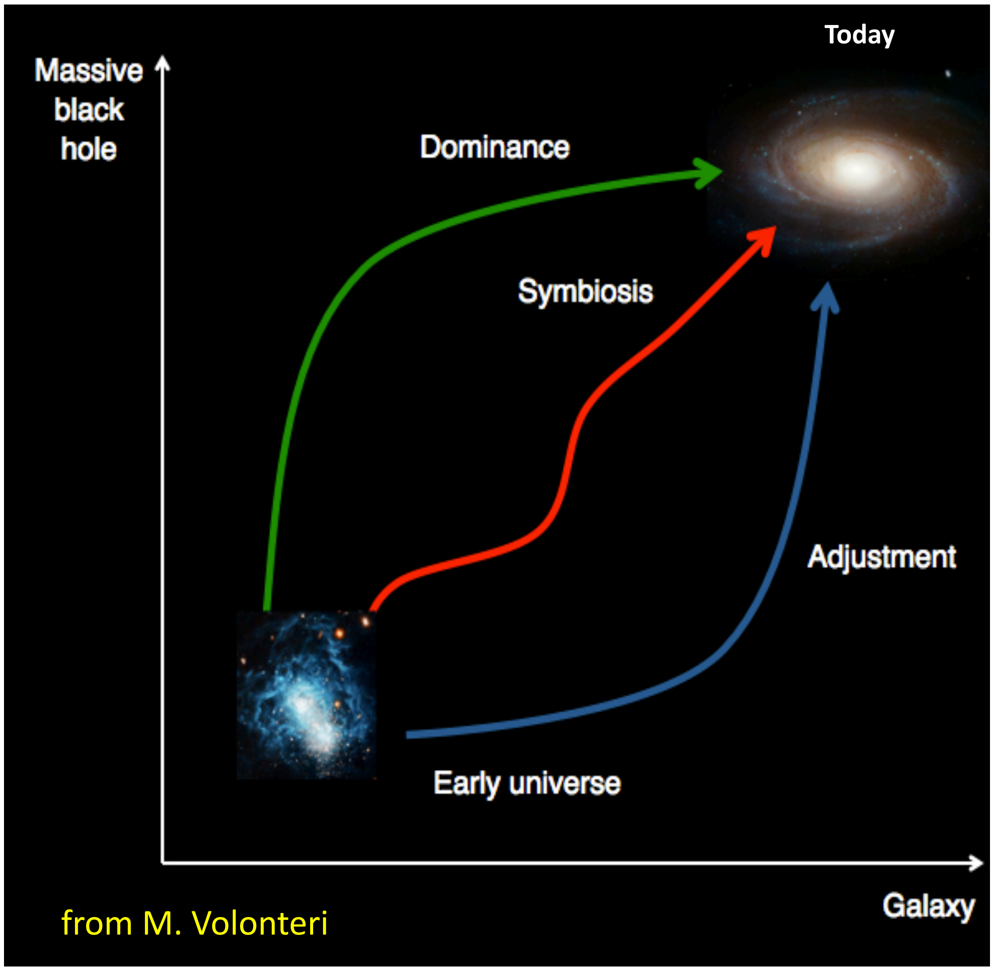
Outflow rates $\dot{m}_{out}$ > $10^{2\text{-}3}$ M_{sun}/yr ($\dot{m}_{out}$> SFR)

M_{gas} = $10^{9\text{-}10}$ M_{sun}

Gas depleted, i.e. SF shut in t = $M_{gas}/\dot{m}_{out}$ = $10^{6\text{-}8}$ yr

➔ SMBH activity may influence the whole host galaxy

BH/galaxy coevolution



Key open questions

When and where BHs form?

Do they form only at early times?

Do they anticipate galaxy formation?

What is their origin (seeds)?

How does a SMBH grow?

accretion → Active Galactic Nucleus phase

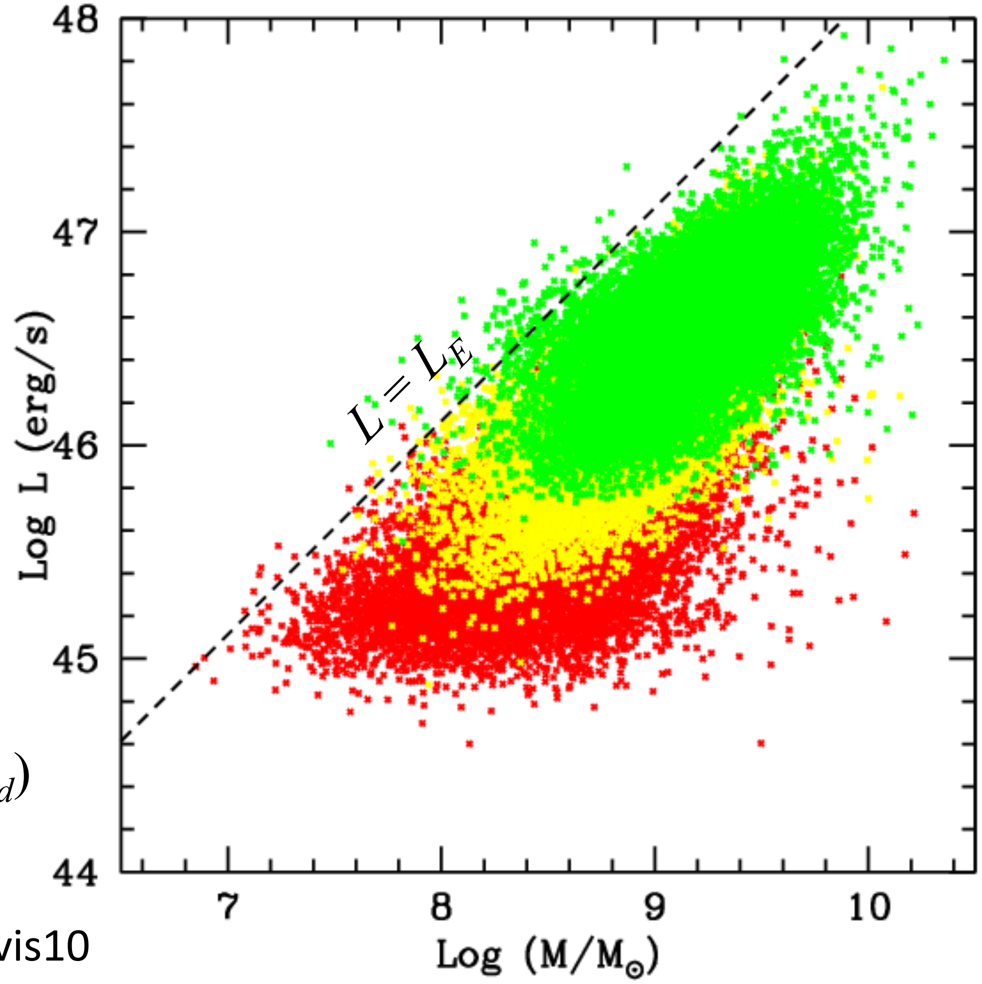
Eddington limit: $F_{rad} <= F_{grav}$. It assumes spherical symmetry and pure HII gas (still robust limit)

$$L_E = \frac{4\pi G m_p c^2 M}{\sigma_T c} = \frac{Mc^2}{t_E}$$

$$= 1.26 \times 10^{46} \frac{M}{10^8 M_\odot} \; erg/s$$

$$t_E = \frac{\sigma_T c}{4\pi G m_p} = 0.45 \; Gyr$$

$$\lambda \equiv L_{bol}/L_E \quad (= \text{Eddington ratio } f_{Edd})$$



Steinhardt&Elvis10

How does a SMBH grow?

$$L_{bol} = \epsilon \dot{m}_{acc} c^2$$

ε = radiative efficiency

Neglecting GR effects:

$L \sim dU/dt = GM\dot{m}_{acc}/r$

For $r = 5R_s$:

$(R_s = 2GM/c^2 = 2$ *AU for* $M = 10^8\ M_{sun})$

$L \sim 0.1\dot{m}_{acc}c^2$, *i.e.* $\varepsilon \sim 0.1$

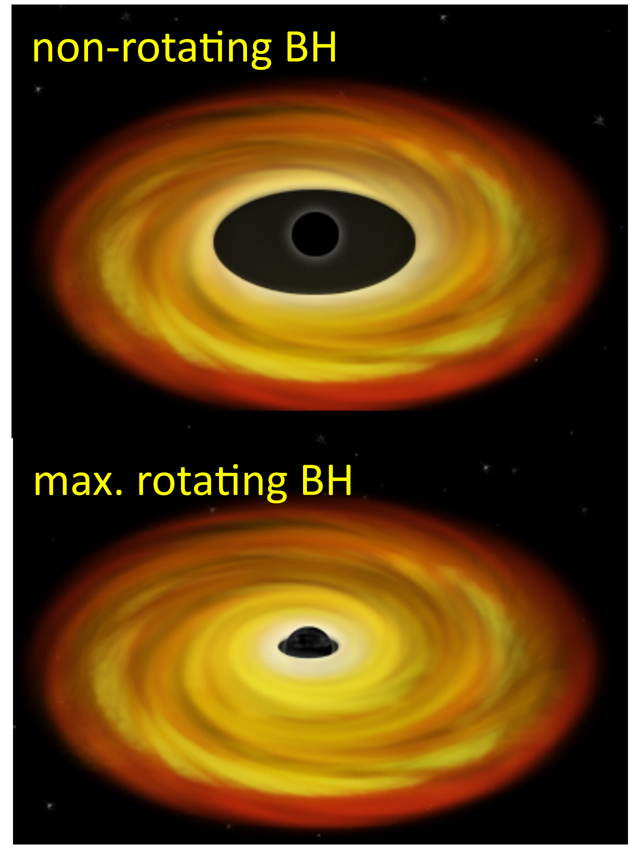
$$\dot{m}_{acc} = \frac{\lambda L_E}{\epsilon c^2} = \frac{\lambda M}{\epsilon t_E}$$

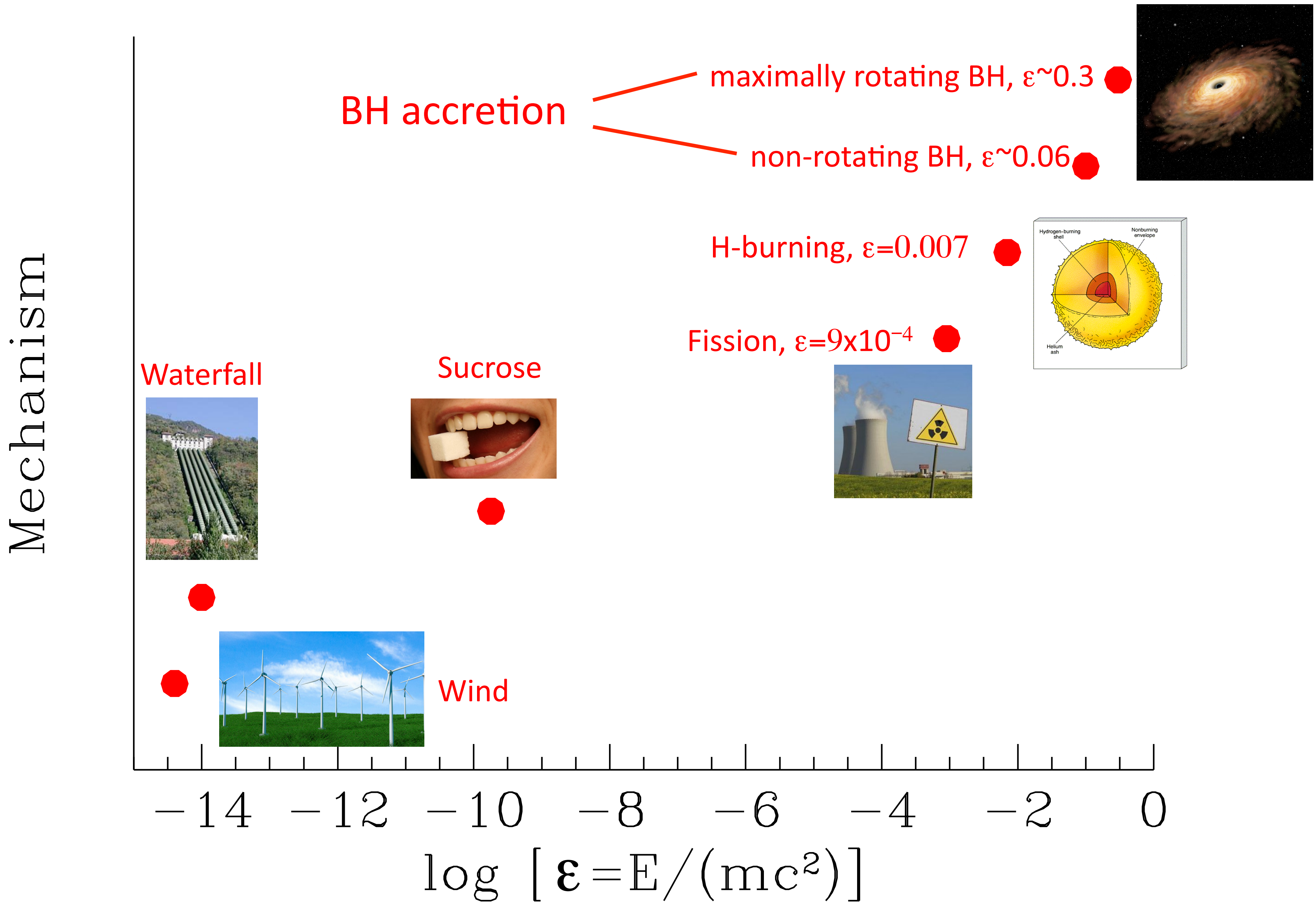
$= 2.2\ M_{sun}/yr$ *for* $M = 10^8\ M_{sun}$, $\lambda = 1$ *and* $\varepsilon = 0.1$

Accretion disk

$\varepsilon \sim 0.06$

$\varepsilon \sim 0.3$





Adapted from G. Ghisellini slides

How does a SMBH grow?

