The evolution of the mass functions of active supermassive black holes and their host galaxies out to $z \sim 2$

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BOSS Lunch Talk
UC Berkeley
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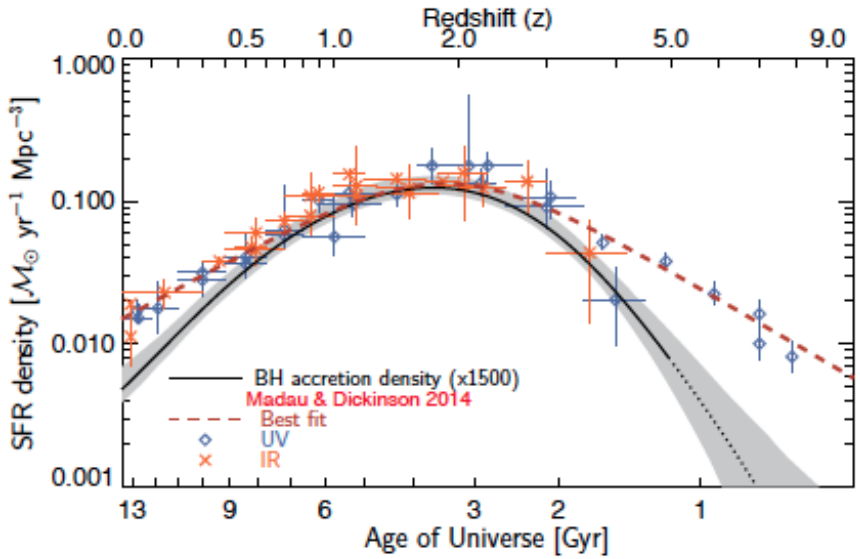
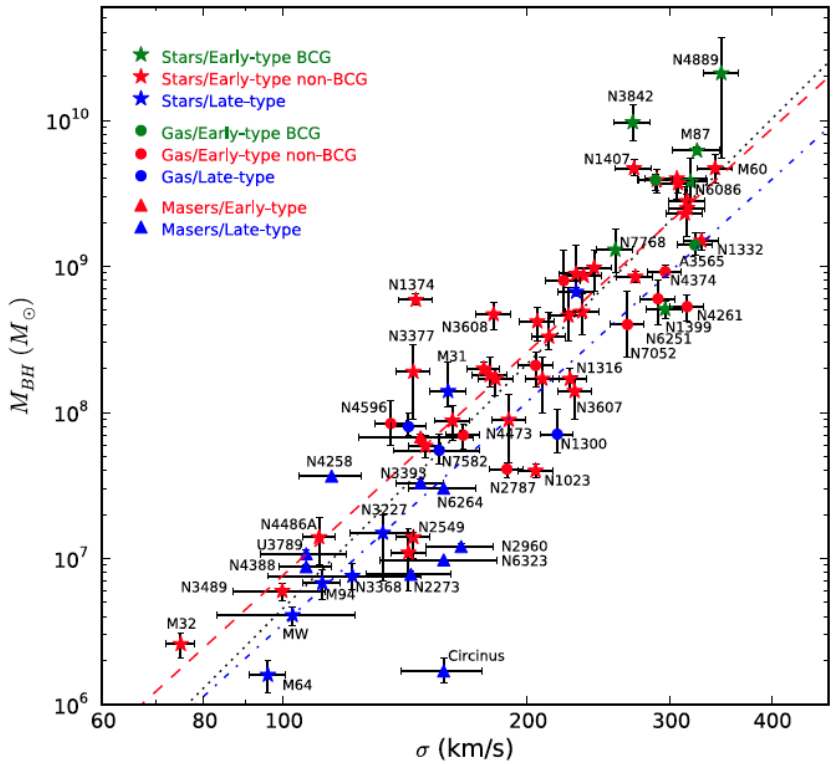
Black hole - galaxy coevolution

integrated cosmic BH accretion history parallel to SF history



Aird et al. (2015)

$M_\bullet - \sigma_*$ relation



McConnell & Ma (2013)

$\Rightarrow$ link between black hole growth and galaxy evolution

$\Rightarrow$ how are black holes growing?

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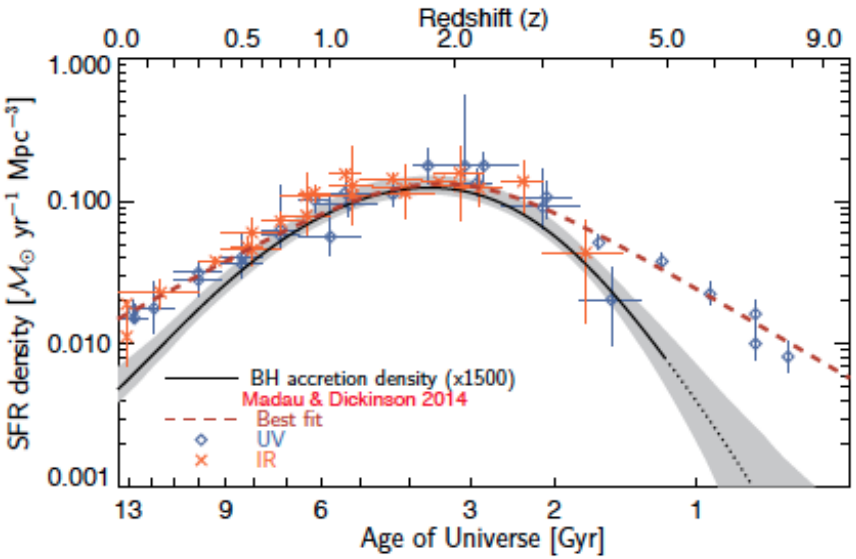

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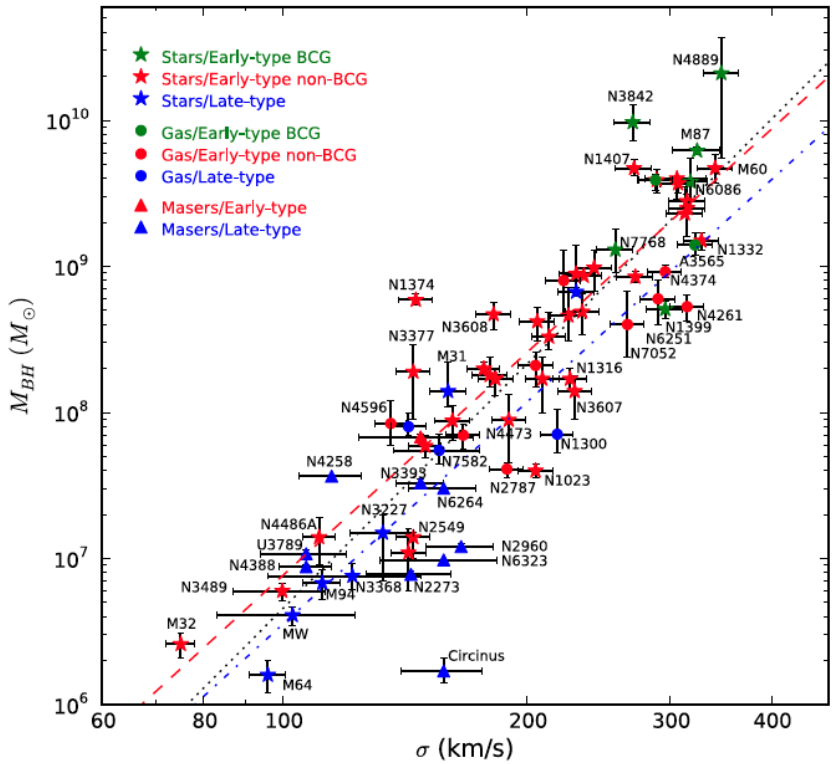
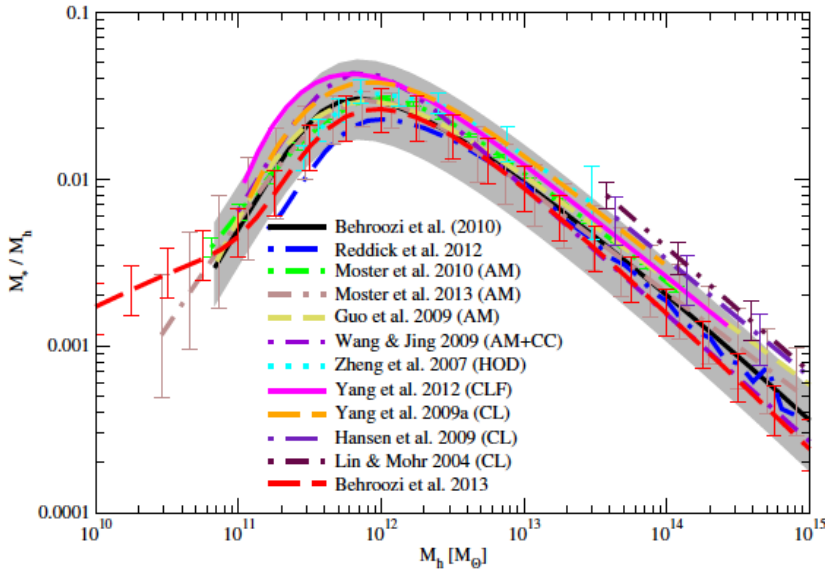


McConnell & Ma (2013)

$\Rightarrow$ link between black hole growth and galaxy evolution

$\Rightarrow$ how are black holes growing? => need census

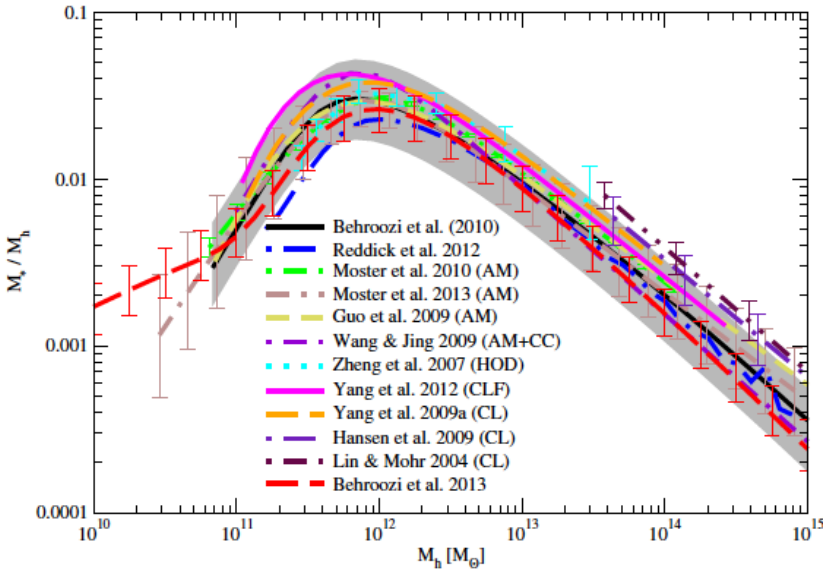
Quenching of star formation: The need for AGN feedback?



Behroozi et al. (2013)

- mechanism required to shut off star formation in massive galaxies => AGN Feedback!?
- transition of galaxies from star forming main sequence to passive red galaxies via SF quenching

Quenching of star formation: The need for AGN feedback?



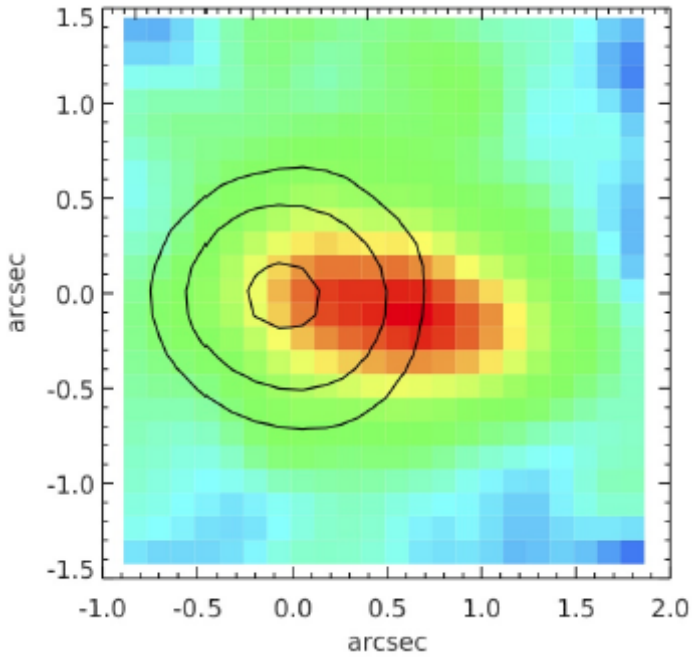
Behroozi et al. (2013)

- mechanism required to shut off star formation in massive galaxies => AGN Feedback!?
- transition of galaxies from star forming main sequence to passive red galaxies via SF quenching

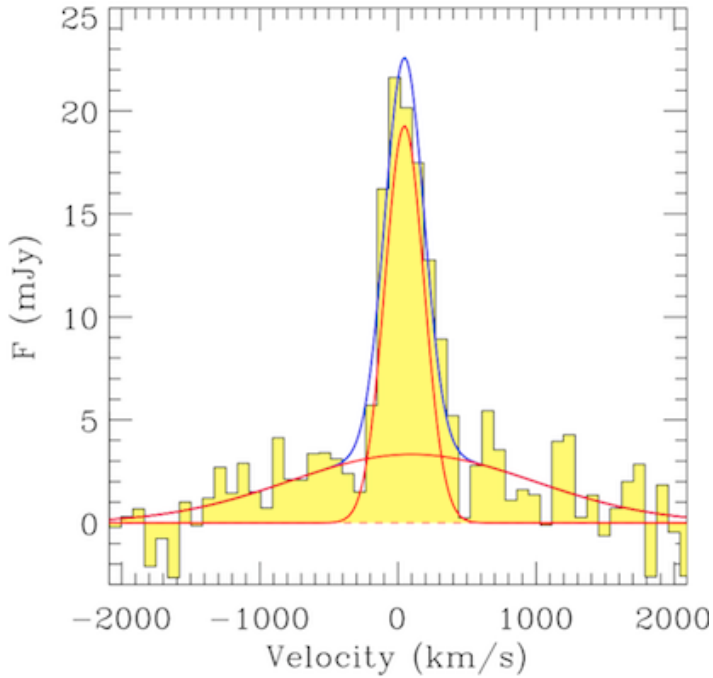
$\Rightarrow$ can AGN provide efficient feedback?