$$\dot{M} = (1-\epsilon)\dot{m}_{acc} = \frac{(1-\epsilon)\lambda}{\epsilon}\frac{M}{t_E}$$

rate of change of a quantity propto the quantity itself ➔exponential growth (like money – or debts… - on your bank account)

$$M(t) = M_0 e^{t/t_{Sal}}$$

$$t_{Sal} = \frac{\epsilon}{1-\epsilon}\frac{t_E}{\lambda}$$ (= 50 Myr for $\varepsilon = 0.1$ and $\lambda = 1$)

it takes 16 (9) Salpeter times , i.e. 0.8 (0.5) Gyr to grow a 10^9 M_{sun} BH starting from 10^2 (10^5) M_{sun}

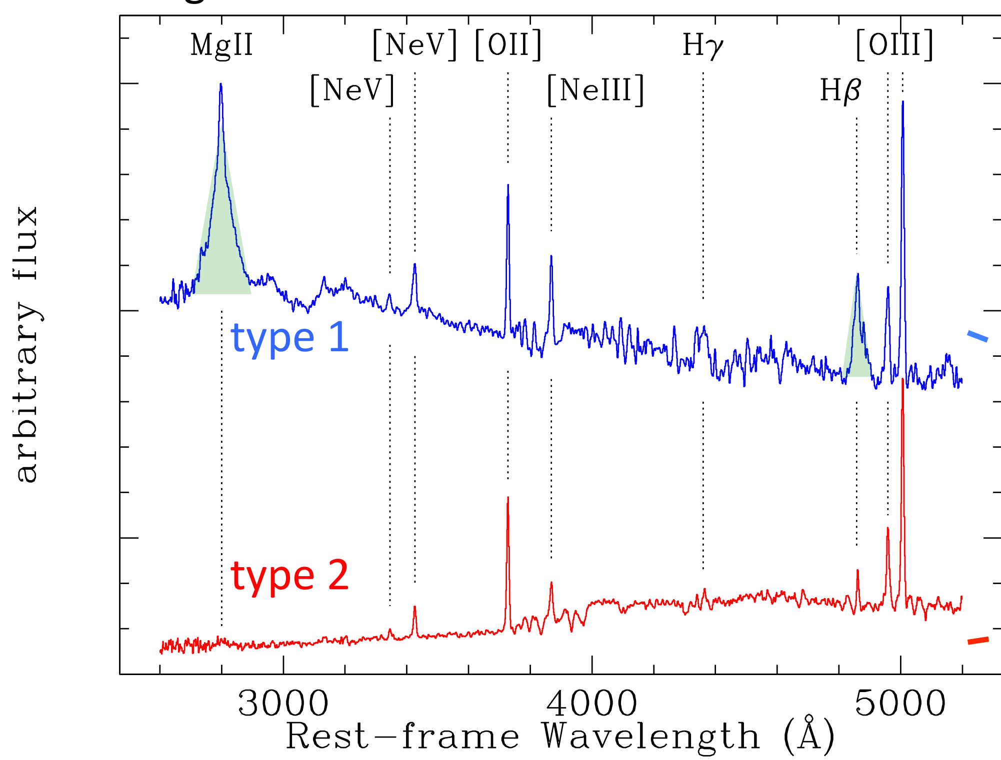
Initial BH mass, i.e. the BH seed, the big unknown!

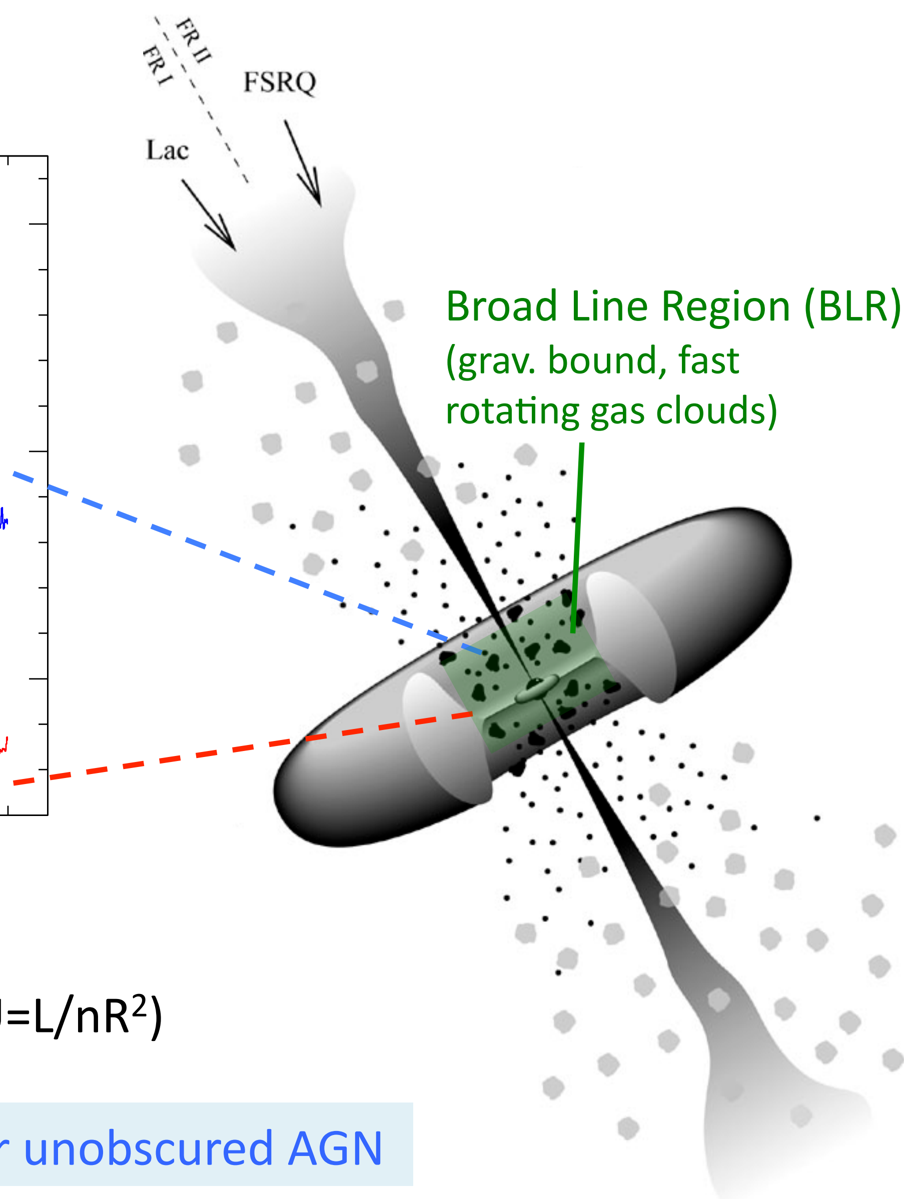
$$L_{bol}(t) = \lambda L_E = \lambda\frac{M(t)c^2}{t_E} = L_0 e^{t/t_{Sal}}$$

$$L_0 = \frac{\lambda c^2 M_0}{t_E}$$

AGN types: (type 1) unobscured vs (type 2) obscured

Mignoli+13



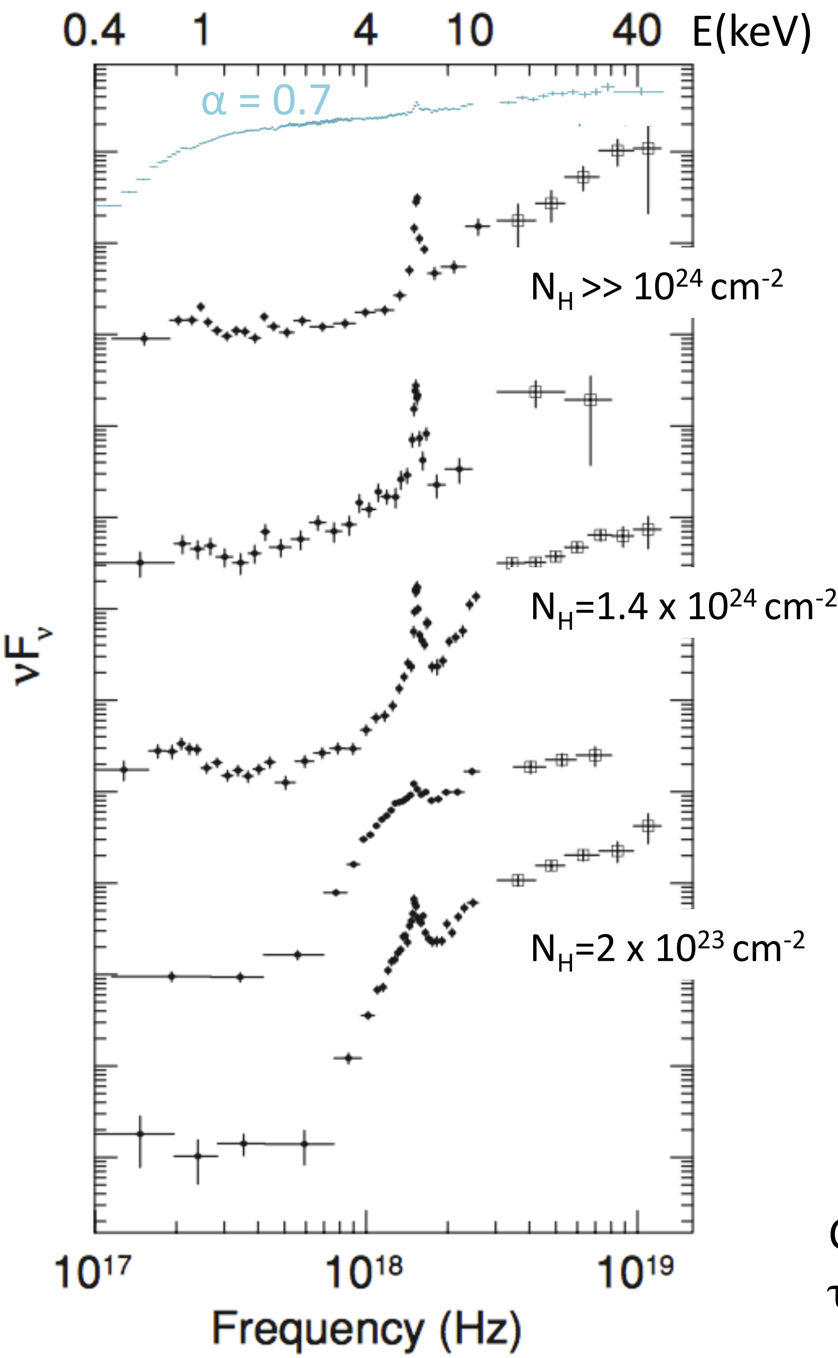


$M_{BH} \approx r_{BLR} v_{BLR}^2 / G$

$v_{BLR} \sim$ FWHM(MgII) ; $r_{BLR} \sim L_{3000}^{0.5}$ (← $U=L/nR^2$)

"direct" M_{BH} estimate for unobscured AGN

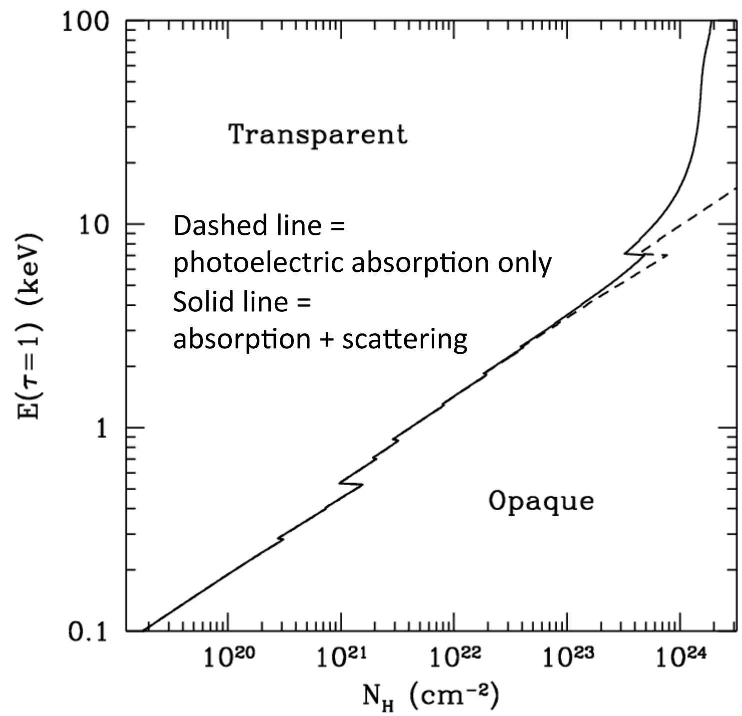
Unobscured vs obscured AGN



$I_u(E) \approx E^{-\alpha} \qquad \alpha = 0.7 - 1.0$

$I_o(E) \approx I_u(E)\, e^{-\tau}$

$\tau = N_H \sigma$

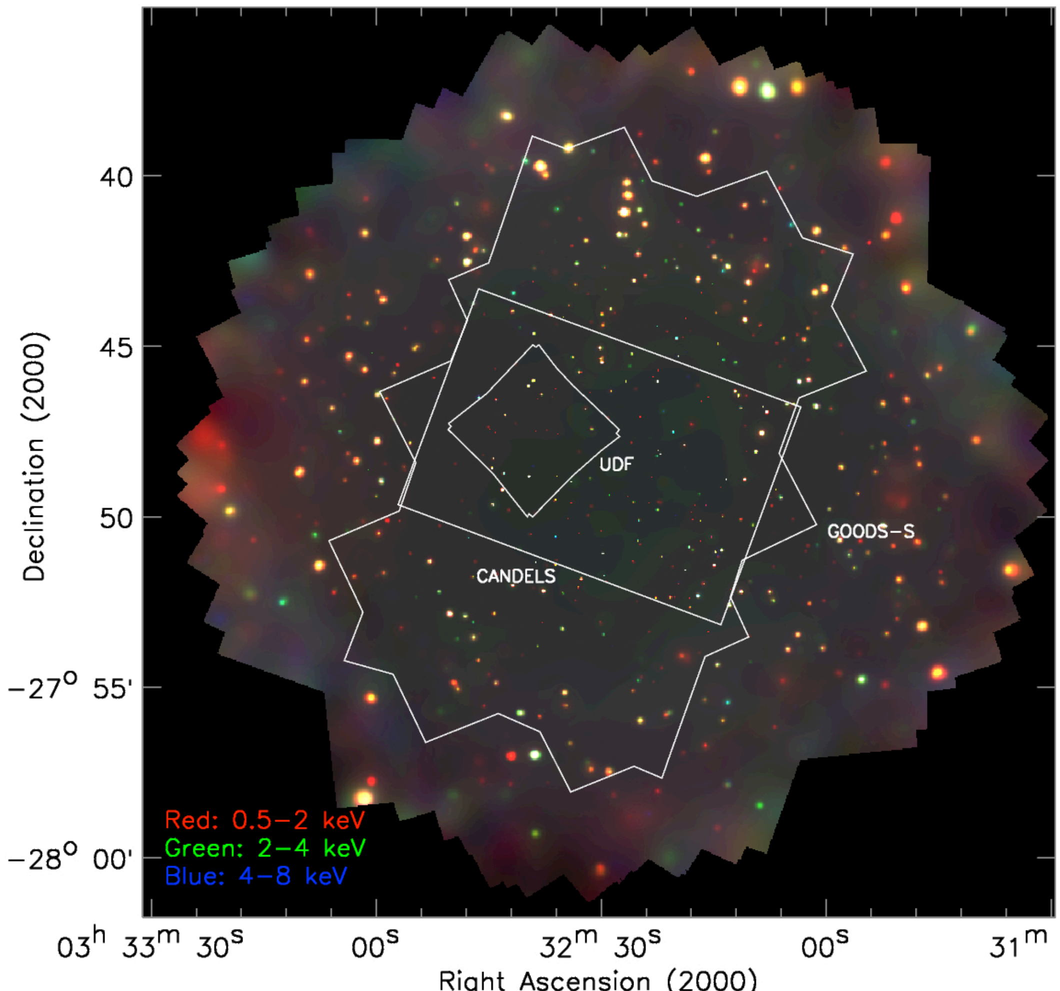


Compton –thick AGN:

$\tau_C = N_H \sigma_T > 1 \;\Rightarrow\; N_H > 1/\sigma_T = 1.5 \times 10^{24}$ cm^{-2}

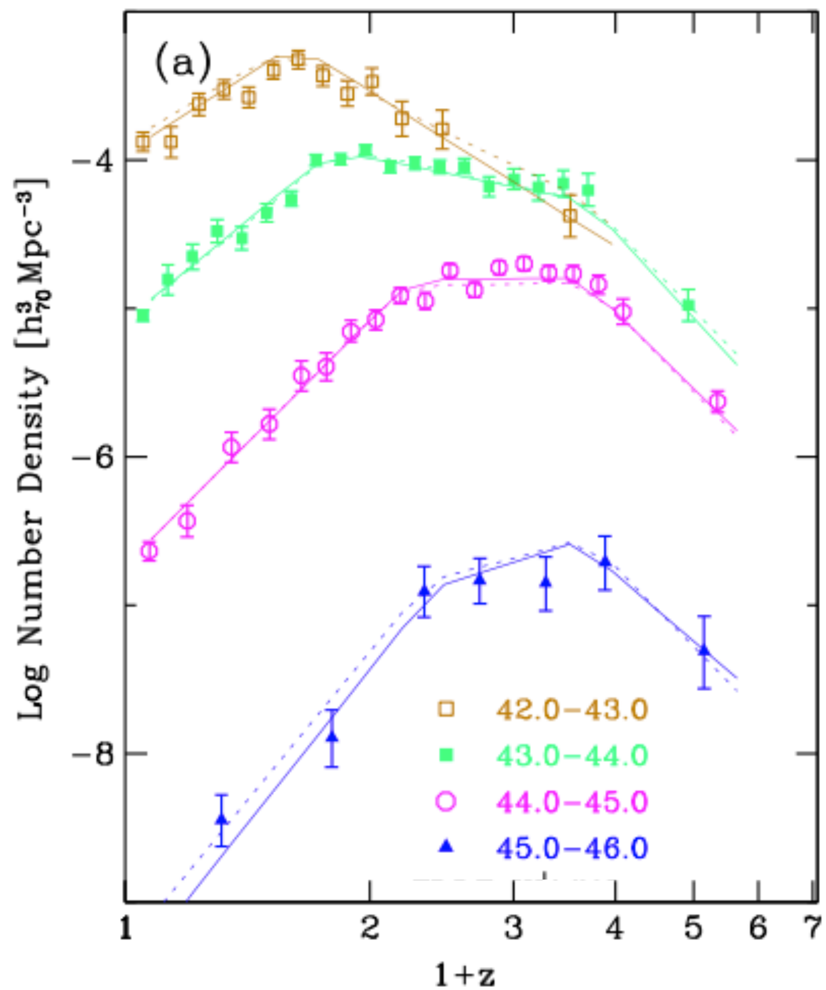
Deep X-ray surveys and AGN evolution

The deepest X-ray image of the Universe:
the 4Ms (1.5 months) Chandra Deep Field South
(will reach 7Ms by Dec 2015)



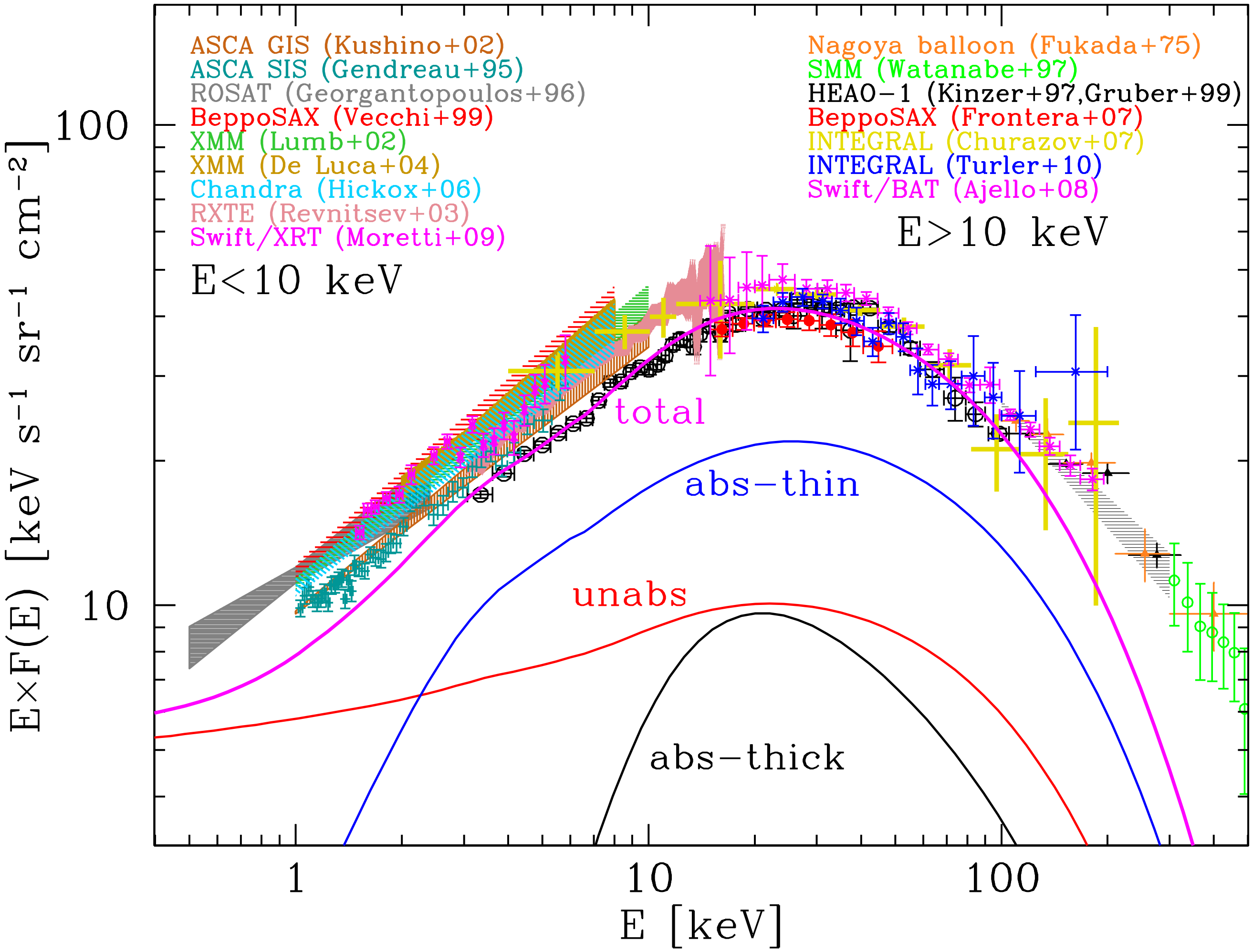
Xue+11

Space density of Compton-thin AGN



Miyaji+15

The cosmic X-ray background

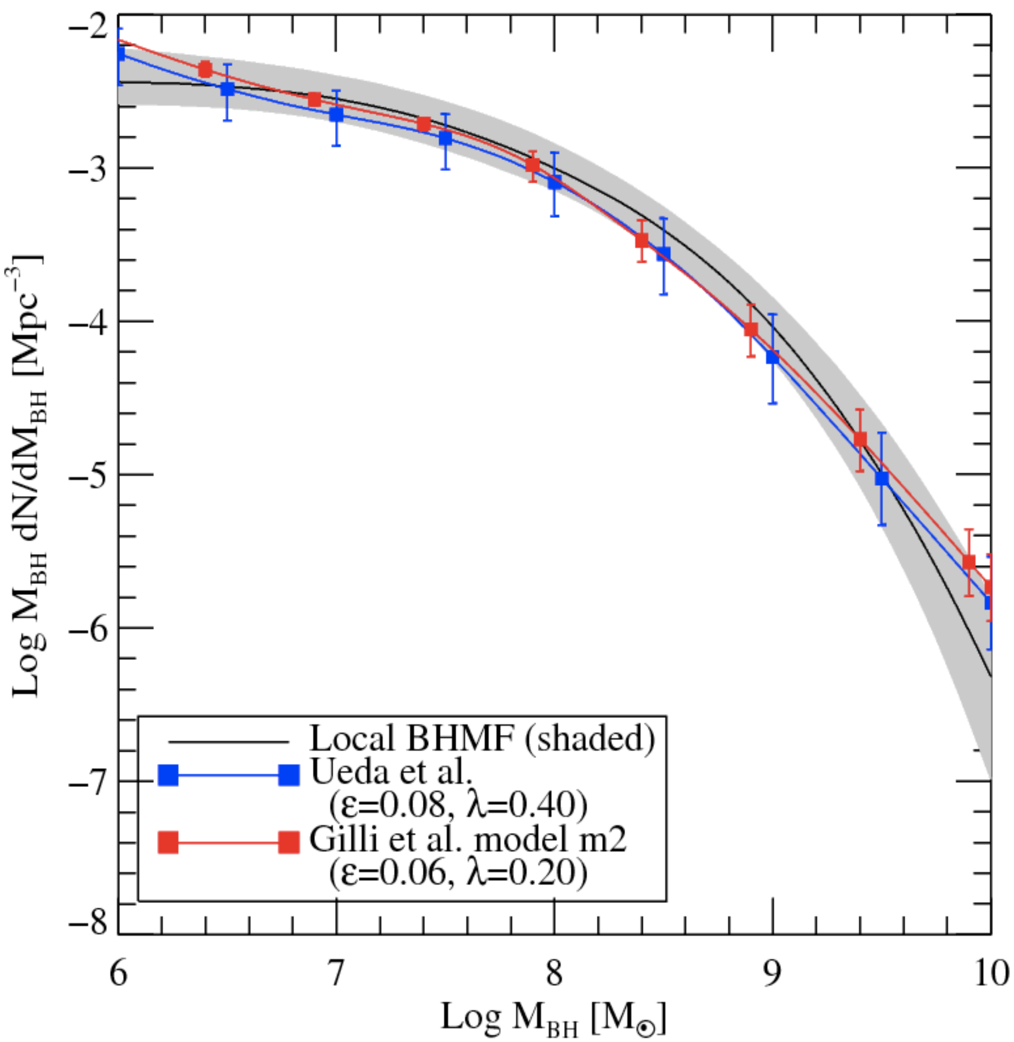


N abs-thin ~ N abs_thick ~ 3 x N unabs ➔

80-90% of SMBHs accretion is obscured; 40% is heavily (Compton-thick) obscured

The local SMBH mass function

relic (accreted through AGN phases) vs measured local BH mass function



Marconi+04, Shankar+04, Merloni&Heinz08, …

.