Evidence for AGN feedback via outflows

massive outflows observed in ionized and molecular gas in many AGN host galaxies at $z > 1$



Cresci et al. (2015)



Maiolino et al. (2012)

demographics of outflows and their impact on its host galaxy still open questions

Questions

$\Rightarrow$ How are black holes growing through cosmic time?

$\Rightarrow$ How does their growth relate to their host galaxies?

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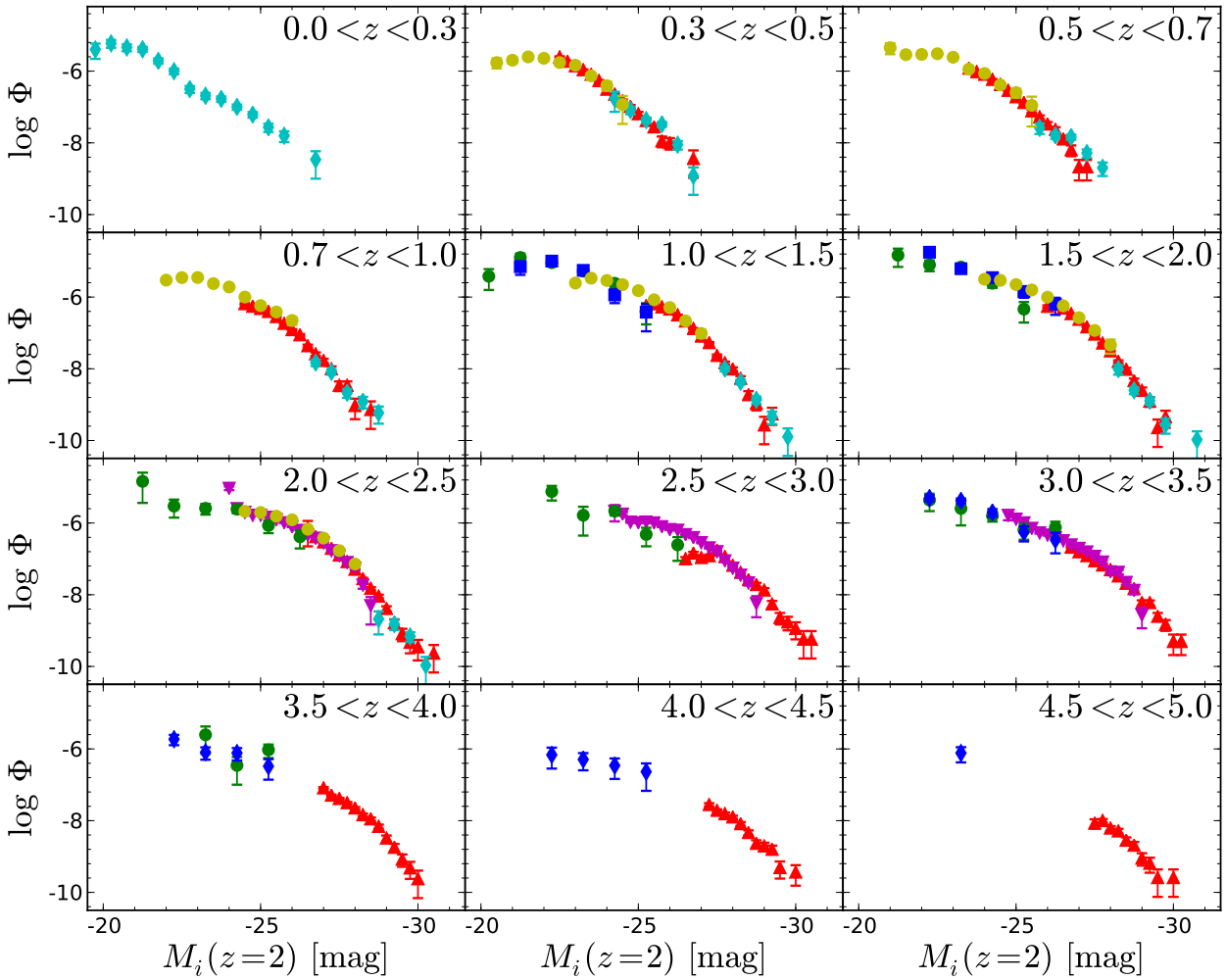
$\Rightarrow$ How does their growth relate to their host galaxies?

$\Rightarrow$ Need a census of black hole growth / AGN activity

AGN demographics: The AGN LF

AGN Luminosity function is main demographic quantity



optical: Schulze et. al (in prep.)

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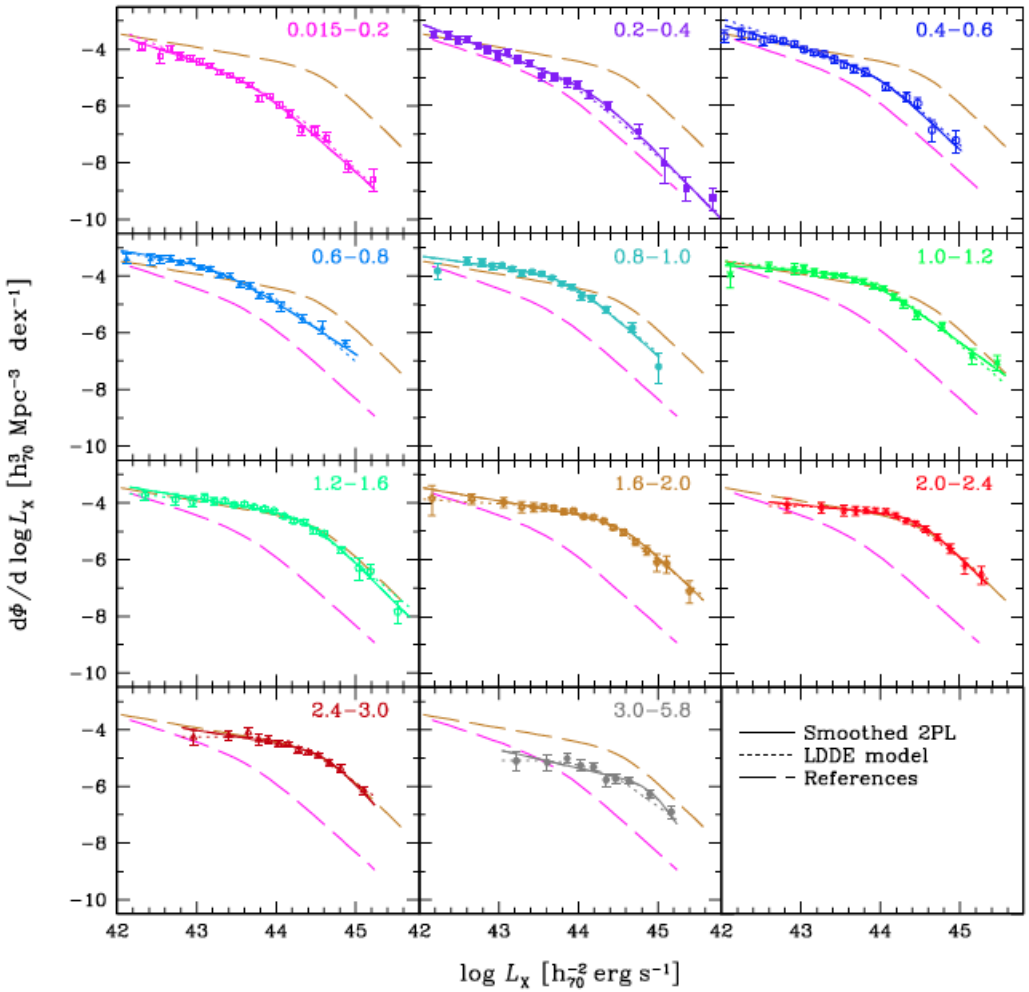
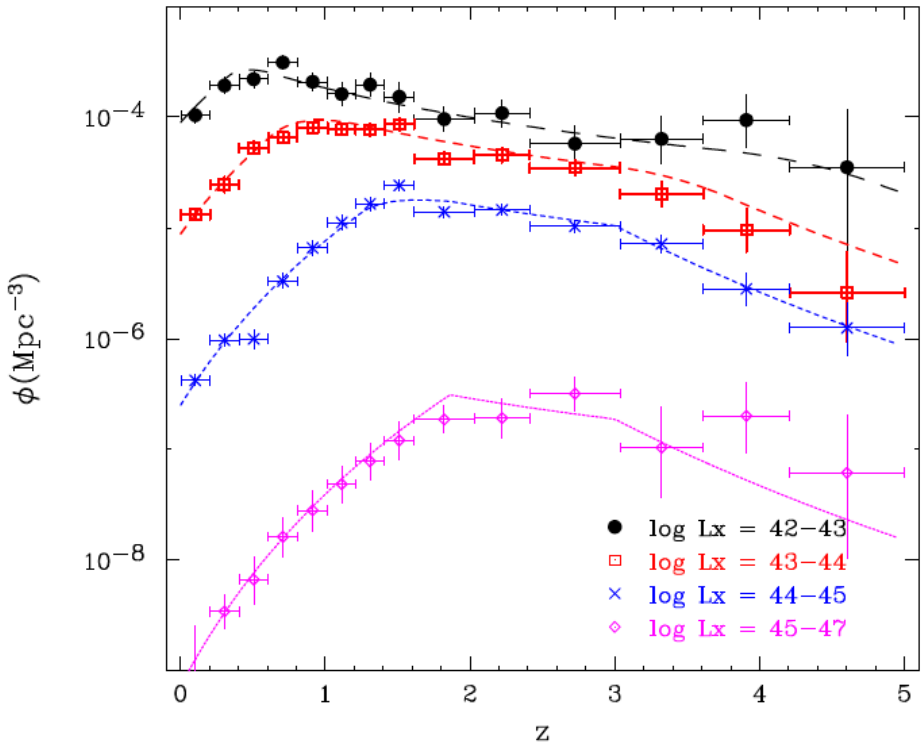


X-ray: Miyaji et. al (2015)

AGN demographics: AGN LF evolution

- space density of bright QSOs peaks at $z \approx 2 - 3$



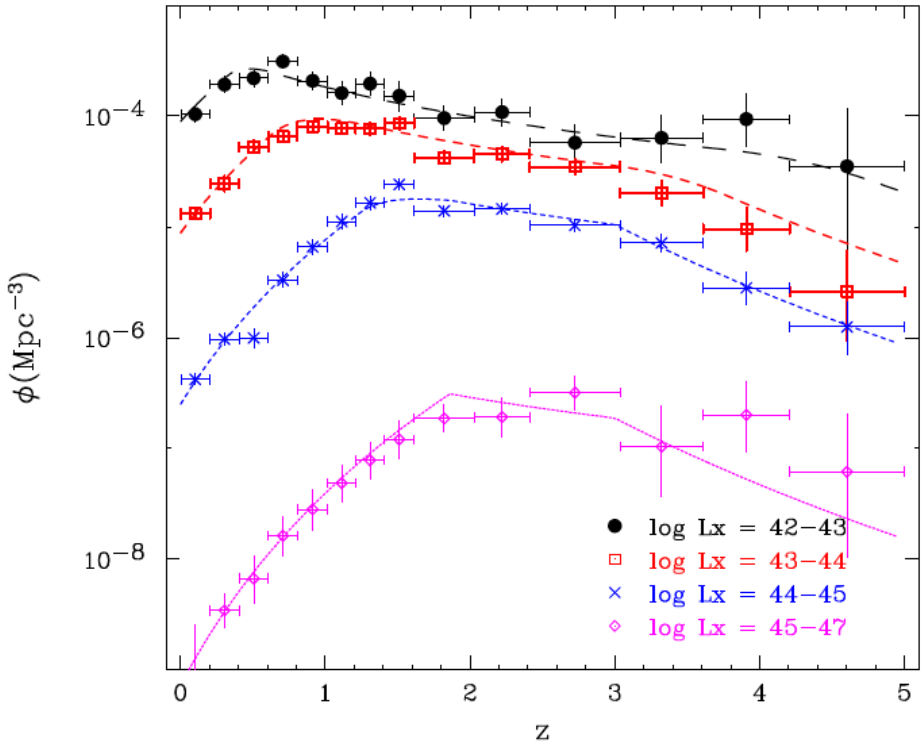
Ueda et. al (2014)

AGN demographics: AGN LF evolution

- space density of bright QSOs peaks at $z \approx 2 - 3$
- peak is shifted towards lower z for fainter AGN