M_{BH}= [(1- ε)/ε] L/c^2 ➔
(integrating over time and population)

ρ_{relic} = [(1- ε)/ε] U_T/c^2

ρ_{relic} = mass density of relic BH
U_T = total bolometric AGN energy density
(i.e. obscured + unobscured)

$\rho_{measured}$ ~ 4 × 10^5 $M_\odot$ Mpc^{-3}

ρ_{relic} ~ $\rho_{measured}$ ➔
local SMBHs appear to have formed through active phases across galaxies' lifetimes

The first black holes

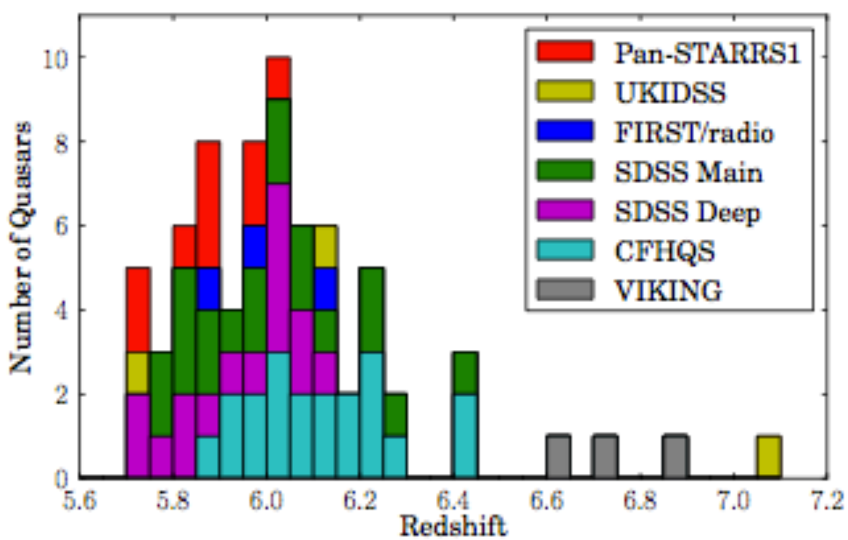
(z>6, $t_{Universe}$< 1 Gyr)

Demography of high-z QSOs

About **80 QSOs known at z>5.7** from wide area optical (SDSS, CFHQS, Pan-STARRS1) and near-IR (UKIDSS, VISTA) surveys
(Fan+00–06; Jiang+08,09; Willott+07,09,10; Banados+14, Mortlock+11; Venemans+13)

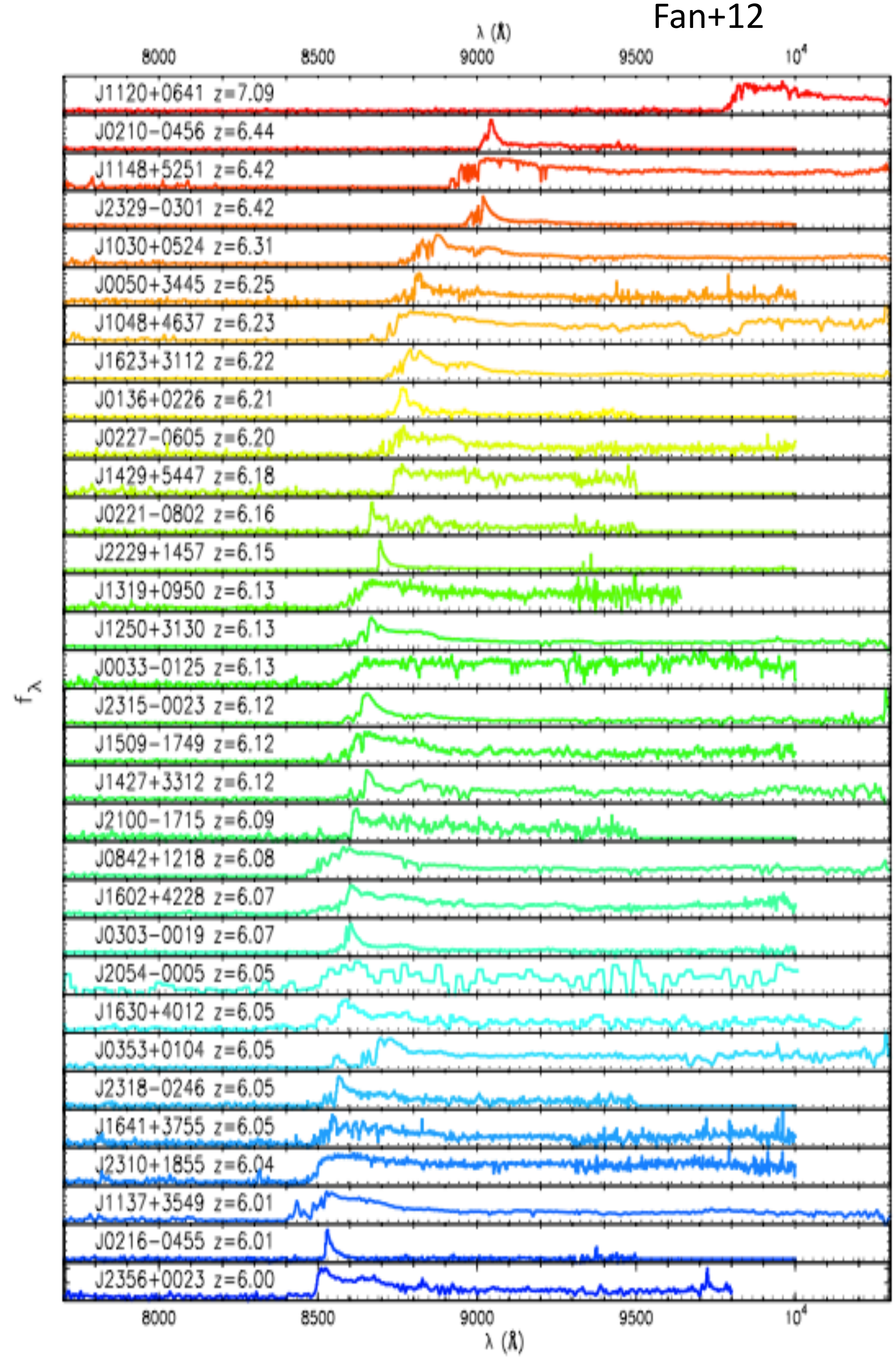
SDSS main and Pan-STARRS1 trace the most luminous QSOs: $M_{1450} \sim -27$, $L_{bol} \sim 3 \times 10^{47} L_{sun}$

SDSS-Stripe82 and CFHQS go ~2 mag deeper

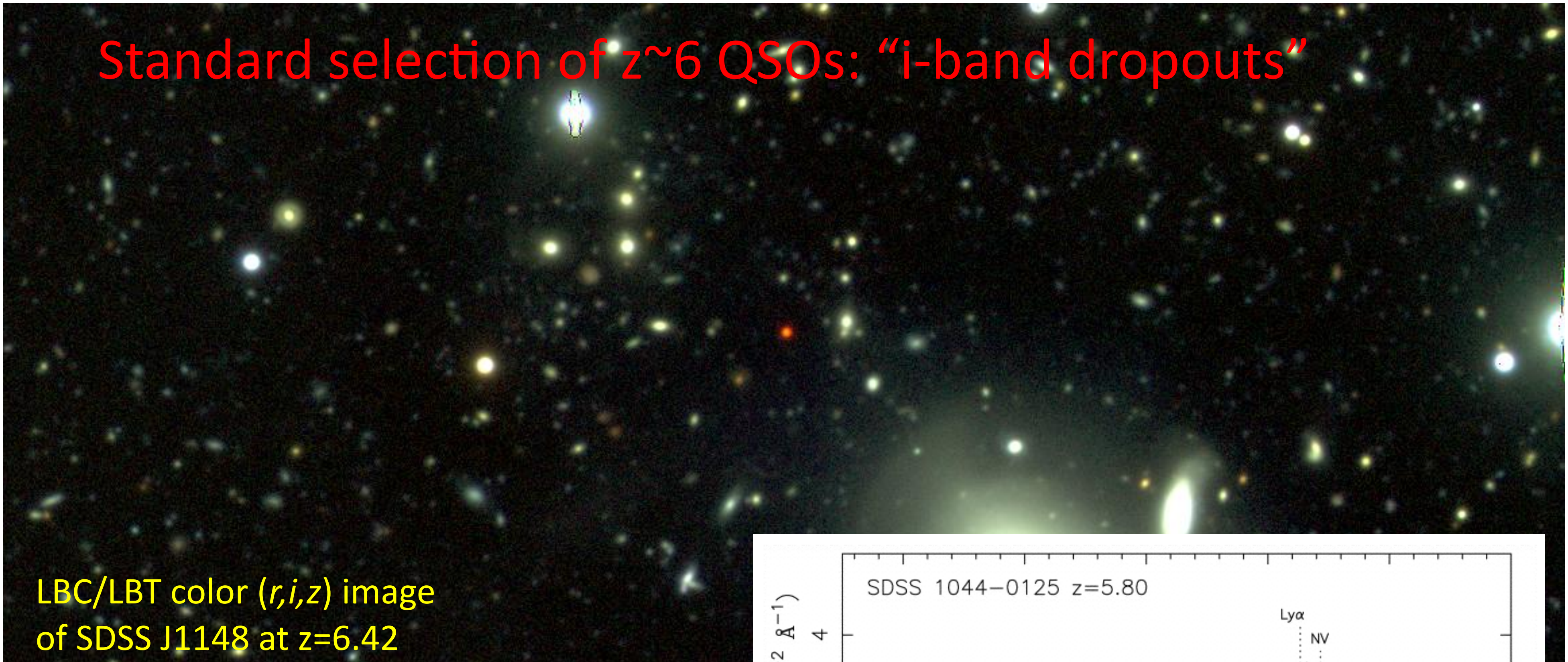


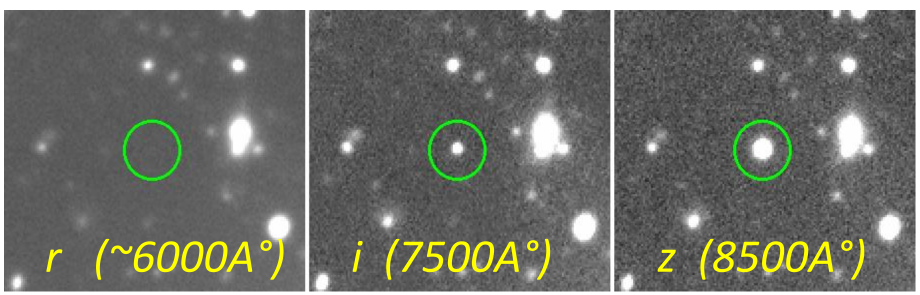
Banados+14

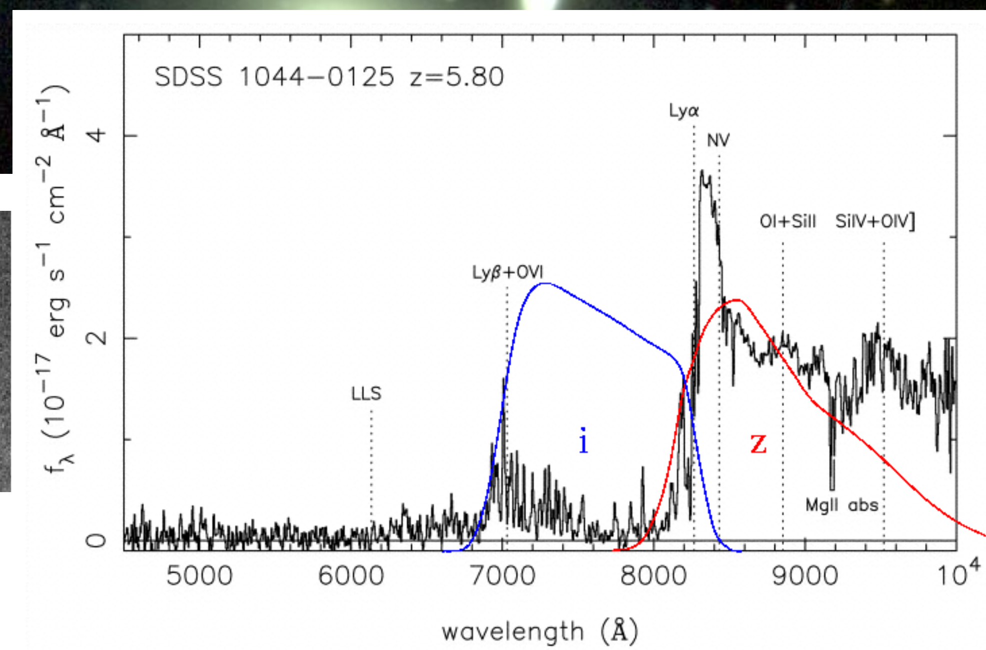
Fan+12



Standard selection of z~6 QSOs: "i-band dropouts"

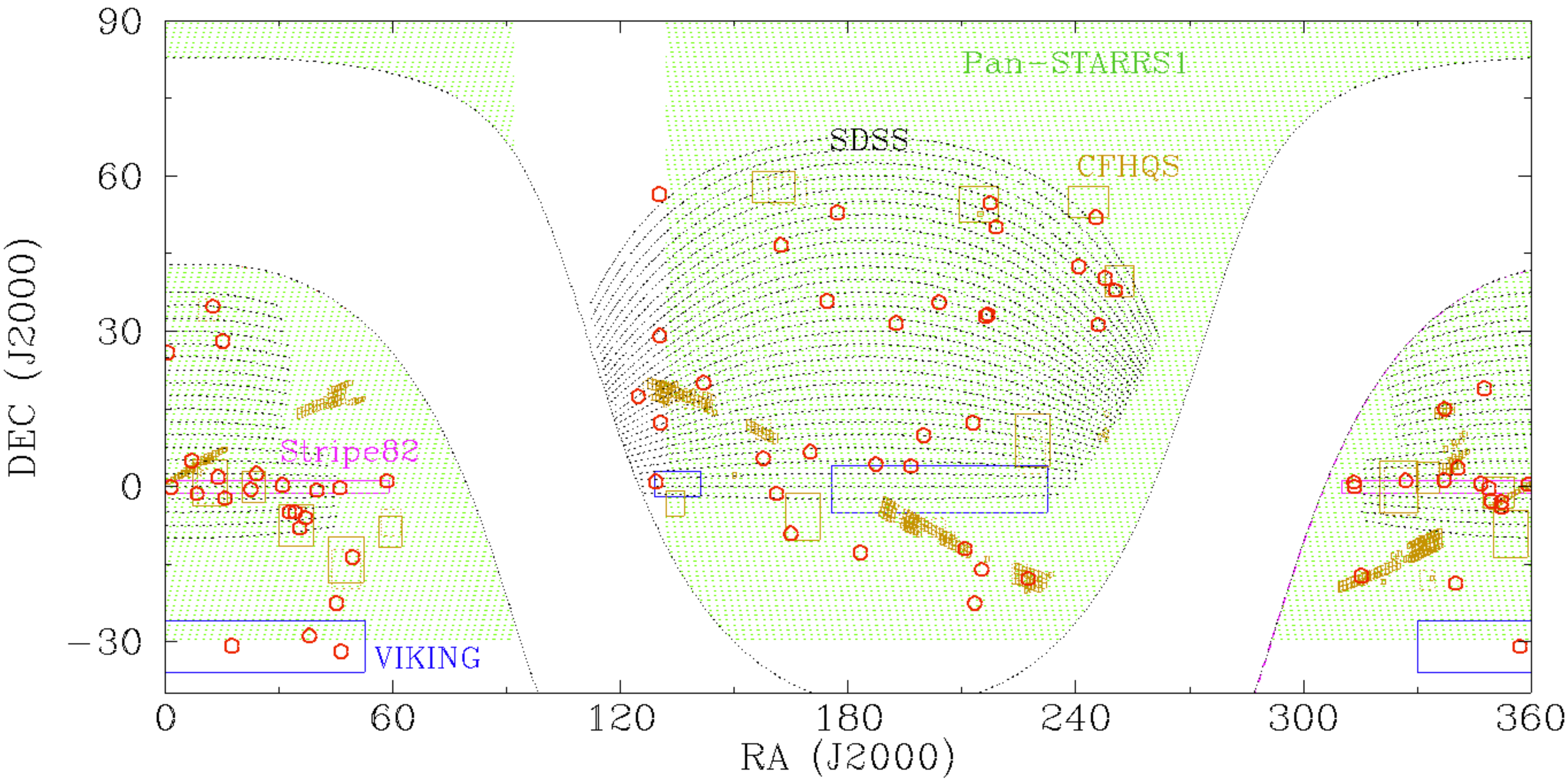






Color selection: i-z >= 2,
no detection blueward of i-band

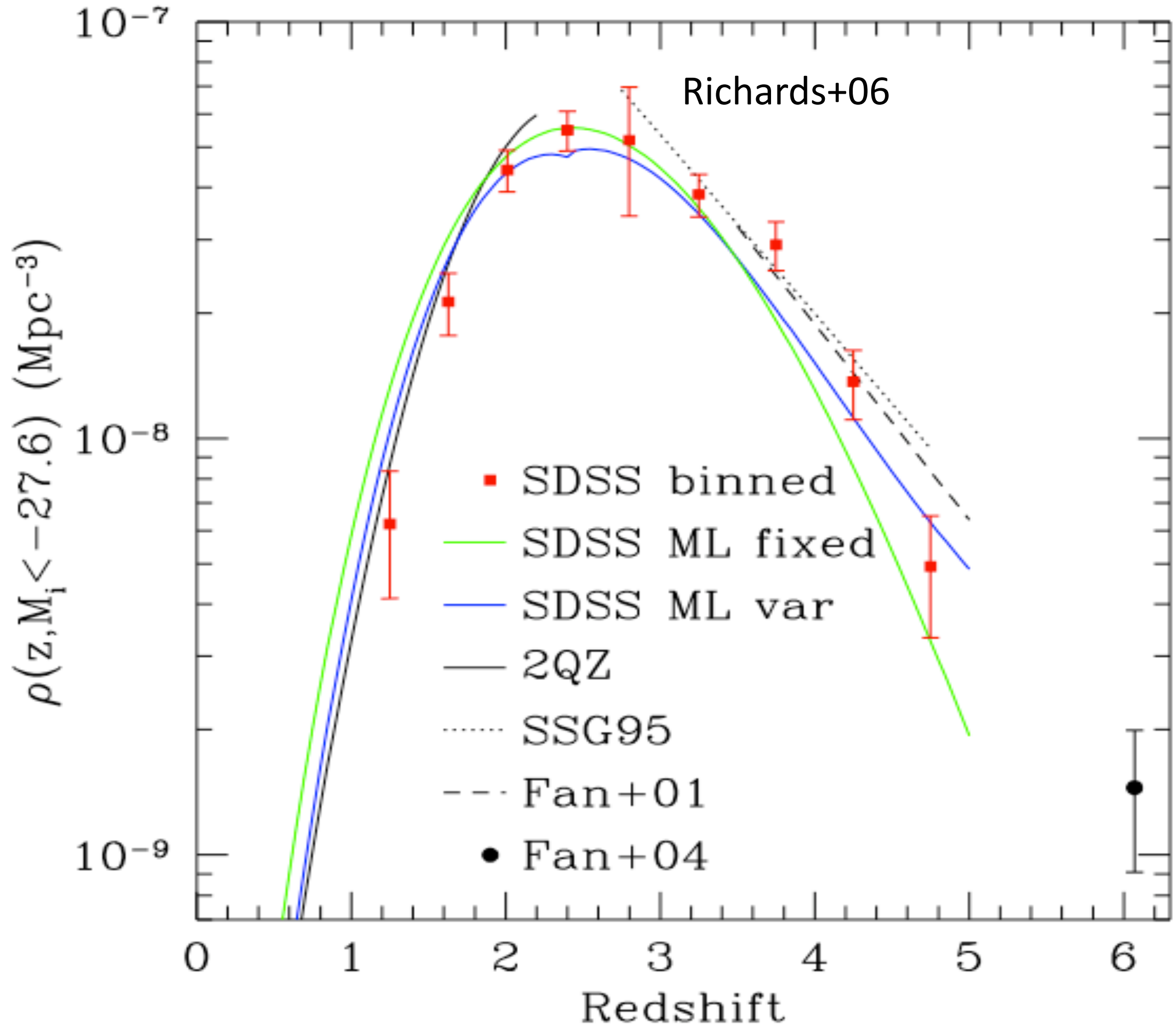
High-z QSOs are rare



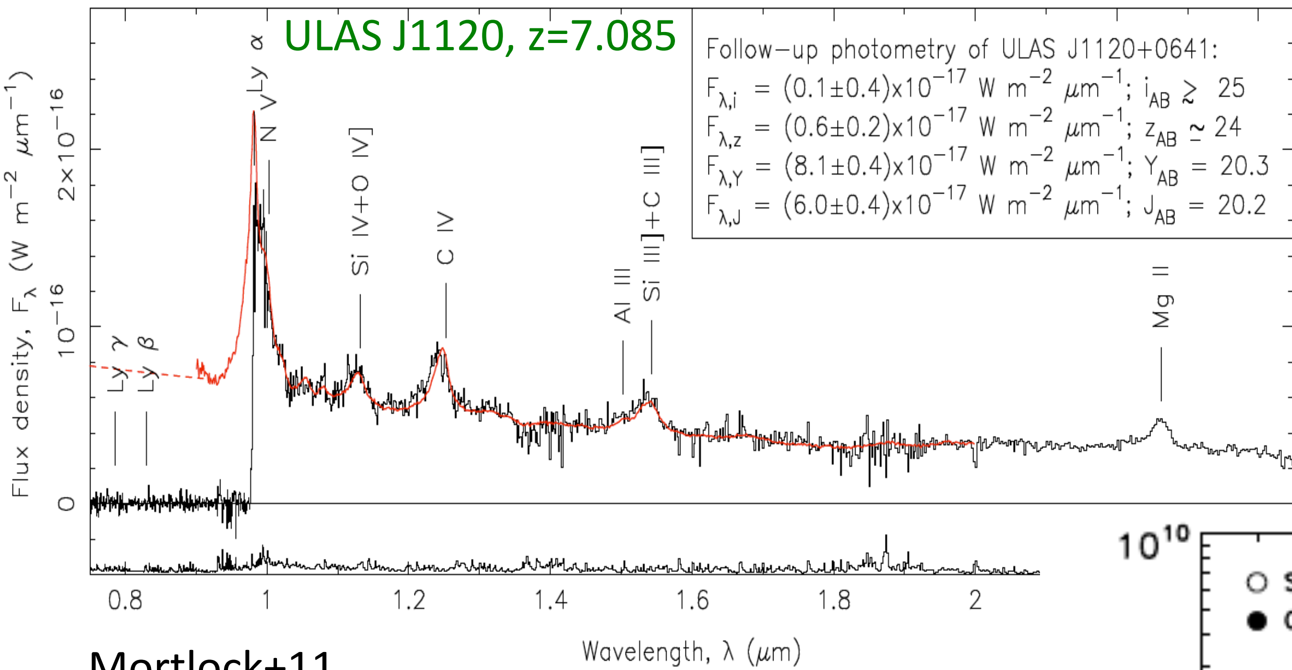
~ 1 every 500 deg^2 at z_{AB}<20 (➔ only ~80 in the whole Universe)

~ 1 every 40 deg^2 at z_{AB}<22

High-z QSOs are rare: 1 per comoving Gpc^3



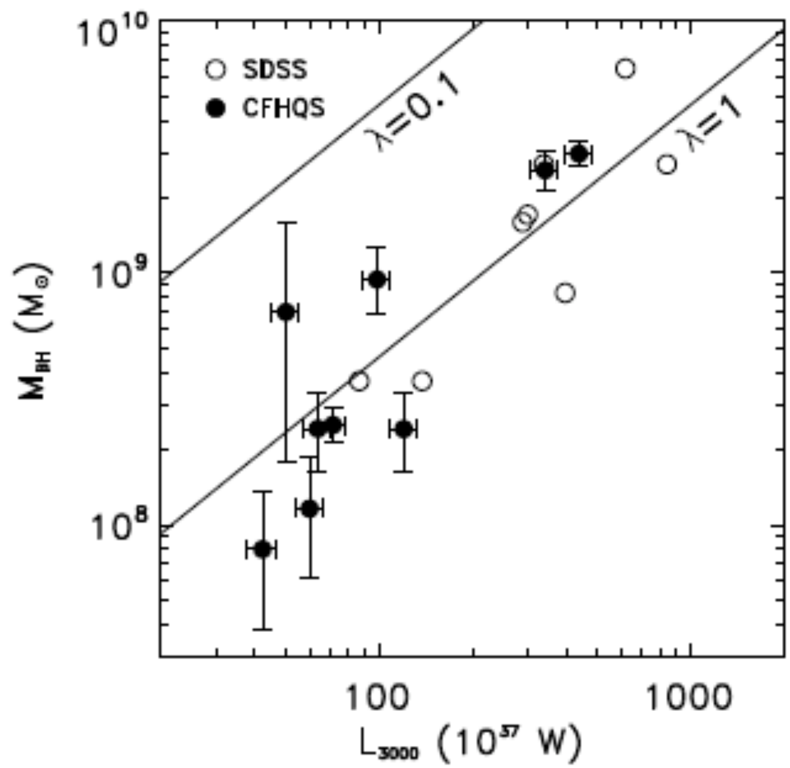
High-z QSOs are similar to low-z QSOs



The most distant QSO known

Mortlock+11

Willott+09



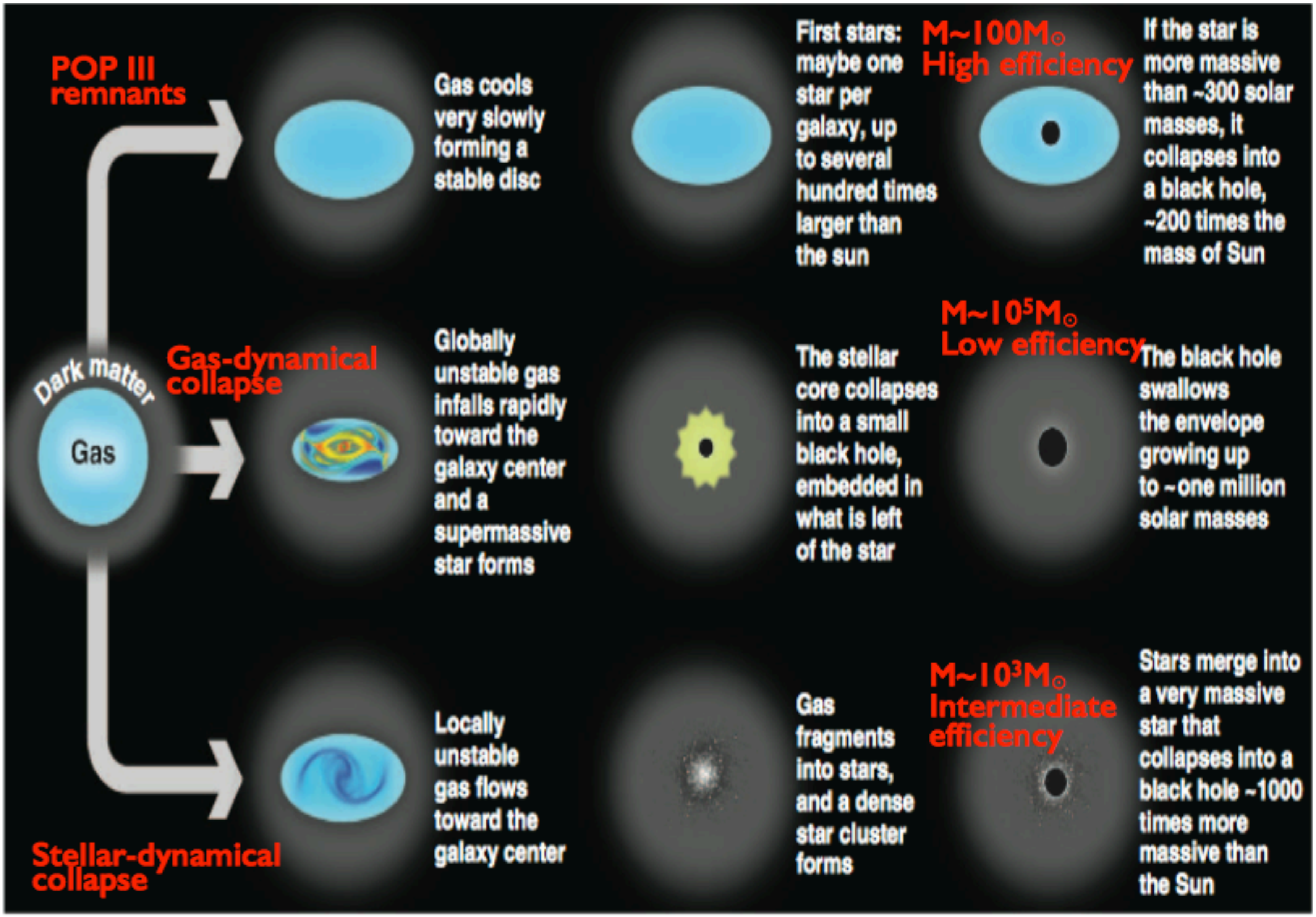
They are powered by massive SMBHs accreting at their Eddington limit