$\Rightarrow$ AGN cosmic downsizing

$\Rightarrow$ implies anti-hierarchical BH growth

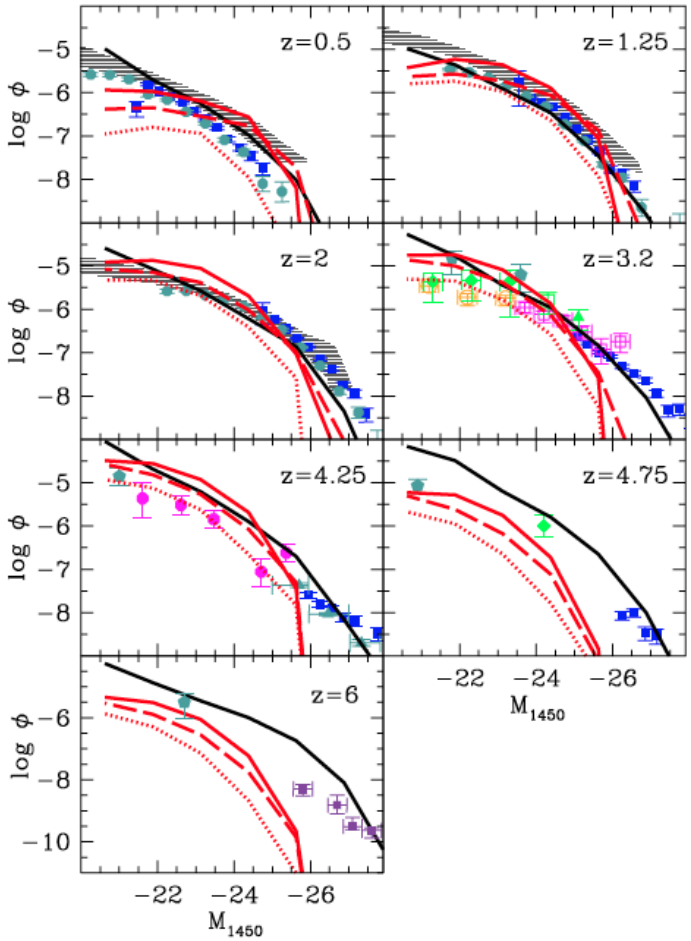


Ueda et. al (2014)

Constraints on theoretical models

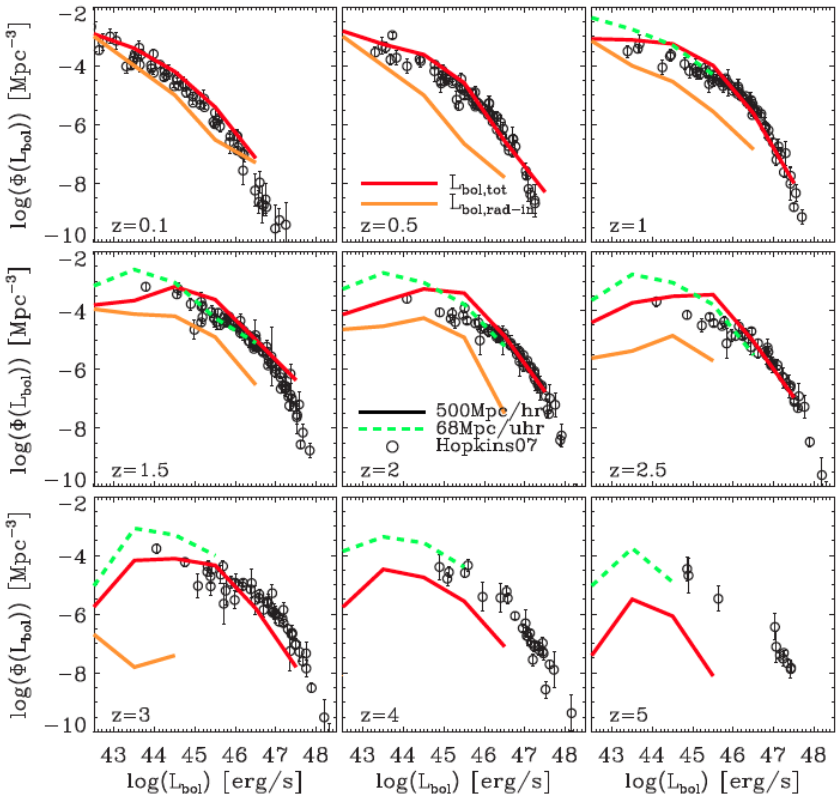
- SAMs & numerical simulations able to reproduce AGN LF and downsizing

SAMs



Menci et. al (2014)

Numerical simulations



Hirschmann et al. (2014)

How can we trace black hole growth?

Limitation of AGN LF:

Physical quantities of black holes:

- black hole mass $M_\bullet$
- accretion rate / Eddington ratio $\lambda = L_{\rm bol}/L_{\rm Edd}$

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Active black hole mass function - $\Phi_\bullet(M_\bullet)$
Eddington ratio distribution function - $\Phi_\lambda(\lambda)$

- well-defined AGN sample
- black hole mass estimates => viral method: $M_\bullet \propto L_{5100}^{0.5} \Delta V^2$

The bivariate distribution function of BH mass and Eddington ratio

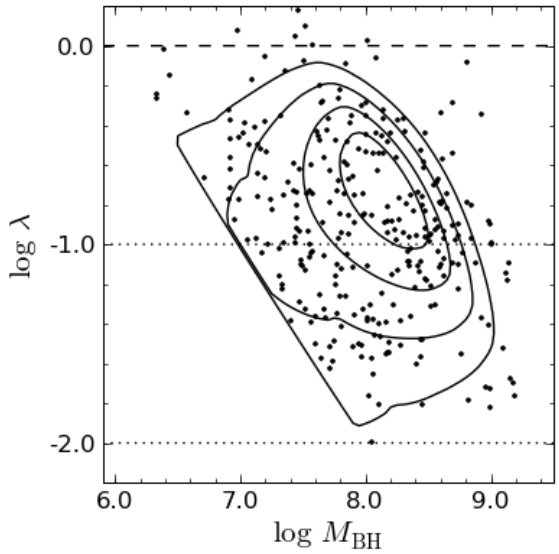
$\Rightarrow$ **active BH:** type-1 AGN with $\log \lambda > -2$

$\Rightarrow$ Black hole mass function (BHMF) and Eddington ratio distribution function (ERDF) determined jointly by fitting probability distribution in $M_\bullet - \lambda$-plane

$\Rightarrow$ via Maximum likelihood method (Schulze & Wisotzki 2010) or via Bayesian framework (Kelly et al. 2009)

ML approach

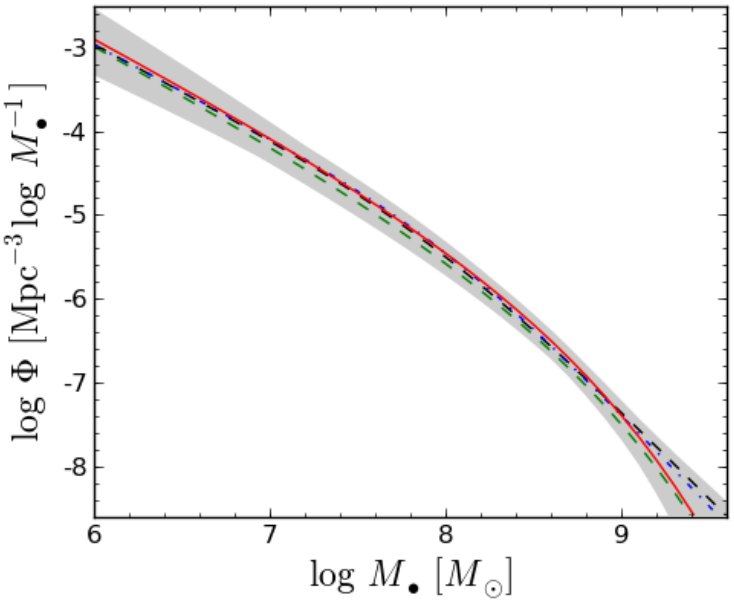
BHMF
$+$ ERDF
$+$ survey selection function
$=$ probability distribution



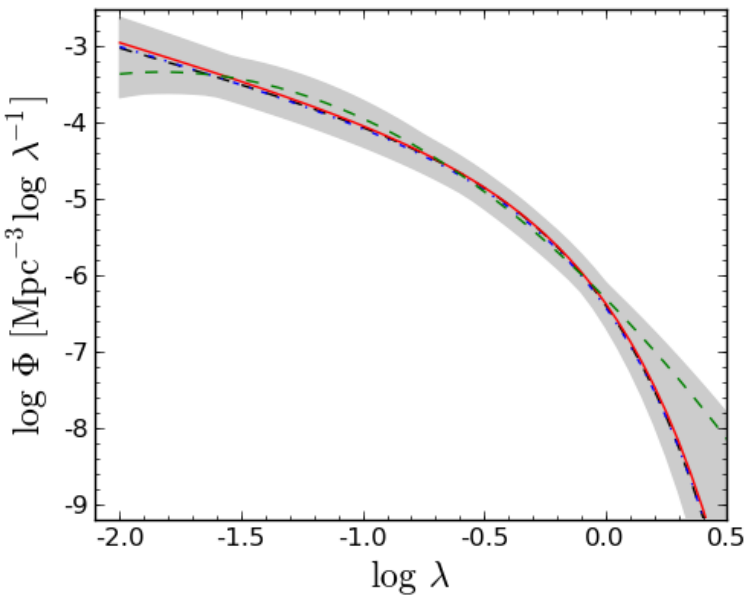
The local active black hole mass function and Eddington ratio distribution function

Local ($z < 0.3$) BHMF and ERDF from the Hamburg/ESO Survey

Active black hole mass function



Eddington ratio distribution function

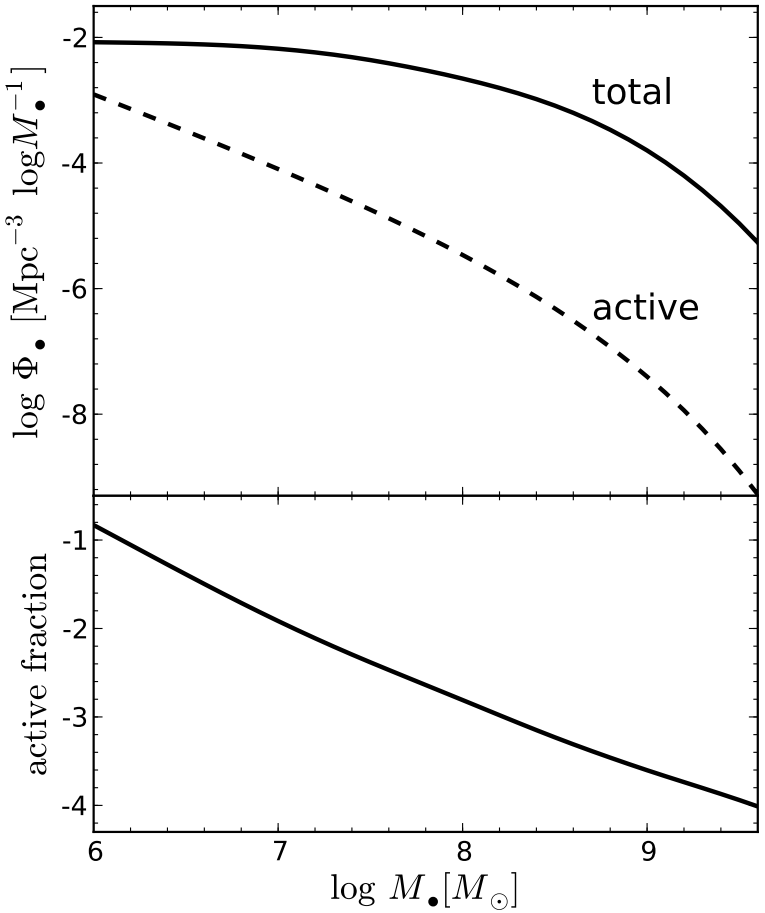


Schulze & Wisotzki (2010)

$\Rightarrow$ No evidence for downturn at low black hole mass or at low Eddington ratio

Active fraction of local black holes

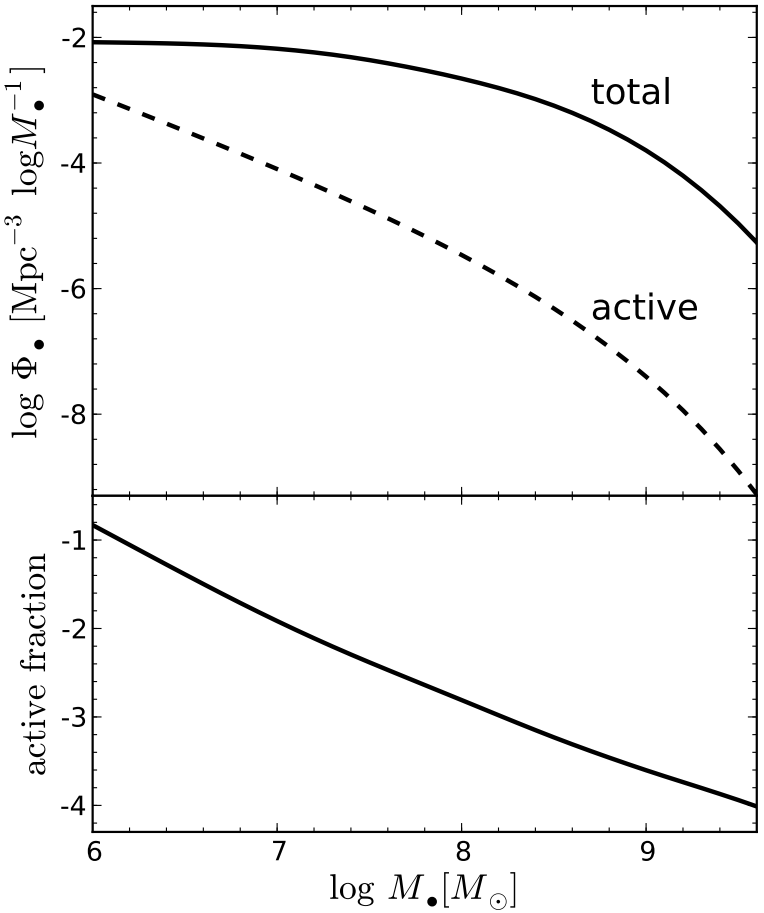
compare to quiescent BHMF of Marconi et al. 2004



Active fraction of local black holes

compare to quiescent BHMF of Marconi et al. 2004

- significant decrease of active fraction toward higher $M_\bullet$
- indication for cosmic downsizing in black hole mass

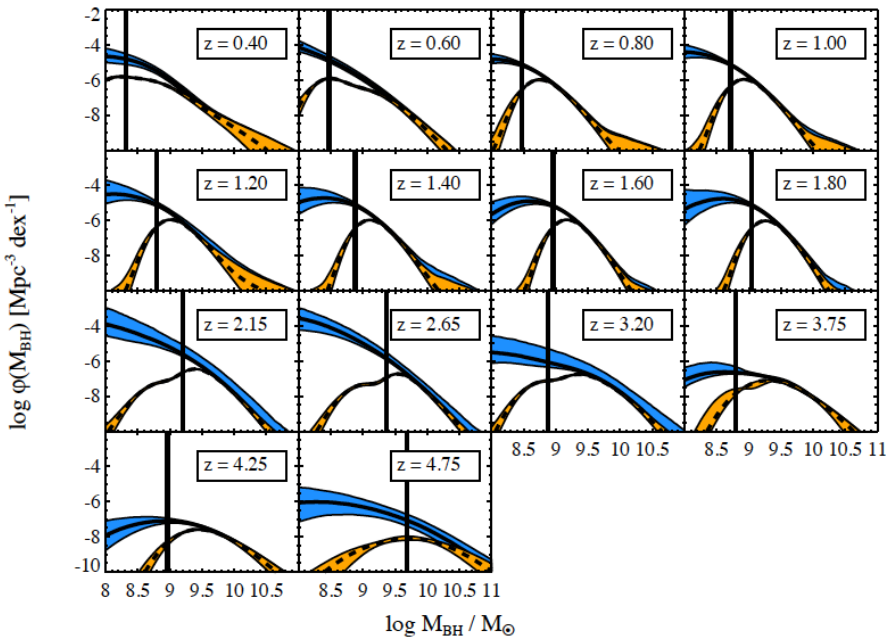


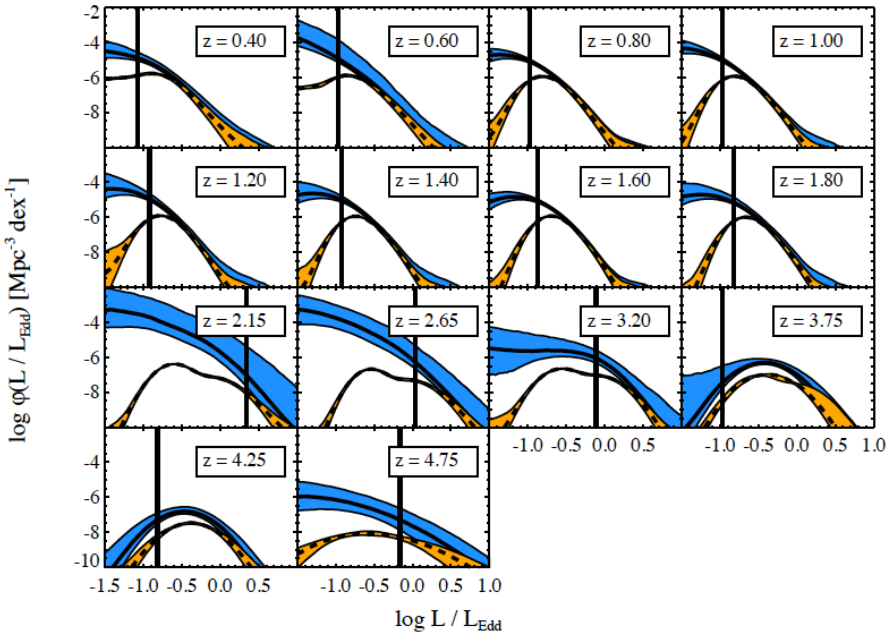
Active BHMF and ERDF at higher redshifts

at $z > 0.4$ BHMF and ERDF determined from SDSS QSO sample

$\Rightarrow$ evidence for black hole mass downsizing

$\Rightarrow$ only high mass end of BHMF, high λ end of ERDF





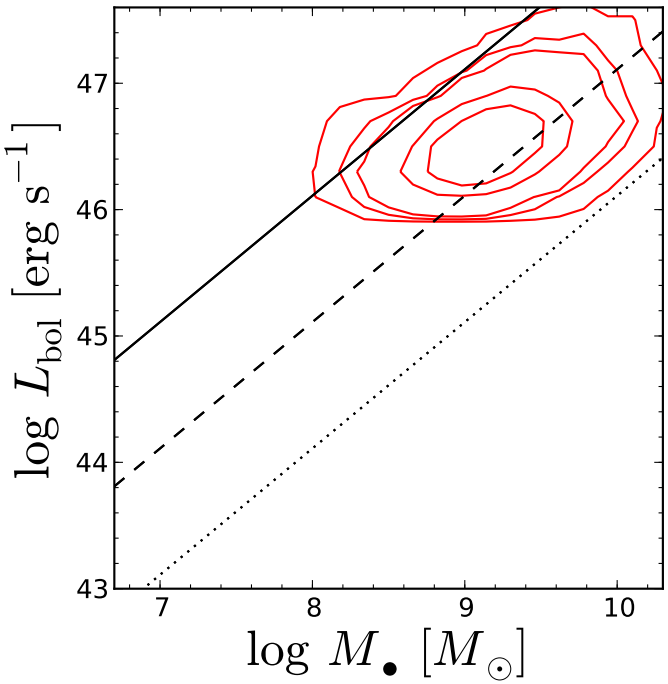
Kelly & Shen (2013)

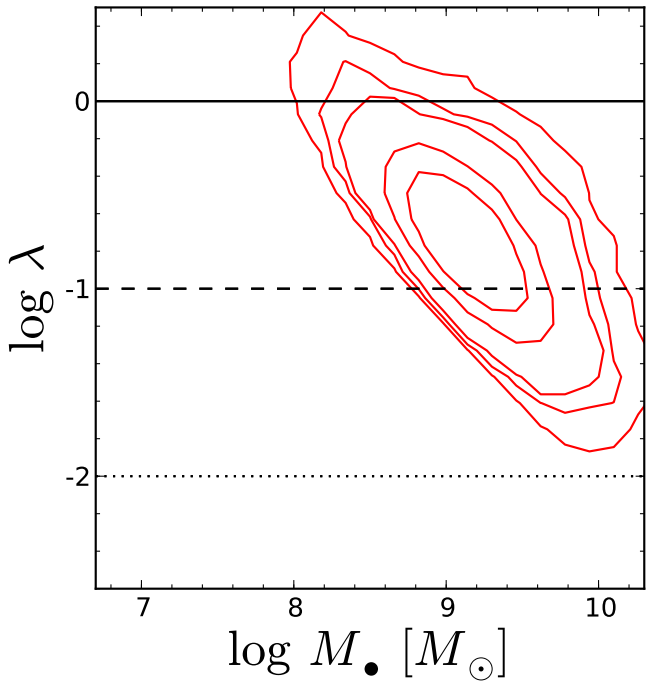
BH demographics at $1 < z < 2$

combine bright, large area surveys (**SDSS**) with deep, small area AGN surveys (**VVDS, zCOSMOS**)

- $\Rightarrow$ 1.1<z<2.1
- $\Rightarrow$ active BH: type-1 AGN with $\log \lambda > -2$

$\Rightarrow$ SDSS: $\sim$ 28000 AGN





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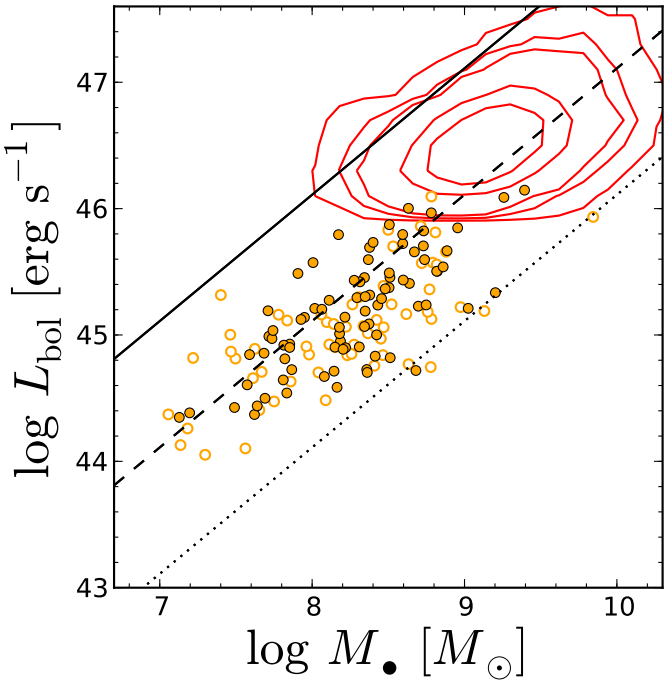