$M_{BH} \sim 10^8 - 10^{10}\ M_{sun}$

$L \sim L_{Edd}$

Some hypotheses on BH seeds

Volonteri 2010

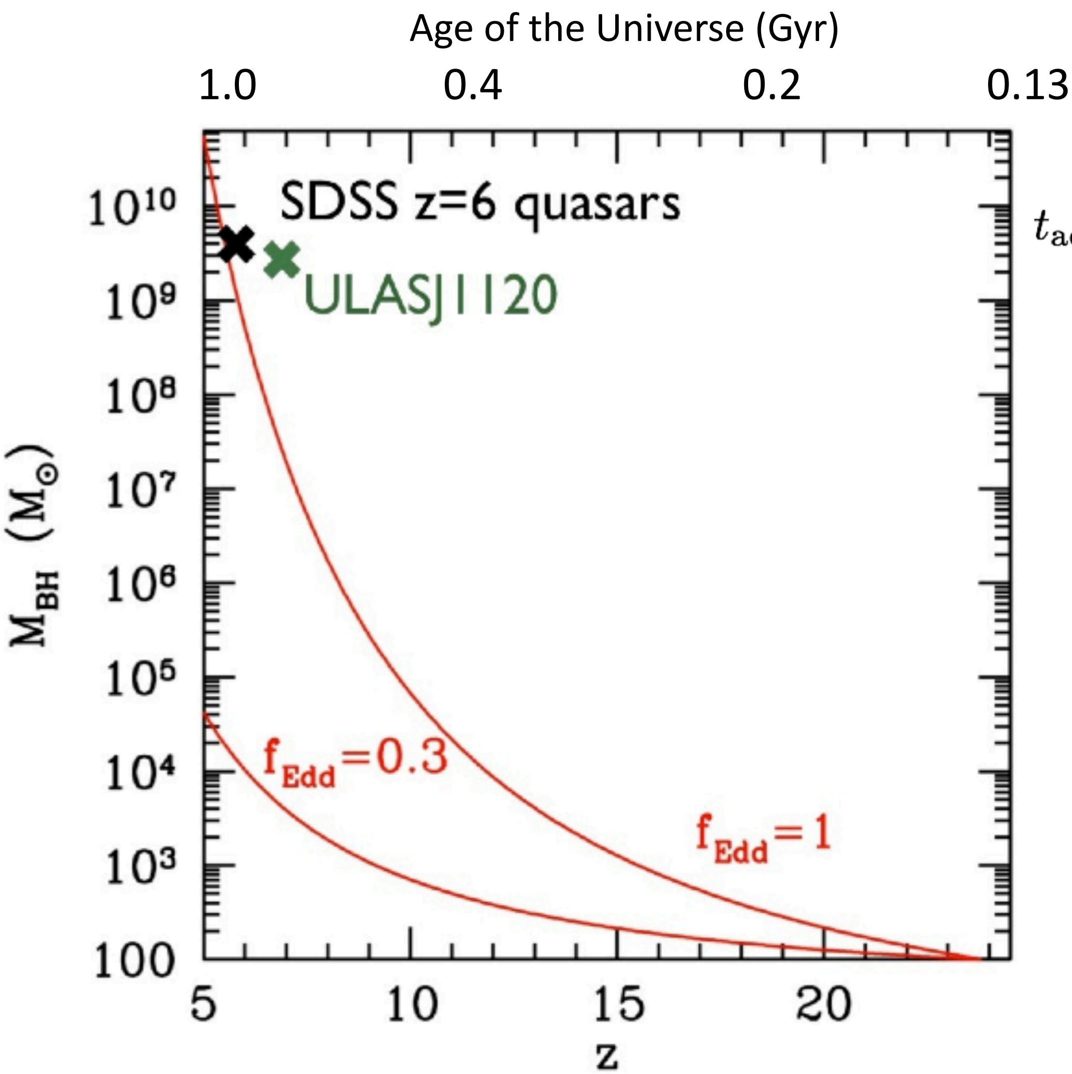


light seeds

heavy

intermediate

How did they grow to 10^9 M_{sun} in less than 1 Gyr?



$$t_{acc} = 0.45 \text{ Gyr} \frac{\epsilon}{1-\epsilon} f_{\rm Edd}^{-1} \ln(M_{\rm fin}/M_{\rm in})$$

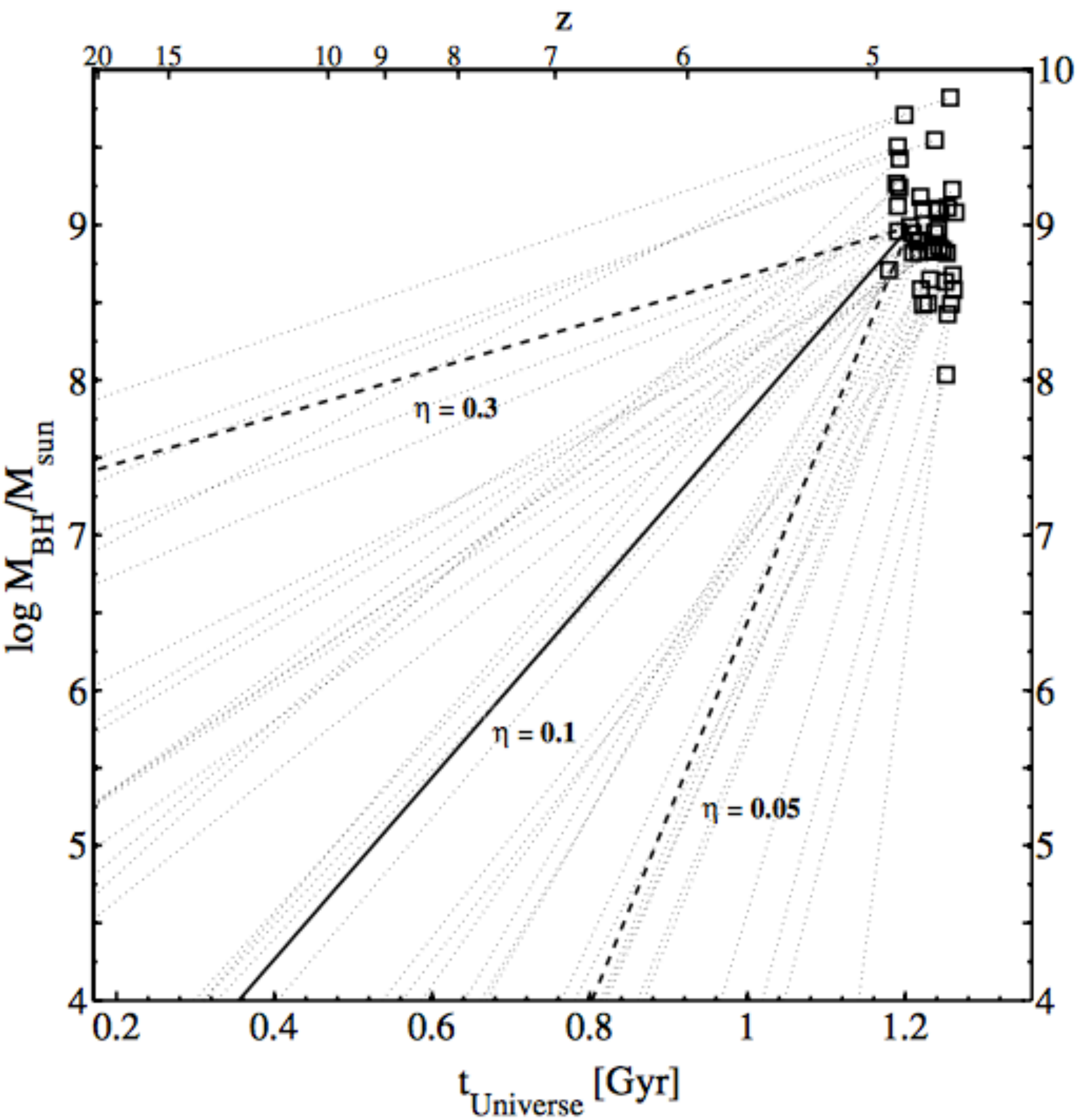
stellar (light) seeds require continuous accretion at f_{Edd}=1 since z > 20 (for ε=0.1)

➔

massive (10^{4-6} M_{sun}) seeds direct collapse black holes?

From F. Haardt

How did they grow to 10^9 M_{sun} in less than ~1 Gyr?

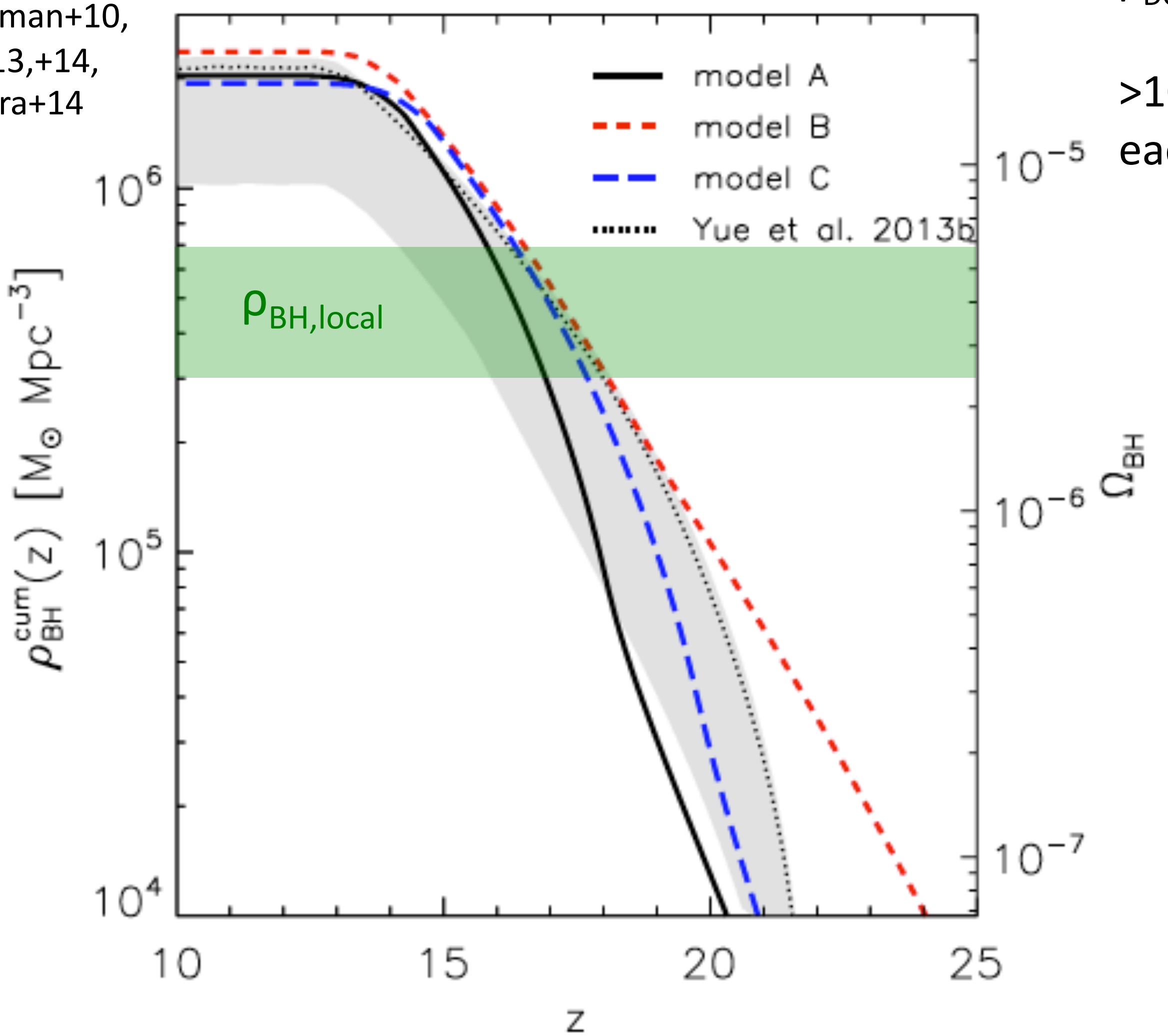


Trakhtenbrot+11

Heavy seeds?

Direct Collapse Black Holes (10^4-10^6 M_{sun})

Volonteri+08,
Begelman+10,
Yue+13,+14,
Dijkstra+14



Yue+14

$\rho_{DCBH} > \rho_{BH,local}$ →

>100-1000 dormant DCBHs for each local galaxy: too many?