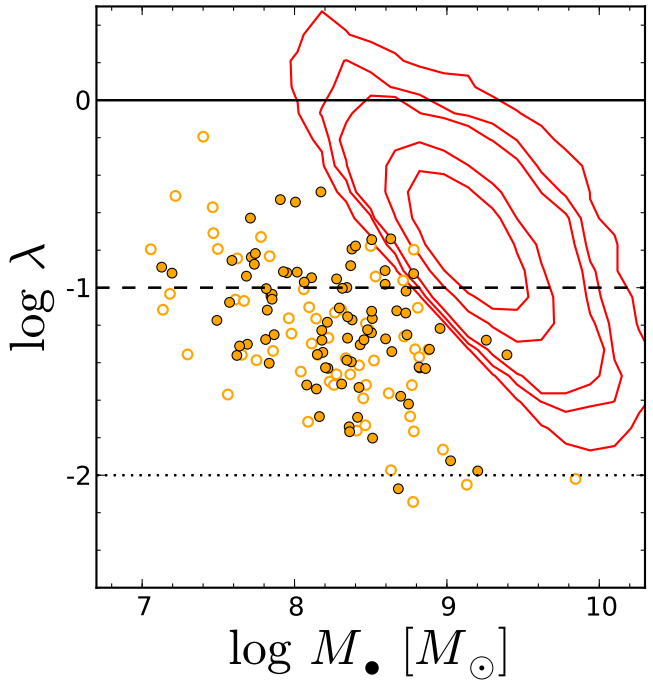

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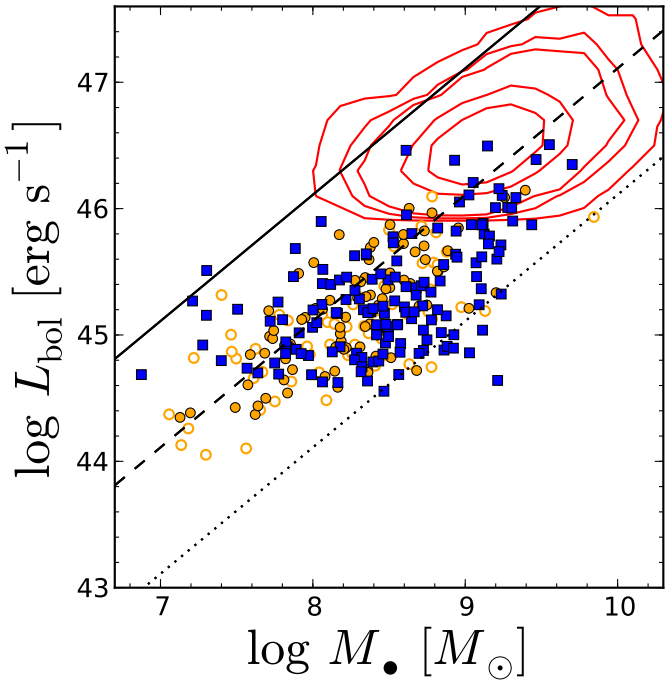
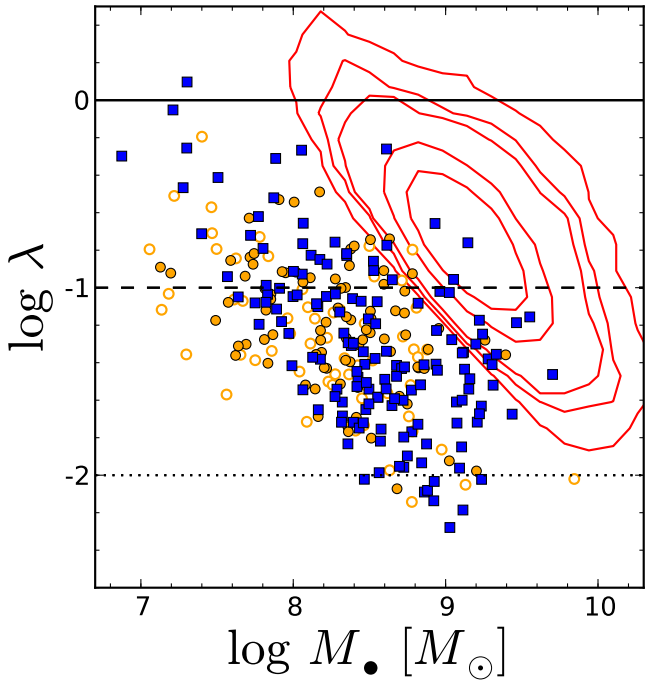
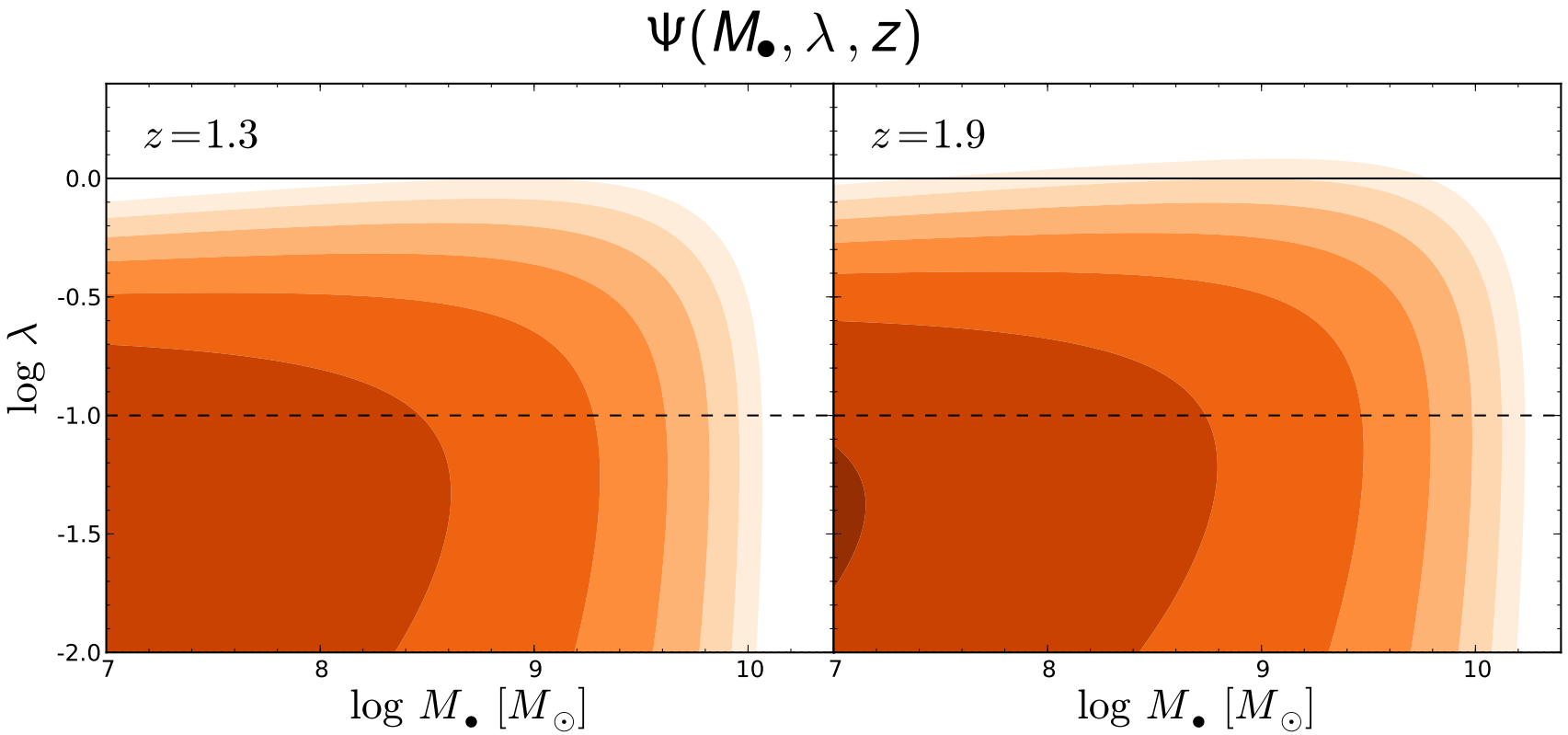




Bivariate distribution function of $M_\bullet$ and λ at $1 < z < 2$



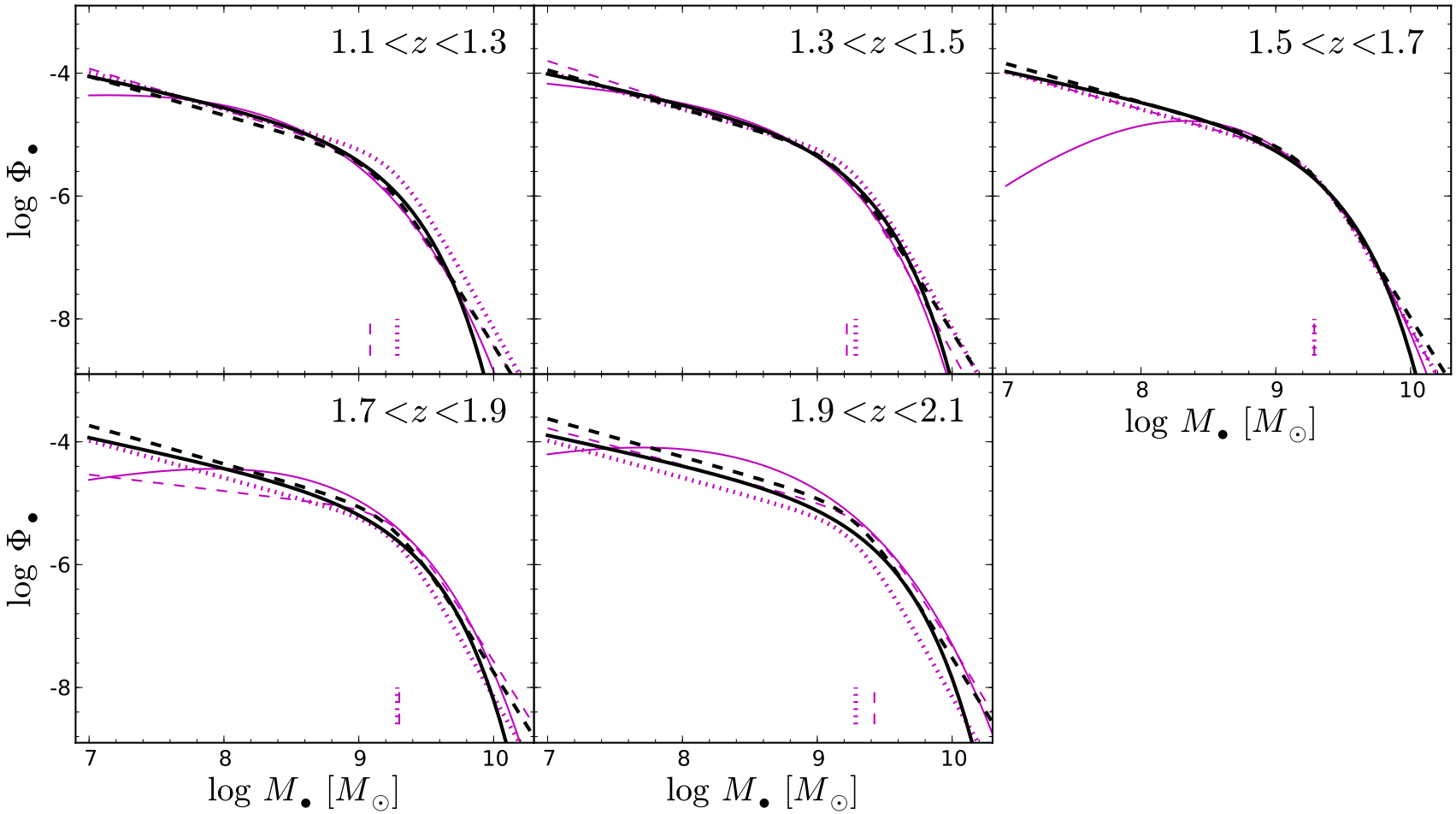
active black hole mass function

$$\Phi_\bullet(M_\bullet, z) = \int \Psi(M_\bullet, \lambda, z) \, \mathrm{d} \log \lambda$$

Eddington ratio distribution function

$$\Phi_\lambda(\lambda, z) = \int \Psi(M_\bullet, \lambda, z) \, \mathrm{d} \log M_\bullet$$

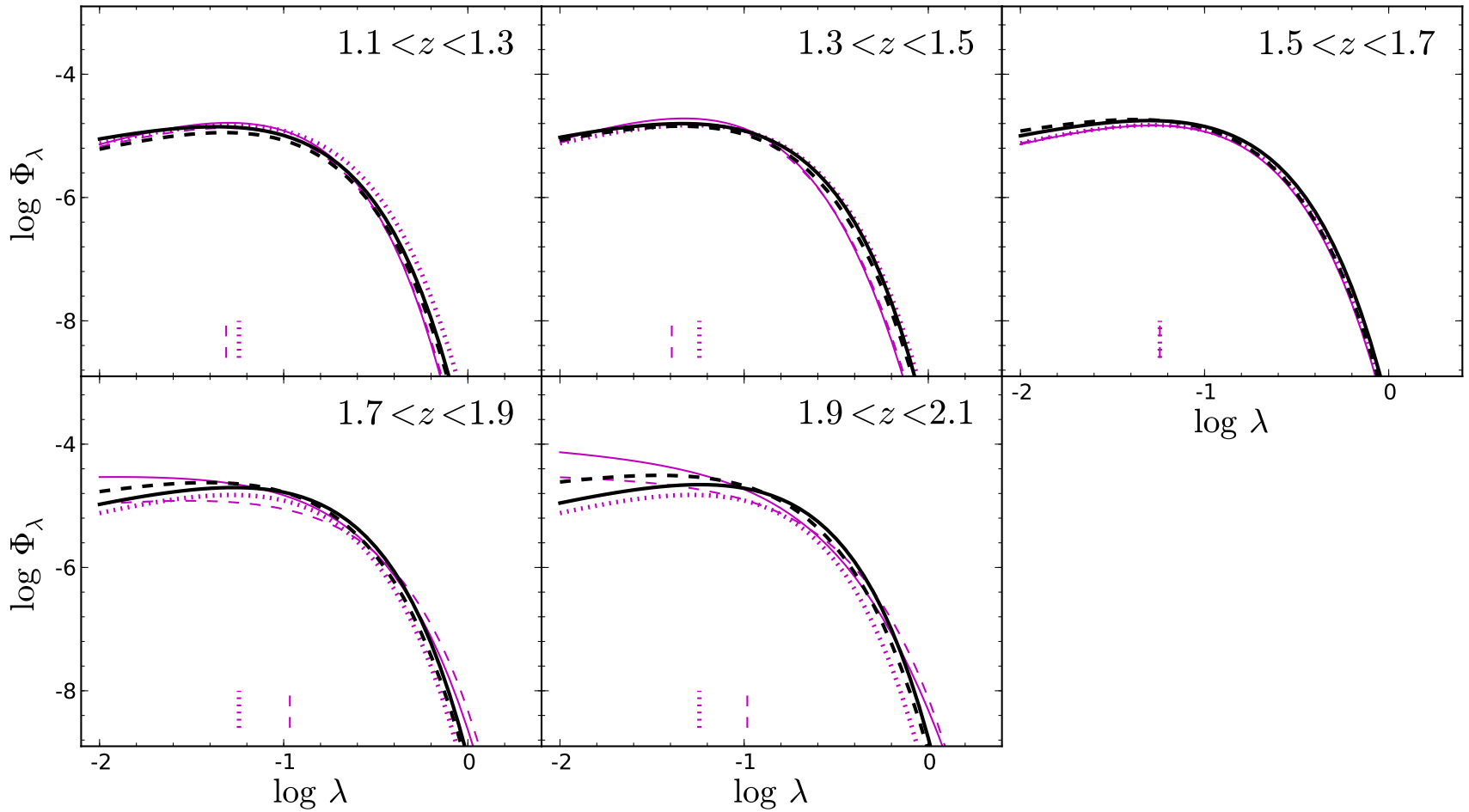
Active black hole mass function at $1 < z < 2$



Schulze et al. (2015)

$\Rightarrow$ increase in the break of the BHMF with redshift

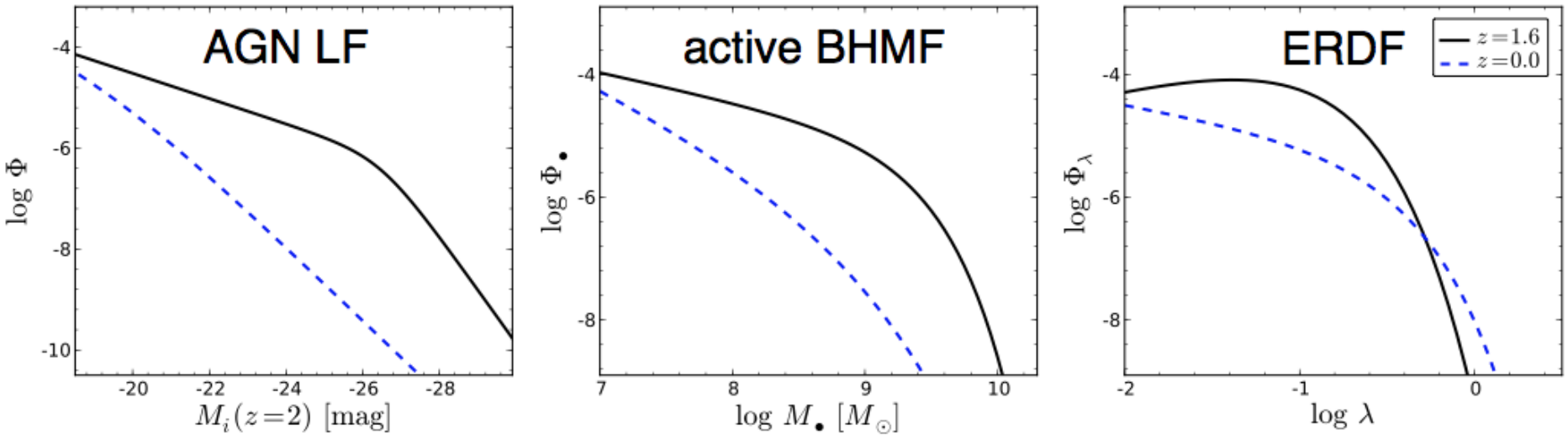
Eddington ratio distribution function at $1 < z < 2$