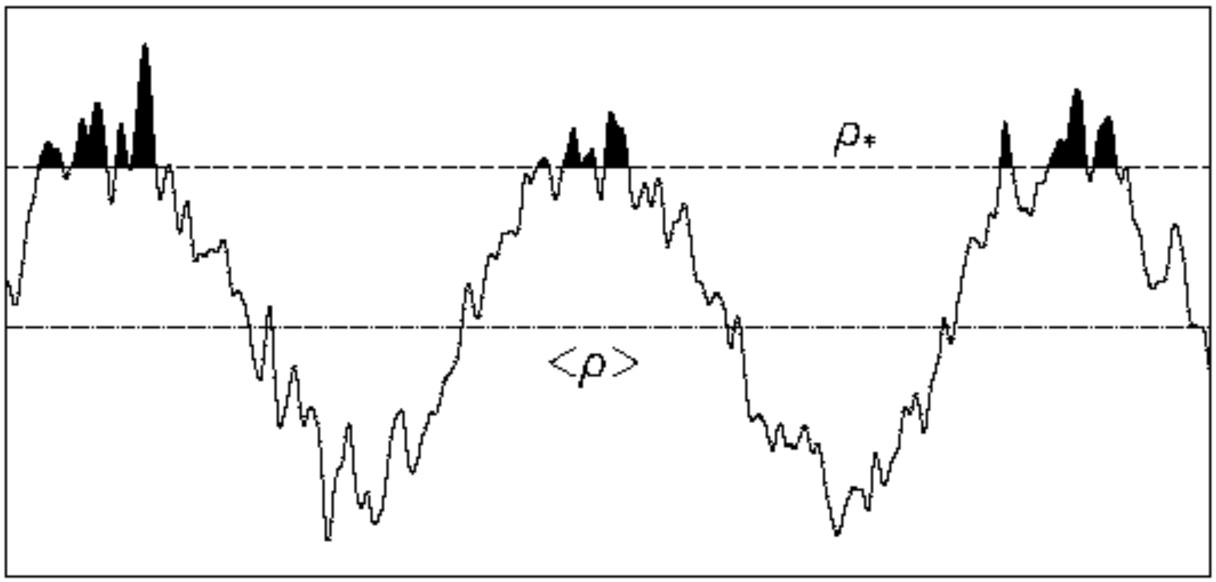
Possible solutions?
Super-Eddington growth from 10^2 M_{sun} seeds (Madau+14, Volonteri & Silk 14)
selective accretion,
multi-seed populations (Schneider & Valiante)

Early accreting SMBHs are:

1) rare. 1 per Gpc^3, like 10^{13} M_{sun} halos (for duty cycle=1)

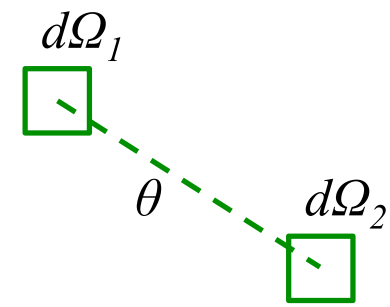
2) big. $M_{BH} = 10^9\ M_{sun} \rightarrow M_* = 10^{11\text{-}12}\ M_{sun} \rightarrow M_{halo} = 10^{12\text{-}13}\ M_{sun}$

are they highly clustered?



Djorgovski 2005

Correlation function



angular correlation function $w(\theta)$

$$dP = n^2[1 + w(\theta)]d\Omega_1 d\Omega_2$$

excess probability over random of finding one galaxy within the solid angle $d\Omega_1$ and another galaxy within $d\Omega_2$ separated by an angle θ

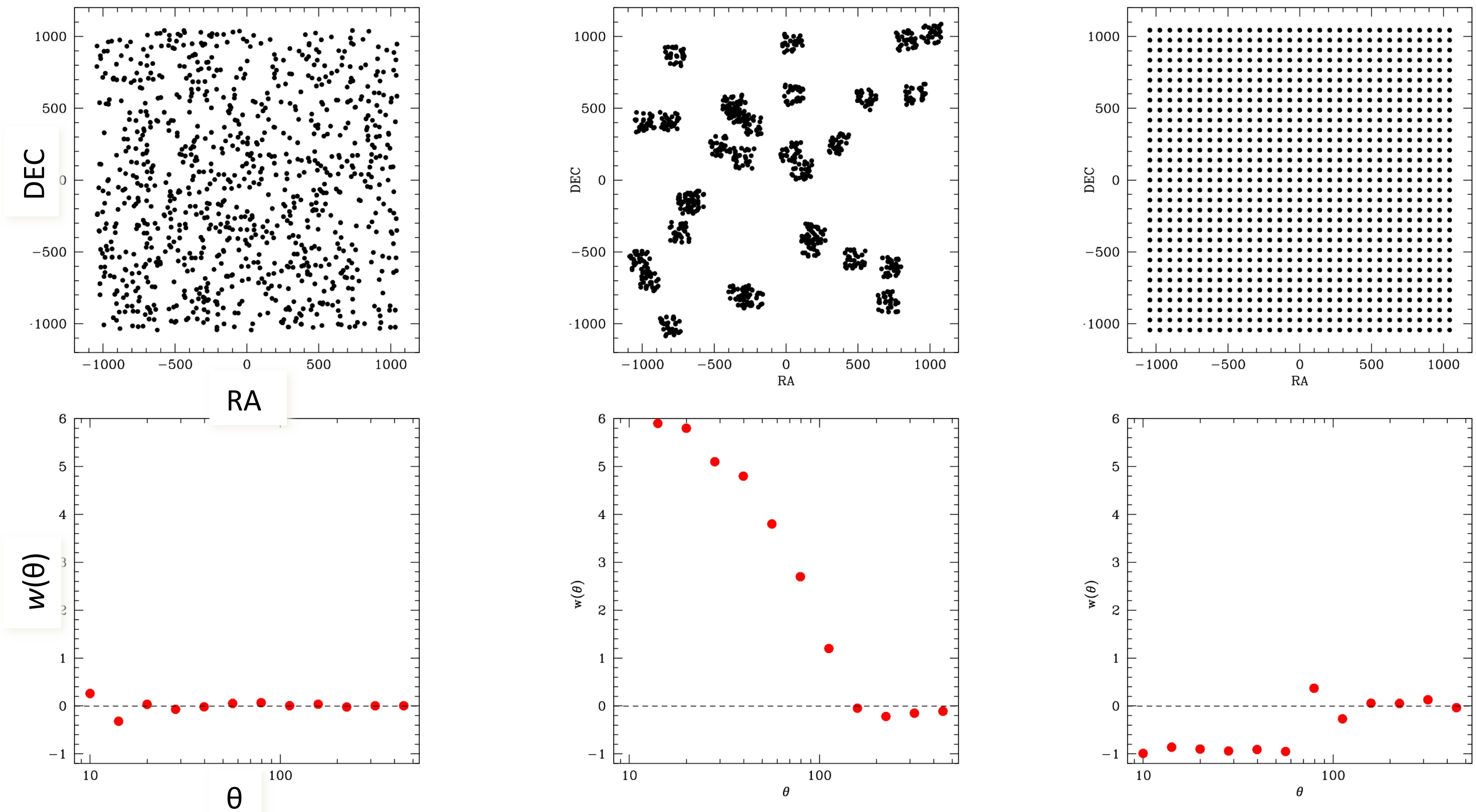
Spatial correlation function $\xi(r)$

$$dP = n^2[1 + \xi(r)]dV_1 dV_2$$

$$\xi(r) = (r/r_0)^{-\gamma}$$

Some examples

$$dP = n^2[1 + w(\theta)]d\Omega_1 d\Omega_2$$



Random

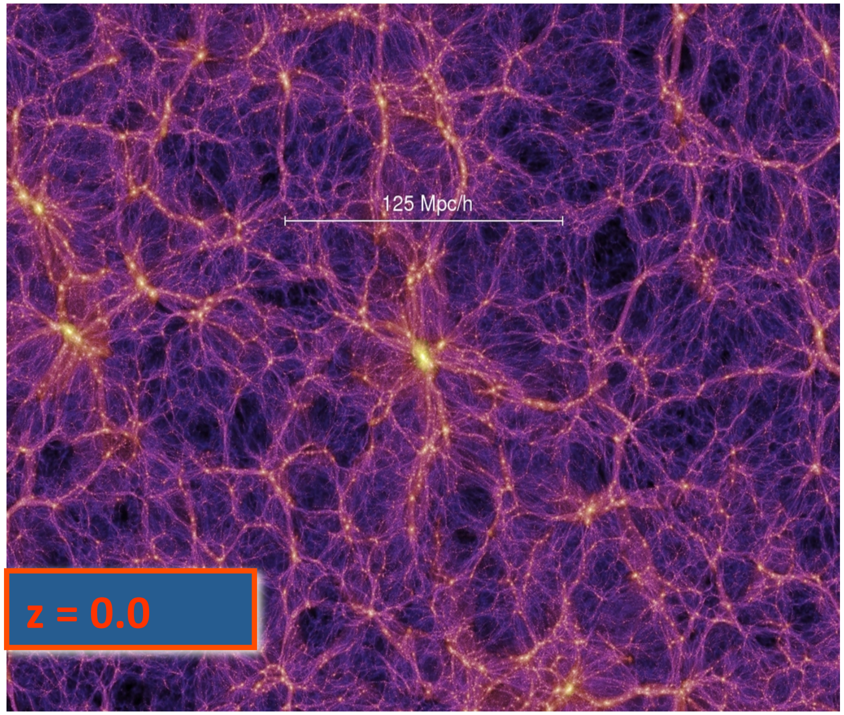
Highly clustered

Grid

Galaxy (or AGN) bias b

$$b^2(r,z,M) = \xi_g(r,z,M)/\xi_m(r,z)$$

ξ_g= galaxy (or AGN) corr. function ξ_m= dark matter corr. function

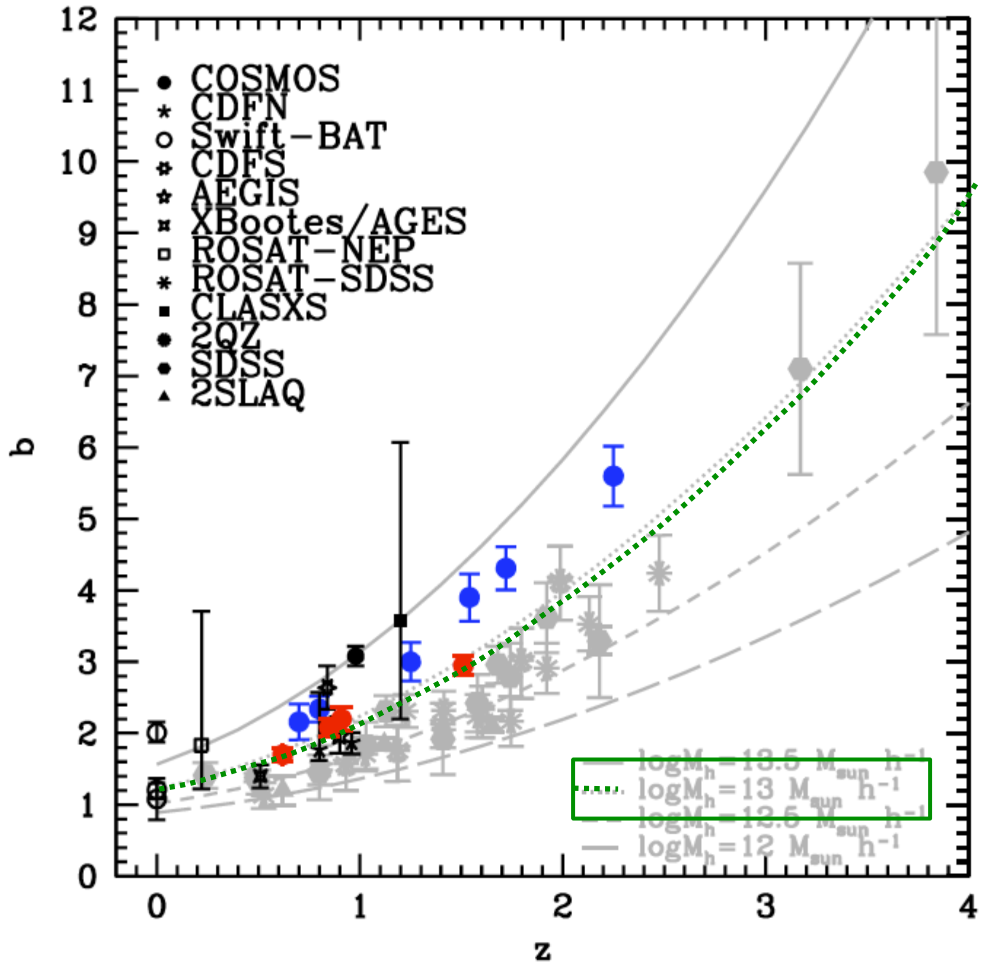


Early accreting SMBHs are:

1) rare. 1 per Gpc^3, like 10^{13} M_{sun} halos (for duty cycle=1)

2) big. $M_{BH} = 10^9$ M_{sun} → $M_* = 10^{11-12}$ M_{sun} → $M_{halo} = 10^{12-13}$ M_{sun}

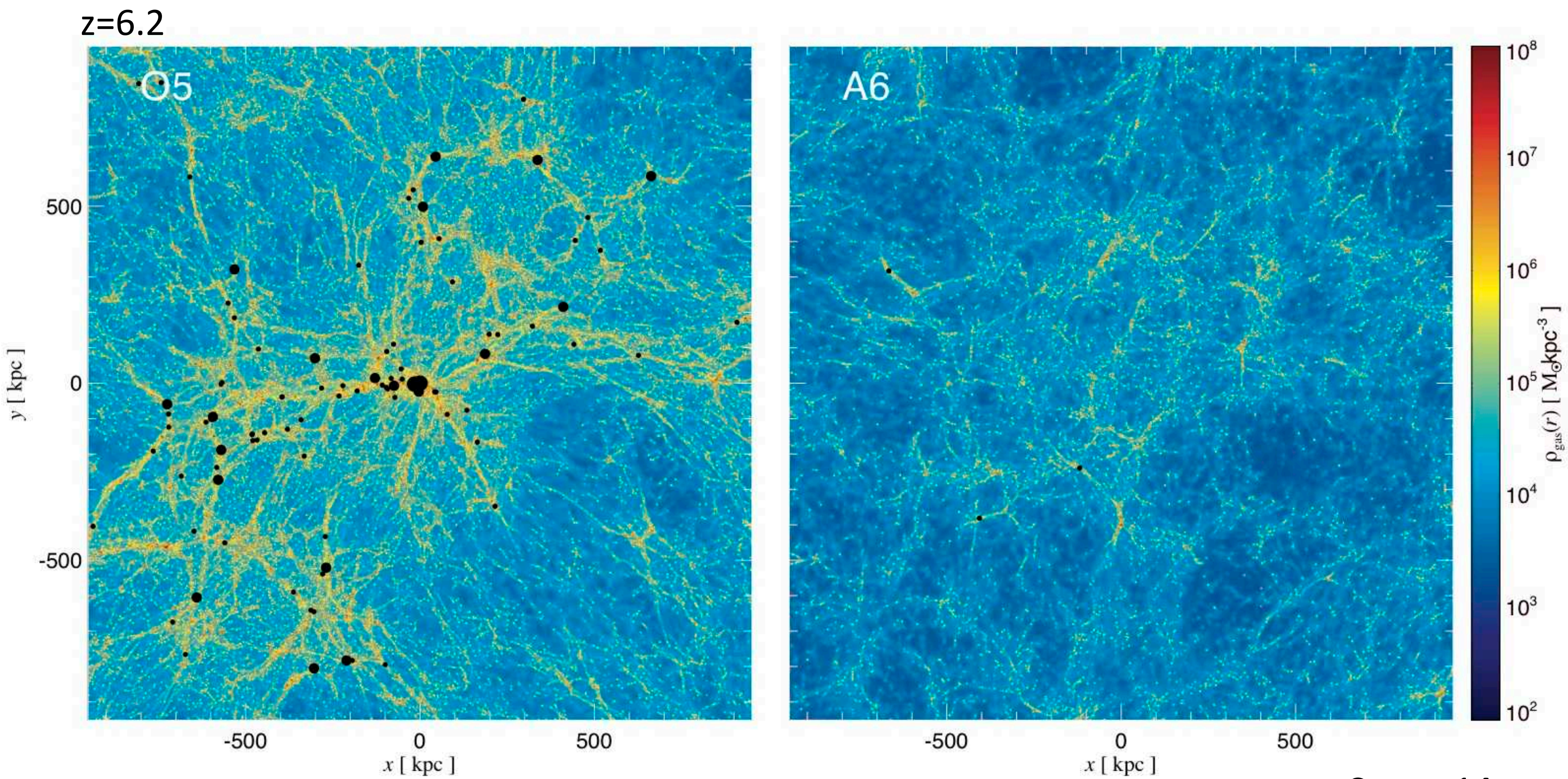
3) likely highly biased → $M_{halo} \sim 10^{13}$ M_{sun} extrapolating from clustering at lower z