Schulze et al. (2015)

$\Rightarrow$ wide intrinsic distribution of Eddington ratios

Evolution of the active black hole mass function and Eddington ratio distribution function



$z \sim 1.5$ Schulze et al. (2015)

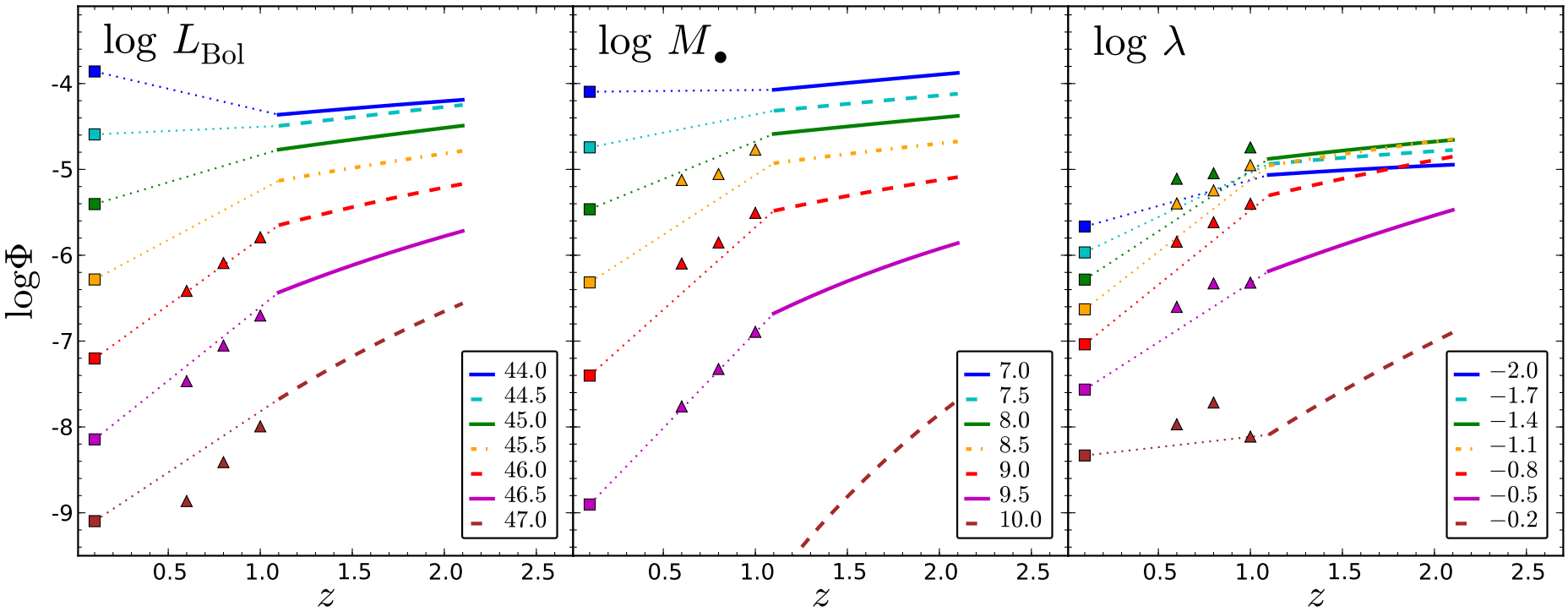
$z \sim 0.0$ Schulze & Wisotzki (2010)

$\Rightarrow$ strong downsizing in the active BHMF

$\Rightarrow$ decrease of average Eddington ratio towards $z = 0$

Evolution of the AGN space density

AGN LF | active BHMF | ERDF



⇒ strong downsizing in the active BHMF

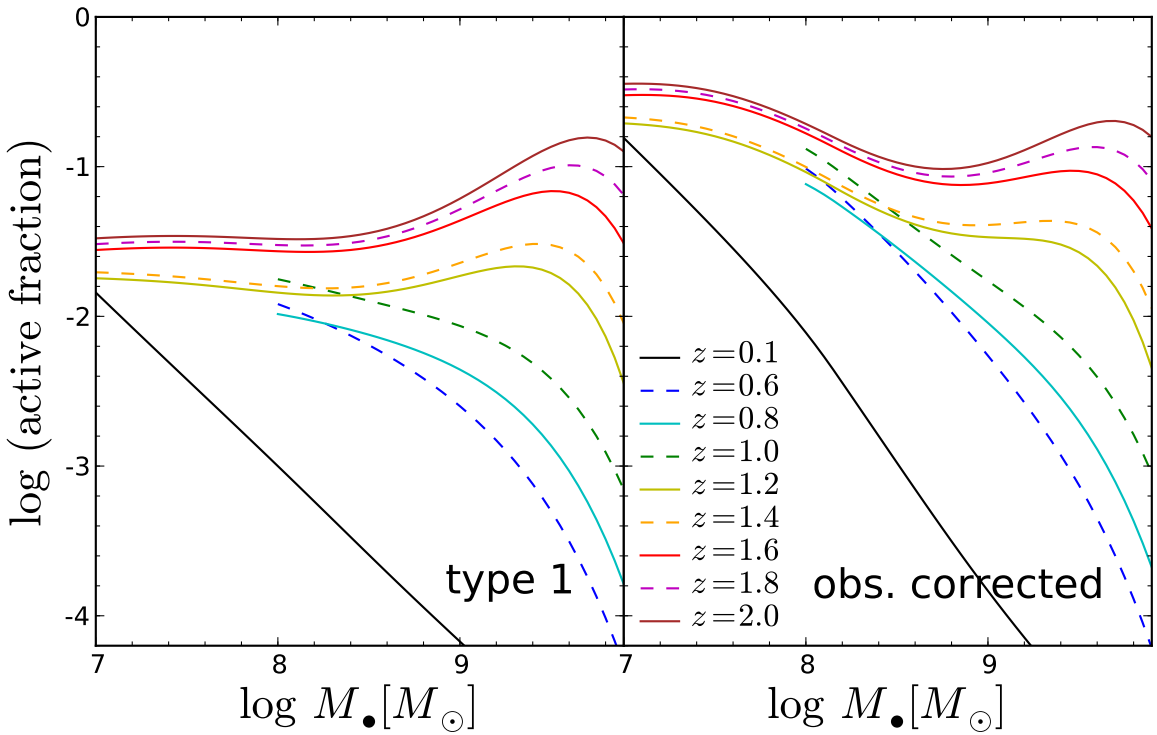
⇒ moderate evolution in ERDF

The evolution of AGN duty cycle

compare to quiescent BHMF derived from stellar MF

week evolution at $\sim 10^7\ M_\bullet$

strong evolution at $> 10^9\ M_\bullet$



$\Rightarrow$ witness shutoff of black hole growth at the high mass end between $z = 2$ and $z = 0$

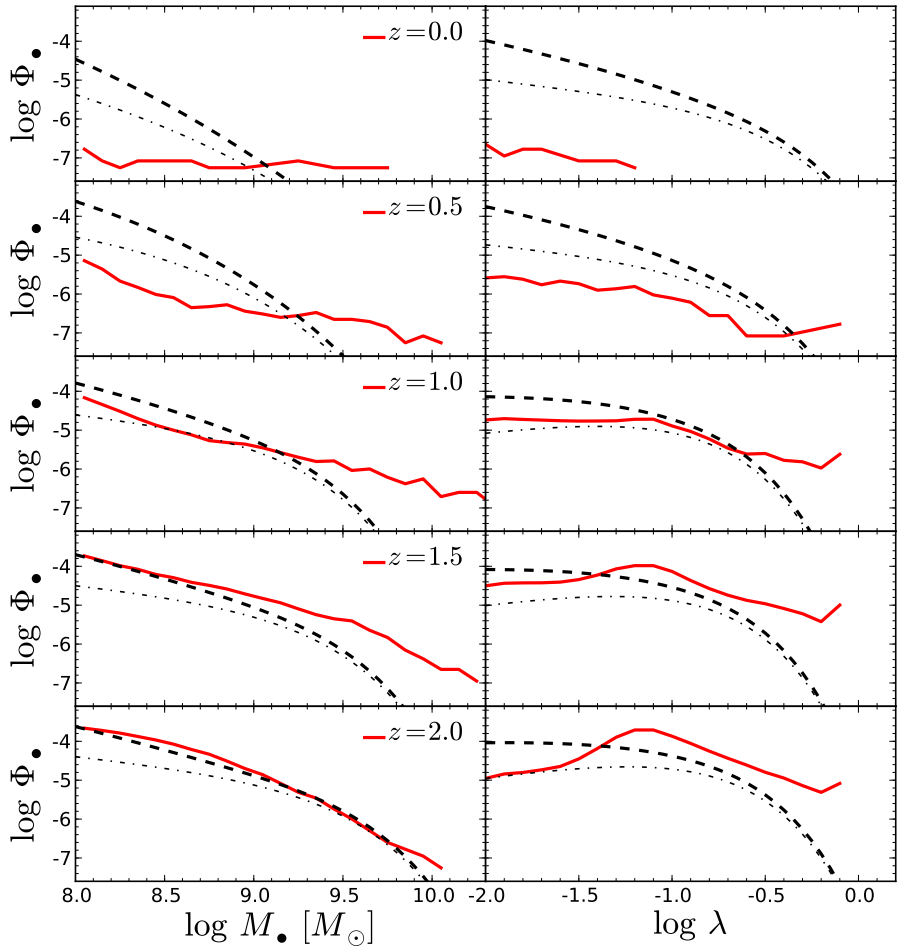
Constraints on theoretical models

⇒ discriminate between different models of galaxy evolution, AGN feedback, . . .

- comparison with numerical simulation from Hirschmann et al. (2014)

⇒ good match at $z > 1$ and $M_\bullet < 10^{9.5}$

⇒ disagreement at low-z and high $M_\bullet$ => caused by radio-mode AGN feedback implementation



Schulze et al. (2015)

Limitations of the active BHMF

- restricted to broad line AGN (obscured AGN not included)
- how does the AGN activity relate to the host galaxy population?

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- how does the AGN activity relate to the host galaxy population?

$\Rightarrow$ study hard X-ray selected samples (include obscured and unobscured AGN)

$\Rightarrow$ use stellar mass $M_\star$ as surrogate for $M_\bullet$

$\Rightarrow$ advantage: directly probe the link to their host galaxies

AGN host galaxy stellar mass function and active fraction

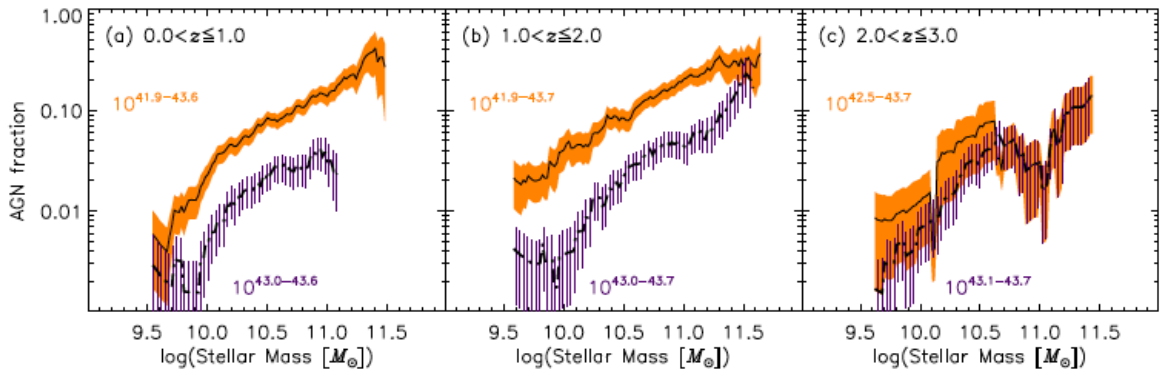
Xue et al. (2010):
$0 < z < 3.0$

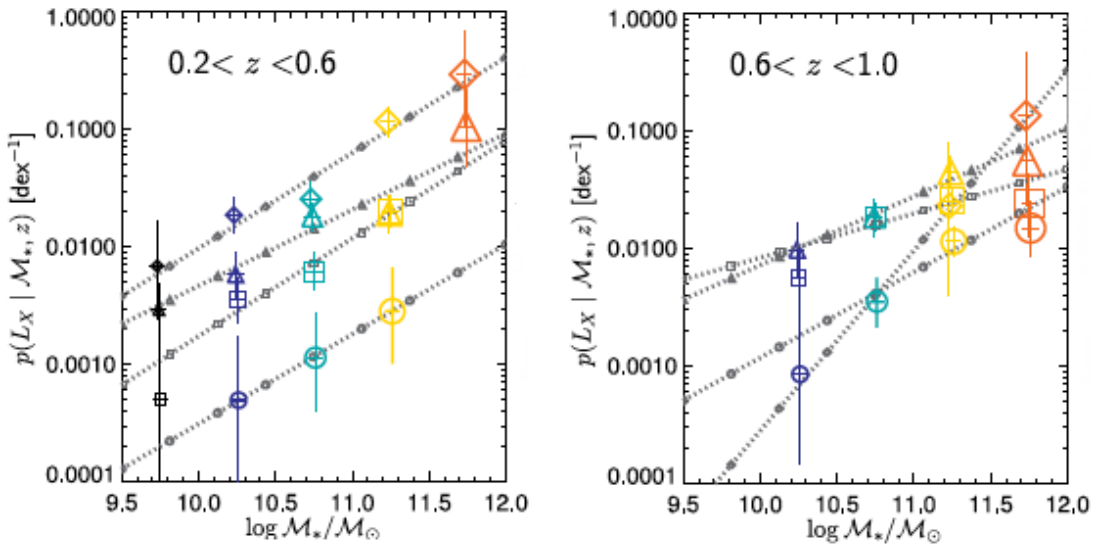
$\Rightarrow$ fraction of galaxies hosting an AGN of given L_X increases with $M_\star$