They likely reside in the most massive halos → search for galaxy overdensities

Adapted from Cappelluti+12

Simulations of early BH formation



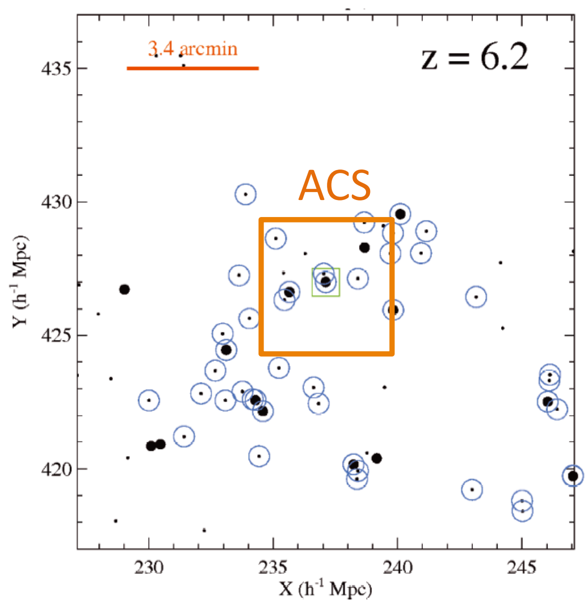
Costa+14

According to (most) simulations, early SMBHs can only form in overdense environments

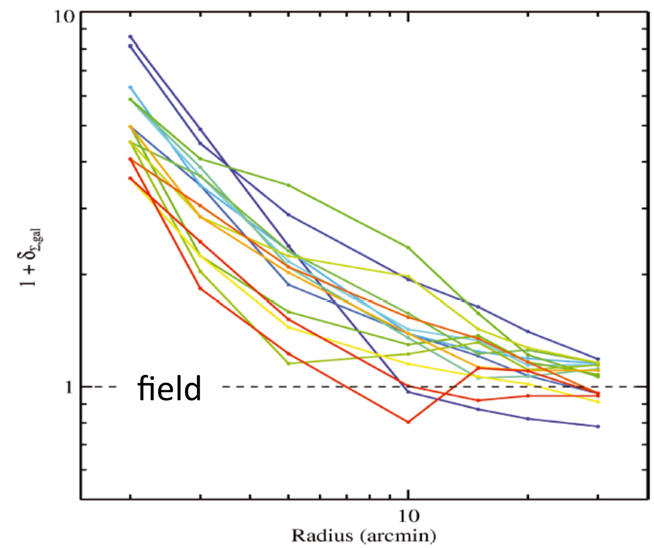
Search for galaxy overdensities around high-z QSOs

Search based on small FoV instruments inconclusive (Stiavelli+05, Kim+09, Husband+13, Banados+13, Simpson+14) e.g. ACS/HST = 3x3 arcmin^2 = 1x1 Mpc^2 at z=6.

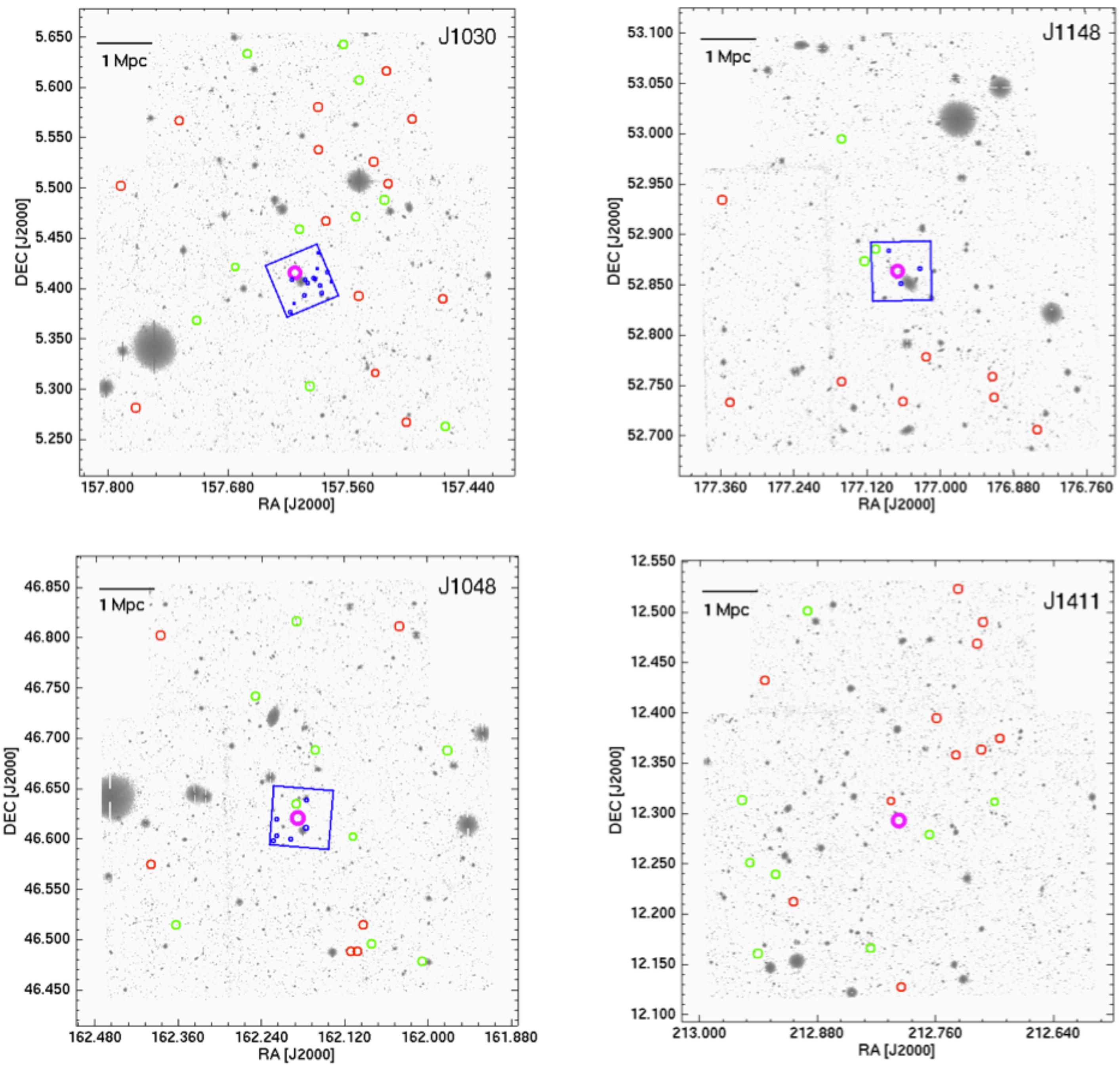
Overdensities might extend up to 30arcmin, i.e 10 phys. Mpc (Overzier+09). Feedback may limit galaxy formation in the QSO vicinity (e.g. Stroemgren radius ~ 2-4 Mpc)



LSSs around protoclusters (Overzier+09)



use LBC@LBT: FoV ~ 25’x25’



Primary cand.

Secondary cand.

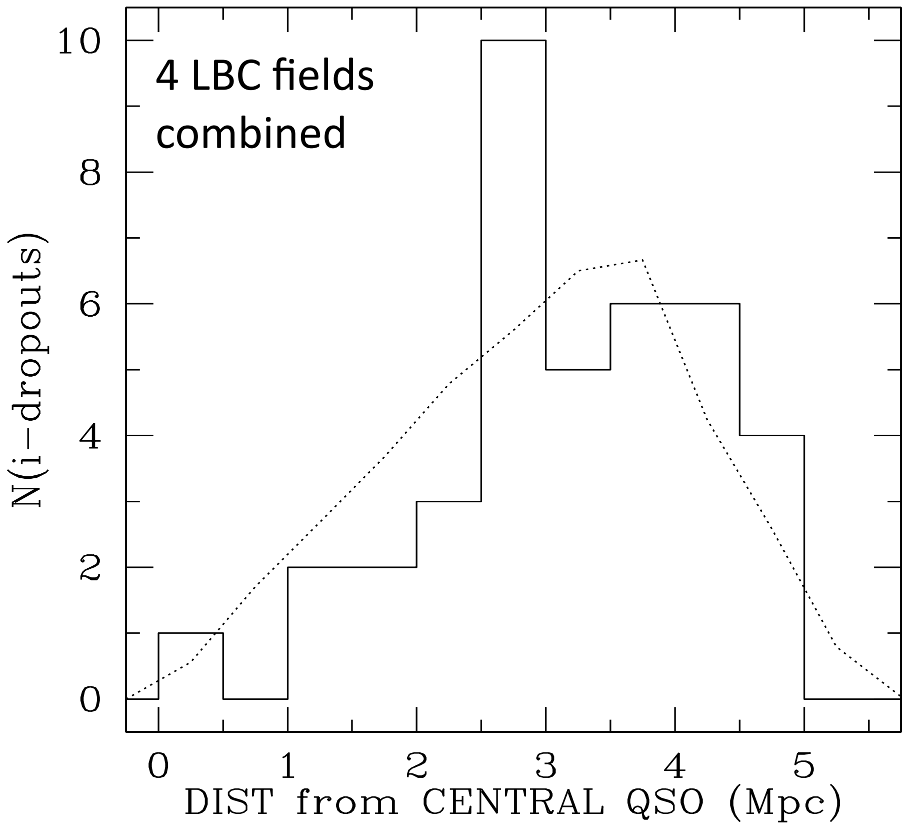
HST/ACS

QSO

Significant overdensities

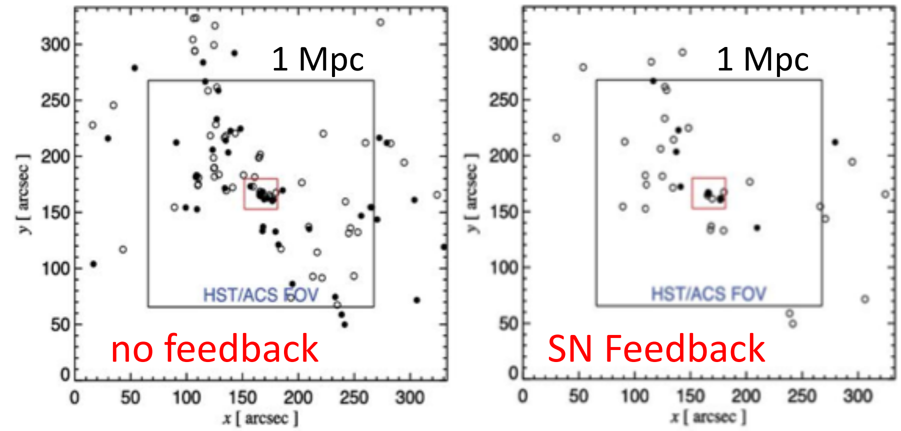
Asymmetric distribution in most fields in agreement with simulations

Reduced galaxy formation close to QSOs?

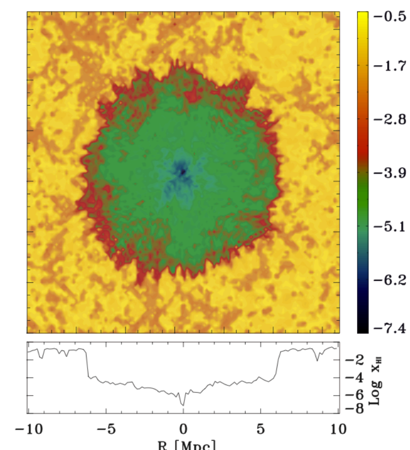


2.4σ evidence for dropout deficit at d<2.5 Mpc
Feedback? (need more statistics)

Stellar winds (e.g. from SNe) Costa+14



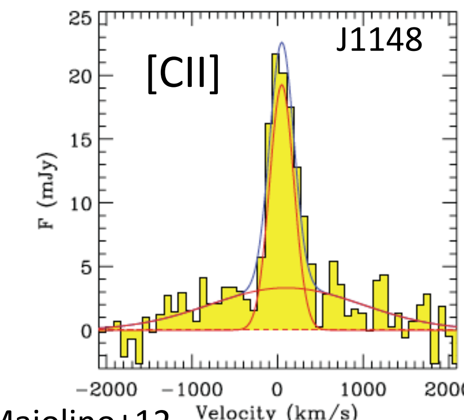
QSO radiation



Maselli+07

R_{Strom} ~ a few Mpc

QSO outflows



Maiolino+12

dM_{out}/dt >3000 M_{sun}/yr
v~1300 km/s
d > 1 Mpc in 10^9 yr