Aird et al. (2012):
$0.2 < z < 1.0$

$\Rightarrow$ same trend for $p(L_X|M_\star, z)$

$p(L_X|M_\star, z)$



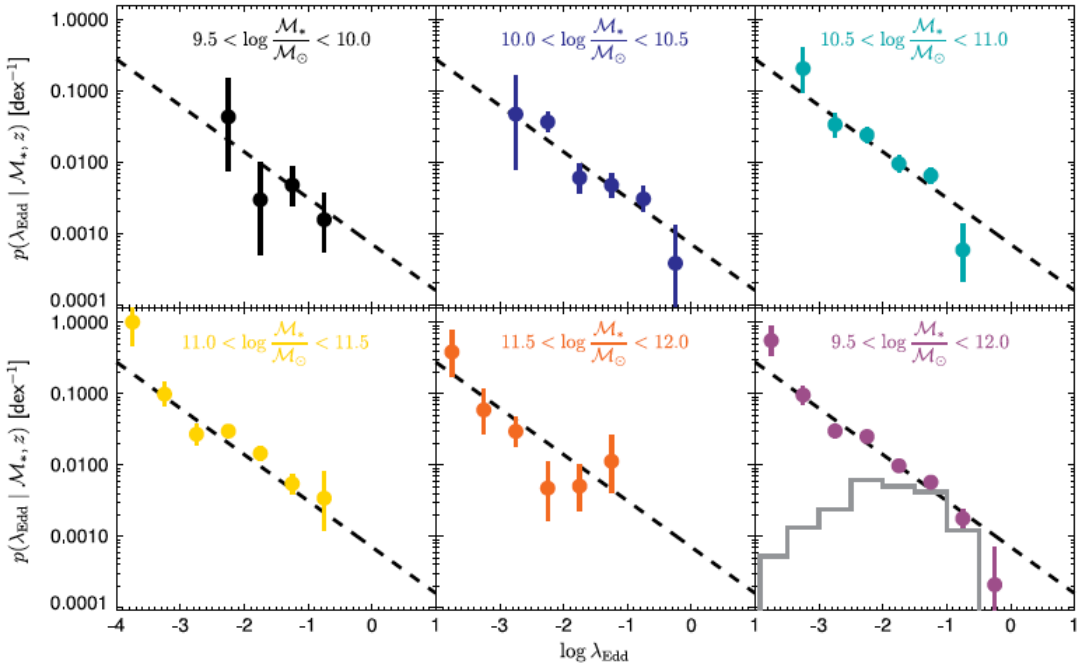


The specific accretion rate distribution of AGN

$p(L_X/M_\star|M_\star, z)$

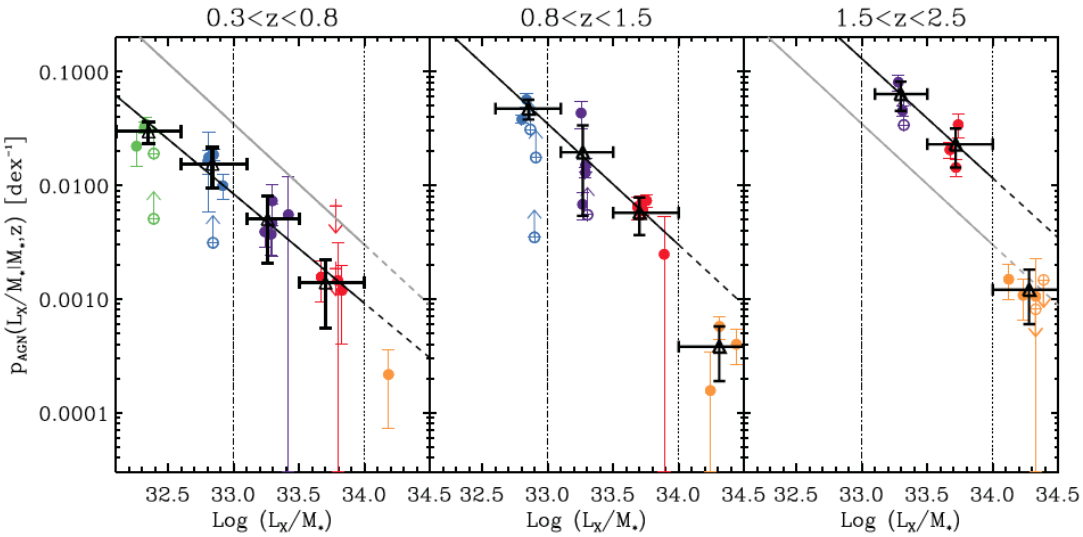
Aird et al. (2012):
$0.2 < z < 1.0$

$\Rightarrow$ distribution of accretion rates follows power law, independent of $M_\star$



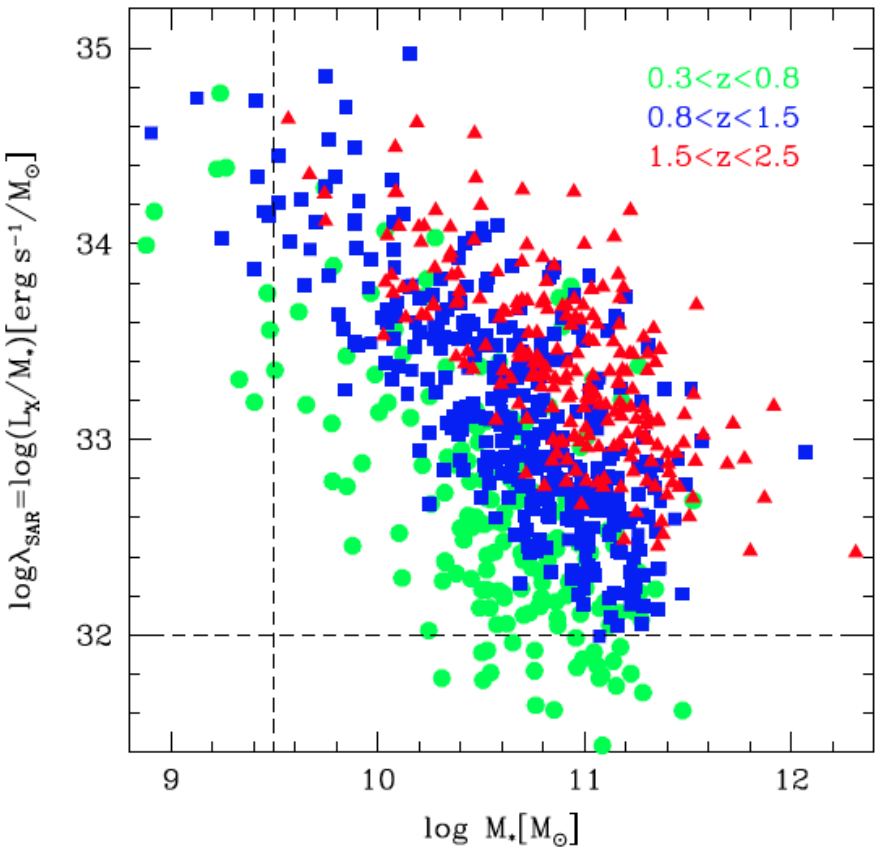
Bongiorno et al. (2012):

$\Rightarrow$ confirmed trend out to $z \sim 2.5$



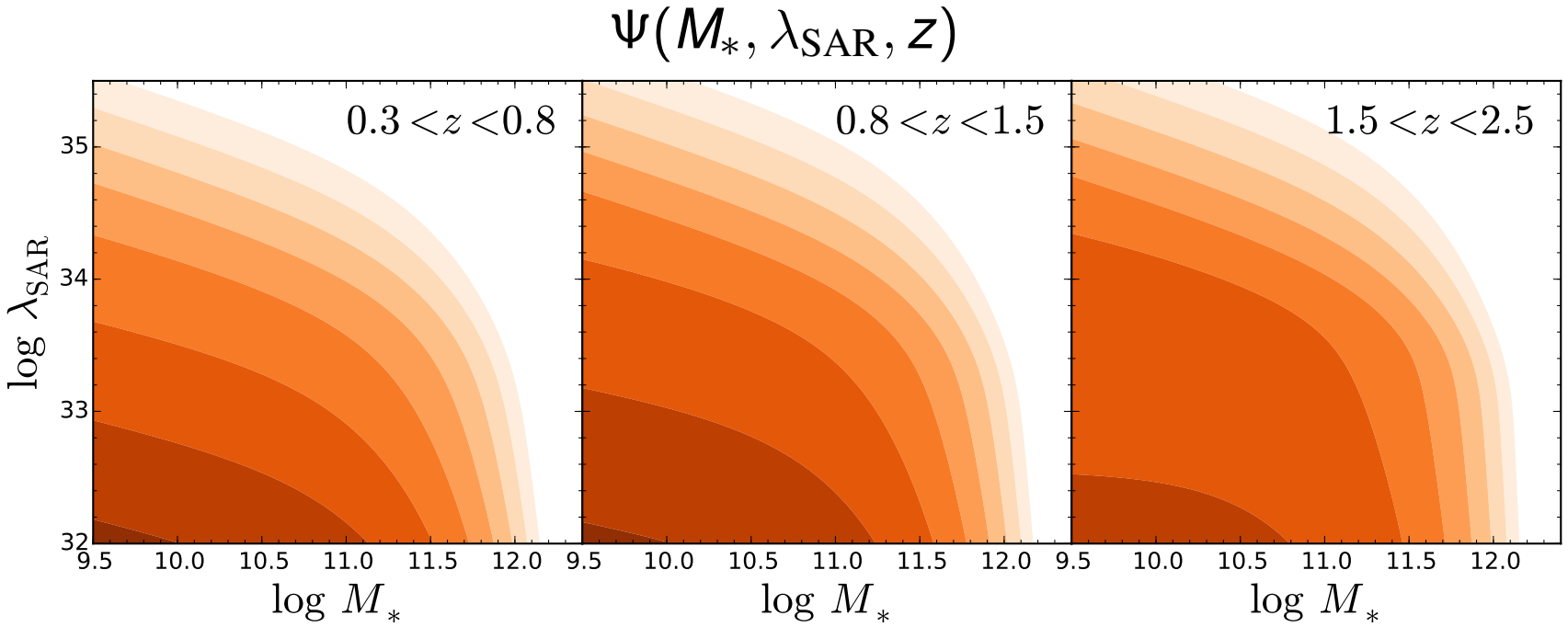
AGN host galaxy mass function in COSMOS

- ⇒ 877 hard X-ray selected AGN from XMM-COSMOS at $0.3 < z < 2.5$
- ⇒ $M_\star$ from SED fitting
- ⇒ define: $\lambda_{\rm SAR} = L_{[2-10{\rm keV}]}/M_\star$
- ⇒ define AGN by cut in specific accretion rate $\lambda_{\rm SAR} > 32$
- ⇒ determine bivariate distribution function of $M_\star$ and $\lambda_{\rm SAR}$



Bongiorno, AS et al. (2016)

Bivariate distribution function of $M_\star$ and $\lambda_{\rm SAR}$



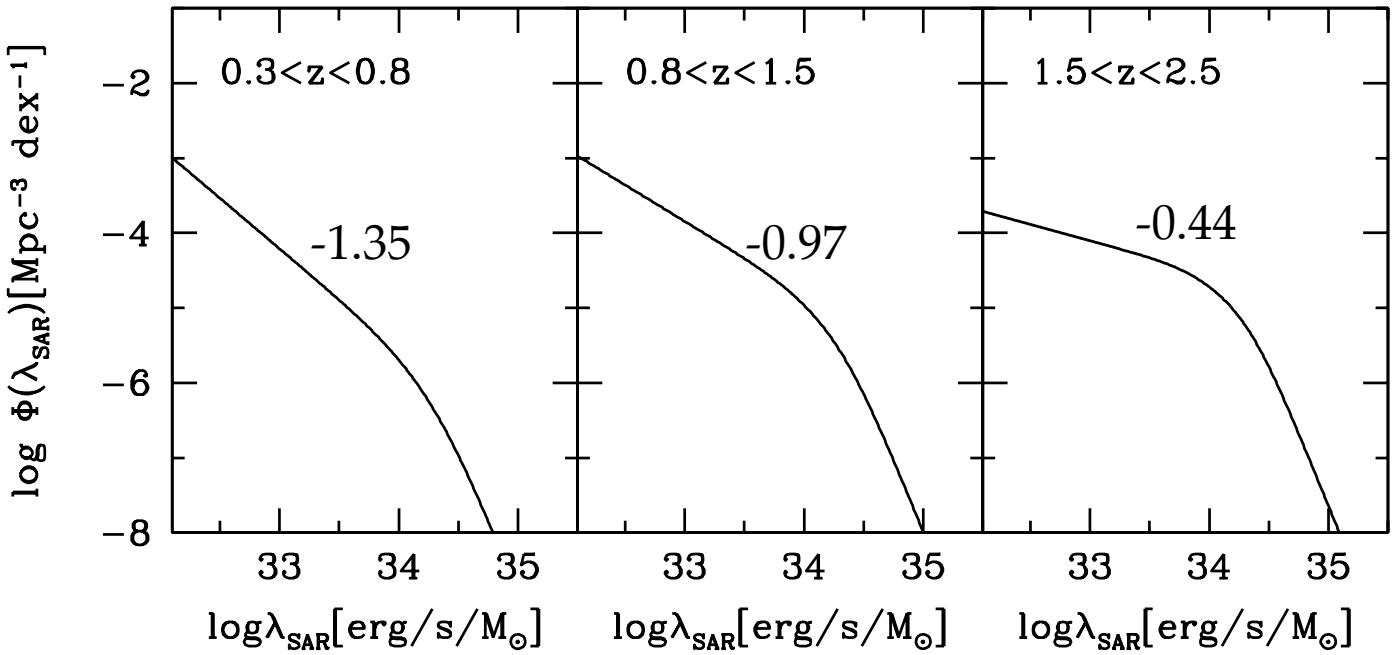
host galaxy mass function (HGMF)

$$\Phi_*(M_*, z) = \int \Psi(M_*, \lambda_{\rm SAR}, z)\, \mathrm{d} \log \lambda_{\rm SAR}$$

Specific accretion rate distribution function (SARDF)

$$\Phi_{\lambda_{\rm SAR}}(\lambda_{\rm SAR}, z) = \int \Psi(M_*, \lambda_{\rm SAR}, z)\, \mathrm{d} \log M_*$$

Specific accretion rate distribution function

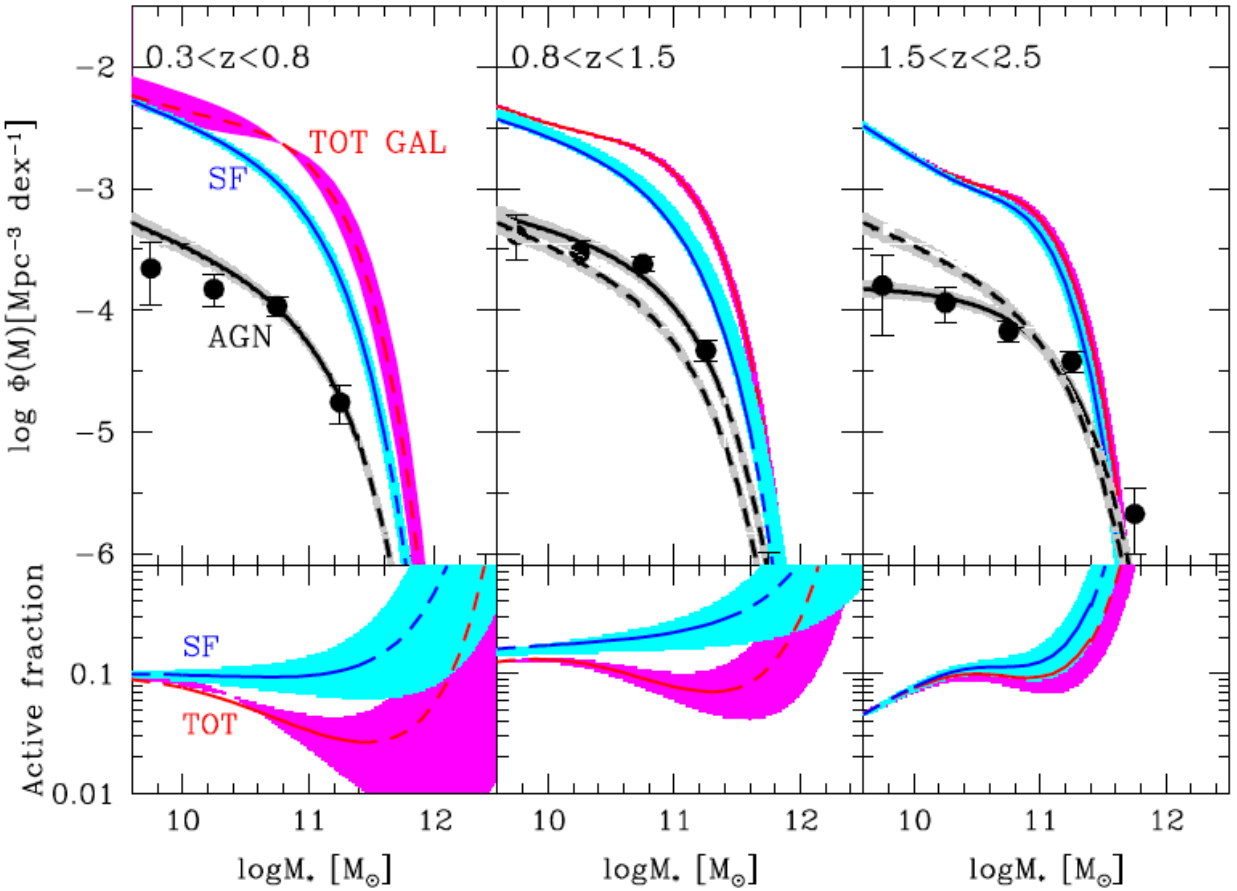


Bongiorno, AS et al. (2016)

$\Rightarrow$ low $\lambda_{\rm SAR}$ slope of double power law flattens with z

$\Rightarrow$ normalization increases with z

Host galaxy mass function



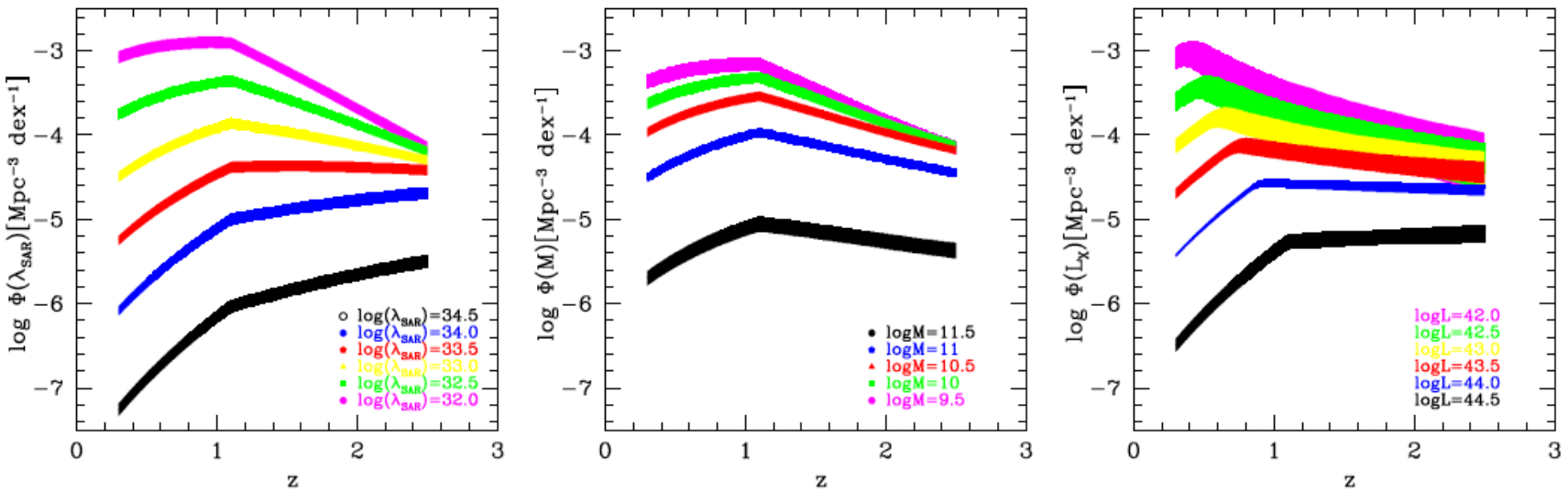
⇒ low mass slope of Schechter function flattens with z

⇒ active fraction shows *z* dependent mass dependence

⇒ density ratio compared to SF galaxies ∼constant with mass

Downsizing in $M_\star$ and $\lambda_{\rm SAR}$

$\Phi_{\lambda_{\rm SAR}}(\lambda_{\rm SAR}, z)$ $\Phi_*(M_*, z)$ $\Phi_L(L_X, z)$

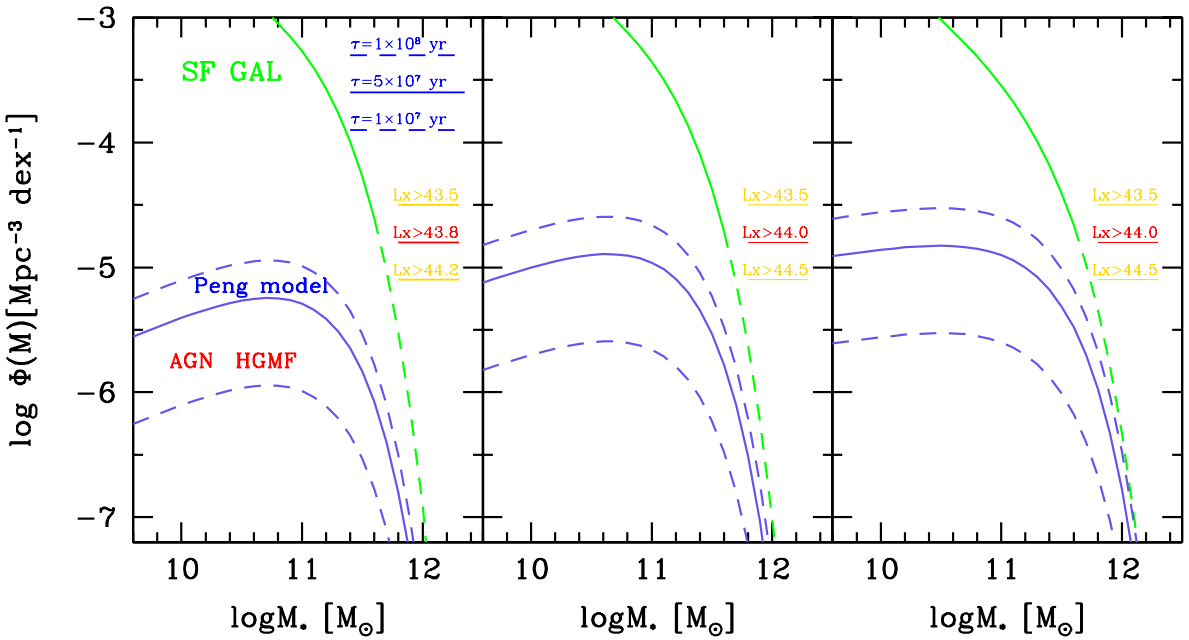


$\Rightarrow$ downsizing in $\Phi_{\lambda_{\rm SAR}}(\lambda_{\rm SAR}, z)$

$\Rightarrow$ moderate downsizing in $\Phi_*(M_*, z)$

AGN as driver for mass quenching of galaxies?

mass function of galaxies in the process of being mass-quenched, based on Peng et al. (2010) model (blue), $\tau_{\rm trans} = 10^6 - 10^7$ yr

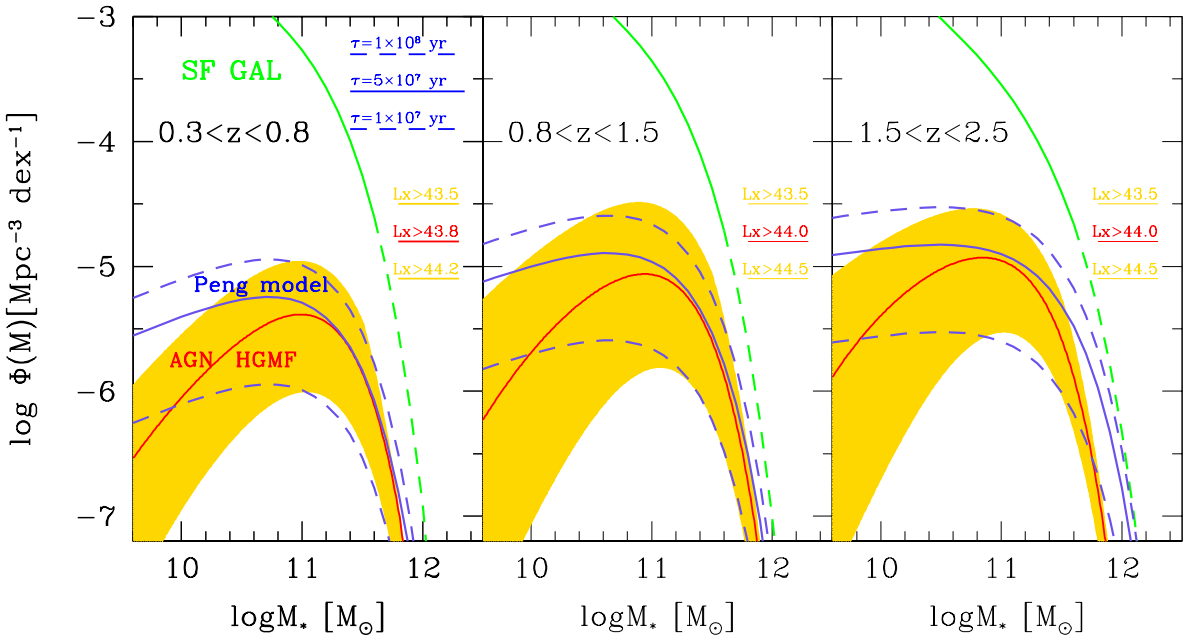


AGN as driver for mass quenching of galaxies?

mass function of galaxies in the process of being mass-quenched, based on Peng et al. (2010) model (blue), $\tau_{\rm trans} = 10^6 - 10^7$ yr

vs.

AGN host galaxy mass function of luminous AGN, $\log L_X > 44$ (red)



⇒ at high mass, the HGMF of Lx>43.5-44.5 AGN can reproduce well the model prediction for the transition population

Conclusions

- active BHMF and ERDF established at $z < 2$

$\Rightarrow$ shutoff of black hole growth at the high mass end from $z = 2$ to $z = 0$ drives AGN downsizing

$\Rightarrow$ new observational constraints for theoretical models of galaxy formation and BH growth

- determined AGN host galaxy mass function and specific accretion rate distribution function at $0.3 < z < 2.5$

$\Rightarrow$ evolution in the shape of BOTH stellar mass function and specific accretion rate distribution function of AGN

$\Rightarrow$ luminous AGN population consistent with quenching of star formation in massive galaxies